CHAPTER 1 - INTRODUCTION

1.1 INTRODUCTION

Sand is an important building block of this part of the north Queensland coast, with eighty-one percent of the coast between Rollingstone and Bowen composed of sand. The coastal area between Rollingstone and Bowen is significant as it has distinct climatic and marine regimes compared to neighbouring areas of north Queensland. This area is referred to in this thesis as the Seasonally Wet Tropics, abbreviated as SWT. The SWT climate can also be referred to as type ‘Aw’ in Köppen’s (1931 as cited in Davis, 1968) widely quoted classification, which is defined as a tropical wet and dry or savanna climate with a pronounced dry season (driest month having precipitation less than 60 mm). There are other regions in north Queensland with a similar SWT (Aw) climate for example the Gulf of Carpentaria and Cape York Peninsula (Figure 1.1). However, this study will focus on the SWT coastal zone in the vicinity of Townsville between Rollingstone and Bowen.

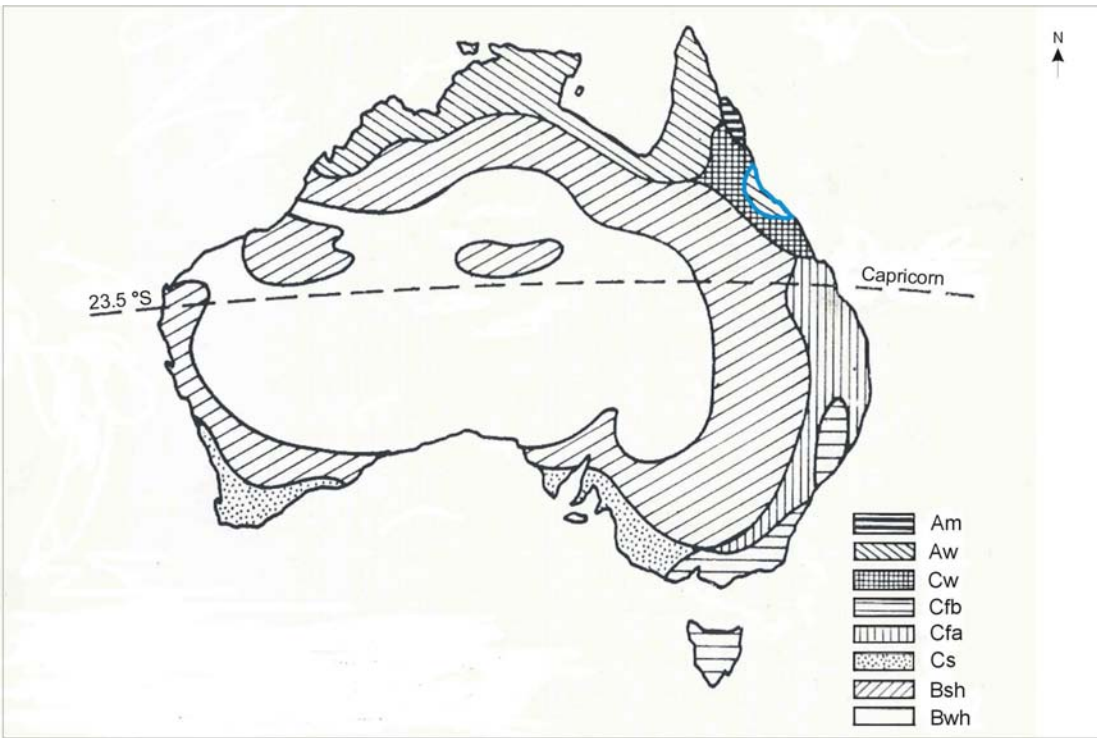


Figure 1.1 The SWT climate can also be referred to as type ‘Aw’ in Köppen’s (1931 as cited in Davis, 1968: 230) classification of the Australian climate. The ‘Aw’ climate is defined as a tropical wet and dry savanna climate with a pronounced dry season (driest month having precipitation less than 60 mm). While there are other regions in north Queensland with a SWT or ‘Aw’ climate, this study will focus on the coastal zone in the vicinity of Townsville between Rollingstone and Bowen (indicated in blue on this map).

Early workers on the SWT coast between Rollingstone and Bowen inferred that most of the coastal sand deposits were supplied by streams draining coastal catchments (Hopley, 1970a; Holmes, 1992); classic climatic geomorphology predicts that catchments experiencing a SWT rainfall regime have amongst the highest sand yields in the world (Fournier, 1960). Thus given the localised high rates of soil erosion in SWT catchments due to variable high intensity rainfall (Yu, 1998); low vegetation cover (Neil and Yu, 1996b); relatively steep coastal rivers (~0.015) and a sand dominated coastline (~81%), it may be inferred that SWT streams supply sand to coast. This assumption is supported by extensive beach ridge plains on the SWT coast between Rollingstone and Bowen which indicate rapid coastal progradation, averaging 1 km every 1 ka since sea level stabilized at ~6 ka BP (Belperio, 1978). Also, recent empirical modelling results suggest that SWT streams are delivering even more sediment to the coast, an estimated four to fifteen times total sediment load (washload, suspended and bedload) due to post-European anthropogenic activities in catchments (GBRMPA, 2001). However, detailed studies of the Normanby River Estuary in the Cape York Peninsula, another SWT region of north Queensland, have found that rather then exporting an average of 100,000 m^3 of sand to the coast (Prosser *et al.*, 2001a), the Normanby is a net importer of marine sediment with fluvial sand being trapped in the lower estuary for at least the last 6 ka (Bryce *et al.*, 1998). In addition, widespread occurrences of exposed mangrove muds along the SWT coast indicate recent coastal retreat (Hopley, 1970a). This mismatch in the literature and current situation on the SWT coast between Rollingstone and Bowen prompts a detailed investigation of coastal sand transfer in this unique study area.

1.2 STUDY AREA

Climatic and geographic features of the SWT coast between Rollingstone and Bowen (see figure 1.2) distinguish this coastal sedimentary system from those in other parts of Australia and overseas, which dominate the literature. The region is too far south to be influenced by persistent summer monsoon systems and too far north to experience more reliable rainfall associated with surface temperate systems common to south-east Queensland (Lyons and Bonell, 1994). As a result rainfall in the SWT is extremely variable. Cyclones can produce intense falls within the region for example 305 mm fell in 2 hours on March 3, 1946 due to a cyclonic depression (Lyons and Bonell, 1994). Rainfall records from Giru, which is located within the Haughton River catchment and is considered to be representative of the SWT region between Rollingstone and Bowen, clearly illustrate the inter-annual variability of rainfall

(Figure 1.3). The mean annual rainfall is 1249 mm, standard deviation of 535 mm. The high standard deviation reflects the inter-annual variability of rainfall in the Haughton catchment. Recent monthly rainfall records from 2000 and 2001 illustrate the marked variation between years and the seasonality (Figure 1.4). Indeed, over 80% of the total yearly rainfall usually occurs between December and April. SWT streams can be described as 'extreme variable discharge rivers' which are defined as rivers where ~90% of the total annual flow occurs during the wet season usually between December and April (Fielding and Alexander, 1996).

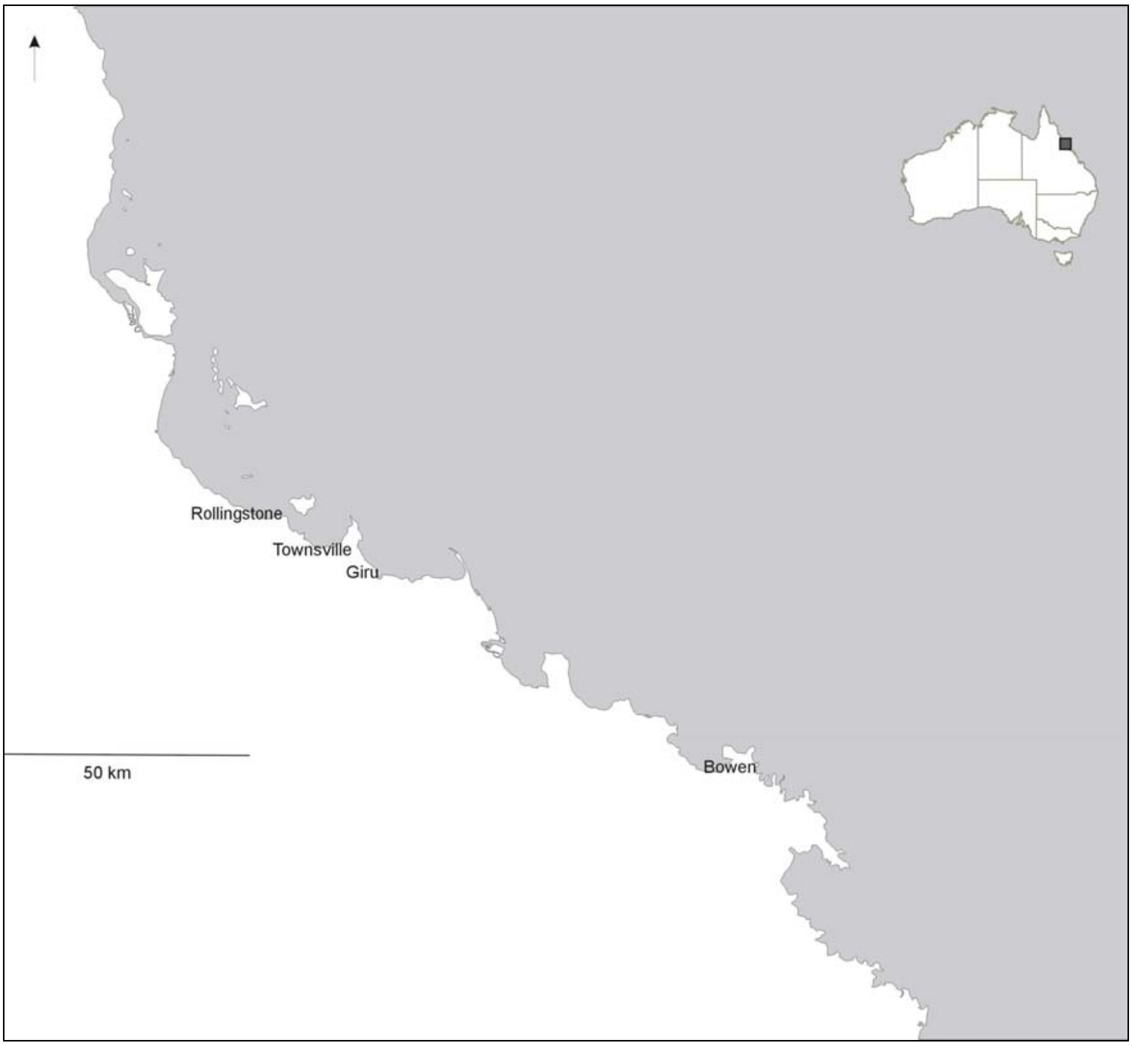


Figure 1.2. The seasonally wet tropics region of north Queensland.

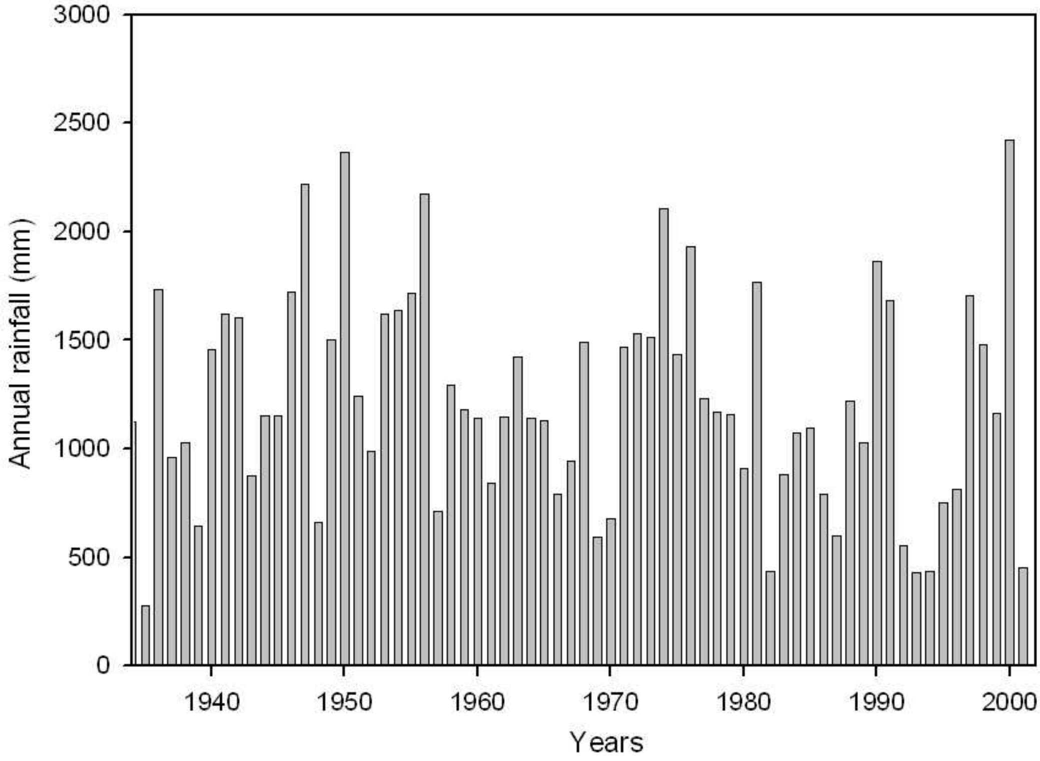


Figure 1.3. Annual rainfall totals for Giru from 1933-2001, showing inter-annual variability (Bureau of Meteorology, 2001).

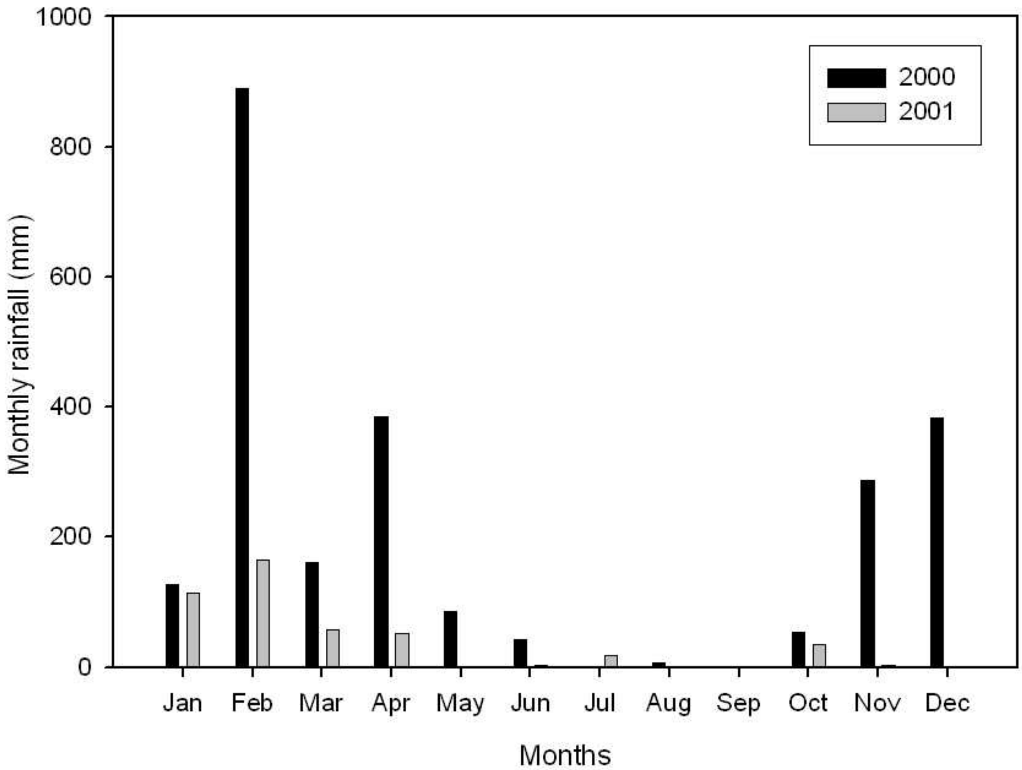


Figure 1.4. A comparison of monthly rainfall totals for Giru for 2000 and 2001, showing high seasonality and inter-annual variability (Bureau of Meteorology, 2001).

The SWT coast between Rollingstone and Bowen experiences a meso-tidal regime, with a maximum spring tide range of 3.8 m. South-easterly trade winds, averaging between 5 - 16 knots (11-20 $km.h^{-1}$) dominate the north Queensland coastline for most of year. However the wind observations for 9 am and 3 pm show that while south-easterly winds may dominate morning conditions, north-easterly winds develop during the afternoon. Dominant south-easterly winds are the main driving force behind wave formation. The proximity of the Great Barrier Reef to the SWT coastline limits the fetch and prevents high energy swell waves from reaching the coast, creating relatively low energy ambient wave conditions. Offshore wave rider buoy data off Cape Cleveland from 1975-1996 reveals relatively low energy ambient wave conditions; significant wave height (the highest one third of waves) is between 0.2 – 0.6 m for almost 50% of the time, with a relatively short wave period of 3 - 5 seconds (BPA, 1996b). However, strong winds associated with tropical cyclones can cause wave heights to increase by an order of magnitude. The highest significant wave height from the Cape Cleveland wave rider buoy data was 2.96 m recorded December 26, 1990 during Cyclone Joy (maximum category 2) (BPA, 1996b). The cyclone season in Australia generally extends from November to May. Between 1969 and 1997 seventeen cyclones have tracked within 100 km of the SWT coast between Rollingstone and Bowen and twelve have crossed the coast (Puotinen *et al.*, 1997). Based on almost 28 years of observations, Puotinen *et al.*(1997) have calculated that cyclones affect this coastline with an average return interval (ARI) of 1.6 years, suggesting that the SWT is one of the most cyclone-affected regions of Queensland (Puotinen *et al.*, 1997). Varying influences of fluvial, tide and wave processes over a broad range of temporal and spatial scales create a complex setting for coastal sand transfer to occur.

1.3 PREVIOUS RESEARCH

Apart from work on the Burdekin Delta by Hopley (1970a and 1970b), Belperio (1978; 1983) and Pringle (1983; 1984; 1991; 2000), few studies have looked at the fate of the coarser fraction of the fluvial sediment load in the unique climatic and low energy coastal setting of the SWT of north Queensland. Recent work in this region has focussed on the fate of suspended sediments due to their potential impact on the Great Barrier Reef (e.g. Larcombe *et al.*, 1995; Larcombe *et al.*, 1996b; Orpin *et al.*, 1999).

Previous studies of fluvial sediment delivery to the north Queensland coast have focussed on the transport of suspended sediment rather than sand (see Neil *et al.*, 2002 for a review). Studies that have focussed on sand transfer have inferred it as a proportion of the total sediment load (usually 10-20%), calculated by using sediment transport equations (e.g. Ackers and White, 1973; Belperio, 1979) or inferred transfer processes and pathways from surficial and sub-surface sediments (Hacker, 1988). Given that fine and coarse sediments have different thresholds of entrainment, transport and settling velocities (Hjulstrom, 1935) it is likely that suspended sediment (<0.02 mm) will move in the direction of the tidally average flow, while sand-sized sediment (0.02 - 2 mm) will be most affected by the highest velocities, and will move in the direction of the maximum current (Dyer, 1995). However in some cases if current velocities are sufficient very fine sand (0.02 mm) may be transported in suspension. Therefore, the examination of the fluvial – marine interface, as occurs in and around estuaries, will be an important part of this research.

The few studies that have actually measured sand transfer in SWT coastal systems are site specific and cover very limited temporal and spatial scales. For example Hopley (1980) measured sand movements around a coral cay in the Great Barrier Reef for a seven day period using sand traps and markers to measure movement over individual tidal cycles. Kana *et al.* (1999) warn that it is problematic and futile to extrapolate these small scale models over the longer term as coastal processes operate on a variety of spatial and temporal scales (see Cowell and Thom, 1994). Thus, sand transfer studies must consider the coastal sedimentary system as a whole, integrating process-based data with a geological understanding of sand sources, pathways and sinks.

1.4 HOLOCENE SAND BUDGET

Sand is such an important component of the SWT coastal zone between Bowen and Rollingstone, however little is known about the source, the spatial and temporal patterns and dominant processes of sand transfer. Temporal patterns can be as short as a tidal cycle (12 h) or as long as the Holocene transgression and stillstand (>10 ka). This study aims to quantify a Holocene sand budget for the SWT coastal zone between Bowen and Rollingstone, and link to detailed examinations of contemporary sand transport processes. The sand budget concept is shown in figure 1.5 (after Chapman *et al.*, 1982) where potential *sources* of sand, for example rivers, dunes and cliff erosion and the inner continental shelf, are indicated by solid arrows and potential *sinks* such as estuaries and longshore drift, by open arrows. Changes in sea level and streams discharging at different locations along the SWT coast during the Holocene (see Hopley, 1970a), influence the spatial distribution of sand deposits on the SWT coast. On time scales of years to millennia the linkages between the patterns and processes of coastal sand transfer in the SWT may be spatially and temporally unrelated. This sand budget defines sand as 'fluvial' and 'marine'. The initial origin of the sand is not disputed as 'fluvial' and 'marine' sand are originally derived from streams. The process of movement to the present site of delivery is the distinguishing factor; sand directly delivered to the adjacent coast by the river is termed fluvial sand, while marine sand (despite originally river-derived) is brought onshore by marine processes including waves and tides or during sea level rise (Roy *et al.*, 1980). Whilst the sand budget approach allows the quantification of sand inputs and outputs of a coastal compartment, it does not necessarily explain dominant processes and patterns of sand transfer within the compartment (Chapman *et al.*, 1982). To address this shortcoming this study will incorporate detailed process studies of individual estuaries within the SWT coastal system. The inferred source of sand to the SWT coast between Bowen and Rollingstone is SWT streams. Fluvial sediment is transported to the sea via estuaries (Dyer, 1995). Estuaries are defined as "a system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave and fluvial processes" (Dalrymple *et al.*, 1992:1132).

Figure 1.5. Conceptual model of the inputs and sinks of a coastal sediment budget (Source Chapman *et al* ., 1982:299).

The quantification of rates of change and dominant processes for the sand budget draws on a variety of methods and information sources covering different time scales. This study includes a historical assessment of coastal change incorporating aerial photograph interpretation and photogrammetry; field data collection including surficial and sub-surface sediment sampling and measuring tidal current velocities; and applying theoretical techniques such as empirical modelling to estimate potential volumes of sand movement by fluvial, tidal and longshore processes. Detailed study of contemporary sand transfer processes in estuaries and then testing these findings against current figures of fluvial sand supply from the literature over last 7 ka will provide a holistic approach to quantifying a sand budget for the study area.

1.5 AIMS AND OBJECTIVES

This introduction has highlighted the apparent anomaly of sand delivery and sand accumulation in the SWT coastal zone between Bowen and Rollingstone. This study will address the current gap in knowledge of the spatial and temporal patterns, dominant processes and controlling factors of sand transfer in meso-tidal SWT coastal systems. The aim of this study is to quantify the coastal sand budget for the SWT between Rollingstone and Bowen within a Holocene timeframe. Specifically, the objectives are to evaluate:

- current estimates of sand supply and source to the SWT coastal zone between Rollingstone and Bowen;

- temporal and spatial patterns of sand transfer over contemporary and Holocene timeframes;

- dominant processes associated with these patterns of sand transfer;

- the relative influence of high magnitude low frequency events on sand transfer.

The research investigates these issues by incorporating geomorphological and process data to understand coastal sand transfer in SWT systems over a variety of time scales. These issues are addressed in the following eight chapters.

1.6 THESIS OUTLINE

This thesis takes the following form. The influence of fluvial sand in the evolution of the SWT coast between Rollingstone and Bowen is reviewed from the literature specific to north Queensland and SWT regions overseas. Chapter three describes and justifies the methods used to determine a Holocene sand budget in the SWT region, where conditions make fieldwork especially challenging. Conceptual models of the spatial and temporal patterns of sand transfer over contemporary timescales are presented for the three study sites. The Haughton River Estuary in chapter four; the Elliot River Estuary in chapter five; and the Black River Delta in chapter six. Chapter seven provides a big picture comparison of the results from individual study sites with a quantification of the sand budget for the SWT coast (Rollingstone - Bowen) over the last 7 ka. The major conclusions of the thesis are presented in chapter eight, together with suggestions for further study.

CHAPTER 2 – SAND TRANSFER IN THE SWT COAST

2.1 INTRODUCTION

The SWT coast between Bowen and Rollingstone, is characterised by extensive beach ridge plains, sandy beaches and sand choked inlets. Large cliffs and dunes are rare along the tropical north Queensland coast and therefore presently contribute little sediment to the beaches (Pringle, 1986). The mid and outer sections of the continental shelf adjacent to the SWT coast between Bowen and Rollingstone is dominated by carbonates associated with reefal structures (Hopley, 1986) making it an unlikely source of siliciclastic sand. Stoddart (1969) reviewed the influence of climate on geomorphology and concluded that the variability of the SWT climate (refer to chapter 1, section 1.2) has the potential to produce the highest sand yielding catchments in the world. Historically it seems that the assumption has been made that the predominance of sand along the SWT coast is a function of high sand yields derived from coastal catchments which are then transported to the coast by streams and deposited on the shoreline or in nearshore environments. From Hopley's (1970a) pioneering research of the geomorphology of the SWT coast to subsequent studies (Bird, 1971; Hopley, 1986; Pringle, 1991; Holmes, 1992) rivers, especially the Burdekin River, have been identified as the main source of sand on the SWT coast. Recently published empirical models indicate an average of 400,000 m^3 of sand is delivered to the coast by SWT rivers (notably the Burdekin, Don, Haughton, Black, Ross, Elliot) each year (GBRMPA, 2001; Prosser *et al.*, 2001a) (see chapters 7, section 7.3 for a discussion on modelling). However scarped dunes and the exposure of mangrove peat observed along the SWT coast (Hopley, 1970a) suggest that sections of the coast are presently eroding, which may indicate a reduction in fluvial sediment supply.

A large literature exists on the morphology, sedimentology and dynamics of sand bodies in the coastal zone and this is well summarised in recent books (e.g. Carter and Woodroffe, 1994; Komar, 1998). Much of this work focuses on high-energy and/or micro-tidal systems from the temperate latitudes where sand is sourced by the strong swell waves continually reworking previously deposited coastal sediments. The influence of sand supply, dominant transport processes and timeframes in the SWT which is subject to highly variable stream discharge, a meso-tidal range and relatively low energy ambient wave conditions, has received much less attention. While there has been considerable research on sediment discharge and dispersal within the SWT coast nearshore and offshore (e.g. Larcombe *et al.*, 1995; 1996b; Orpin, 1999; Orpin *et al.*, 1999; Devlin *et al.*, 2001) this work has largely concentrated on the dynamics of suspended sediment (silt and clay < 0.02 mm) rather than the fate of coarser bedload sediments (sand > 0.02 mm. The purpose of this review is to examine relevant literature from similar highly seasonal climate zones in temperate areas, and other SWT regions overseas and in Australia to determine the dominant processes of sand transfer along the SWT coast between Rollingstone and Bowen. Specifically this review will critique:

- classifications of Australian clastic coastal environments;
- classifications to accommodate the influence of the SWT climate on coastal sand transfer processes;
- the influence of low frequency high magnitude events on sand delivery to the coast;
- the Holocene evolution of SWT clastic coastal environments.

2.2 CLASSIFICATION OF CLASTIC COASTAL DEPOSTIONAL ENVIRONMENTS

Once fluvial sediment reaches the mouth of a coastal river it is subject to marine processes. This junction of a river and the sea may be referred to as an *estuary, delta, river mouth* or *inlet* (Dyer, 1995). Estuaries have been the focus of many studies - a search of the key word *estuaries* in the Ovid journal database 'Current Contents' revealed that 410 papers in 2004 were published in journals ranging from Marine Chemistry to Micropalaeontology. Estuaries are complex environments and are studied for a variety of reasons by different disciplines from biologists to geologists. Complexity creates ambiguity and conjecture in the literature regarding the exact definition and spatial and temporal boundaries of these systems prompting the use of the term *'trans-fluviomarine'* environments by some authors (e.g. Cooper, 1993). This review will follow Harris *et al.* (2002) and refer to them generally as clastic coastal depositional environments. Variations in the relative influences of river, tide and wave energy effect the geomorphology and sand transfer processes of these clastic coastal depositional environments (Dalrymple *et al.*, 1990) prompting the classification of these environments in three main ways:

1. Geomorphological;
2. Process based;

3. Morphological which includes elements of 1 & 2;

Perillo (1995) provides an excellent summary of these three classification methods.

Jennings and Bird (1967) were the first to apply a process-based classification on a regional basis to Australian clastic coastal depositional environments. Kench (1999) later applied Fairbridge's (1980) geomorphological-based classification to Australian estuaries and deltas. More recently Heap *et al.* (2001) classified Australian estuaries according to their geomorphological characteristics defined by Dalrymple *et al.*'s (1992) facies model which was constructed based on both process and evolutionary criteria. The process model uses river, tide and wave parameters; the evolutionary model uses the rate and source of sediment input, shoreline shape and rate of relative sea-level change to classify the response of delta, strandplain, tidal flat, lagoon and estuarine environments (Boyd *et al.*, 1992). Heap *et al.* (2001) extended this concept to incorporate the quantification of river, tide and river energy (see Harris *et al.*, 2002 for details) to classify environments as: tide or wave-dominated estuaries; tide or wave-dominated deltas; lagoons; strandplains; or tidal flats/tidal creeks.

Roy *et al.* (2001) used a geological framework to classify south-east Australian estuaries in terms of relative maturity - the stage in evolutionary progression. This follows on from Boyd *et al.*'s (1992) theory that estuaries are ephemeral over geological timescales, continually infilling with sediment to produce a delta (river-dominated) or a straight prograding coastline (wave/tide-dominated) (Figure 2.1). However unlike Boyd *et al.*'s (1992) classification Roy *et al.* (2001) do not distinguish between environments in terms of dominant sediment transport mechanisms, for example river, wave and tide processes. Rather, river dominance is linked to estuarine evolution to avoid being unduly influenced by river size.

None of these classification systems seem particularly suited to estuaries in the SWT. However Dalrymple *et al*.'s (1992) analysis of estuaries over evolutionary timeframes may accommodate the influence of the highly variable SWT climate.

Figure 2.l The evolutionary classification of coastal sedimentary systems for Dalrymple *et al.* (1992:1132) showing the role of river, wave and tidal processes on different geomorphic settings. The relative influence of each process can change thought time as a system evolves.

2.3 SAND TRANSFER IN SWT COASTAL SYSTEMS

SWT streams are ephemeral or intermittent with highly variable discharges over seasonal and inter-annual time scales (see chapter 1, section 1.2) (Mitchell and Furnas, 1996). Long periods of drought produces low vegetation cover in the catchments and the relatively frequent occurrences of high intensity rainfall (Yu, 1998) create ideal sand-yielding conditions in the catchments. Fournier's (1960) model of sand yield potential for global climate regions suggests that the SWT region has the highest sand yielding catchments in the world. Indeed in a recent literature review of fluvial bedload supply studies, SWT streams are estimated to contribute 33% of the total fluvial sand supply for the Queensland coast (Brown and Root, 2001) Much of this literature was based on little data, with bedload delivery figures derived from extrapolation, interpolation and speculation, often from catchment erosion predictions (e.g. Fournier, 1960). Linking predictions of sediment delivery to the stream from the catchment and the volume of sediment delivered to the coast by the stream is complicated. For instance, Wasson *et al.* (1996; 1997) acknowledge that only a small percentage (~3%) of the sand estimated to be eroded from the catchment is actually delivered to the coast in Australia. Increasingly, detailed quantitative studies on individual estuaries highlight the inaccuracies of relying on these models.

As indicated in chapter 1, section 1.1, modelled estimates of sand yield to the coast in the Normanby River Estuary, located in a SWT region further north near Cape York Peninsula, do not match field studies (Bryce *et al.*, 1998). Contemporary sedimentation patterns were inferred from extensive bedform analysis, surficial sediment sampling and vibrocoring in the context of long-term sedimentation records (Bryce *et al.*, 1998). Although suspended sediments (silt and clay) being flushed out of the estuary during the wet season, the direction of net bedload transport is landward into the estuary all year round (Bryce *et al.*, 1998). Dominant flood tide currents are competent to transport sand into the estuary during spring tides (Bryce *et al.*, 1998). The net landwards transport of bedload has been documented in other SWT estuaries, for example the Salum and Casmance Rivers in Senegal, Africa (Barusseau *et al.*, 1985). However the Normanby River was classified as a delta by Heap *et al.* (2001) based on the geomorphology (protruding from the coast and sand choked mouth) and the quantification of river verses marine energy (see Harris *et al.*, 2002 for details on quantification used in Heap *et al.*, 2001),

High maximum instantaneous stream discharges associated with monsoonal and cyclonic rainfall would be considered the dominant process when compared to wave and tide energy in Harris *et al.'s* (2002) quantification, especially considering that the SWT is meso-tidal and subject to relatively low ambient wave energy. However the estimation of river power used in Harris *et al.'s* (2002) quantification did not include extreme discharge associated with flood events, but rather was based on mean annual discharge calculated from catchment area, mean annual rainfall and the runoff coefficient which was divided by the area of open water for each waterway to determine river flow (Harris *et al.,* 2002). Mean annual discharge is a misleading representation of stream flow for these extreme variable discharge streams, where discharge is event driven and episodic. Therefore the application of Heap *et al.'s* (2001) classification to clastic coastal depositional environments in the SWT is problematic, and in terms of sediment transport mechanisms even Harris *et al.* (2002) concede that fluvial sediment contributions would be mostly associated with episodic flooding events. Hence it seems that comparison of mean annual discharge with tide and wave energy would not be an accurate method for classifying estuaries and deltas in the SWT region of north Queensland due to the extremely variable nature of stream discharge. This may also explain why Harris *et al.* (2002) found that mean annual fluvial discharge does not vary significantly between deltas and estuaries in Australia. Indeed two thirds of all Australia's deltas and almost half of the prograding strand plains and tidal flats located on the north-east and Gulf of Carpentaria coasts (Harris *et al.*, 2002) are subject to highly variable seasonal and inter-annual stream flow. Therefore, the frequency and duration of storm events have more to do with the infilling of Australian coastal depositional systems by river-derived sediments than processes related to mean annual stream flow (Harris *et al.*, 2002).

2.4 FREQUENCY AND MAGNITUDE

Cyclones and associated floods are thought to control the timing and volume of terrigenous sediment delivery to the otherwise low-energy SWT coast (Bird, 1971; Woolfe *et al.*, 1998). Cyclones are categorized from one (weak) to five (severe) with the central pressure used as a measure of severity (Puotinen *et al.*, 1997). Cyclones have a two fold effect: 1. Intense rainfall events which cause the streams to flood; and 2. Strong winds which can increase wave heights by an order of magnitude. For simplicity, the fluvial and marine impacts of cyclones on SWT sandy coasts are examined separately.

2.4.1 FLUVIAL PROCESSES

The relative size of a flood can be defined in terms of recurrence intervals derived from maximum instantaneous discharges derived from stream gauge data (Wolman and Miller, 1960). Types of floods discussed in the fluvial literature include:

- Frequent/minor floods (ARI 1-2 or <5 years) (Wolman and Miller, 1960);
- Major floods (ARI 20-30 years) (Bryce *et al.*, 1998);
- Extreme/catastrophic floods (ARI 50-100 years) (Wolman and Miller, 1960) (ARI 30 years) (Cooper, 1990; Erskine, 1996; Coppus and Imeson, 2002);
- Rare/cataclysmic/extraordinary floods (ARI > 500 years) (Baker and Costa, 1987) (ARI 100-1000 years) (Osterkamp and Coasta, 1987; Osterkamp and Friedman, 2000). Sometimes the term 'catastrophic' is used to describe these types of floods as well.

Major or extreme floods (i.e. events which are orders of magnitude greater than the so-called ‘annual flood’) are usually referred to as ‘exceptional’ by geomorphologists, but these events are not so exceptional in the SWT (Fielding and Alexander, 1996). SWT streams can be described as ‘extreme variable discharge streams’ – which are characterised by floods where discharge increases by two to four orders of magnitude typically in less than 24 hours, in response to seasonal but erratic rainfall (Fielding and Alexander, 1996). Often floods with the largest maximum instantaneous discharge values do not produce the greatest stream power or shear stresses, indicating that the duration of the flood is also an important factor in sediment transport (Baker and Costa, 1987). Indeed Costa and O’Connor’s (1995) theory of geomorphically effective floods is very applicable to the SWT. SWT stream reach high maximum instantaneous discharges for short periods (less than a few days) (Fielding and Alexander, 1996); limiting the ability of the stream to do geomorphic work.

Much of the previous research that has examined the relative importance of extreme or catastrophic events and more ordinary events in terms of their geomorphic effectiveness has occurred in temperate regions of North America (Wolman and Miller, 1960; Magilligan *et al.*, 1998). Wolman and Miller (1960) found that more frequent flood events (1-2 years and less than 5 years) do more geomorphic work and thus generally have greater geomorphic effectiveness compared to extreme or catastrophic events (50 – 100 years). Therefore the greatest part of total sediment load was removed from discharge basins during the period of record carried by small – moderate floods (Wolman and Miller, 1960). Magilligan *et al.* (1998) demonstrated the poor relationship between flood magnitude and geomorphic impact, concluding that an extreme flood in the Upper Mississippi River did not have a major impact on sand transfer.

Research in semi-arid environments of South America fails to support Wolman and Miller’s (1960) theory suggesting that ideas developed for temperate streams are not always applicable in other environments. Rainfall in semi-arid areas occurs in high intensity summer storms and like SWT environments these high magnitude low frequency events are assumed to dominate sediment transport processes (Coppus and Imeson, 2002). Coppus and Imeson’s (2002) research in a semi-arid valley in southern Bolivia, suggests that extreme events (1:30 year flood event) have more of an impact in terms of soil erosion and sediment transport than the majority of smaller flood events that play a minor role (Coppus and Imeson, 2002).

Research in other SWT regions from overseas also provides little support to Wolman and Miller's (1960) theory. Cooper (1990) suggests that catastrophic flood events play an important role in estuarine sedimentation in SWT estuaries in South Africa. A 120-150 year flood in 1987 in the Mgeni River flushed out sand and gravel which had been stored in the estuary since 1917, when the last catastrophic flood event occurred (Cooper, 1990). Cooper (1990) proposes that the increased stability of instream bars by permanent vegetation in regulated river-dominated systems, has increased the importance of high magnitude floods. Greater floods are now required to cause significant morphological change and transport of coarse sediment downstream (Cooper, 1990). Cooper (2002) recognizes a difference in the impact of floods on estuaries depending whether they are river or tide-dominated. Cooper (2002) also suggests that floods are important to re-activating coastal sediments in tide-dominated estuaries but they do not require floods as large as in river-dominated estuaries. Significant sand transfer also occurs during minor floods because the sand is sourced from coastal bars and barriers in tidal dominated estuaries rather than from inchannel fluvial bars. This realization prompted this thesis to examine a range of estuary types in the SWT.

It is often assumed that high magnitude low frequency events control influence over the delivery of fluvial sediment to the SWT coast of north Queensland (Bird, 1971; Woolfe *et al.*, 1998), however recent research suggests otherwise. Bryce *et al.*'s (1998) study of the Normanby River in a SWT region of far north Queensland found that fluvial sediment has been trapped in the estuary for the last 6 ka, most likely because the channel capacity of the Normanby River decreases downstream. A major flood (ARI >1:30 y) has a maximum discharge an order of magnitude greater than the bankfull capacity of the channel which means that only a small proportion (~5%) of water will travel in the channel and the rest will flow overbank (Bryce *et al.*, 1998). Modelling in the Normanby River Estuary suggests that a flood (ARI >50 y) transports 6,000-32,000 t of sand which is equivalent to four months to one year of transport into the estuary by tidal currents (Bryce *et al.*, 1998). Thus high magnitude low frequency events have little influence over sand transfer processes in this example of a tide-dominated SWT estuary.

There are examples where extreme events dominate sedimentation. For instance, the Pioneer River Estuary in Mackay north Queensland, although not technically in the SWT region has been classed as an extreme variable discharge river. Investigations of the Pioneer River have associated the transport of coarse bedload sediment with flash flood flows caused by exceptionally heavy rainfall events. Following 530 mm of rainfall in 5 hours flood flows transport very coarse bedload made up of sand, gravel and even cobbles up to 250 mm long into the estuary (Hacker, 1988). These apparent differences demonstrate the diversity of north Queensland estuaries and highlight the need for more detailed investigation of SWT coastal systems.

2.4.2 MARINE PROCESSES

The relatively frequent occurrence of cyclones (ARI 1.6 years) (Poutnien *et al.*, 1997) in an otherwise low-energy marine environment, as in the SWT of north Queensland, prompts an evaluation of the influence of cyclones on redistributing coastal sediment compared to ambient conditions. The frequency versus magnitude debate is common in coastal geomorphology literature, for example whether the beach ridges are a result of storms or ambient processes has been fiercely debated in the past (see section 2.5 for a discussion).

Insights are gained by examining examples from micro-tidal low-energy coasts of north America A study of beach volume changes along the Texas coast reveals that the impact of storms on sand dispersal and shoreline movement covers spatial scales of kilometres and temporal scales of decades (Morton *et al.*, 1995). This area of coast, San Luis Pass is usually subject to low wave energy except during hurricanes that occur at a frequency of about two storms every three years (Morton *et al.*, 1995). In this micro-tidal low-energy setting ambient conditions are too weak to transfer sand between beach compartments so the by-passing of sand is restricted to episodic high energy events. Therefore in this system low-frequency high-magnitude events dominate large-scale sand transfer (Morton *et al.*, 1995).

Work along the north Queensland coast has also shown storm deposits that have remained a feature in the Whitsundays (Heap *et al.*, 1999) and in Halifax Bay (Kirsch and Larcombe, 1999). Heap *et al.* (1999) discovered evidence of storm-dominated sedimentation in the protected basin in the Nara Inlet, Whitsundays that has remained because the ambient wave and tide conditions are too weak to rework the cyclone deposited sediments. Similarly, very large dunes composed of gravely-sand that were discovered in Halifax Bay could have only been deposited during a cyclonic event. The ambient conditions were too weak to rework the coarse sediments so the features remain at a depth of 9 m in the bay (Kirsch and Larcombe, 1999). However few studies have investigated the overall influence of cyclones on sand transfer along the north Queensland coast.

Apart from these localised areas and features mentioned above, Woolfe *et al.*, (1998) suggest that cyclones have had relatively little long-term sedimentary and geomorphic expression along the north Queensland coastline. Woolfe *et al.*(1998:618) concluded that “they (cyclones) play a relatively minor role in the long-term redistribution and deposition of this sediment because of the frequency and strength of the southeast trade winds and the waves and currents induced by them”. Orpin and Woolfe (1999) extended on previous work to develop a model of sediment distribution in a typical north Queensland coastal embayment. This model depicts an embayment with a net influx of sediment driven by the south-easterly driven swell waves.

Insights from other SWT regions overseas and within Australia fail to support the assumption that high-magnitude low-frequency events control the delivery of fluvial sand or its distribution along the coast. However, given that relative influence does depend on the type of estuary, characteristics of flooding and channel morphology that impact of particular events on the SWT estuaries examined in this thesis will be assessed individually and generalisations avoided. The influence of cyclones on coastal sand transfer at both contemporary and Holocene timescales on two SWT estuaries and one delta will be further examined in this thesis.

2.5 HOLOCENE EVOLUTION OF SWT CLASTIC COASTAL ENVIRONMENTS

Previous geomorphic research on the SWT mainland coast has focussed on the three main coastal depositional environments: mangroves; cheniers; and beach ridges. Extensive mangrove forests are restricted to sheltered coastlines, particularly the leeward sides of northward facing embayments where fine-grained sediment accumulates due to hydrodynamic controls (Orpin and Woolfe, 1999). Recent work on sediment transport in mangrove creeks in the SWT region suggest they are ebb-dominated (Larcombe and Ridd, 1995; Bryce, 2001; Bryce *et al.*, 2003) exporting fluvial suspended sediment to the coast.

Cheniers are ridges of coarse and predominantly shelly material. However they may be composed of terrigenous sands or gravels and form on relatively sheltered coasts (Chappell and Grindrod, 1984). In Hopley *et al.*'s (1980) summary on cheniers in north east Queensland, the exact process of chenier formation was still unclear. Features further south dated at older than 5 ka are thought to be formed during periods of low sediment supply leading to the erosion of mangrove deposits and development of a ridge from the coarser lag deposits (Cook and Polach 1977 as cited in Hopley *et al.*, 1980). However locally, Hopley (1974) had observed the emplacement of a chenier in Bowling Green Bay during Cyclone Althea in 1971. Chappell and Grindrod (1984) describe cheniers as having an 'internal dynamic' with the main factors affecting formation being the ability of the mangrove fringe to trap storm drifts of shelly material and mud and the availability of shell material. Thus cheniers form as the result of low frequency high energy events such as tropical cyclones provided sedimentation conditions in mangroves are suitable and there is an adequate supply of shell material. Chenier ridges are not as common as beach ridges - in the last 2 ka six times more beach ridges have formed than chenier plains in northern Australia (Chappell and Grindrod, 1984).

Beach ridges are depositional features (Otvos, 2000). A narrow fringe of beach ridges up to 5 m high composed of quartz sand, occur along the SWT coastline particularly in locations exposed to the prevailing south easterly winds (Hopley, 1980). Komar (1998) describes beach ridges as a series of long parallel ridges that were originally formed individually as a shoreline deposit. The process behind the formation of these ridges has been the source of debate in the literature over the last century (see Graham, 1993 for a good review). Graham (1993) suggests while most authors assumed that beach ridges were formed by storm waves depositing sediment above high tide there is growing support that they are formed during ambient conditions. Wheeler's (1902 as cited in Graham, 1993) theory suggests that where an excess of sediment exists in the nearshore, waves progressively shift sediment onshore to restore equilibrium. More recent reviews from (Tanner, 1995; Taylor and Stone, 1996; Otvos, 2000) provide additional support concluding that beach ridges form where abundance of sediment exists and the offshore gradient is low and that rises in sea level have initiated their development. Indeed in Australia, where beach ridges are common along the entire east coast, it is suggested that a reduction in the rate of sea-level rise once it reached the low gradient inner shelf permitted the onshore transport of nearshore sediment (Taylor and Stone, 1996). Further debate exists over the role of fluvial sand supply in their further development.

The majority of work on the evolution of barriers and beach ridges in Australia has been on the high-energy micro-tidal NSW coast (see Wright, 1970; Roy *et al.*, 1980; Thom *et al.*, 1981; Thom and Roy, 1985; Young *et al.,* 1996). Roy *et al*.'s (1980) evolutionary model for the NSW coast show two sources of sediment: 'fluvial' (river delivered); and 'marine' (nearshore sand moved onshore). The onshore movement of marine sand during the Holocene transgression and subsequent stillstand phase led to the formation of coastal barriers and estuaries that progressively infilled with fluvial deposits. This process has been observed in the Port Stephens – Myall Lakes area in NSW, where low sediment yielding rivers have infilled behind the barrier but have remained trapped and have had little influence on coastal development (Thom *et al*., 1981). This is not the case in the Shoalhaven River Delta where the relatively high sediment yielding river has rapidly infilled the estuary behind the coastal barrier and relatively strong tidal currents have led to the intermixing of fluvial and marine sediments (Roy *et al*., 1980). Roy *et al.* (1980) suggest that the Shoalhaven River only started to supply sand to the coast and adjacent beach ridges in the last 2 ka. However Young *et al*. (1996) suggest a far more rapid infilling of the estuary supporting earlier conclusions by Wright (1970) that fluvial sand has been delivered to the barrier system since its initiation at about 6 ka. While recent work by Umitsu *et al*. (2001) suggests a more complex re-introduction of fluvial sand delivery to the coast, it essentially supports Wright (1970) and Young *et al.*'s (1996) suggestion that for the Shoalhaven River Delta unlike other NSW estuaries, fluvial sand supply has superseded the influence of marine sand in beach ridge/barrier development. A similar situation has been reported in West Africa where the duality of sand source (i.e. marine and fluvial) has fuelled the development of beach ridges. This duality exhibits a temporal pattern wherein nearshore sand supplies have been supplemented and eventually superseded by supplies from rivers (Anthony *et al*., 1996).

Studies of the coastal development of the SWT (Hopley, 1970a; Hopley and Murtha, 1975; Pringle, 1984; Pringle, 2000) and wet tropics (Bird, 1973; Graham, 1993) coasts of north Queensland have concluded that the models of coastal evolution proposed for NSW coastal barriers (Roy *et al.*, 1980; Thom *et al.*, 1981) do not apply to these northern examples. This is not surprising considering that the NSW coast is characterised by high wave energy and low sediment yielding rivers, while the north Queensland coast is subject to low wave energy and what have been regarded as high sand yielding rivers. Thus while detailed studies have only been conducted in the Barron River Delta, Cairns and the Moresby embayment, near Innisfail in the wet tropics region, they maintain Hopley's (1970a) overall view of beach ridge development. Current literature suggests that that influence of fluvial sand supersedes marine sand in the Holocene development of the SWT coast around Townsville. However, analysis of the estimated ages of SWT beach ridges reveals similarities with their southern counterparts.

Radiocarbon dates from the most seaward beach ridges in SWT region between Bowen and Rollingstone, namely the Bohle and Cape Cleveland complexes revealed ages of 2, 460 ± 80 y (GaK-1508) and 3, 460 ± 100 y, respectively (Hopley, 1970a) Thom *et al*. (1981) found a similar pattern of progradation on the NSW coast with the formerly rapid progradation around 6 ka BP ceasing at ~3-4 ka BP. This supports the theory that the beaches are initiated by sea-level rise between 10-6 ka BP. The progradation of the beach ridges would have continued after sea level stabilised ~6 ka BP. The onshore movement of excess marine sand in the nearshore would have seen the progradation continue until equilibrium was restored.

Research into the coastal development in other SWT regions of Australia, for example, the macro-tidal South Alligator and Daly River Delta's of the Northern Territory (Woodroffe *et al.*, 1989; 1993) suggest a much different evolution. The Holocene marine transgression caused the influx of marine clay, silt and fine sands into the estuaries by strong tidal currents and while some chenier ridges were formed, no beach ridges occur. There are two likely explanations: 1. Greater tidal range (macro-tidal coast > 4 m); 2. Lack of sandy sediment common to the east coast of Australia.

Historically SWT streams have been regarded as high sand yielding therefore fluvial sand is thought to be the major source of material for coastal development. This review has demonstrated similarities with the long-term evolution of estuaries further south despite differing fluvial and marine regimes, therefore questioning the relative influence of fluvial sand in the development of the SWT coast. Large scale coastal development, i.e. the progradation of beach ridges on the SWT coast, like in other parts of eastern Australian was instigated by sea level rise 10-6 ka BP and continued through the stillstand until ~3 ka BP.

2.6 CONCLUSION

This review has demonstrated the lack of research which examines the influence of fluvial sand and dominant processes associated with coastal development in the SWT region of north Queensland. The extreme variable discharges characteristic of SWT streams do not fit well into current classifications of clastic coastal environments. SWT streams are quoted in the literature as delivering significant amounts of sand to the coast, however this often based on empirical modelling rather than site specific data. The highly variable nature of discharge in SWT streams is likely to have a substantial impact on the delivery of fluvial sand to the coast which is often not considered in modelling. Analysis of current literature has revealed that the influence of high frequency low magnitude events on fluvial sediment delivery and redistribution along the coast varies according to the characteristics of flooding and channel morphology and dominate processes in the estuary. This review reveals similarities between the long-term evolution of SWT estuaries with those further south – despite differing fluvial and marine regimes. Thus, doubt exists over whether fluvial sand supply has had more of influence on SWT coastal development than marine sand. This realisation highlights the need for the detailed study of SWT estuaries to determine the role of fluvial sand in coastal development.

CHAPTER 3 – METHODOLOGICAL APPROACHES

3.1 INTRODUCTION

The SWT coastline between Rollingstone and Bowen has changed both spatially and temporally. Therefore, an understanding of its modern geomorphology needs to be based on geological processes and time frames. Changing sea level has altered the position of the coast on the continental shelf and as a result the position of river mouths has also changed. Hopley's (1983) sea level curve for the SWT is still considered most accurate given doubts over the reliability of Larcombe and Carter's (1998) more recent sea level re-construction for the region (Hopley *et al*., 2007). Climatic changes cause variations in fluvial activity, for example Nott *et al*., 2002 has linked climatic data with the development of alluvial fans in north Queensland. Hopley's (1970a) detailed study of the SWT region reveals that many of the coastal features are relict. Modern processes, measured over a few tidal cycles over a couple of years and under ambient conditions in a SWT setting with high inter and intra-annual climatic variability, must be interpreted in the context of long-term geological timescales.

In order to quantify a sand budget for the SWT, studies of sand transfer over Holocene and contemporary timeframes were conducted in individual coastal systems in the SWT. The eighty-one streams between Rollingstone and Bowen were classified according to their physical characteristics (e.g. length, catchment area, slope, tidal limit and exposure to waves) to which systems would provide representative model of sand transfer processes in region. The Haughton, Elliot and Black coastal systems were considered the most appropriate because they all have the potential to deliver sand to the SWT coast under different dominant processes. For instance, the Haughton coastal system is considered to be tidally dominated, the Black wave-dominated, while the Elliot is influenced by both tidal and wave processes.

A variety of methods and data sources encompassing Holocene and contemporary timeframes were used to develop conceptual models of sand transfer in these three coastal systems which in combination provide a model of sand transfer in the SWT region. Sand movement over contemporary timeframes (from years to hours) was interpreted from aerial photograph analysis and bedform mapping in conjunction with volumes estimated from modelling equation based on tide and wave data. The textural and sorting characteristics of all three study sites were mapped to provide insight into the source of the sediment and dominate transfer processes. Stratigraphic sediment analysis and radiocarbon dating in the Haughton and Elliot estuaries established a chronology of sediment deposition over a Holocene timeframe, which provided a context to the interpretation of contemporary sand transfer processes.

This chapter begins with a description of how the study sites were selected with a detailed description of the sites included in their respective chapters (4, 5 and 6). A detailed discussion of the specific methods and justification of their appropriateness to the study will follow.

3.2 SELECTION OF STUDY SITES

3.2.1 CLASSIFICATION OF SWT COASTAL SYSTEMS

Eighty-one streams discharge into the Great Barrier Reef lagoon along the SWT coast between Rollingstone and Bowen. They range in size from the Burdekin River which is over 600 km long and drains 129, 500 km^2 down to numerous unnamed streams less than 1 km long and draining areas of less than 2 km^2. Data on the source of streams, catchment area, channel length, and percentage of estuarine channel was collated by the author from topographic maps and is detailed in Appendix A. This data was used to classify SWT coastal systems, including estuaries, deltas, tidal inlets and mangrove creeks, into five categories is shown in Table 3.1.

Table 3.1. Selected physical parameters used to classify SWT streams.

System type (Total number in SWT)	Source	Catchment Area (km^2)	Channel Length (km)	Percent estuarine channel	Fluvial Influence	Example(s)
Large complex systems (11)	Escarpment or residual hill	> 100	> 30	< 20 %	Seasonal	Burdekin River, Don River, Haughton River, Black River, Elliot River, Ross River
Small complex systems (22)	Escarpment or residual hill	20 – 99	10 – 29	< 20 %	Seasonal	Althaus Creek, Leichhardt Creek
Perennial Systems (2)	Residual hill	20 – 99	10 – 29	< 20 %	All year	Rocky Ponds Creek
Large coastal inlets (13)	Coastal plain	20 – 60	>10	> 40 %	negligible	Crocodile Creek
Small coastal inlets (33)	Coastal plain	< 20	< 10	> 75 %	negligible	Salmon Creek

Only two streams between Bowen and Rollingstone are classified as ‘perennial’ due the occurrence of natural springs. The majority of streams between Bowen and Rollingstone are intermittent due to highly variable rainfall of the SWT region. Therefore a study of sand transfer in these coastal systems would not be representative of the SWT. ‘Large and small complex systems’ are influenced by fluvial processes (though seasonal) compared to ‘large and small coastal inlets’ where fluvial processes are considered to have a negligible influence on sand transfer processes within these systems. Therefore achieve the aim of this study and quantify the coastal sand budget for the SWT between Rollingstone and Bowen, it was considered most appropriate to focus on those systems which have the greatest potential to be significant contributors of sand to the coast. Despite Pringle’s (1983; 1984) findings that distributary channels in the Burdekin Delta supply sand to the coast during major flooding, most SWT coastal inlets are no longer active distributary channels (Prosser, et al., 2001a). Consequently coastal inlets are not considered likely to contribute substantial quantities of sand to the coast and were not selected for detailed study.

Beach ridge plains adjacent to the large complex systems (Belperio, 1978; Holmes, 1992) and empirical modelling (Kinhill et al., 1993; Prosser et al., 2001a) suggest that the larger complex systems such as the Haughton, Elliot and Black Rivers have the greatest potential to deliver sand to the coast compared to the smaller complex systems such as Leichardt, Bluewater or Althaus Creeks. Therefore, the selection the study sites were refined to only include ‘large coastal systems’ which have the greatest potential to be significant contributors of sand to the coast. However, to develop a comprehensive sand transfer model for the SWT, it was essential to select ‘large coastal systems’ that were subject to varying influences of fluvial, tide and wave processes. Therefore the potential delivery and dominate processes of sand delivery to the coast in conjunction with the practical considerations such as the proximity to Townsville, availability of data and accessibility to the mouth resulted in the selection of the Haughton, the Elliot and the Black coastal systems as the focus of this study.

Despite having the potential to be a significant contributor of sand to the coast and therefore having a major influence on coastal sand transfer in the SWT, the Burdekin coastal system was not chosen as the focus of this study. At 600 km in length and draining a catchment of 129,500 km^2, the Burdekin is an order of magnitude bigger than the second and third largest systems the Don (length: 60 km; catchment area: 3985 km^2) and the Haughton Rivers (length: 90 km; catchment area: 3600 km^2) in the SWT. The vastness and complexity of this system would have limited the extent of this study to one study site rather than a representative sample of SWT systems. Also the Burdekin Delta has been widely studied when compared to other SWT systems (see Hopley, 1970b, Belperio, 1978; 1983, Pringle, 1983; 1991; 2000) and these findings were incorporated into the model of sand transfer for the SWT in chapter 8, section 8.4. Therefore while the Burdekin coastal systems is not the subject of detailed study in this thesis, it's influence on the sand transfer in the SWT is still accounted for in the resultant conceptual model.

3.3 AERIAL PHOTOGRAPH ANALYSIS

Available large scale (1: 12,000) vertical aerial photography spanning 60 years (see Appendix B) was analysed using standard photogrammetry techniques to map the evolution of the estuaries and adjacent coastlines over the recent past. Aerial photograph analysis is one of the most efficient and economical methods for understanding large-scale coastal behaviour over historical time scales (Hapke and Richmond, 2000), and is widely used by coastal geomorphologists and engineers (Harris and Jones, 1988; Pringle, 2000). Comparing sequences of large scale (e.g. 1:12,000) vertical aerial photographs taken at frequent intervals (e.g. every 5 years) over timeframes of 50-100 years gives a visual record of historical coastal evolution and rates and patterns of change. This method was the primary source of information for Pringle's extensive work (Pringle, 1983; 2000) on the Burdekin Delta, north Queensland. Aerial photograph analysis can even be used to detect smaller scale changes in the morphology of estuaries. A sediment transport model was developed for Moreton Bay (Harris and Jones, 1988) from assessing morphological changes in large-scale bedforms (sandwaves) from a series of aerial photographs over a 26-year period.

Developing historical models of coastal change and sediment transfer within estuaries has its difficulties. Aerial photographs are a snap shot of the estuary at that particular moment in time and may represent atypical conditions or morphologies (Stafford and Langfelder, 1971; Smith and Zarillo, 1990). For instance, a photograph that was taken immediately after a storm may show unusual bedforms that lasted only a few days before the ambient conditions returned. Fixed time lapses between aerial surveys, for example Beach Protection Authority (BPA) photographs taken at five years intervals, may also result in an inaccurate interpretation of the transport processes in the estuary. Comparing the position of the coastline recorded in historical aerial photography is the most common way to estimate rates of coastal erosion and/or accretion. The accuracy and precision of aerial photographic measurements is limited by difficulties in locating coastline position (Smith and Zarillo, 1990; Thieler and Danforth, 1994). This problem has previously received little attention in coastal geomorphology literature (Galgano and Douglas, 2000), prompting calls to establish a precise and consistent method among coastal researchers. Current techniques fail to provide an adequate basis for quantifying the many errors inherent in mapping the coastline from aerial photographs which range from image space distortion on the aerial photographs due to the lack of precise ground control points through to using small scale photographs (> 1: 20,000) (see Thieler and Danforth, 1994 for a good discussion). Coastline position is most frequently taken as the wet/dry line on the beach assumed to be the high water line (after Dolan *et al.*, 1980; Crowell *et al.*, 1991) as it is easily identified on aerial photographs by the colour difference between wet and dry sand (Thieler and Danforth, 1994). The high water line has its limitations as the indicator of coastline position especially on low sloping beaches where the position of the wet/dry line due to wave, tide or wind effects can range over several tens of metres (Thieler and Danforth, 1994). Therefore in this study the use of the high water line as the indicator of coastline position is made more robust as it is commonly associated with another coastline indicator, the vegetation line i.e. the seaward limit of coastal vegetation. While a lack of ground control points at all three study sites reduced the precision of coastline change measurements, error was minimised by using large scale (1:12,000) photographs.

Aerial photographic data was used to determine coastal change by mapping coastline positions at the time of the photographs and comparing linear measurements of changing coastline position. To develop an illustrative map of changing coastline position aerial photographs were scanned at high resolution (600 dots per inch) and imported into Corel Draw 9.0 graphics program. The photographs were orientated until they lined up with permanent features on an overlayed digital topographic (1:25,000) map. The position of the coastline for each photograph was heads up digitized using a different colour for each year. The resultant maps provide a useful visual record of the changing position of the coastline, however more precise and accurate techniques were derived from linear measurements taken directly from the aerial photographs. A line was drawn between two permanent features identified throughout the photograph record and on topographic maps, for example easily identified features on Pleistocene beach ridges. Transects (~250 m apart) were drawn perpendicular to the base line allowing the distance to the high water line to be measured from the same location on each aerial photograph. Distances from baseline to coastline were measured to 0.1 of a millimetre using a planimeter. Operator's measuring accuracy from 1:12,000 scale photography is estimated at ± 0.5 mm (Barker *et al.*, 1997; Galgano and Douglas, 2000). These figures could have been improved with more accurate ground control, however permanent survey markers are not located at the study sites. As high tide mark is used to denote the location of the coastline, there may be some differences in the height of the tide. However as the BPA photographs used are consistently taken at low tide on winter spring tides the tides error was minimised.

Sand volumes can not be accurately quantified unless photogrammetric techniques are used like integrating field survey data with the photograph data in computer models. For example, Hapke & Richmond (2000) have developed a method of producing 3D topographic models (Digital Terrain Models) and orthophotographs from digitized aerial photography. The lack of permanent survey markers at the study sites prevented the use of such techniques to give an accurate quantification of coastal change so volumes were estimated by using the average height of the coastline or bedforms (after Kidson and Manton, 1973). While this method is not considered to be as accurate as more recent developments in digital softcopy photogrammetry (e.g. Hapke and Richmond, 2000) this part of the study was limited by available data. A conservative average height of 1 m was used in the volume calculations allowing for reasonable confidence in the accuracy of volume estimates. The estimated volumes are only used to give an indication of the order of magnitude, that will be tested against modelling estimates as part of the sediment budget for the SWT between Bowen and Rollingstone (refer to Chapter 7).

3.4 SEDIMENTS

3.4.1 BEDFORMS

The morphology of estuarine sedimentary deposits is the result of the interaction between fluvial, tide and wave induced currents combined with the geometry and sedimentology of the estuary (Harris, 1988). The morphology and distribution of bedforms was observed on low spring tide on the intertidal flats of the Haughton, Elliot and Black estuaries in August 2001 by adopting similar methods used in Harris and Jones's (1988) study of bedforms in Moreton Bay, Queensland and FitzGerald *et al.*'s (2000) study in the Kennebec River Estuary, Maine U.S.A. Bedforms that were considered representative of approximately a 5 m radius of the intertidal flats were selected for detailed observation and mapped. The location of the bedform was recorded with a handheld Garmin Etrek GPS and a vertical photograph was taken. The height and wave length was measured and where the bedforms were asymmetrical the direction of the lee side was noted. Mapping of the distribution and orientation of the bedforms allowed the interpretation of patterns of sand movement within the estuaries (after Harris and Jones, 1988; Nichols, 1999).

3.4.2 SEDIMENT SAMPLING AND ANALYSIS

"Grainsize distributions are a sedimentary response to the geological processes of transport, re-suspension, deposition, mixing and sediment modification by biota and chemical mixing"(Orpin and Ridd, 1996:128). A surficial sediment sampling regime was designed for the study sites to allow the mapping and comparison of sediment facies in the upper, mid and lower estuary, offshore and on the adjacent coast. The results of the surficial sediment sampling is the basis of the conceptual model similar to the method used by Dalrymple *et al.* (1992) to develop a conceptual model of the sediment dynamics in macro-tidal estuaries. Sediment samples were collected in all three estuaries using a Van Veen grab sampler and a dredge deployed from a boat to retrieve samples off the sea and riverbeds. A small spade was used to collect samples from the dunes, beach and intertidal flats at low tide. The sample location was recorded using a hand held Garmin Etrek GPS.

The textural characteristics of sand samples were determined using standard dry sieving techniques (Lindholm, 1987) as it was considered the most efficient and cost effective method. Those samples containing fine sediment were analysed using a laser particle size analyser the Malvern Mastersizer 1000. Both sets of particle size data were analysed using the software package GRADISTAT: a grainsize distribution and statistics package for the analysis of unconsolidated sediments (Blott and Pye, 2001). While the GRADISTAT program gives the results in both methods of moments and graphical measures, only the results from the latter (graphical measures) were used in the interpretation as it is considered more likely to accurately describe the general characteristics of bulk samples (Blott and Pye, 2001). This study and many other recent studies (e.g. Anthony, 2000; Stewart *et al.*, 2000; Malvarez *et al.*, 2001) apply the same basic principles to interpret the origin and dominant transport processes of sediment from textural and sorting characteristics, together with assessments of angularity and feldspar content as Folk and Ward (1957) and Friedman (1961) did over 40 years ago. Some common relationships included linking poorly sorted, coarse sediment to fluvial environments, and well-sorted finer sand containing shells to marine environments (Folk and Ward, 1957; Friedman, 1961). Discriminant analyses, using mean grain size, sorting, skewness and kurtosis, have been successfully used for the recognition and discrimination of modern fluvial, beach and dune samples in the Burdekin Delta (Orpin, 1999).

3.5 HYDRODYNAMICS

3.5.1 WAVES

The BPA has two waverider buoys collecting offshore wave data one at Cape Cleveland (BPA, 1996b) and one at Abbot Point (BPA, 1996a). Every hour on the hour the buoy records water surface elevations which are transmitted to the receiver station on the mainland and stored in 26.62 minute intervals. In this thesis wave data is described in terms of significant wave height (H_{sig}) and the highest individual wave in the record (H_{max}). H_{sig} is the highest one third of the wave heights measured in a 26.6 minute wave record and are considered by the Bureau of Meteorology to have the most influence on wave processes (BPA, 1996b). H_{max} is reported in association with major meteorological events. As the buoys are located in deep water depths of >10m, the wave data must be manipulated using wave hind casting to provide an indication of nearshore sand transport.

Potential longshore sand transport volumes were calculated from significant deepwater wave height and wind data using equations developed by the U.S. Army Corps of Engineers (USACE, 1984). These equations form the basis of an interactive computer-based design and analysis tool called the Automated Coastal Engineering System (ACES 1.07) (Leenknecht *et al.*, 1992), which has been recently used to calculate potential longshore transport at Fox Island, U.S.A. (Miller *et al.*, 2002). Wind data (speed and direction) collected by the Bureau of Meteorology from Townsville, Ayr and Bowen recording stations were inputted into the ACES to calculate potential longshore transport volumes. Details of the calculation procedures and all results are given in Appendix C.

Wave refraction diagrams were also manually constructed from wind records to increase the applicability of the offshore waverider buoy data to nearshore sand transfer. Wave refraction maps were constructed for Abbot Bay using a template derived from King's (1972) graph illustrating the relationship between water depth, wave period and wave length. Three maps were drawn, for south easterly, easterly and north easterly winds using five second wave interval (five second wave interval is common in nearshore bays of north Queensland due to the proximity of the Great Barrier Reef) and 20 wave crest spacing. However, as the SWT region is subject to relatively low ambient wave conditions the focus of the hydrodynamic field studies was on the collection of tidal data.

3.5.2 TIDES

The most common method of collecting tide data in estuaries is to deploy a data logging S4 current meter for periods of up to a month to record ebb and flood current velocities (Bryce *et al.*, 1998). However the S4 current meters were unavailable. Therefore an alternative method had to be devised. A hand held digital flowmeter (General Oceanics model 2035) was deployed off a boat at selected sites throughout the Haughton River Estuary. This method required additional effort compared to the S4 current meter allowing detailed data collection at only one of the three study sites. However, this method provided a valuable advantage over the static S4 current meter, as variations in tidal energy in different locations of the estuary could be compared. Three sites were selected along the main estuarine channel of the Haughton representing the upper, mid and lower sections and one site on the smaller tidal channel. Current velocities were recorded every 15 minutes at 1 m above the bed and at 20%, 40% and 60% of the depth during a complete twelve-hour tidal cycle during spring and neap tides (June and July 2002 & 2003). Current velocities 1 m above the bed are most commonly used to estimate rates of bedload transport (see Larcombe and Ridd, 1995; Bryce *et al.*, 1998).

Mathematical models similar to those used to estimate fluvial sediment yield (e.g. Ackers and White, 1973) are applied to quantify bedload transport into and out of estuaries (Miles, 1991). The tidal current velocity data collected was used to model potential volumes of bedload transport into and out of the estuaries. Three bedload equations from Engelund and Hansen, (1967); Gadd *et al.*, (1978); and Hardisty, (1983) that have been previously used to model sand transport in north Queensland tidal settings (e.g. see Larcombe and Ridd, 1995; Bryce *et al.*, 1998) were applied in this study. Larcombe & Ridd (1995) compared the predictions from these equations with actual measurements of bedload transport in a tidal creek located in the SWT of north Queensland. They concluded that while there was some overestimation, overall the predictions of bedload transport were good (Larcombe and Ridd, 1995).

3.6 VIBROCORING

Estuarine evolution occurs over time scales of thousands of years and must be viewed within a context of changing environments and sea levels to interpret modern sand transfer processes and morphology (Cowell and Thom, 1994). Past estuarine conditions and dominant processes can be interpreted from the analysis of the stratigraphy and sedimentology of estuarine deposits (Nichols, 1999). Vibrocoring and radiocarbon dating is a common method of analysing estuarine deposits and formed the basis of a depositional model for the macro-tidal Alligator River Estuary in the Northern Territory (Woodroffe *et al.*, 1989). A similar strategy was applied in this study with six vibrocores retrieved from the Haughton River Estuary and four from the Elliot River Estuary (Figure 3.1). Vibrocoring was considered the most appropriate method given the shallow bathymetry in the estuary and the need to take the cores in nearshore locations where large vessels capable of taking deeper cores could not access. The cores were sub-sampled at 10-20 cm intervals and the textural and sorting characteristics were determined using the methods described in section 3.4.3. Organic material, for example mangrove peat, found in the cores and likely to be in situ was sent to Waikato University, New Zealand to be radiocarbon dated. Establishing a chronology for patterns of sedimentation aids in the interpretation of the evolution of the estuaries and dominant processes influencing sand transfer (Woodroffe *et al.*, 1989).

Figure 3.1 Vibrocoring intertidal sand flats at the Haughton River Estuary during low tide.

3.7 CONCEPTUAL MODELS

Conceptual models have been used to explain differences in the morphology and facies distribution of estuaries (e.g. Boyd *et al.*, 1992; Dalrymple *et al.*, 1992; refer to chapter 2, section 2.2). In such models the estuary is divided into a landward zone dominated by fluvial sedimentation, a seaward zone dominated by marine sedimentation and a mixed zone. The morphology and distribution of sandbodies at the estuary mouth are used to distinguish between the wave and tide dominated classifications. A number of factors can modify these models including the length of the estuary, the valley shape and stage of estuarine evolution (FitzGerald *et al.*, 2000).

Conceptual models provide an effective and efficient way of communicating and synthesising the extremely complex processes occurring in SWT coastal systems. Conceptual models can be used as part of a decision support system for environmental managers, and as a tool for comparative assessment in which a more integrative approach to the components can be applied (Ryan *et al.*, 2003). They provide a framework for organising knowledge, in order to help users understand processes and demonstrate the links between them (Ryan *et al.*, 2003). By incorporating the morphological, sedimentological and hydrodynamic data over contemporary and geological time scales a conceptual model of sand transfer was developed for SWT coastal systems. This model may assist coastal managers to consider the dynamics of coastal systems at temporal and spatial scales appropriate for decision-making.

3.8 SUMMARY

This study applies a multi-disciplinary approach integrating morphological, sedimentological and hydrodynamic data over contemporary and geological time scales to produce a conceptual model of coastal sand transfer for the SWT. A combination of aerial photo analysis and bedload modelling was used to quantify the volumes and dominant processes of sand transfer over contemporary timescales. Stratigraphic sediment analysis and radiocarbon dating established a chronology of sediment deposition over a Holocene timeframe to be incorporated in the interpretation of contemporary results. The Haughton, Elliot River Estuaries and the Black River Delta were selected for this study from a classification of all SWT coastal systems, as they were considered to have the greatest potential to deliver sand to the coast and are subject to varying influences of fluvial, tide and wave processes. Table 3.2 summaries the data collection methods used in each study site.

Table 3.2 Summary of the data collected in each study site

Study Site	Aerial photo analysis	Bedform mapping	Surfical sediment sampling	Subsurface sediment sampling	Tidal current data	Bedform sediment transport modelling	Wave sediment transport modelling	Radio-carbon dating
Haughton River Estuary	1942-2000	Yes	150 samples	6 vibrocores	Yes	Yes	Yes	Yes
Elliot River Estuary	1942-1998	Yes	95 samples	4 vibrocores	No	No	Yes	No
Black River Estuary	1942-2000	Yes	68 samples	No	No	No	Yes	No

CHAPTER 4 – THE HAUGHTON RIVER: A TIDE-DOMINATED ESTUARY

4.1 INTRODUCTION

The Haughton River Estuary (Lat. 147.126, Long. -19.416) is the largest of the three study sites and was studied in the most detail. The results of the aerial photograph analysis, sedimentological and hydrodynamic studies on the Haughton River Estuary are presented and briefly discussed here; a more detailed discussion continues in chapter seven. The results are synthesised in a conceptual model that relates contemporary processes to the existing geomorphology, to help explain the evolution of the system.

4.2 GEOMORPHOLOGY

The Haughton River Estuary is located ~30 km south of Townsville near Giru (Figure 4.1). Table 4.1 summarises the main physical attributes of the largest system within the SWT, after the Burdekin. The steep descent (0.0147) of the fluvial reach of the river the Great Escarpment (maximum height 1000 m) is contrasted by the gentle descent (0.0003) of the estuarine reach, which discharges into Bowling Green Bay. The average width of the channel along most of it is length is ~50 m, widening rapidly at the mouth to 2 km. Well developed sand bars and islands throughout the channel are indicative of the large quantities of sand originating from weathered granites and diorites of the Hervey Range and the Mount Elliot Complex (Kinhill *et al.*, 1996). The sinuosity of the channel increases from 1.4 to 2.1 about 18 km from the coast due to tidal influence. This estuarine section of the channel is flanked by about 25 km^2 of mangroves (Heap *et al.*, 2001). The Estuary is dominated by sandy sediments in the form of a large flood and/ ebb tidal delta of 9.7 km^2 (Heap *et al.*, 2001).

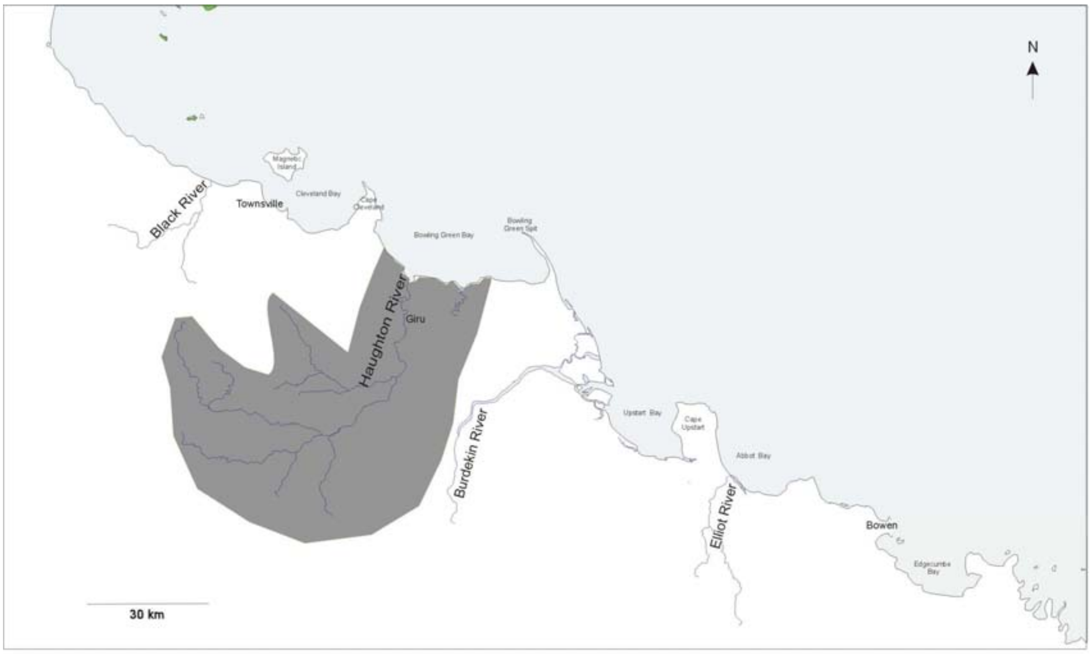


Figure 4.1 The Haughton River catchment.

Table 4.1. Physical characteristics of the Haughton River Estuary

Catchment area	3600 km^2
Channel length	90 km
Channel width	50 - 2000 m
Slope	Fluvial reach: 0.0147 Estuarine reach: 0.0003
Sinuosity	Fluvial reach: 1.4 Estuarine reach: 2.1
Percentage of channel estuarine	20%
Mean annual rainfall	1249 mm
Modifications	• 78% of catchment cleared for grazing and small areas of agriculture; • 1977 Giru Weir (AMTD 15.1 km); • 1982 Val Bird Weir (AMTD 22.7 km); • Sand extraction (>560,000 m^3 since 1984) (Kinhill *et al.*, 1996); • Altered flow due to irrigation.

The present geomorphology of the river and its estuary is the result of thousands of years of evolution and must be viewed within the context of sea level rise. Prior to 6 ka BP the Haughton River acted as a left bank distributary of the Burdekin River when it discharged into Bowling Green Bay via the Barrattas (see appendix F) (Hopley, 1970b). The large number of distributaries and lagoons in the floodplain indicate that the Haughton River has changed parts of its course many times (Kinhill *et al.*, 1996).

4.3 SETTING

The Haughton River exhibits the typical characteristics of a highly variable discharge stream (see chapter 2, section 2.4.1). Table 4.2 summarises the flow gauge data used in Figure 4.2 which illustrates the marked intra and inter-annual variability of stream flow in the Haughton River. Approximately 88% of total stream flow occurs between December and April. Discharge also varies markedly between years which is highlighted by comparing annual stream discharges as a percentage of the maximum annual flow volume for the Haughton River. Sixty-three percent of the years on record registered below a quarter of the maximum annual flow volume. Flooding in the Haughton River can be described as episodic and flashy. Figure 4.3 illustrates the rapid rise of flow reaching high maximum instantaneous discharges; however the duration of maximum flow is short, declining rapidly. For instance, the duration of a flood with an average return interval (ARI) of greater than 20 years is less than one day. Table 4.2 details downstream decreasing channel capacities, which reduce the channel's ability to convey flow (Kapitzke *et al.*, 1998). The channel capacity in the lower reaches of the Haughton River decreases by over 90%.

Table 4.2. Summary stream flow characteristics for the Haughton River Estuary (Source Kapizke, *et al.* 1998).

Gauging station	Powerline
Distance from stream mouth	33 km
Catchment area at gauging station	1735 km^2
Gauged area/catchment area	48%
Available records	1970-2001
Maximum annual flow volume	1,750,000 ML in 1991
Minimum annual flow volume	4,6000 ML in 1987
Maximum instant discharge	3964 $m^3.s^{-1}$ in January 1972
Maximum period of no flow	10 months in 1986/87
Bankfull capacity (13 km upstream of the mouth)	<400 $m^3.s^{-1}$
Outflow discharge	>3600 $m^3.s^{-1}$
Outflow (% of bankfull capacity on upper floodplain)	>90 %

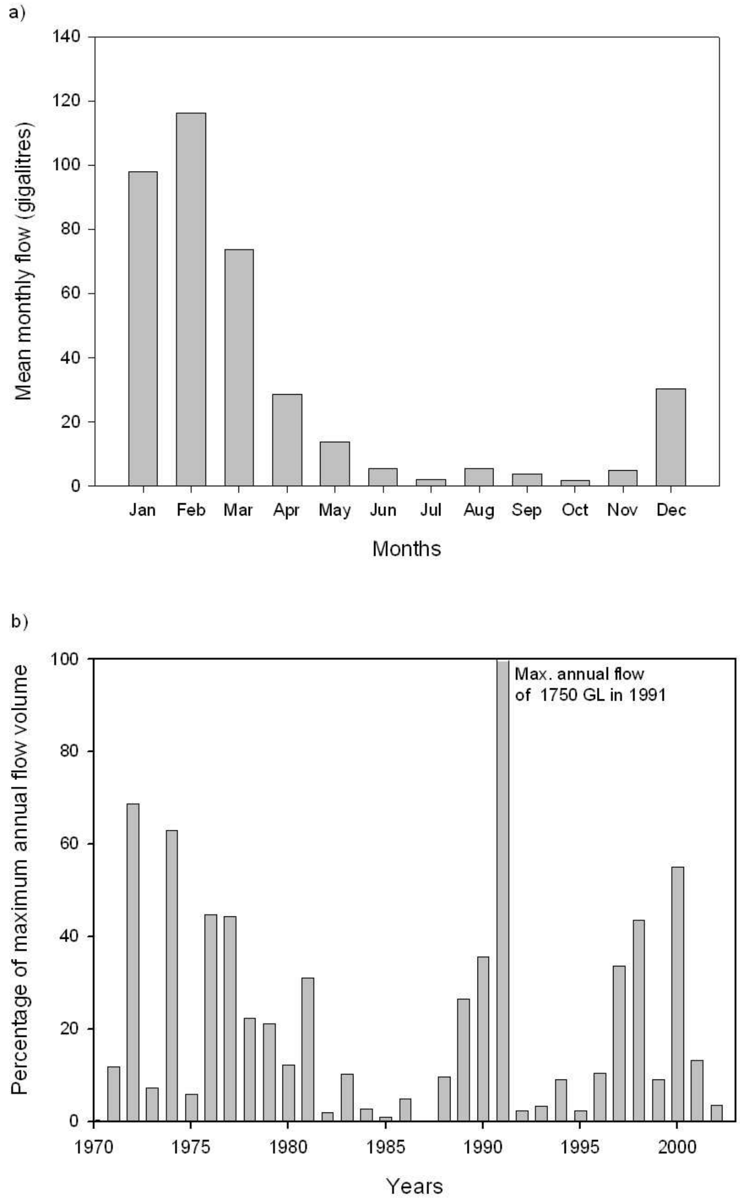


Figure 4.2 Stream flow characteristics for the Haughton River recorded at the Powerline gauge from 1970-2002 (DNR, 2002), mean monthly flow volumes (a) and annual flow volumes shown as a percentage of the maximum flow volume (b).

Waverider buoy records from off Cape Cleveland are the best data available to indicate offshore wave energy for the Haughton River Estuary. Modal significant wave height ranges from 0.2 - 0.4 m (BPA, 1996b). However it is likely that lower significant wave heights occur at the estuary mouth, given that Cape Bowling Green shelters the bay from the dominant wind driven south-easterly waves. The Haughton River Estuary experiences a diurnal meso - tidal regime with a maximum spring tide range of 3.8 m (Queensland Transport, 2003).

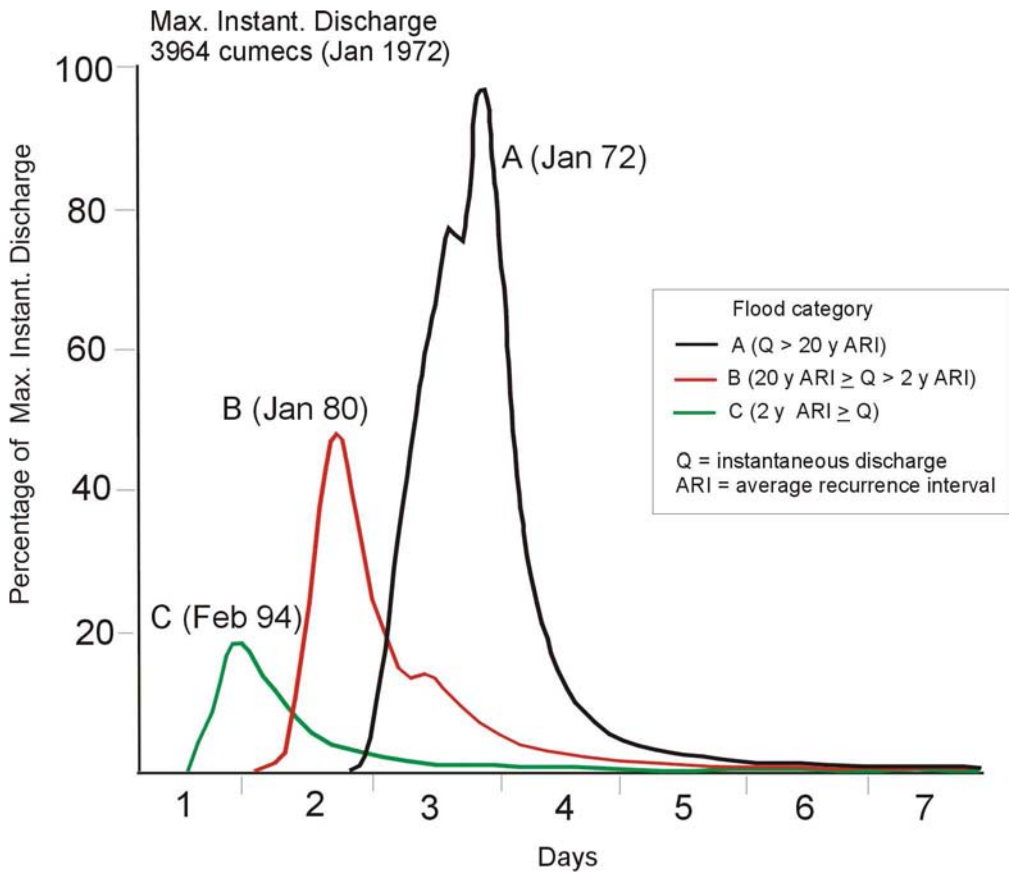


Figure 4.3 Flood hydrograph for the Haughton River reproduced from Kapitzke *et al.* (1998:42)

4.4 RESULTS

4.4.1 AERIAL PHOTOGRAPH INTERPRETATION

Analysis of aerial photographs from the last 60 years, incorporating Hopley and Rassmussen data from 1942-1995 and this study from 1952-2000 (see Appendix B), revealed a net average shoreline retreat of ~100 m on the western side of the Haughton River Estuary since 1942 (Figure 4.4). Figure 4.6 presents the linear measurements of erosion and accretion between 1974 and 1998 along the 3 km stretch of coastline on the western side of the estuary near the settlement of Cungulla (see figure 4.5 for the location of transects). Most of the transects (transects 2-5) have experienced erosion with an average of 1.2 m of shoreline retreat per year, which over 1.9 km of coast (assuming 1 m height - see chapter 3, section 3.3.1) yields 54,340 m^3 of eroded sand. However, accretion has also occurred since 1974 with transects 1, 6 and 7 prograding rapidly since 1974. Transect 6 and 7 indicate the rapid growth of a large spit orientated landward into the estuary. While transects 8 and 9 show erosion rates of 3 m and 2 m per year, respectively. Approximately 60,000 m^3 of sand has been added to the spit between 1995 and 2000. Accretion at transect 1 indicates the accumulation of sand to the south, which has been observed in the aerial photograph record migrating south approximately 300 m between 1961 and 2000. Similar volumes of erosion (54,340 m^3) and accretion (60,000 m^3) suggest that sand is contained within the Bowling Green Bay coastal compartment (see chapter 7, section 7.44).

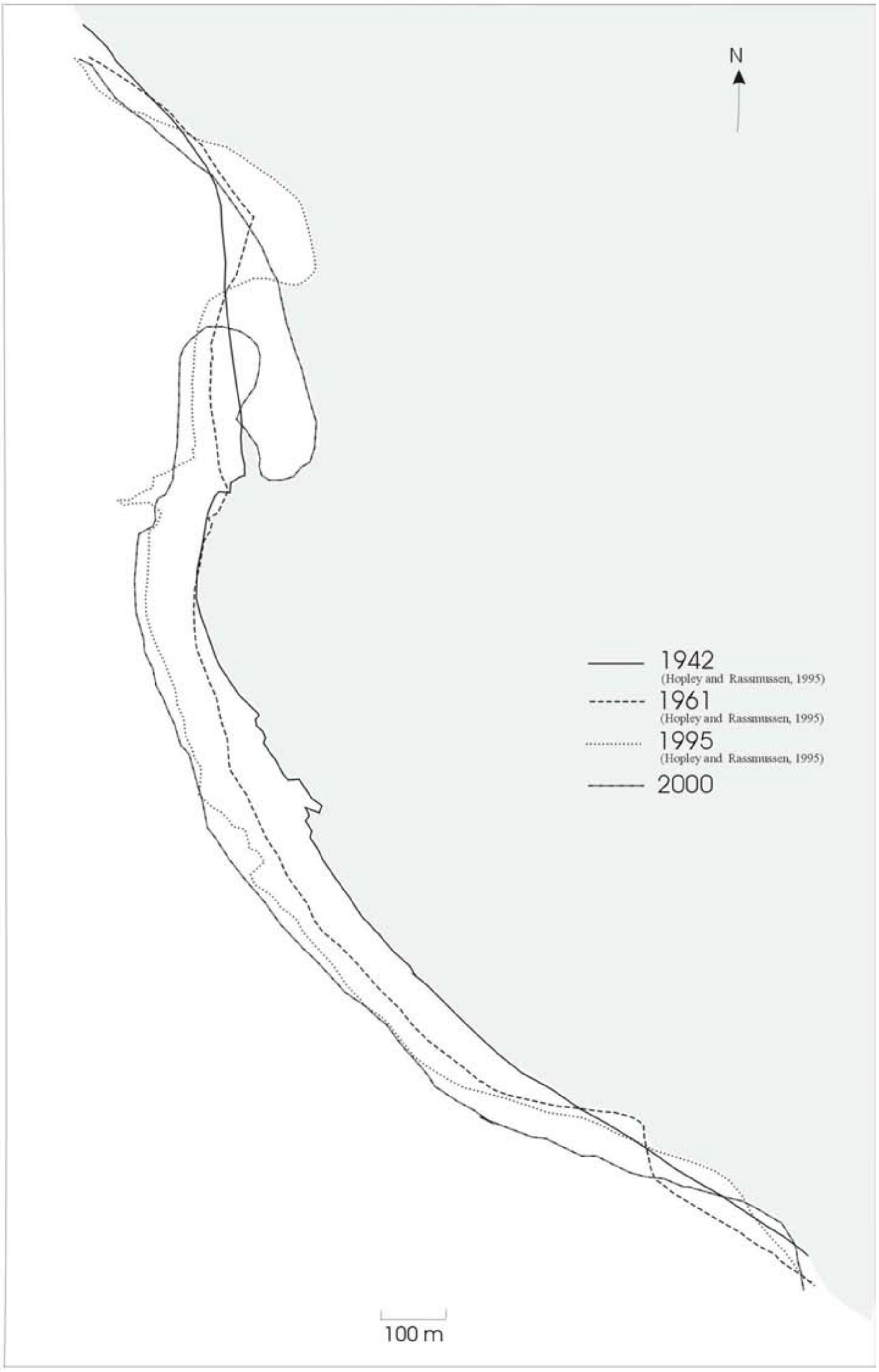


Figure 4.4 Coastal change along the western side of the Haughton River Estuary. The 1942, 1961 and 1995 shoreline position derived from Hopley and Rassmussen (1995), while the 2000 data was collected by the author (see figure 4.5 for the location of transects).

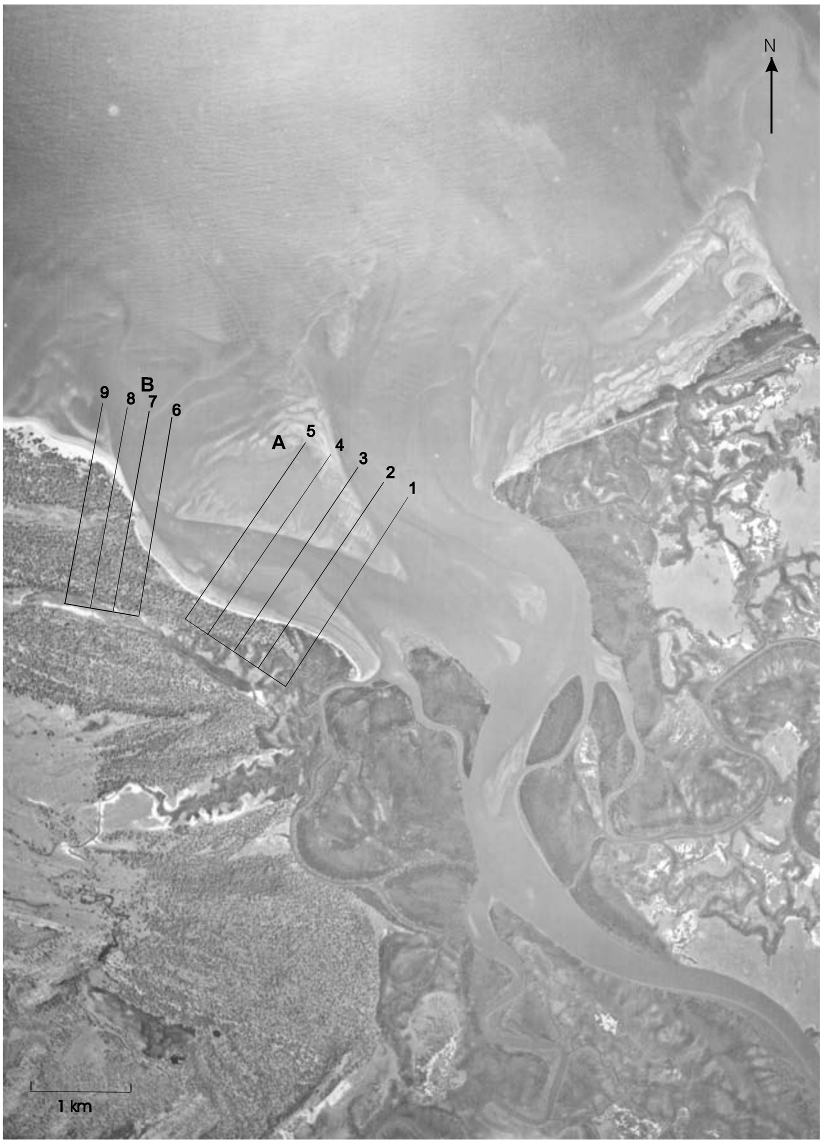


Figure 4.5 Location of transects used to measure coastal change on the western side of the Haughton River Estuary shown on the 1942 aerial photograph. A and B indicate locations of the bedforms shown in figures 4.7 and 4.8 respectively.

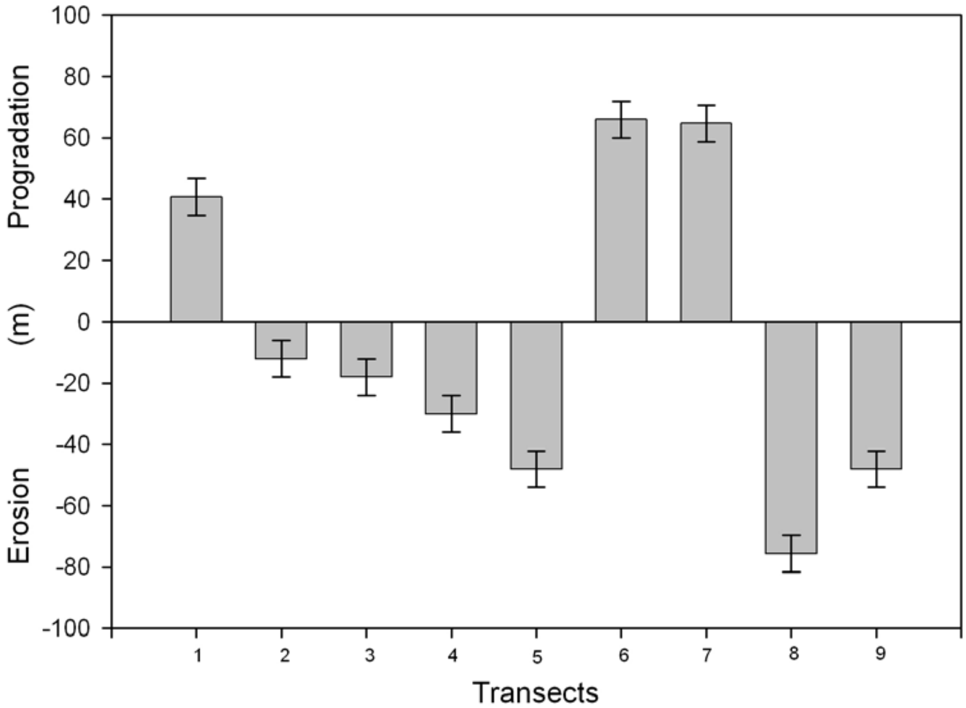


Figure 4.6 Shoreline progradation and retreat along the Haughton River Estuary measured from 1974 and 1998 aerial photographs. Standard error of measurement estimated at 6 m for 1:12,000 scale photography. (See figure 4.5 for locations of transects).

4.4.2 BEDFORMS

Bedform morphology can be used in certain setting to infer sand transport patterns and processes (see chapter 3, section 3.3.2). For example if flood tide bedforms persists for identification at low tide it suggests flood tide dominance of sand transport within the estuary (Bryce *et al.*, 1998). The most common type of bedform observed on the intertidal sand flats at low spring tides were small current ripples with an average height of 2 cm and a wavelength of 10 cm (Figure 4.7). The majority of these ripples were asymmetric, with their lee sides facing shoreward. Larger bedforms, megaripples, were observed in both the main and secondary tidal channels. These megaripples have an average height of 0.2 m and wavelength of 5 m (Figure 4.8). The lee sides of the megaripples were also orientated towards the shore. The only evidence of the outgoing tide were small current ripples (1 cm high, 5 cm wavelength) orientated towards the sea which were superimposed upon the megaripples.

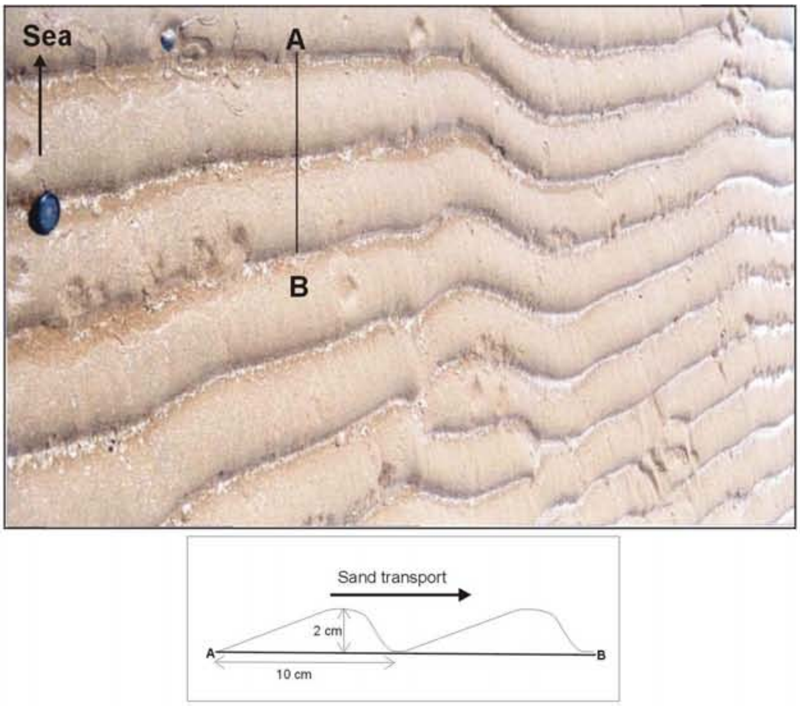


Figure 4.7. Current ripples observed at low tide at the Haughton River Estuary indicate sand transport into the estuary. Location marked as A on figure 4.5.

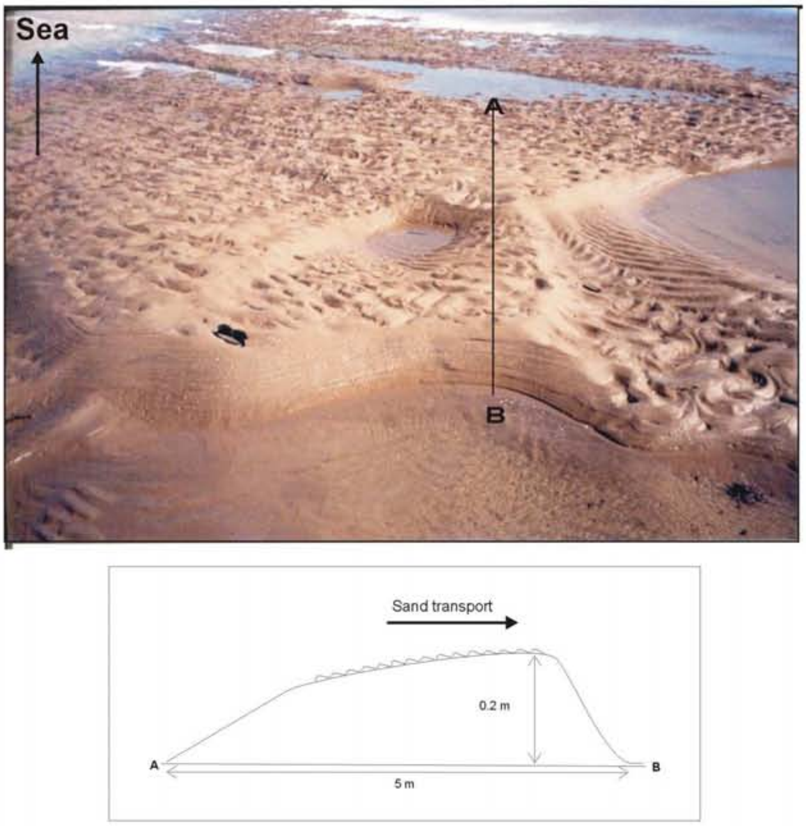
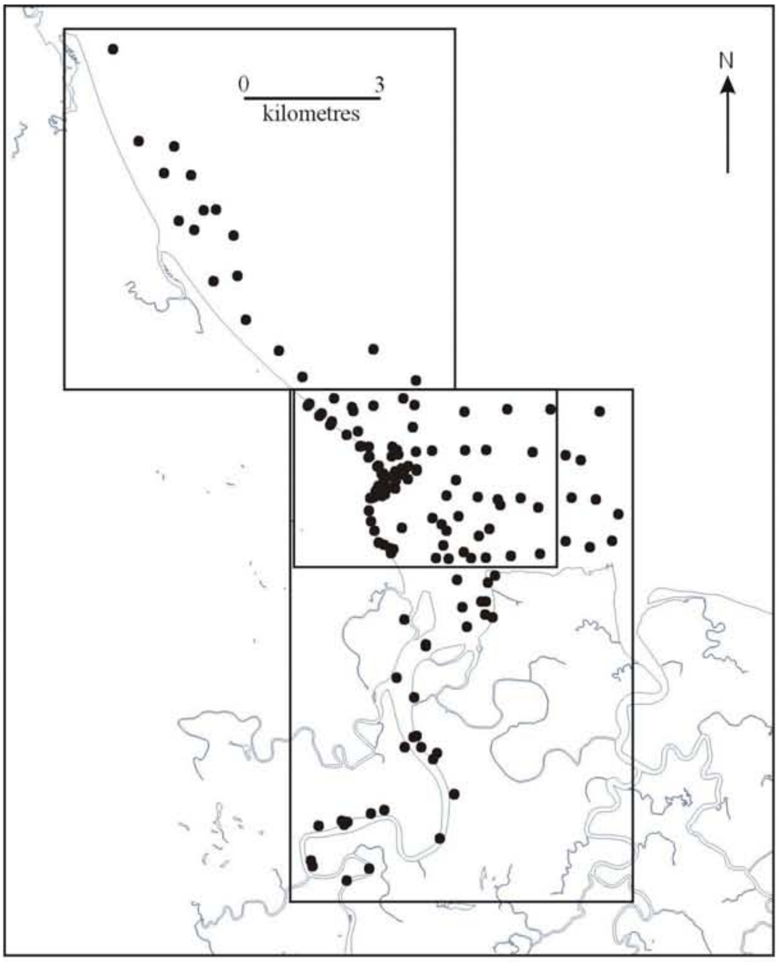


Figure 4.8. Megaripples observed at low tide at the Haughton River Estuary also indicates sand transport into the estuary. Small seaward facing current ripples occur on the crest of the megaripple. Location marked as B on figure 4.5.

4.4.3 SEDIMENTOLOGY

Over 150 surficial sediment samples and six vibrocores penetrating a maximum of 3 m below AHD were collected from the Haughton River Estuary and the adjacent coastline (see chapter 3, section 3.3.3 and 3.4.1). The locations of surficial samples and vibrocores are shown in figure 4.9 a and b. Figure 4.10 provides a summary of the results of textural analysis of the surficial samples (see Appendix D) showing the spatial distribution of sediment types. The beaches and intertidal flats are predominantly composed of well-sorted fine sand (mean grain size 0.204 mm), while well-sorted medium sand (mean grain size 0.32 mm) occurs within the tidal channels. Offshore deposits are also predominantly sandy but contain increasing proportions of silt. The only coarse, poorly sorted sediment (mean grain size 0.649 mm) was sampled from a discrete bar in the upper section of the estuarine channel.



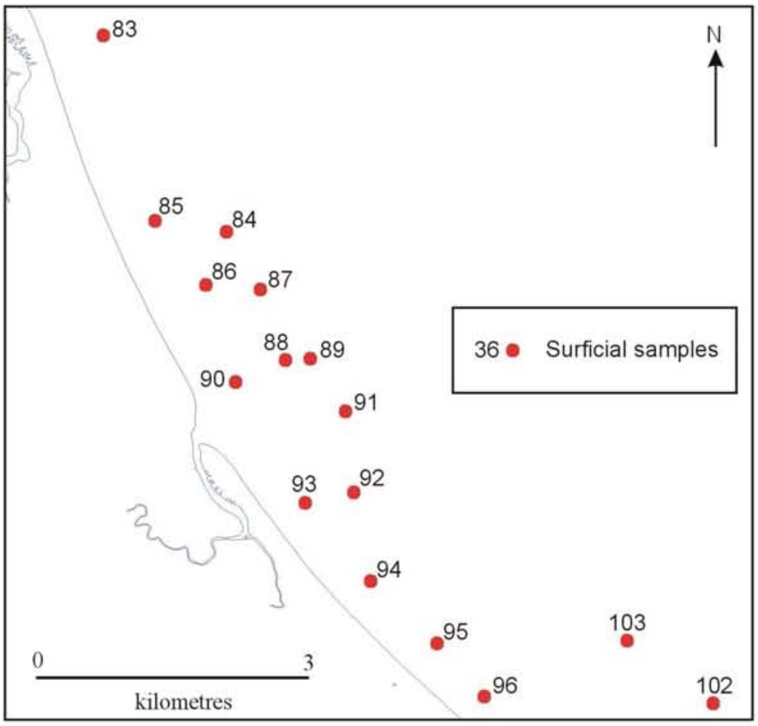


Figure 4.9 a. Locations of surficial and subsurface sediment samples taken at the Haughton River Estuary. (See Appendix D for the results of the textural analysis of samples).

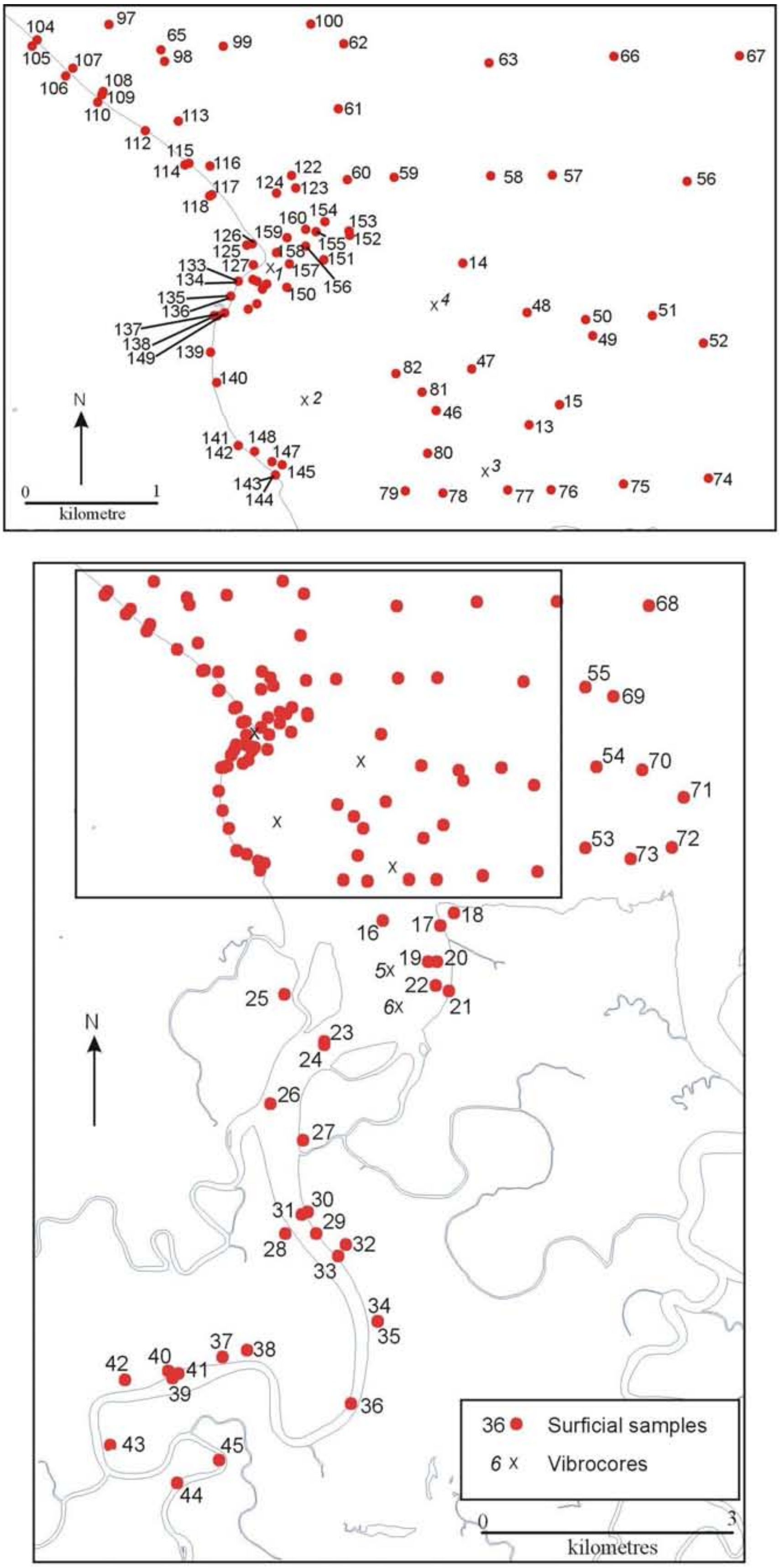


Figure 4.9 b. Locations of surficial and subsurface sediment samples taken at the Haughton River Estuary. (See Appendix D for the results of the textural analysis of samples).

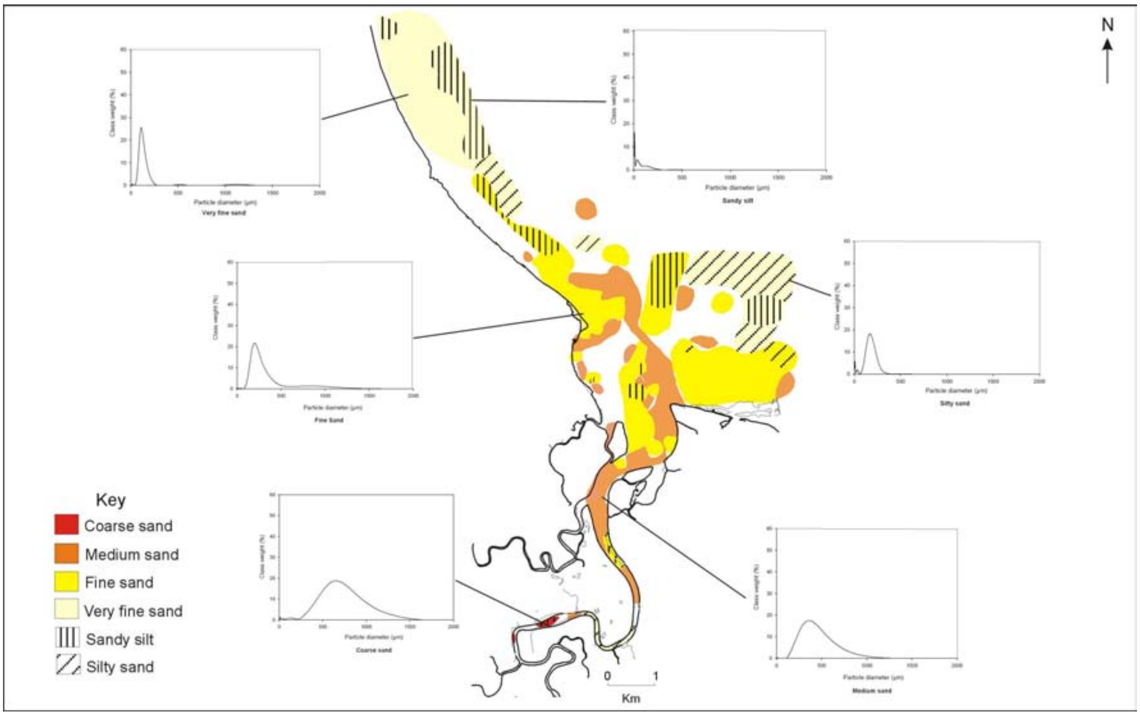


Figure 4.10. Summary of the results of textual analysis of surficial samples from the Haughton River Estuary. Histograms show the distribution of a typical example of each sediment class.

All six vibrocores had similar stratigraphies. They were predominantly composed of medium to fine sand, interspersed with silt and shell beds with occasional mud clasts. Figure 4.11 shows a cross section of the stratigraphy inferred from the estuary mouth offshore. The lack of organic material prevented a detailed chronology of sedimentation. However, mangrove peat found in HRVC 2 at 2.6 m below AHD and shells found in HRVC 4 at 0.8 m below AHD were dated (Figure 4.12). The results of conventional radiocarbon dating were 1035±105 years BP CAL (Wk10904, atmospheric data from Stuiver *et al.*, 1998; OxCal v3.5 Bronk Ramsay, 2000, see Appendix E) from mangrove peat at 2.6 m below AHD in HRVC 2 and 2378±73 years BP CAL (Wk10905, marine data from Stuiver *et al.*, 1998; Delta_R 10±7; OxCal v3.5 Bronk Ramsay, 2000, see Appendix E) from a bulk shell sample 0.8 m below AHD.

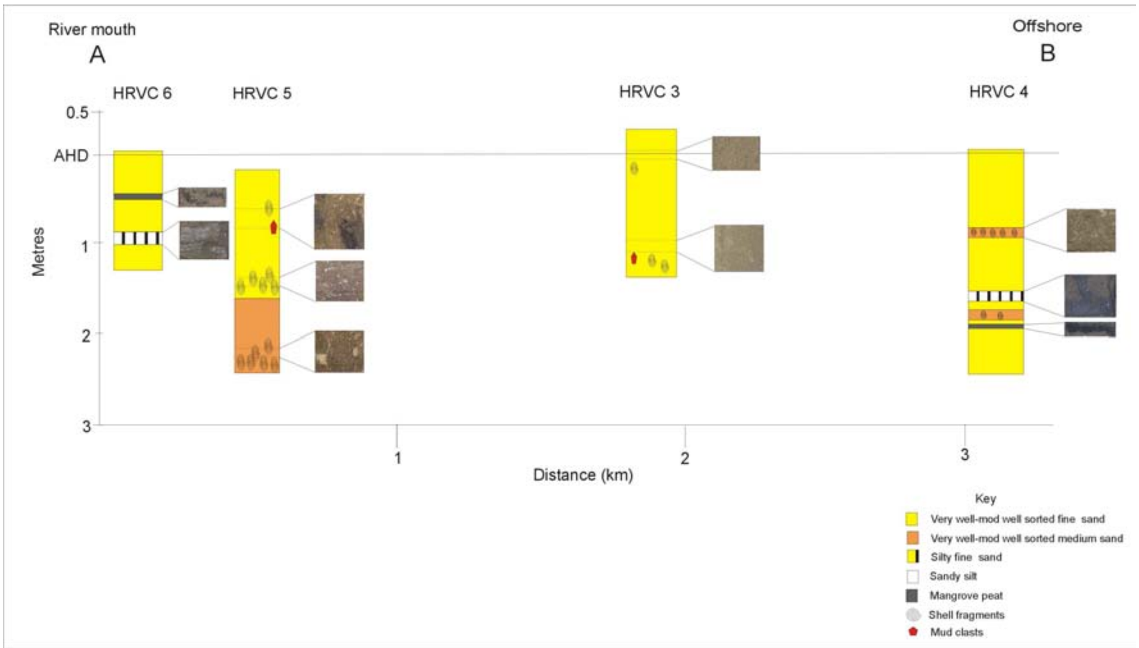


Figure 4.11. Cross-section of stratigraphy of the Haughton River Estuary including photographs of selected beds.

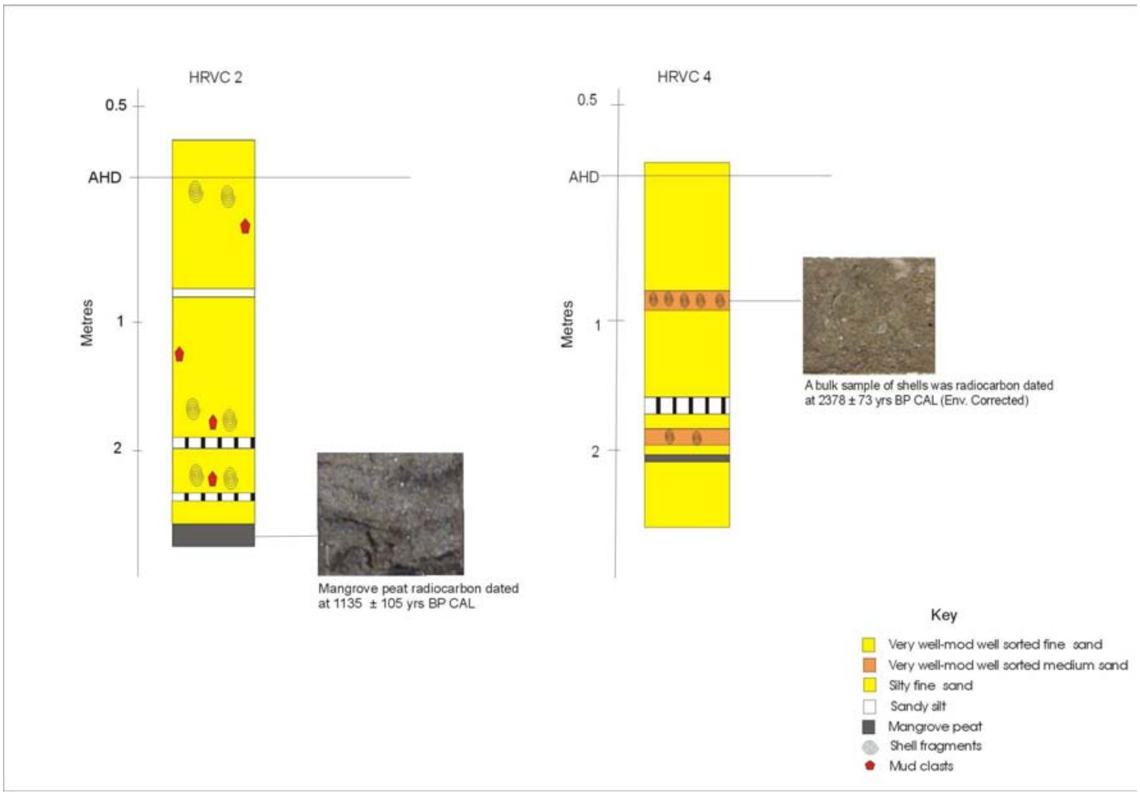


Figure 4.12. Radiocarbon dates from HRVC 2 and HRVC 4 from the Haughton River Estuary.

The textural and sorting characteristics of sediment such as grain size, sorting, skewness and kurtosis can often indicate transport processes (see chapter 3, section 3.3.2). Figure 4.13 part a-d compares subsurface, offshore, intertidal, beach and dune sediment samples according to mean grain size, sorting, skewness and kurtosis characteristics after Friedman (1961). The lack of separation of the different settings according to textural and sorting characteristics suggests that sediment has had a similar origin and transport history, despite being sampled from different locations throughout the estuary. Table 4.3 lists the textural and sorting characteristics identified in the discriminant analysis (see chapter 3, section 3.3.2) which distinguish between samples from different sedimentary environments. The closer the value to +1 or –1, the more significant the descriptive parameter is within the function. Sorting (0.863) was the most significant variable within function one. Kurtosis (0.794) was the most significant in the second function. Figure 4.14 plots the sites according to these functions i.e. sorting on the x-axis and kurtosis on the y-axis, however there is little separation of the samples according to their environment. The lack of variation of sedimentological characteristics throughout the Haughton River Estuary is further emphasised by a comparison of the different depositional environments with beach ridge sand analysed in this study and another completed over thirty years ago (Hopley, 1970a) (Table 4.4). Despite differences in their location, similar grain sizes suggests that the same amount of energy was required to transport the sediments. As sorting is a reflection of the origin and transport history of the sediment, being all fairly well sorted sands indicates substantial reworking of the sediment (Nichols, 1999). While the modern surface fine sand and that retrieved from the vibrocores have low kurtosis values the beach ridge sand has a high kurtosis value indicating a complex transport history (Hopley, 1970a). Skewness indicates the area of deposition, often dune sands are positively skewed and beach sands are negatively skewed (Hopley, 1970a) however, while most of the modern beach samples are coarsely skewed the dune and intertidal samples do not favour one skewness category.

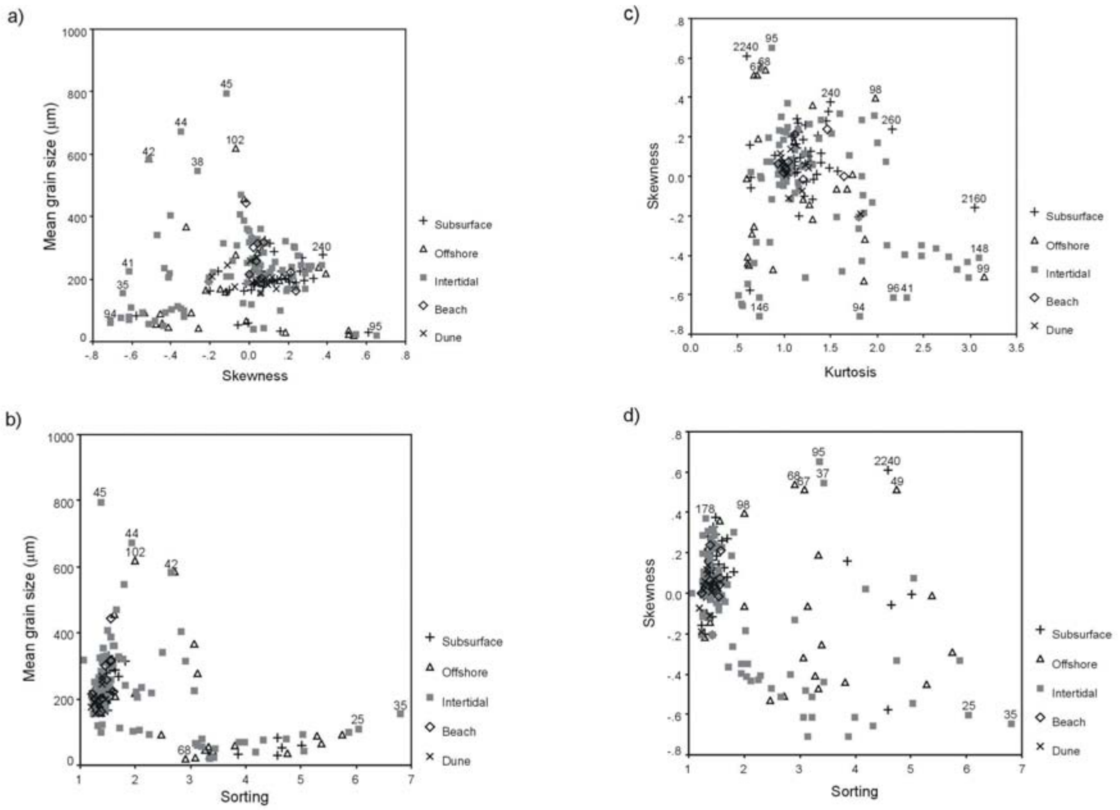


Figure 4.13 part a-d. A comparison of the surficial and subsurface sediment samples according to their mean grain size, sorting, skewness and kurtosis characteristics for the Haughton River Estuary.

Table 4.3. Structure matrix of the discriminant analysis of textural characteristics.

Variables	Function			
	1	2	3	4
Sorting	0.747*	0.487	-0.422	0.166
Kurtosis	-0.650*	0.472	0.498	0.327
Mean grain size	0.156	0.627	0.707*	0.286
Skewness	0.233	-0.214	0.511	0.800*

* indicates the largest absolute correlation between each variable and any discriminant function.

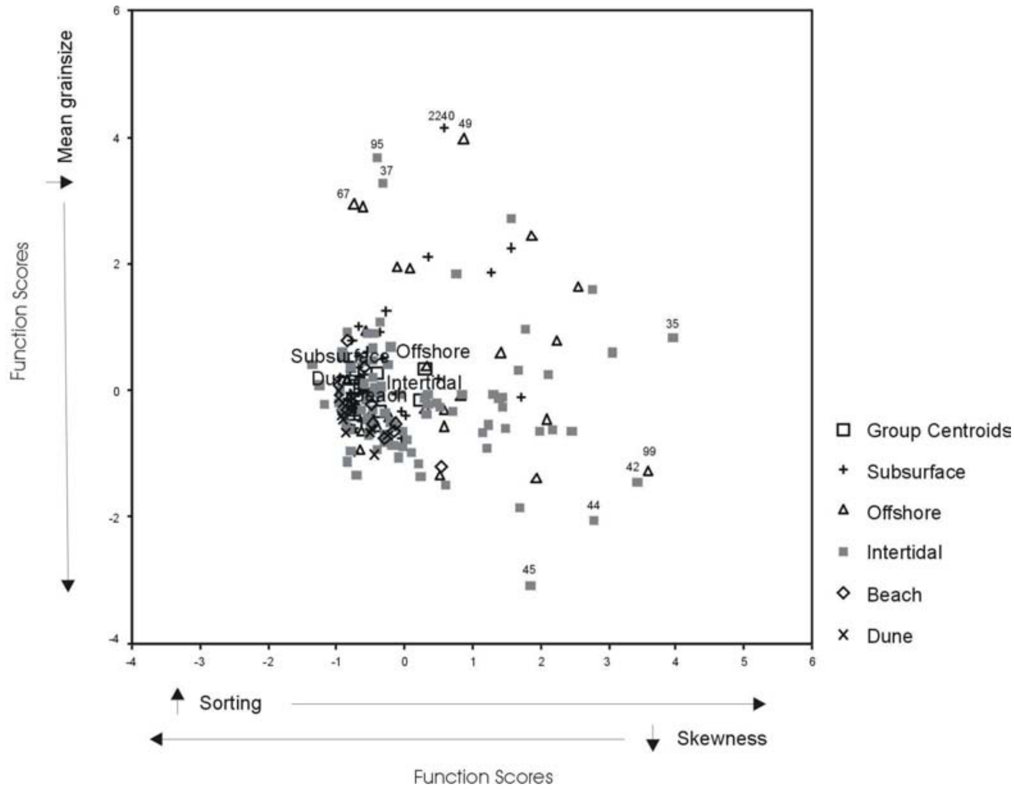


Figure 4.14. Scatter plot showing the results of the discriminant analysis using all descriptors for the Haughton River Estuary.

Table 4.4. A comparison of modern, old and beach ridge sand from the Haughton River Estuary.

Measure (Folk and Ward method)	**Modern fine sand (dune, beach, intertidal)**	**Old fine sand (Vibrocores up to 3 m deep in intertidal)**	**Beach ridges fine sand [Hopley, 1970 #50]**
Mean grain size	**Beach:** 2.376 Φ (0.195 mm) **Intertidal:** 2.250 Φ (0.213 mm) **Dune:** 2.368 Φ (0.196 mm)	2.347 Φ (0.198 mm)	2.579 Φ
Sorting	**Beach:** mod well- very well **Intertidal:** mod well- very well **Dune:** mod well- very well	0.491 Φ (0.001 mm) Well	Moderately
Skewness	**Beach:** Negative **Intertidal:** Positive, Symmetrical and Negative **Dune:** Positive, Symmetrical and Negative	-0.095 Φ Symmetrical to negative (coarse)	Negative (coarse)
Kurtosis	**Beach:** <2 **Intertidal:** <2 **Dune:** <2	0.966 – 3.049	1.466 – 12.749

4.4.4 HYDRODYNAMICS

Tidal prism calculations revealed that over 30 million cubic metres of water is exchanged during maximum spring tide (3.8 m) (Table 4.5). Cross-sectional profiles and specific data collection sites in the main and secondary tidal channels are shown in figure 4.15. For methods of tide data collection refer to chapter 3, section 3.3.4. Channel cross sections in the main channel (Sites A-C) were asymmetrical and some variation in current speed and duration was observed across the four recording sites. Figure 4.16 a-d shows the results of near bed current velocity recordings at each site during spring tidal cycles with ranges >2 m. Figure 4.17 shows field measurements of near bed tidal currents mid-estuary during a neap tide with a range of 0.8 m. The negative current velocities shown on the y-axis represents the ebb phase of the tide and the positive values the flood phase. The x-axis represents one complete tidal cycle (twelve hours). Spring tidal currents have a maximum current speed of 0.75 $m.s^{-1}$ while neap tidal currents only reach a maximum of 0.2 $m.s^{-1}$. Marked inequalities were observed in terms of the duration and maximum current velocities reached in flood and ebb phases of the tide. Data from sites A-C revealed a brief but intense flood phase lasting an average of 3 hours and reaching a maximum current speed of 0.5 $m.s^{-1}$, compared to the ebb tidal phase that lasts an average of 4.5 hours and reaches a maximum current speed of only 0.3 $m.s^{-1}$. Flood tide dominance is exacerbated in the secondary tidal channel with the flood phase lasting only 1 hour and 45 minutes and reaching a maximum current speed of 0.75 $m.s^{-1}$.

Table 4.5. Tidal prism for the Haughton River Estuary at spring and neap tides.

Tide	**Tide range**	**Low tide water volume**	**High Tide water volume**	**Tidal Prism**
Maximum spring tide	3.8 m	12,337,500 m^3	44,043,750 m^3	31,706,250 m^3
Average neap tide	1 m	12,337,500 m^3	20,681,250 m^3	8,343,750 m^3

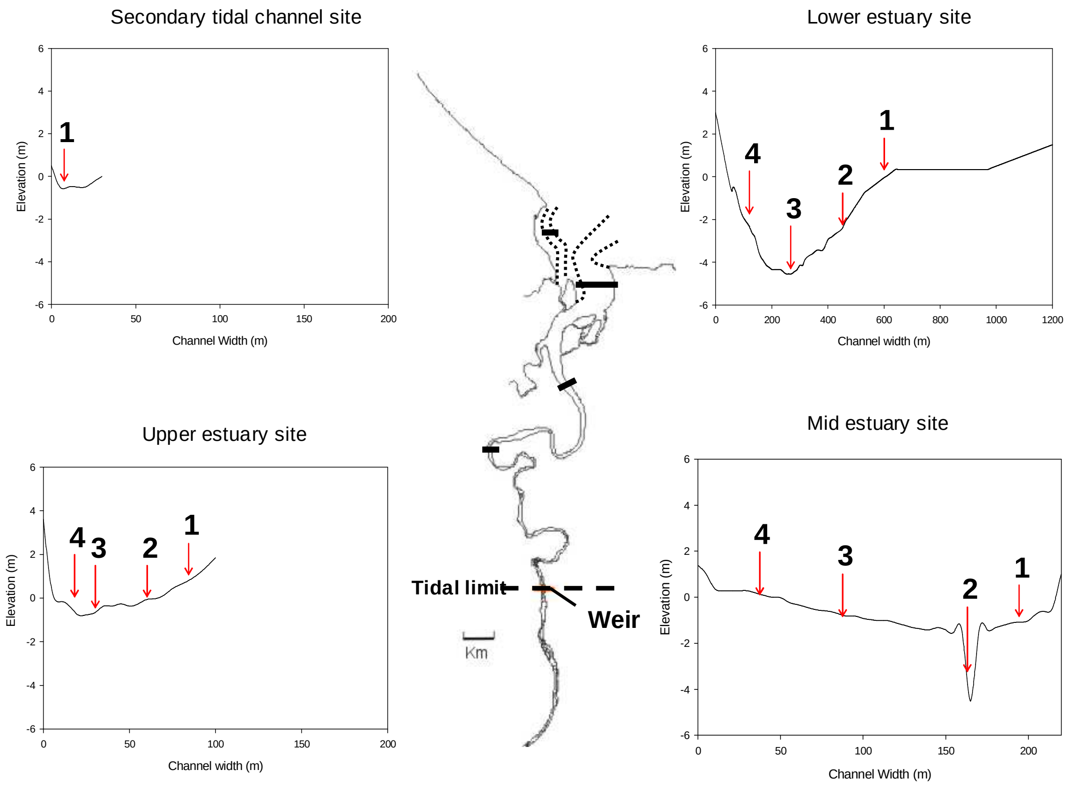


Figure 4.15. Locations and cross-sections of tidal current data collection sites, Haughton River Estuary.

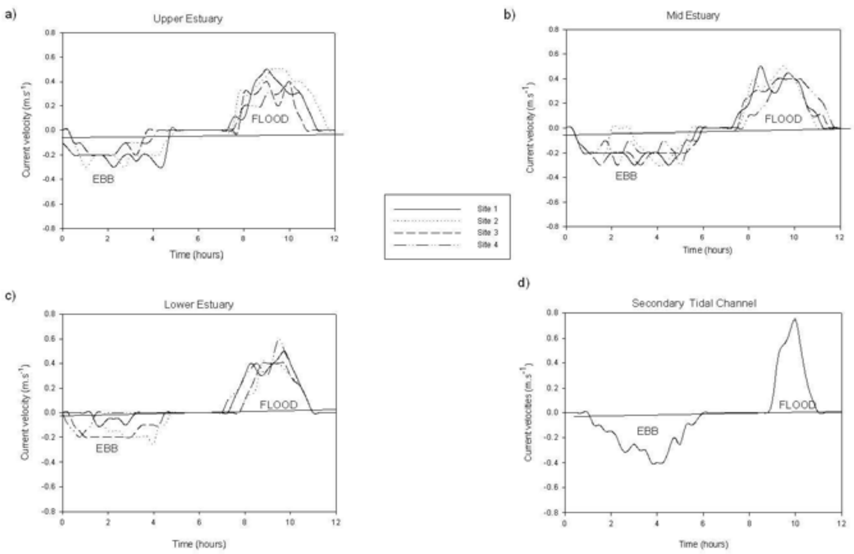


Figure 4.16 a-d. Spring tide current velocities for upper, mid and lower estuary sites and secondary tidal channel. Note: Negative current velocity values represent ebb and tide currents and positive values flood tide currents.

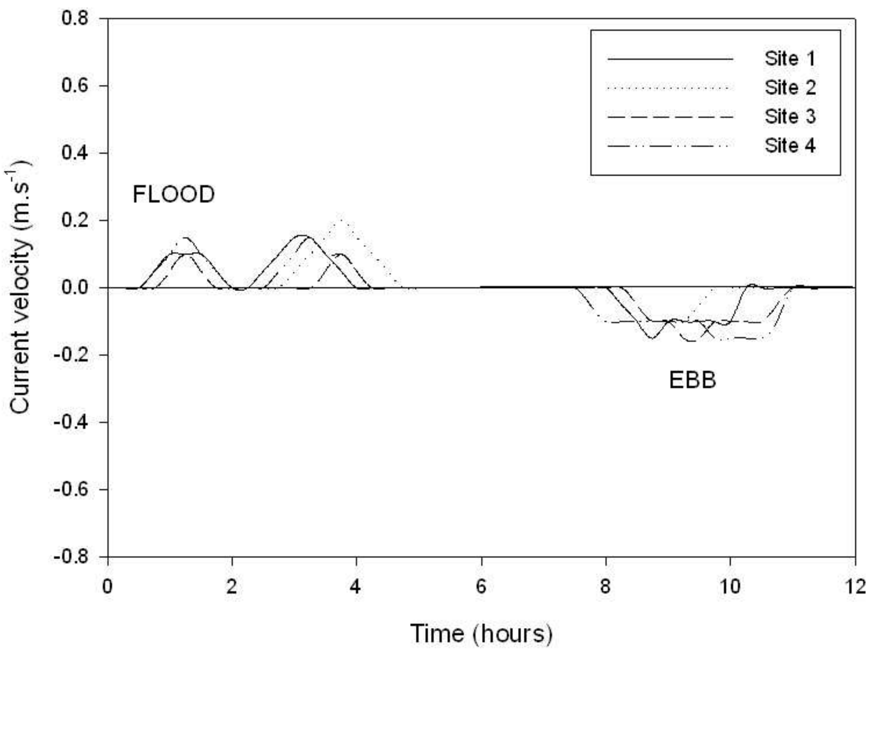


Figure 4.17. Near bed (1 m above) current velocities during a neap tide at the mid estuary site fo the Haughton River.

4.4.5 TIDAL SAND TRANSPORT MODELLING

As indicated in chapter three, section 3.3.4.2, three bedload equations (Engelund and Hansen, 1967; Gadd *et al.*, 1978; Hardisty, 1983) were used to model potential sand transport by tidal currents. Modelling of bedload transport predicts the movement for one particular grain size not the total sediment load. Equations by Gadd *et al.* (1978) and Hardisty (1983) use sediment transport thresholds from fine (0.18 mm) and medium sand (0.45 mm). The estuary is dominated by fine-medium sand with a modal grain size of 0.32 mm. As available equations do not support this exact grain size (equations support only grain sizes of 0.18 mm and 0.45 mm), the predicted volumes of fine and medium sand represent the upper and lower boundaries for transport. A sediment transport threshold of 0.16 $m.s^{-1}$ and 0.19 $m.s^{-1}$ derived from Gadd *et al.'s* (1978) equation was applied to calculate the potential volumes of fine (0.18 mm) and medium (0.45 mm) sand that could potentially be transported in and out of the estuary by tidal currents. Figure 4.18 shows that current velocities recorded during a neap tide at the mid-estuary (Site B) do not have the competency to transport fine or medium sand. Sufficient current velocities were reached during ebb and flood phases of spring tides at all four sites to transport both fine and medium sand (Figure 4.19 parts a-d). Flood tide currents during spring tides are up to five times more competent to transport fine and medium sand than ebb tidal currents, assuming a linear relationship.

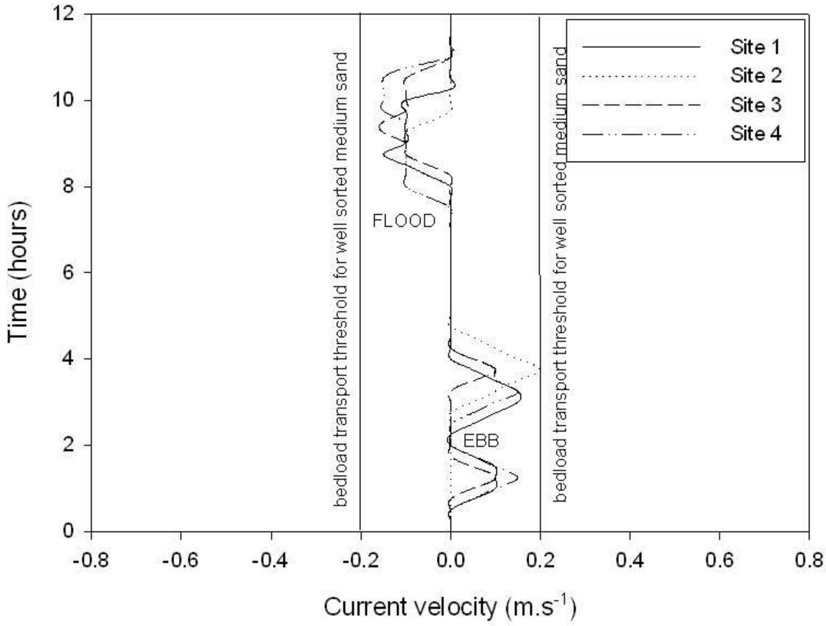


Figure 4.18. Competency of neap tide currents measured at the mid estuary site to transport bedload. Note: Negative current velocity values are flood tide currents and postive values are ebb tide currents.

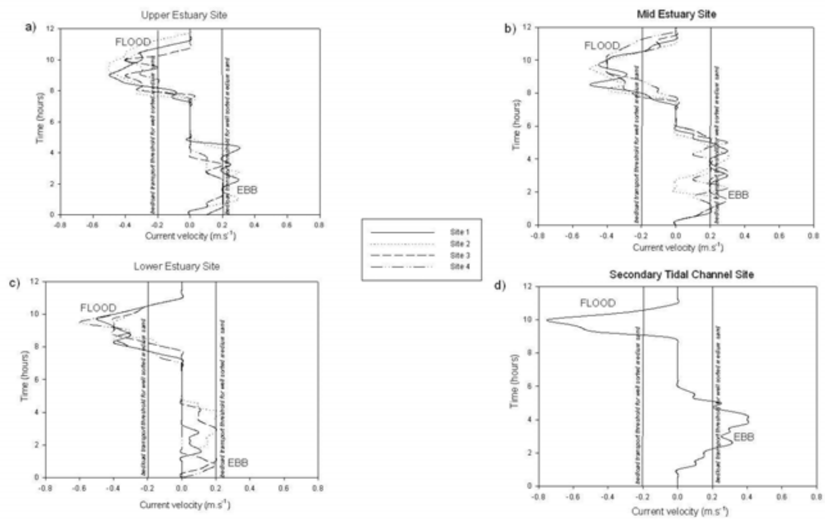


Figure 4.19 parts a-d. Competancy of spring tide currents to transport bedload for all sites. Note: Negative current velocity values are flood tide currents and positive values are ebb tide currents.

Predicted volumes of medium and fine sand potentially transported landward or seaward per spring tidal cycle using all three equations (Engelund and Hansen, 1967; Gadd *et al.*, 1978; Hardisty, 1983) are shown in figure 4.20 and 4.21. The predicted volume of medium sand does not include volumes of fine sand. Potential volumes of transport were calculated for the four recording sites across the upper, mid and lower estuary sites and secondary tidal channel and then averaged for each location. The direction of net sand transfer is clearly into the estuary due to flood tide dominance. Potentially an average of 11 times more fine sand and 18 times more medium sand is predicted to be transported into the estuary than out to sea. Figure 4.22 shows the volumes of fine and medium sand that could be potentially transported landward into the estuary per year, which ranges from 33,750 – 175,000 m^3 and 13,750 – 34,375 m^3 for fine and medium sand, respectively.

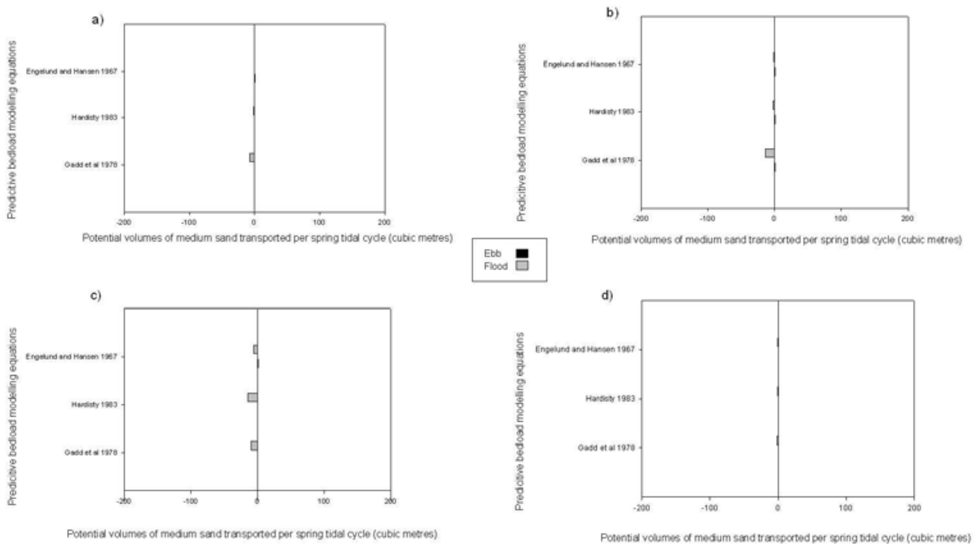


Figure 4.20 a-d. Predicted volumes of medium sand potentially transported landwards and seawards of the Haughton River Estuary per spring tidal cycle. Note: The scale of the x-axis is an order of magnitude smaller than the volumes of fine sand presented in figure 4.21.

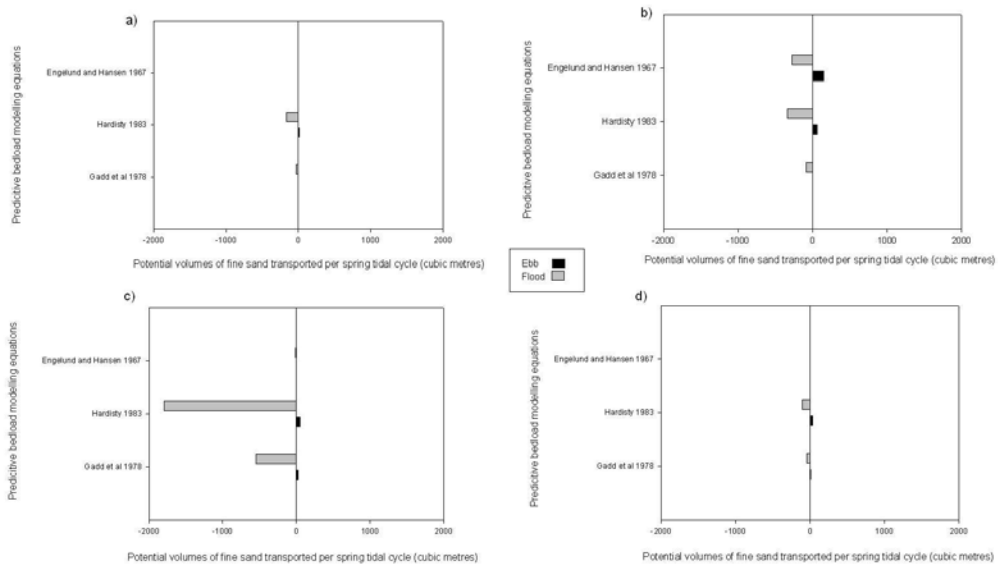


Figure 4.21 a-d. Predicted volumes of fine sand potentially transported landwards and seawards of the Haughton River Estuary per spring tidal cycle. Note: The scale of the x-axis is an order of magnitude larger than the volumes of fine sand presented in figure 4.20.

4.5 CONCLUSIONS

A conceptual model of the spatial and temporal patterns of coastal sand transfer in the Haughton River Estuary was developed based on the sedimentological, stratigraphic and hydrodynamic data collected.

4.5.1 COASTAL CHANGE

The results from aerial photo analysis revealed the dominance of tidal processes on sand transfer in the Haughton River Estuary. Previous work by Hopley and Rasmussen (1995) attribute the rapid changes on the western side of the estuary identified in section 4.2.1, to a localised cycle of erosion and deposition of coastal deposits as a consequence of the secondary tidal channel migrating across the estuary. This theory is supported by predicted volumes of fine sand transport out of the estuary. Erosion has yielded 54,000 m^3 from the Cungulla coast in the last 24 years and 60,000 m^3 of fine sand has been added to the spit between 1995 – 2000. This suggests that even though the secondary tidal channel is a flood-dominated tidal channel, ebb tidal currents are still capable of moving volumes of fine sand seawards. Predictions by Hardisty (1983) using a sediment transport threshold of 0.16 $m.s^{-1}$, suggest that ebb tides have the potential to transport 10,674 $m^3.y^{-1}$ of fine sand. This transport rate equates to 53,372 m^3 over 5 years. The remarkably similar volumes being eroded from the coast and deposited on the spit suggest that reworked coastal deposits are contained within the Bowling Green Bay coastal compartment. There is little evidence of change in other parts of the estuary with location of the eastern bank of the estuary remaining stable and the mangrove fringe becoming more established over the 60 year record.

4.5.2 BEDFORMS

The investigation of bedforms supported the conclusion that sand transfer in the Haughton River Estuary was dominated by tidal processes. Landward facing dunes and ripples flood-dominated) consistently persist at low tide, suggesting that the direction of net sand transfer is into the estuary. Bryce *et al.'s* (1998) observations of landward facing bedforms in the Normanby River Estuary were also indicative of net landward transfer of sand.

4.5.3 SEDIMENTS

The results of sedimentoligcal investigations provide further evidence that sand transfer in the Haughton River Estuary is dominated by tidal processes which results in the net landward transfer of sand. Rounded grains and low proportions of feldspars (< 5%) in the majority of samples taken from the estuary suggest the sands are mature and probably of marine origin (Friedman, 1961; Roy *et al.*, 1980). The similarities of sand characteristics throughout the estuary and the adjacent beach ridge complex suggest that a likely source for this sand is offshore reserves (Hopley, 1970a). Belperio (1978) identified large sand reserves in Bowling Green Bay which were relict deposits from when the Burdekin River discharged into the bay prior to 6 ka BP. The original source of the coarse sediment found in the upper reach of the estuarine channel seemed likely to be fluvial. However on closer inspection, the angularity of the grains and the isolation of the bar within a widened section of the channel, suggests that it was not transported there from upstream but is locally derived from scouring of the adjacent banks. This is similar to the shoals Woodroffe *et al.* (1986) identified in the tidal rivers of the Northern Territory.

Comparisons of grain size, sorting, skewness and kurtosis have failed to distinguish between sediment sampled from different environments within the Haughton River Estuary (see figure 4.13 part a-d). The outliers are commonly samples 42, 44, 45 that were taken from the discrete coarse sediment bar in the upper reaches of the estuarine channel which as discussed previously is the result of localised bank erosion. Moreover a discriminant analysis of the sediment characteristics and sampling location revealed that only 38.9% of samples were correctly classified to their environmental setting by sorting and kurtosis characteristics. The textural characteristics of the majority of the samples (> 60%) do not match their environmental setting. This supports Visher's (1969) comment that the use of grain size distributions to determine environment is problematic because the same sedimentary processes occur within a number of settings and the consequent textural response is similar. The lack of variation between samples also suggests the majority of sediments in the Haughton River Estuary may also be derived from the same source. Similarly the comparison to beach ridge sediments collected by Hopley (1970a) revealed distinct similarities between modern and past sediments, suggesting that modern surficial sediments may be the result of reworked previously deposited sediments. No fluvial sand could be identified in the sub-surface samples retrieved from the Haughton River Estuary. Bryce *et al.* (1998) results show less than 1% terrigenous sand in the cores from the Normanby River Estuary, suggesting that both estuaries have been infilling with marine sand.

Sub-surface sediments (up to 2.6 m below AHD) collected from the river mouth revealed a similar pattern of marine sedimentation over at least the last 1 ka. The results of a conventional radiocarbon date from mangrove peat 1035±105 years BP CAL at 2.6 m below AHD (Wk10904, atmospheric data from Stuiver *et al.*, 1998; OxCal v3.5 Bronk Ramsay, 2000) suggest that the estuary has been infilling with medium to fine marine sand at an average rate of 2.5 $mm.y^{-1}$ over the last 1 ka. While the shells dated at 0.8 m below AHD were dated at more than twice that of the peat at 2378±73 years BP CAL (Wk10905, marine data from Stuiver *et al.*, 1998; Delta_R 10±7; OxCal v3.5 Bronk Ramsay, 2000), this date must be interpreted in context. The age was derived from a bulk sample of a number of different shell fragments indicating reworking. Therefore, while the organisms may have died over 2 ka BP their shells were probably buried many years after. However it is reasonable to believe that the mangrove peat is in situ and evidence of minimal bioturbation through all the cores provides further assurance that this date is reliable. Consequently average sedimentation rates are inferred from the mangrove peat date rather than the shells.

4.5.4 TIDAL SAND TRANSFER

Measurements of near bed tidal currents during spring tides show that both ebb and flood currents have the competency to transport medium to fine sand (0.32 - 0.20 mm). However, maximum near bed flood currents are five times more competent to move sediment than the ebb currents, suggesting that the direction of net sand transfer is into the estuary. Larcombe and Ridd (1995) compared predictions from these same equations with actual measurements of bedload transport in a tidal mangrove creek, Gordon Creek near Townsville, and found that overall the predictions of sediment transport were good. The large disparity between the predictions of the three equations is common to other studies (Larcombe and Ridd, 1995). The predicted volumes in this study showed a similar pattern to the results from Larcombe and Ridd (1995) with the volumes predicted, using Gadd *et al*.'s, (1978) equation, several orders of magnitude larger than that predicted by the other two equations. The predictions derived from Hardisty's (1983) equation were considered the most accurate, given the results of Larcombe and Ridd's (1995) experiments. Predictions using Engelund and Hansen (1967) equation were much lower than the volumes predicted using the other equations, probably due to the relatively low tidal current velocities occurring in the Haughton River Estuary compared to those upon which the equation was originally derived. In this study the calculation of Gadd *et al's.* (1978) and Hardisty's (1983) equations were based on sediment thresholds from Guy *et al.* (Guy *et al.*, 1966) which are derived from flume measurements of bedload transport (0.16 $m.s^{-1}$ for fine sand and 0.19 $m.s^{-1}$ for medium sand) and agree with the widely used Hjulstrom (1935) curve. However Larcombe and Ridd (1995) use a much higher threshold velocity for medium sand of 0.4 $m.s^{-1}$ based on a regression analysis of the results from actual measurements of megaripple migration in Gordon Creek. Recalculation of Gadd *et al.* (1978) and Hardisty (1983) formulas for medium sand using the threshold velocity of 0.4 $m.s^{-1}$ still shows a net landward transfer of medium sand into the estuary but at much lower volumes (see table 4.6). Using the higher sand transport threshold resulted in predictions of no seaward transfer of medium sand as ebb tide velocities did not reach the sediment transport threshold of 0.4 $m.s^{-1}$.

Table 4.6. Results of sand transport modelling for medium sand using equations from Engelund (1967), Gadd *et al*. (1978) and Larcombe and Ridd (1995).

	Upper Estuary Site (kg per spring tide)	**Mid Estuary Site (kg per spring tide)**	**Lower Estuary Site (kg per spring tide)**	**Secondary Tidal Channel (kg per spring tide)**
Gadd *et al*. (1978) using sand (0.45 mm) transport threshold of 0.19 $m.s^{-1}$ (Guy, 1966)	12081.85	20931.36	151137.56	13489.00
Gadd *et al*. (1978) using sand (0.45 mm) transport threshold of 0.4 $m.s^{-1}$ (Larcombe and Ridd, 1995)	166.35	115.03	4617.96	2779.56
Hardisty (1983) using sand (0.45 mm) transport threshold of 0.19 $m.s^{-1}$ (Guy, 1966)	1734.07	3337.66	22791.68	885.85
Hardisty, (1983) using sand (0.45 mm) transport threshold of 0.4 $m.s^{-1}$ (Larcombe and Ridd, 1995)	820.80	822.38	8143.20	812.70
Engelund (1967) for mean grain size of 0.45 mm (no transport threshold data was used in the equation)	492.10	754.65	8236.00	64.80

Like Larcombe and Ridd (1995) the predictions derived from the Hardisty (1983) equation were chosen as the most likely representation of sand transfer volumes in the Haughton River Estuary, however the lower sediment transport thresholds of Guy *et al.* (1966) were used. Potential volumes of annual sand transfer into the estuary were extrapolated from the predictions for one tidal cycle and are used in the following conceptual model. Extrapolating the predictions from one tidal cycle over 12 months compounds the error already associated with these predictions. For example Larcombe and Ridd (1995) found a strong diurnal inequality in tides measured close to Townsville. However as this data is not available in this study, the estimated volumes of sand that could potentially be transported into the estuary are presented to indicate the order of magnitude rather than absolute figures.

Hydrodynamic and bedload modelling investigations suggest that the secondary tidal channel in the Haughton River Estuary is flood dominated. Tide-dominated estuaries in the literature are often reported as having mutually exclusive tidal channels (one flood and one ebb dominated) (Dalrymple *et al.*, 1992; Heap *et al.*, 2001), however in the Haughton River Estuary both tidal channels are flood dominated. Hopley and Rasmussen (1995) previously identified this channel as ebb dominated based on morphological evidence. As previous classifications of tide-dominated estuaries have been derived from studies of macro-tidal estuaries, the meso-tidal range of the Haughton River Estuary may contribute to this anomaly. Other variations from the literature description of a tide-dominated estuary have been noted in the Haughton River Estuary, for example the lack of a well-developed funnel-shaped mouth commonly associated with tide-dominated systems in macro tidal settings (Wright and Coleman, 1973; Woodroffe *et al.,* 1986). Indeed, Bryce (2001) attributed the lack of a well-developed funnel-shaped mouth in other tide-influenced systems of tropical north-east Queensland to their meso-tidal setting.

4.5.5 CONCEPTUAL MODEL OF SAND TRANSFER

The resultant conceptual model (Figure 4.22) incorporates these findings over contemporary and evolutionary time scales. The sand delivery rates used in this model were calculated for the Haughton River using discharge data from the Powerline gauge and modelling software (MIKE II) based on Ackers and White (1973) equations (Kinhill *et al.*, 1996). The use of these figures are far from ideal due to the error associated with using yearly averages in highly variable discharge rivers, like the Haughton River (Hean and Nanson, 1987). Thus, these figures must be taken as ‘potential’ amounts of bedload transport given that the availability of sand is limited and that the short duration of flooding and morphology of the channel are not conducive to transporting sand into the estuary (see section 4.3), even during flood events (ARI > 20 years). Indeed only 2% of the estimated potential sand load at Powerline Gauge is modelled to reach the estuary. That any sand is delivered to the estuary may be an overestimate considering that deposits of fluvial sand could not be identified downstream of the tidal limit, with the only coarse sand derived from local bank scour and not transported from upstream (see section 4.3.3). Despite the questionable accuracy of these figures, they demonstrate that a relatively minor proportion of fluvial sand is potentially delivered to the estuary from upstream compared to the potential influx of marine sand by flood tide currents.

Indeed the dominance of tidal processes is further evidenced by the comparison of tidal and fluvial discharges. The exchange of over 30 million cubic metres of water at maximum spring tide (range of 3.8 m, see table 4.5), which occurs three times a year, produces a discharge of 2936 $m^3.s^{-1}$ over a 3 hour flood tide phase. Only four fluvial events (1971/2 – 3964 $m^3.s^{-1}$, 1977/8 – 3865 $m^3.s^{-1}$, 1990/1 – 3547 $m^3.s^{-1}$ recorded at the Powerline Gauge) have exceeded that discharge since 1971.

While tidal sand transport figures are also predictions of the ‘potential’ volume of medium to fine sand that could be moved into the estuary by flood tidal currents, given that the sand supply is unlimited and energy is only partially limited, these figures could be quite conservative. The two most likely sources of the fine to medium marine sand that dominates the estuary are relict reserves of Burdekin River sand or adjacent beach ridge deposits. Belperio (1978) identified major reserves of terrestrial sand offshore of the Haughton River and interpreted them as deposits from the Burdekin River when it discharged in to Bowling Green Bay prior to 6 ka BP (Hopley, 1970a). Additional sources of sand include the reworking of coastal deposits. For example increased significant wave heights associated with tropical cyclones may increase erosion of the lower Haughton Estuary as reported during Cyclone Althea, December 1971 (Hopley and Rasmussen, 1995). The frontal dunes of the adjacent beach ridge complex are showing signs of erosion with notable scarping (Figure 4.23). Truncation of the southern end of the beach ridge complex indicates reworking of these coastal deposits by tidal and perhaps wave processes in the past and present (Hopley and Rasmussen, 1995).

Predictions of contemporary sand transfer processes must be interpreted in the context of the evolution of the estuary. Sub-surface sediment analysis and radiocarbon dating (see section 4.3.3) suggest that the estuary has been infilling with medium to fine sand at an average rate of ~2.5 $mm.y^{-1}$ for the last 1 ka. Over the area of the lower estuary that rate equates to an average influx of 20,650 m^3 per year, which is four times the volume predicted using Hardisty’s (1983) equation (sediment transport threshold of 0.19 $m.s^{-1}$) and similar to the predictions using Gadd *et al.’s* (1978) equation (sediment transport threshold of 0.19 $m.s^{-1}$) for medium sand. Predictions of the annual influx of fine sand into the lower estuary are nine and 28 times greater than this using Gadd *et al.’s* (1978) (sediment transport threshold of 0.19 $m.s^{-1}$) and Hardisty’s (1983) (sediment transport threshold of 0.19 $m.s^{-1}$) equations respectively. However predictions using Engelund and Hansen’s (1967) equation were an order of magnitude lower than the estimated annual influx of 20,625 m^3. Predictive bedload modelling in the Normanby River estuary suggest a landward influx of medium sand at a similar rate of 17,500 $m^3.y^{-1}$ (Bryce *et al.*, 1998). Predictive bedload modelling together with the lack of coarse, poorly-sorted, angular sediments within the estuary suggests that the relative proportion of sediment derived from the Haughton River is minor compared to the influx of marine sediment. The data suggests that the modern Haughton River Estuary is a sink for marine sediment. The conceptual model fits Dalrymple *et al.* (1992) model for estuaries as long-term sediment sinks infilling with sediment since drowning following the Holocene marine transgression (chapter 2, see section 2.2).

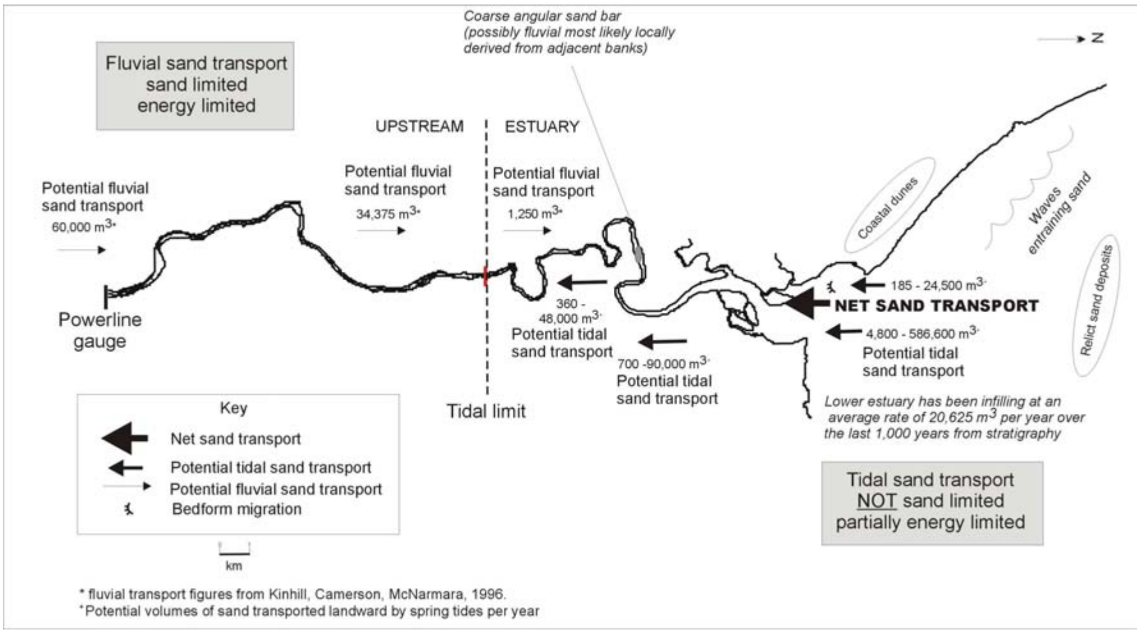


Figure 4.22. Summary diagram of net sand transport trends at the Haughton River Estuary as indicated by bedform orientations, grain size patterns and dominant current directions. Flood tide currents are the most dominant, hence net estuarine sand transport direction is into the estuary.

Figure 4.23. Erosion scarp (~2m high) on frontal dunes of beach ridges adjacent to the Haughton River Estuary (07/03/01).

CHAPTER 5 – ADDING WAVES TO THE EQUATION: THE ELLIOT RIVER ESTUARY.

5.1 INTRODUCTION

The Elliot River Estuary is a good example of coastal system influenced by waves and tides. The results of the aerial photograph analysis, sedimentological and hydrodynamic studies of the Elliot River Estuary are presented and briefly discussed in this chapter (see chapter seven for a more detailed discussion). Contemporary and evolutionary patterns and processes of sand transfer are inferred from the results and presented in a conceptual model. Comparisons are drawn with the results from the Haughton River Estuary (chapter four).

5.2 GEOMORPHOLOGY

The Elliot River is located ~200 km south of Townsville (Figure 5.1). The physical attributes of the system are summarised in Table 5.1. The Elliot River is 40 km long and drains a catchment area of 478 km^2. Compared to the Haughton River, the Elliot River has a comparatively gentle descent to the coast (fluvial reach 0.0064; estuarine reach 0.0025). The mouth of the Elliot River estuary is constricted by the rapid growth of sand spits from the north-west and a 4.25 km long sand barrier complex to the south east. The estuary is dominated by sandy sediments with large flood and ebb tidal deltas. Directly adjacent to the mouth of the Elliot River is Cape Upstart, a sub-circular granitic outcrop joined to the mainland by a tombolo that consists of a double barrier complex. The Elliot River is thought to have contributed large volumes of sand to the tombolo in the past (see appendix G) (Hopley, 1970a). The creation of the tombolo changed the hydrodynamic conditions in both Abbot and Upstart Bay.

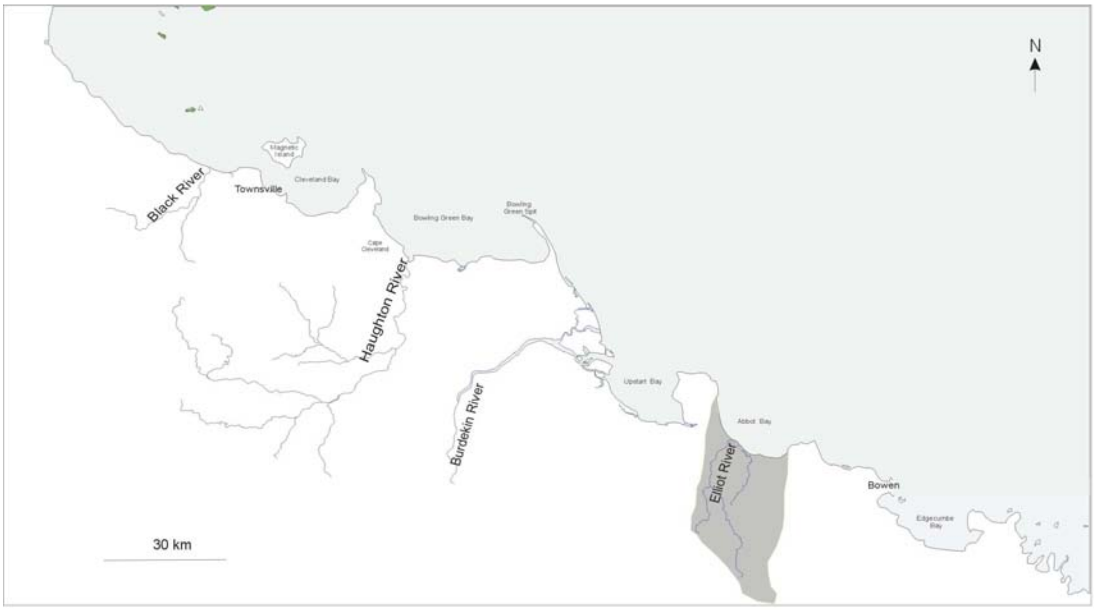


Figure 5.1. The Elliot River catchment.

Table 5.1. Physical characteristics of the Elliot River Estuary

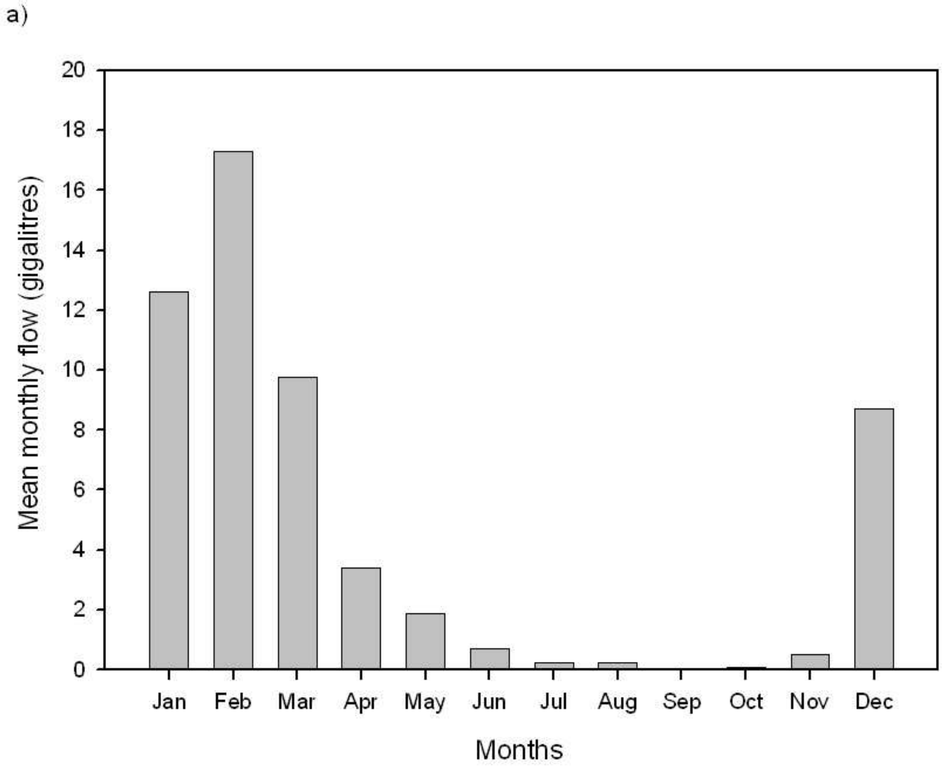
Catchment area	478 km^2
Channel length	40 km
Channel width	100-375 m
Slope	Fluvial reach: 0.0064 Estuarine reach: 0.0025
Sinuosity	1.3
Percentage of channel estuarine	5%
Mean annual rainfall	1022 mm
Modifications	Nil

5.3 SETTING

Like the Haughton River, the Elliot exhibits the typical characteristics of an extremely variable discharge stream (chapter 2, section 2.3). Table 5.2 summarises the flood gauge data used in Figure 5.2 which illustrates the marked intra and inter-annual variability of stream flow in the Elliot, with ~93% of total stream flow occurring between December and April. Seventy-nine percent of annual stream discharges registered below a quarter of the maximum annual flow with several years recording almost no flow at all. Typical of other SWT streams, floods are episodic and flashy (Figure 5.3) and result in over bank flooding.

Table 5.2. Summary of stream flow characteristics for the Elliot River Estuary.

Gauging station	Guthalungra
Distance from stream mouth	7.5 km
Catchment area at gauging station	273 km^2
Gauged area/catchment area	94%
Available records	1973-2001
Maximum annual flow volume	360,000 ML in 1991
Minimum annual flow volume	2,200 ML in 1987
Maximum instant discharge	1430 $m^3.s^{-1}$ in March 1988
Maximum period of no flow	7 months in 1995/96



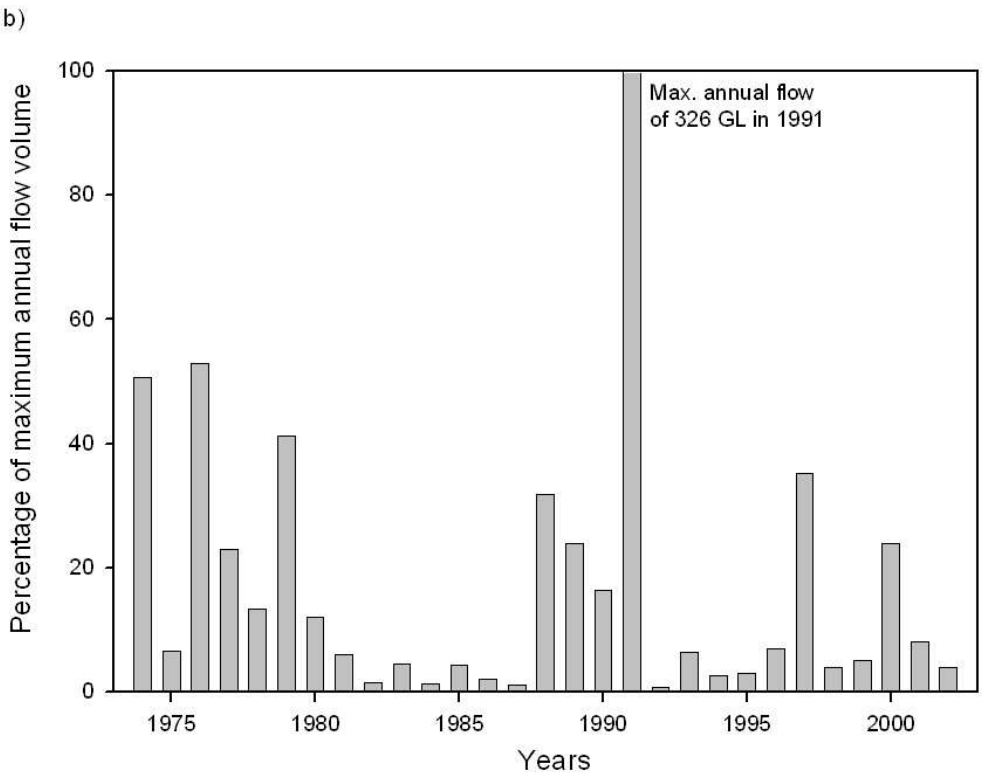


Figure 5.2. Stream flow characteristics for the Elliot River recorded at the Guthalungra gauge from 1974-2002 (DNR, 2002), mean monthly flow volumes (a) and annual flow volumes shown as a percentage of the maximum flow volume (b).

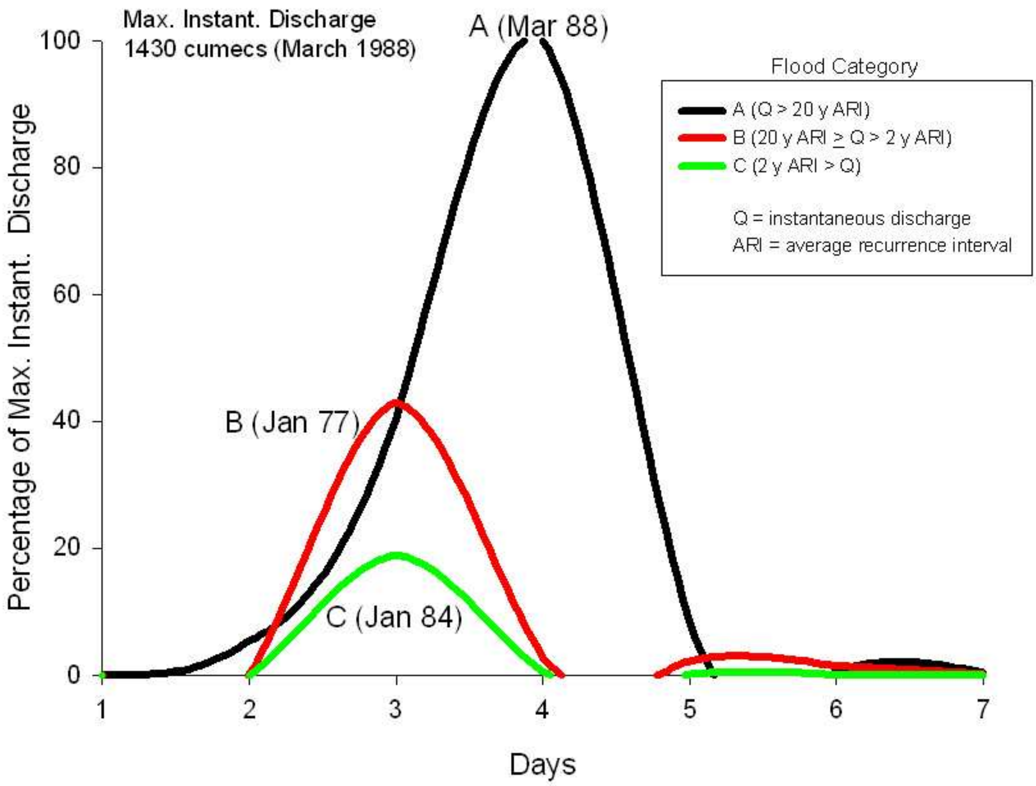


Figure 5.3. Flood hydrograph for the Elliot River recorded at the Guthalungra gauge.

Waverider buoy data collected off Abbot Point represents wave conditions offshore of the Elliot River Estuary. Modal significant wave height ranges from 0.2 - 0.4 m. However for 75% of observations significant wave height ranged from 0.2 – 0.8 m (BPA, 1996a), creating higher energy wave conditions than experienced in Bowling Green Bay. Though still classed as meso-tidal, the Elliot is subject to a smaller maximum spring tide range than the Haughton, of 3 m (Queensland Transport, 2003).

5.4 RESULTS

5.4.1 COASTAL CHANGE

Figure 5.4 shows the position of the coastline from Cape Upstart to Mt Curlewis recorded on aerial photographs taken in 1942, 1974 and 1998. The coastline was taken as the high tide mark. For a discussion of the errors associated with photogrammetry see chapter 3, section 3.4.1. The coastline north west of the mouth has been relatively stable, however rapid progradation and retreat has occurred in other areas. Measurements of coastline position at transects 250 m apart (Figure 5.5) adjacent to the river mouth indicate a complex pattern of retreat and progradation over the 56 years between 1942 and 1998. Measurements of progradation and retreat along each transect from 1942 - 1974 and 1974 - 1998 are illustrated in figure 5.6.

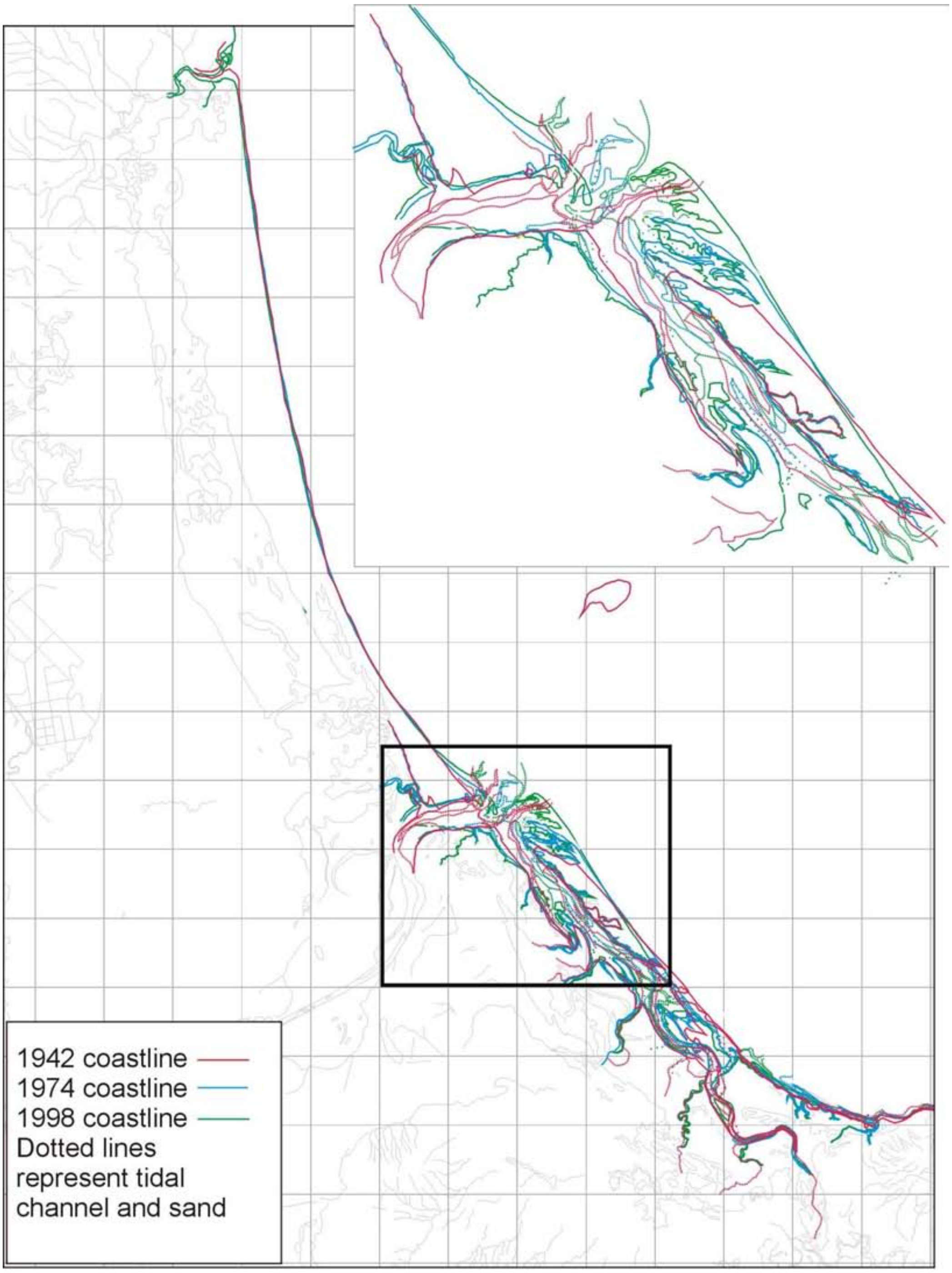


Figure 5.4. Changes in the position of the coastline from Cape Upstart to Mt Curlewis from 1942-1998. Each square on the grid represents 1 km^2 and the vertical lines indicate north.

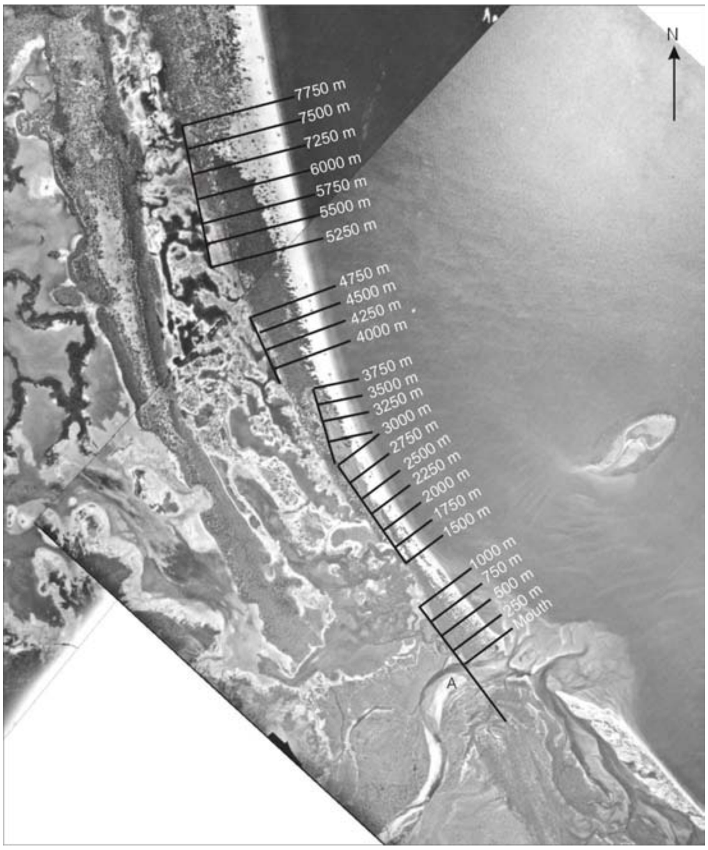


Figure 5.5. Location of transects from which coastal change measurements were derived. 1942 aerial photograph of the Elliot River Estuary. 'A' indicates the location of bedforms shown in figure 5.9.

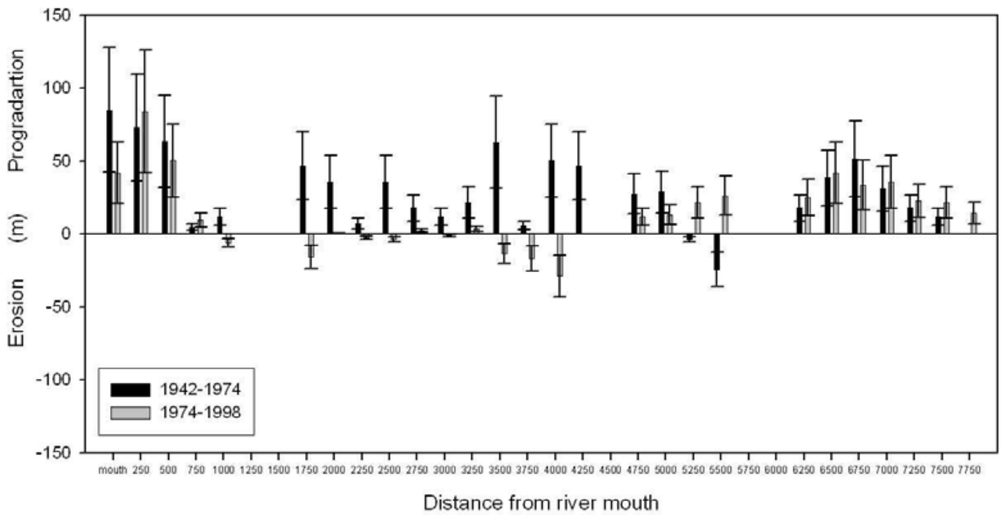


Figure 5.6 Shoreline progradation and retreat along the Elliot River Estuary measured from 1974 and 1998 aerial photographs. Standard error of measurement estimated at 6 m for 1:12,000 scale photography. (See figure 5.5 for locations of transects).

The highest rates of coastline advance occur directly adjacent to the mouth of the Elliot River. This section of coast prograded an average of 59 m from 1974 - 1998, an average annual rate of 2.4 m between 1974 - 1998. The mid section of the coastline between the mouth and Cape Upstart (from 2 - 5 km) is very dynamic and has prograded an average of 32 m or at a rate of 1 $m.y^{-1}$ between 1942 - 1974. This rapid advance was followed by a retreat along this whole 3 km stretch of coast in more recent years (1974 - 1998). The area 5.5 km north of the river mouth eroded 24 m from 1942 - 1974 and has since recovered, prograding 26.4 m during the subsequent 24 years to 1998. The rest of the coast close to the Cape (6-7.5 km from the mouth) has steadily prograded from 1942 - 1998, advancing an average of 50 m from 1942 - 1998 or at a rate of 0.9 $m.y^{-1}$ adding to the Holocene barrier system which has accumulated over the last 5 ka.

The north-west bank of the estuary mouth has eroded an average of 60 m since 1942. Approximately 11,300 m^3 (calculated by assuming a conservative height value of 1 m, see chapter 3, section 3.4.1) of sand has been added to the coastline directly adjacent to the river mouth from 1974–1998, building the coast out to 84 m. A small recurved spit extending from this coastline appears in the 1974 photograph and has continued to grow across the mouth until the 1998 photograph.

The position and morphology of the barrier spit at the mouth of the estuary has changed rapidly since it was completely detached from the coast in 1991. Local residents believe that this is associated with a flood in February 1991, estimated to be a 1 in 60 year event, however it is also possible that wave action caused the breach. This breach led to the erosion of an estimated 36,360 m^3 of sand from the end of the spit between 1991 and 1998, as well as the addition of an estimated 38,736 m^3 of sand to the front of the spit since 1991. Comparison of aerial photographs (Figure 5.7 part a-c) reveals the impact of the February 1991 flood event on the estuary. Pre-flood photographs available from 1985 were compared with post flood photographs taken five months after the February 1991 event. The post-flood 1991 photographs show the sand barrier detached from the shore (Figure 5.7 part b). In the main channel little change was noticed initially but in subsequent photographs sand is building up in the mouth and an ebb tidal delta formed at the breach. The 1998 photograph shows accretion at the front of the barrier extending across the estuary mouth (Figure 5.7 part c). Figure 5.8 part a-c is a schematic model showing the impact of the February 1991 flood on the estuary. It is likely that sand from the breached end of the barrier is the source of the sand added to the front of the barrier.

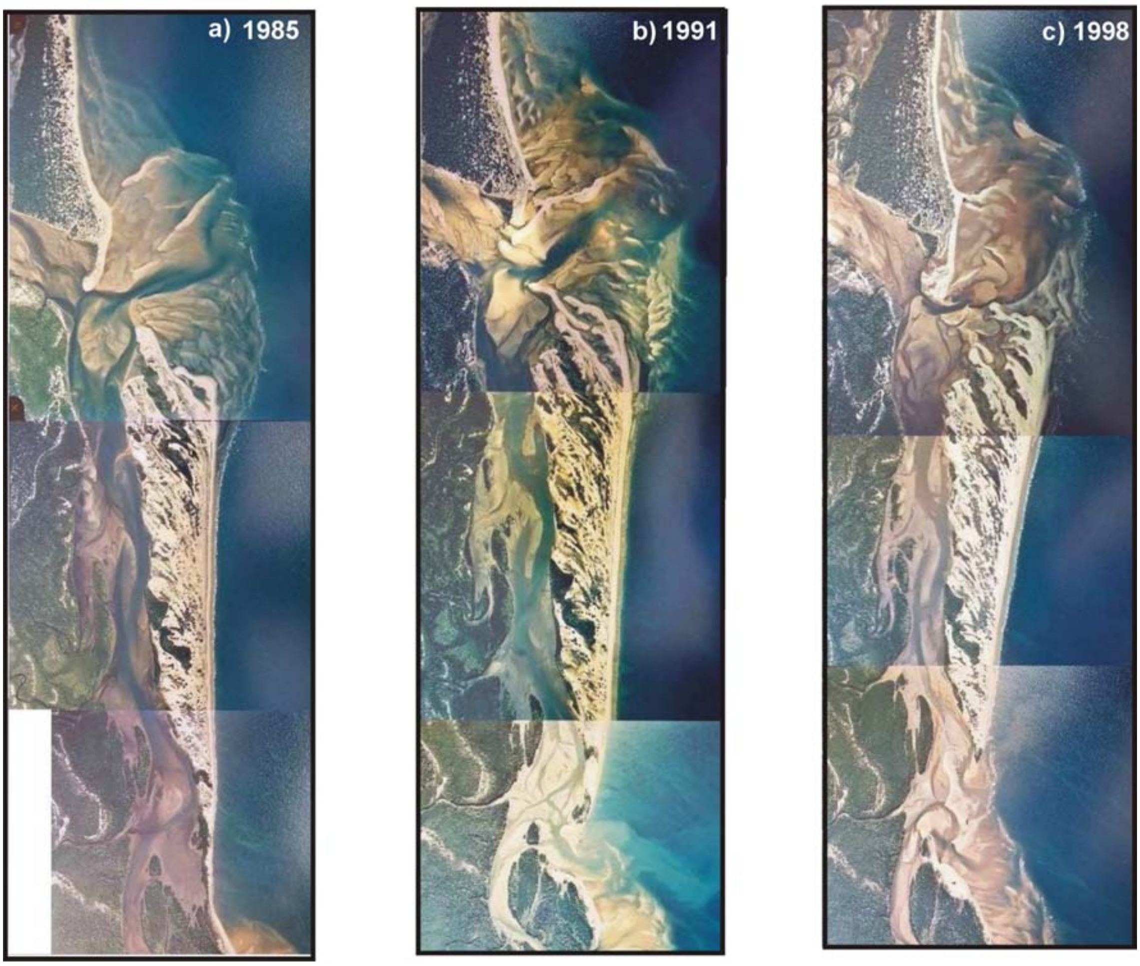


Figure 5.7 a-c. Vertical aerial photographs of the Elliot River Estuary which were used to develop figure 5.8 a-c. Copyright: The State of Queensland (Department of Natural Resources and Water) 1985 (a), 1991 (b), 1998 (c).

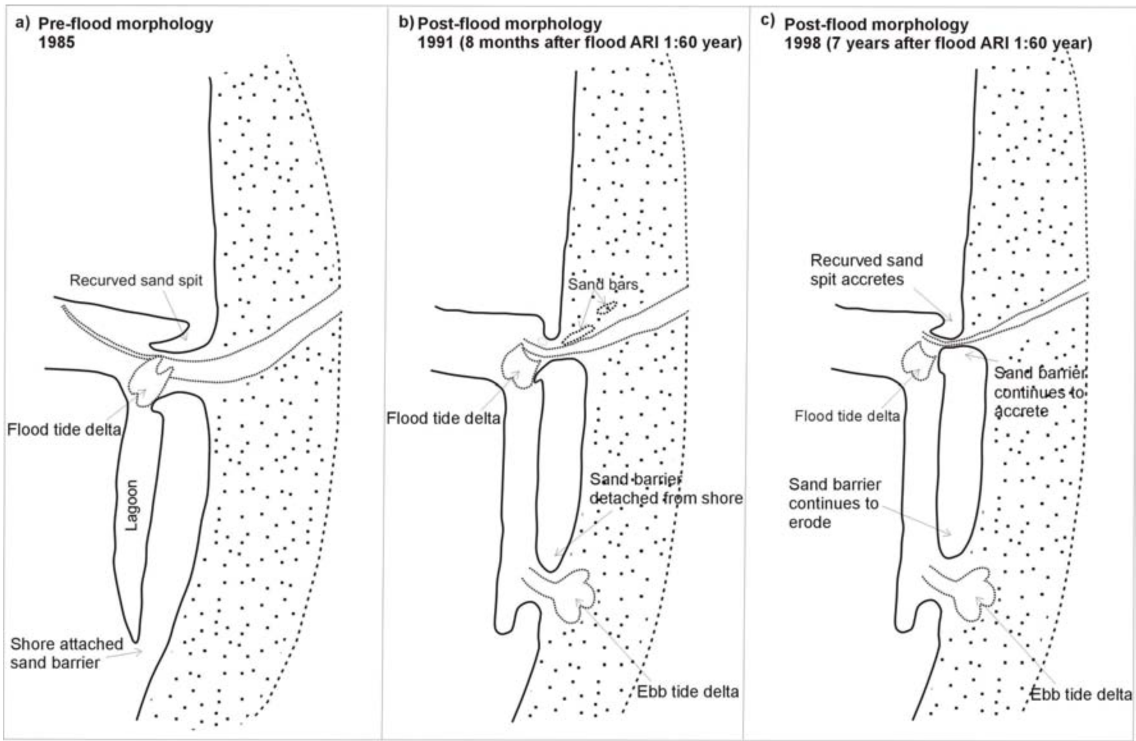


Figure 5.8 a-c. Schematic model illustrating the impact of a flood (ARI 1:60 year) on the morphology of the Elliot River Estuary.

5.4.2 BEDFORMS

Shoreward facing ripples averaging 5 cm in height with wavelengths of 40 cm were observed at low tide in the lower estuarine channel (Figure 5.9). Megaripples up to 0.2 m in height with wavelengths of 5 m were observed at low tide along the landward side of the barrier. These megaripples were orientated to the south east towards the end of the barrier.

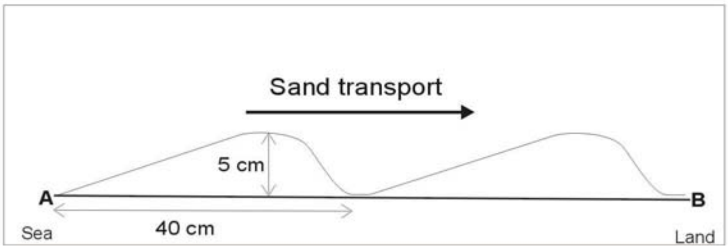


Figure 5.9. Current ripples observed at low tide at the Elliot River Estuary indicate sand transport into the estuary. Location marked as 'A' on figure 5.5.

5.4.3 SEDIMENTOLOGY

Ninety-nine surficial sediment samples and four vibrocores which penetrated 3.2 m below AHD, were collected from the Elliot River Estuary and the adjacent coastline. The locations of surficial samples and vibrocores are shown in figure 5.10. Figure 5.11 provides a summary of the results of textural analysis of the surficial samples (see Appendix D) showing the spatial distribution of facies. Sediment within the study area ranges from very coarse sand (grain size of 1 - 2 mm) to fine sand (grain size of 0.125 - 0.25 mm) with silty fine sand offshore (Figure 5.11). Silty sand deposits appear universally associated with dense seagrass meadows and thus likely to reflect the effect of baffling and binding (Perry, 1999). Moderately sorted very coarse (1.138 mm) – coarse sand (0.769 mm) is predominant in the fluvial and estuarine reaches of the channel, the barrier spit and occurs offshore of the adjacent coast. Angular very coarse gravel (~32 mm) densely overlies the very coarse sand (1.138 mm) in the fluvial reaches (Figure 5.12) and then intermittently throughout the estuarine channel (Figure 5.13). An isolated deposit of very coarse sand (1.226 mm sample 48) is found about 500 m offshore from the middle of the coastline (3.5 km transect). Onshore sediment deposits become finer and better sorted on the adjacent coast with well sorted medium (0.357 mm) to fine (0.208 mm) sands up to Cape Upstart. However, an isolated section of coarse sand (0.559 mm sample 30) was found on the shore about 7.25 km north of the estuary mouth. Despite a northward fining trend in the nearshore sediments <500 m further off the coast, coarse sediment is consistently found along the coast until just south of Cape Upstart. Concentrated wave energy on this section of coast may explain the anomalous presence of coarse and very coarse sediment deposited in the nearshore area (Figure 5.14). Sub-angular to sub-rounded grains were found in all size ranges.

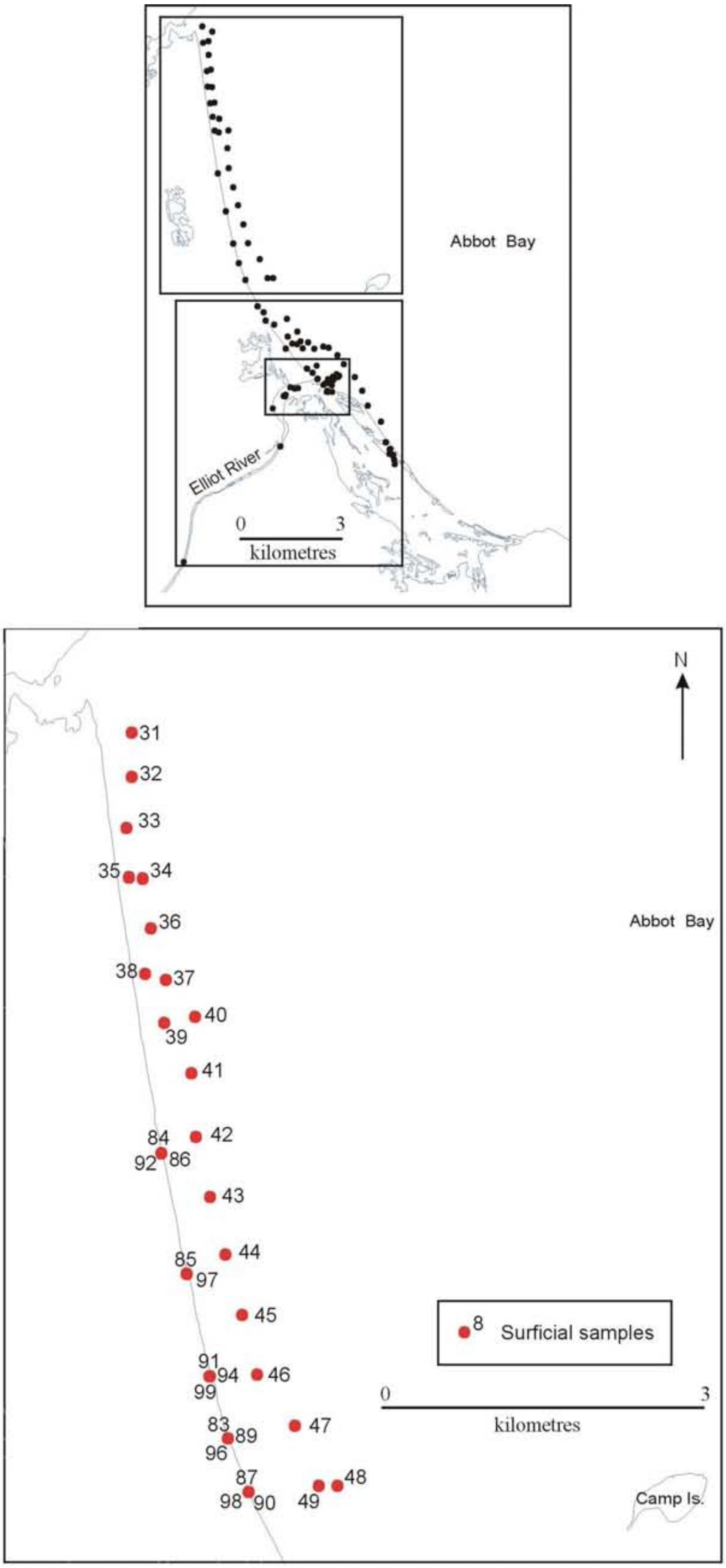


Figure 5.10 a. Locations of surficial and subsurface sediment samples taken at the Elliot River Estuary. (See Appendix D for the results of the textural analysis of samples).

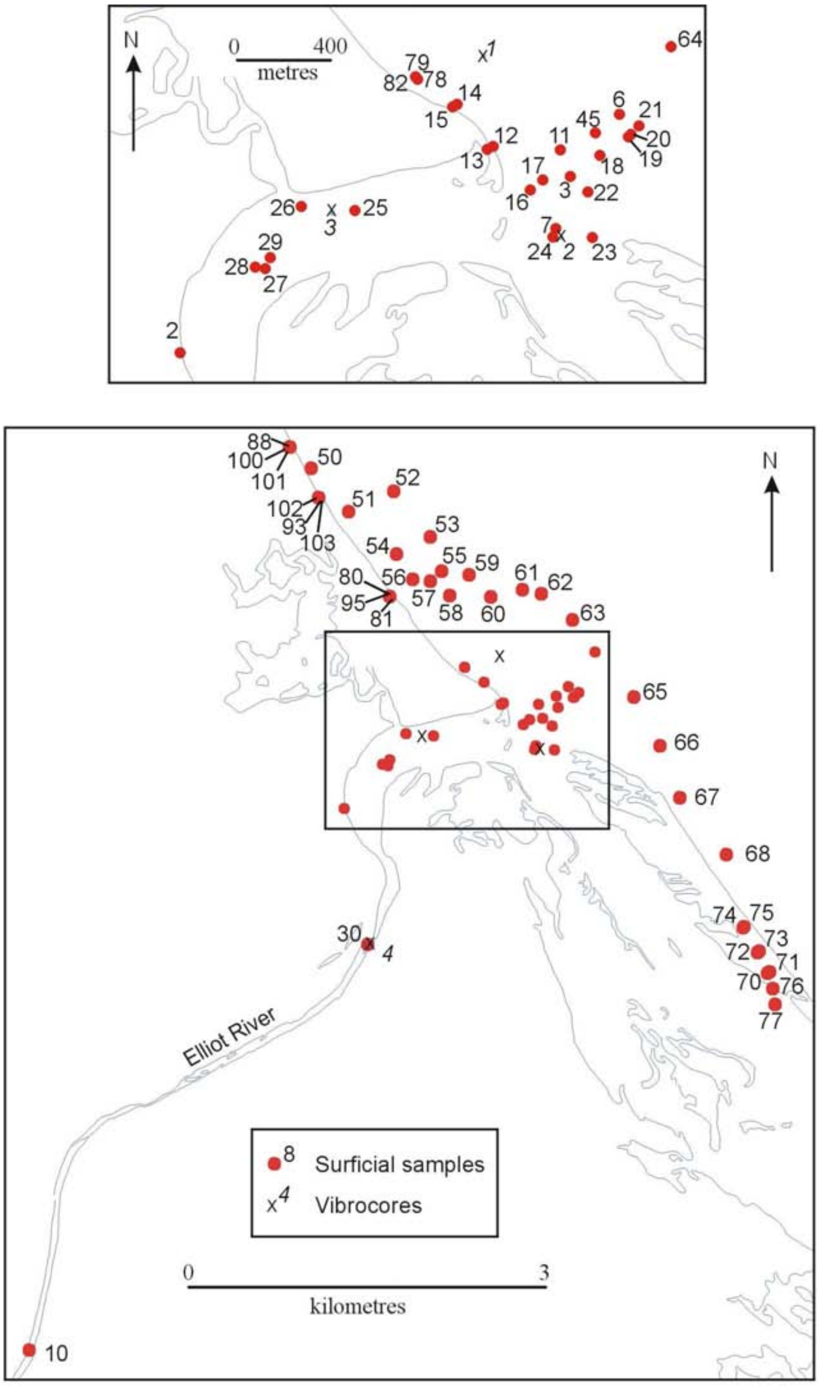


Figure 5.10 b. Locations of surficial and subsurface sediment samples taken at the Elliot River Estuary. (See Appendix D for the results of the textural analysis of samples).

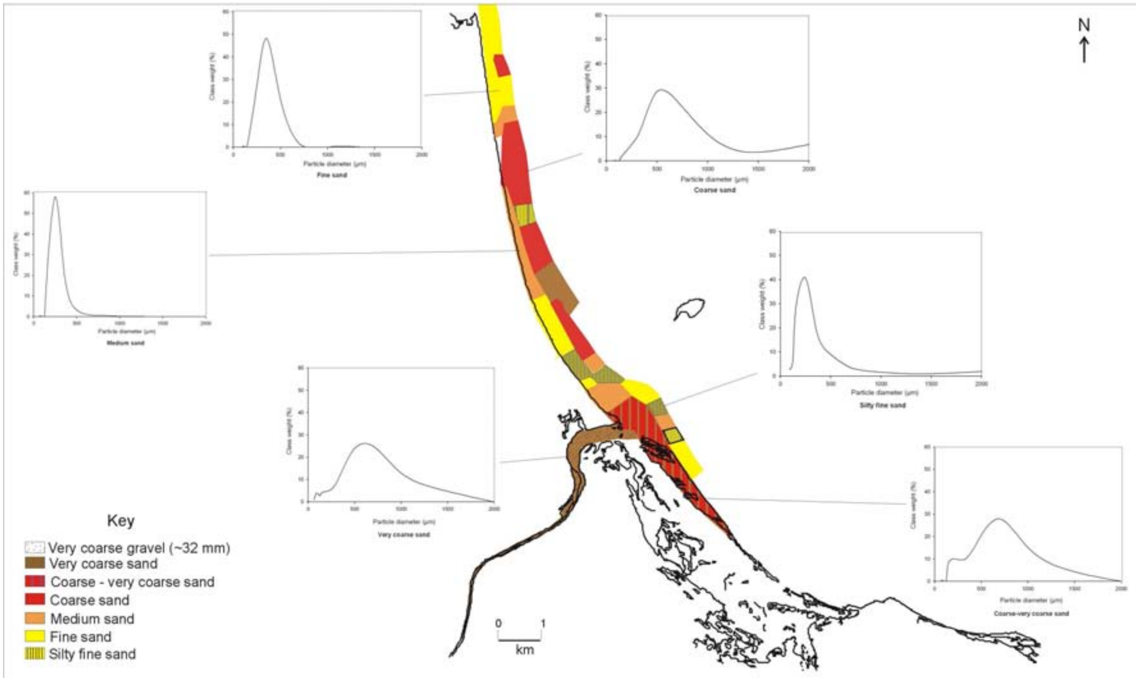


Figure 5.11. Summary of the results of textural analysis of surficial samples from the Elliot River Estuary. Histograms show the distribution of a typical example of each sediment class.

Figure 5.12. Angular coarse gravels densely overlay the very coarse sands in the fluvial reaches of the Elliot River. Photograph taken (07/03/02) looking downstream from the Bruce Highway Bridge.

Figure 5.13. Angular very coarse gravels overlay very coarse sand to a lesser extent in the estuarine reaches of the channel. Photograph taken (07/03/02) looking seawards.

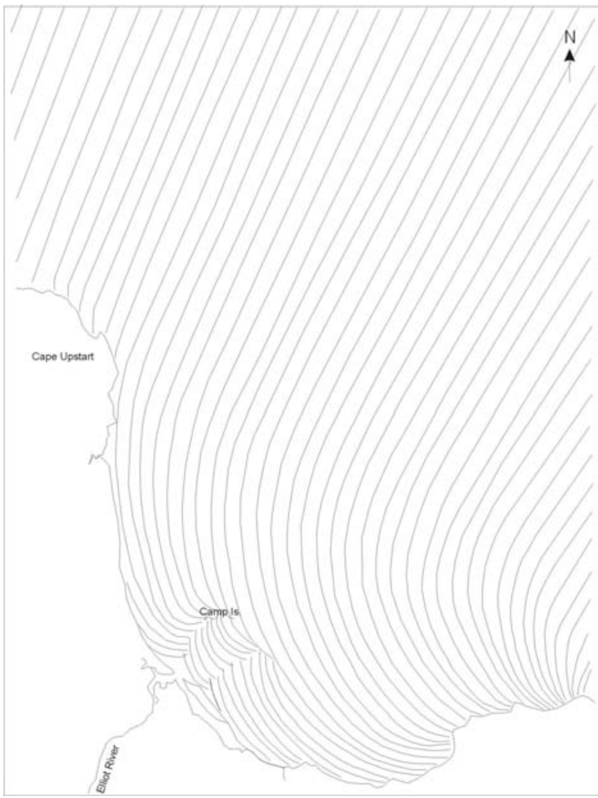


Figure 5.14 a. Wave refraction pattern for 5 second wave intervals and 20 wave crest spacing generated by south easterly winds.

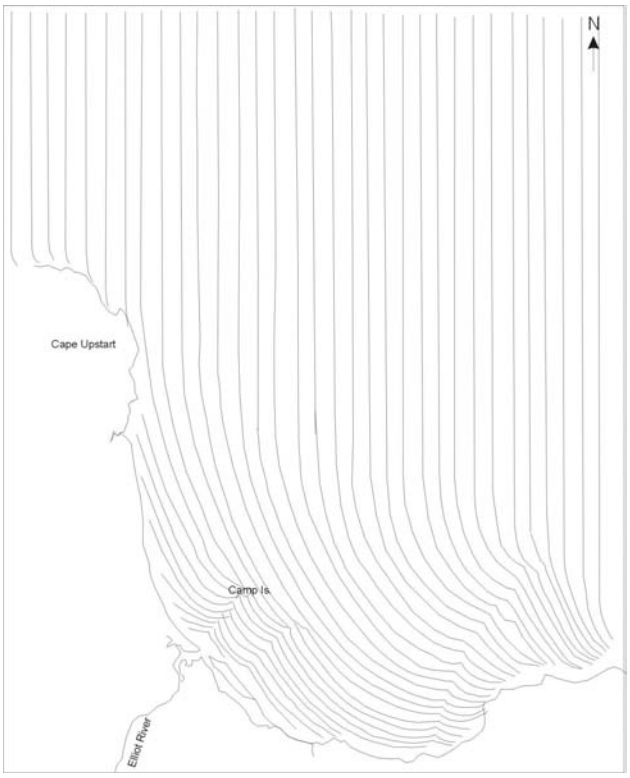


Figure 5.14 b. Wave refraction pattern for 5 second wave intervals and 20 wave crest spacing generated by easterly winds.

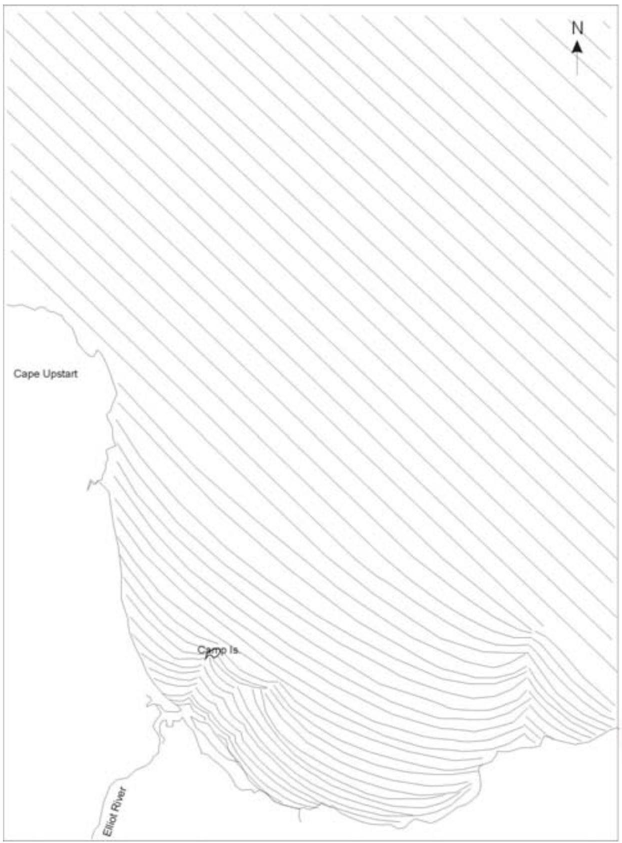


Figure 5.14 c. Wave refraction pattern for 5 second wave intervals and 20 wave crest spacing generated by north easterly winds.

All four vibrocores have similar stratigraphies and are composed of very well to moderately well-sorted very coarse sand, with shells, mud clasts and even coarse gravel interspersed throughout (Figure 5.15). Only one core (ERVC 1) contained units of medium sand ~ 3.2 m below AHD. ERVC 3 and ERVC 4 contain very coarse gravel identical to that observed on the estuary floor today. The lack of organic material in the cores prevented an investigation into the chronology of sedimentation using radiocarbon dating. While some shells were present in the cores, they were fragmented and interspersed throughout, thus not suitable for even a bulk radiocarbon date.

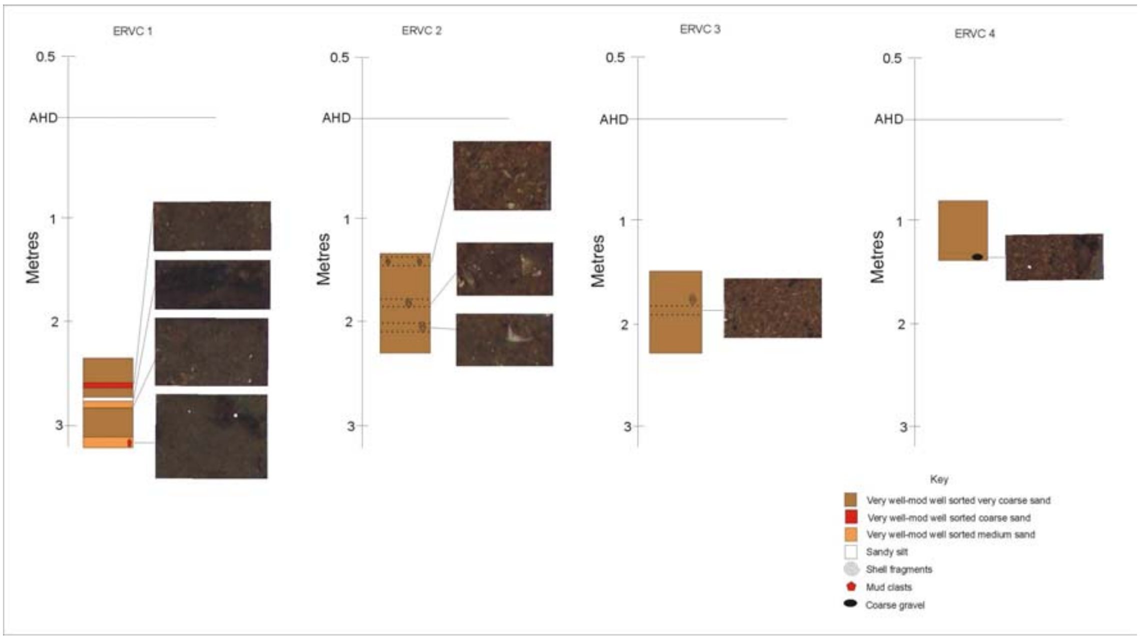


Figure 5.15 Stratigraphy of vibrocores from the Elliot River Estuary including photographs of selected beds.

Figure 5.16 part a-d compares the surficial and sub-surface sediment samples according to mean grain size, sorting, skewness and kurtosis characteristics after Friedman (1961) (see chapter 3, section 3.4.3). There is little consistent separation according to setting across all four plots. Table 5.3 shows the results of a discriminant analysis preformed on the data to determine how well the descriptive parameters distinguish between environmental settings. Kurtosis (0.499) was the most significant variable within function one, while both mean grain size (0.879) and kurtosis (-0.617) are the most significant variables in function two. The results of the discriminant analysis are plotted (Figure 5.17) according to these functions with sorting on the x-axis and mean grain size and kurtosis on the y-axis, illustrating minimal separation of samples according to their environment.

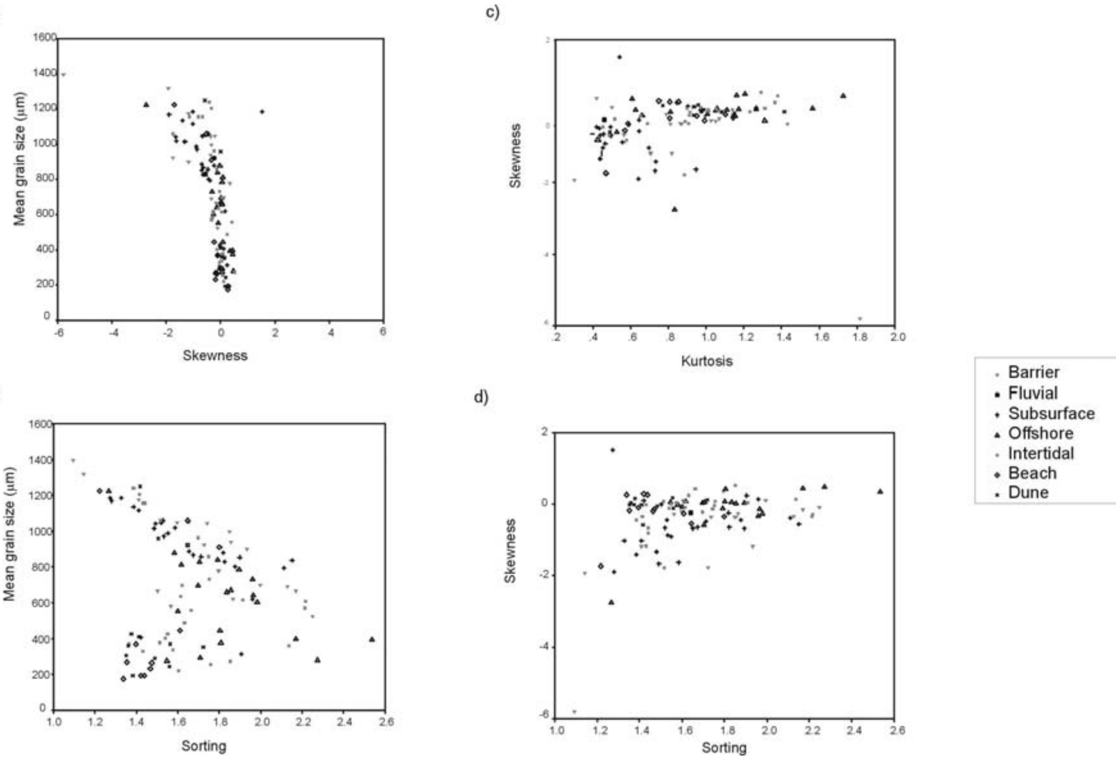


Figure 5.16 a-d. A comparison of the surficial and subsurface sediment samples according to their mean grainsize, sorting, skewness and kurtosis characteristics for the Elliot River Estuary.

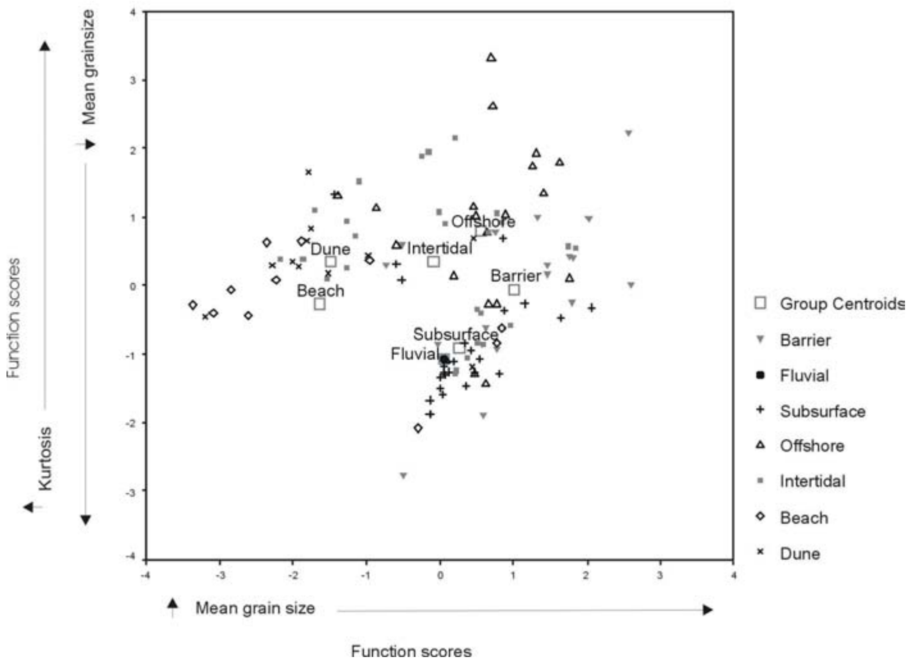


Figure 5.17. Scatter plot showing the results of discriminant analysis using all descriptors fro the Elliot River Estuary.

Table 5.3. Structure matrix from the discriminant analysis for Elliot River Estuary.

Variables	Function			
	1	**2**	**3**	**4**
Mean grain size	-0.063	0.879*	-0.380	0.281
Kurtosis	0.499	-0.617*	0.180	0.581
Skewness	-0.251	-0.476	0.700*	-0.469
Sorting	0.481	0.302	0.067	-0.821*

* indicates the largest absolute correlation between each variable and any discriminant function.

5.5 CONCLUSIONS

A conceptual model of the spatial and temporal patterns of coastal sand transfer in the Elliot River Estuary was developed based on the aerial photographic, sedimentological and hydrodynamic data collected.

5.5.1 COASTAL CHANGE

The dynamic nature of the section of coast directly adjacent to the mouth is probably a result of wave refraction around Camp Island (Figure 5.14). Aggradation and erosion of beaches has been related to slight changes in wind patterns in many locations (e.g. in Byron Bay, northern New South Wales, Hopley, 1967). Analysis of wind data for Bowen 1969 - 1998, reveals significant changes in the wind regime beginning in the late 1970's. There is a strong (R^2 = 0.8713) decrease in the frequency of winds from all directions between 1-10 $km.h^{-1}$ from 1969 – 1998 (Figure 5.18). Similarly there is a trend (R^2 = 0.4949) towards an increase in the frequency of winds over 30 $km.h^{-1}$ during that same period (Figure 5.19). While the winds have increased in velocity from 1969 – 1998, the frequency of winds from each direction has remained constant over time, with dominant south easterlies (occurring 38% of the time) (Figure 5.20) and easterlies (occurring 22% of the time) (Figure 5.21). However, there have been significant increases in the velocity of these dominant south east and east winds since 1969 with R^2 values of 0.9053 and 0.457 respectively (Figures 5.20 & 5.21). Also while the frequency of strong north-east winds over 21 $km.h^{-1}$ has remained constant (Figure 5.22), the frequency of north-east winds of all speeds has decreased significantly (R^2 = 0.7999) from 1969-1998 (Figure 5.23).

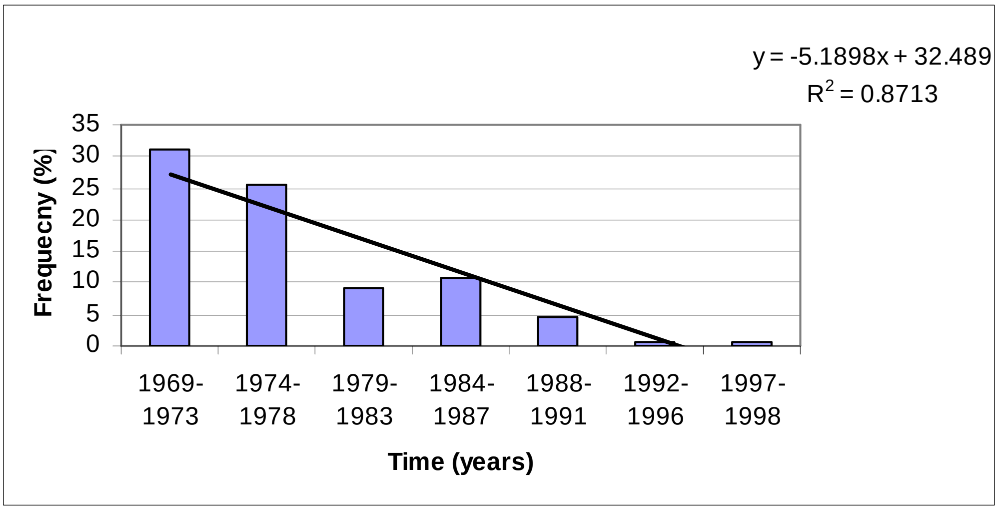


Figure 5.18. Significant decrease in the frequency of winds from all directions between 1-10 km.h^{-1} from 1969-1998. Bowen wind data 1969-1998 from the Bureau of Meteorology.

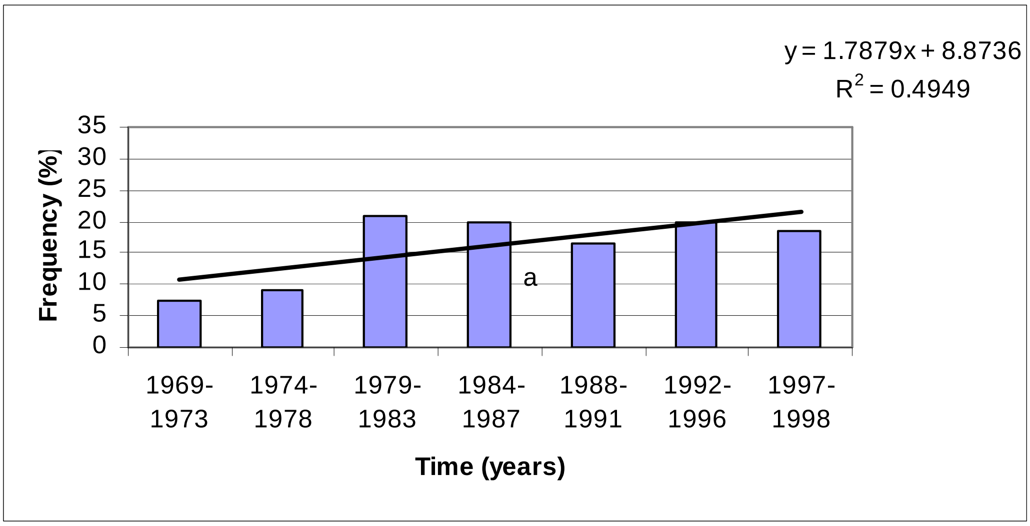


Figure 5.19. Significant increase in the frequency of winds over 30 km.h^{-1} from 1969-1998. Bowen wind data 1969-1998 from the Bureau of Meteorology.

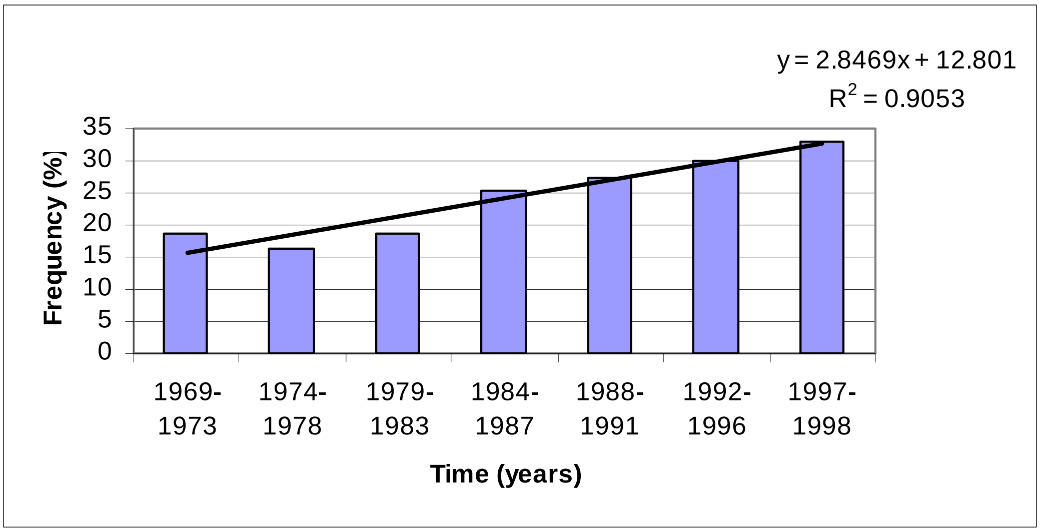


Figure 5.20. Significant increases in the velocity of south-easterly winds over 21 km.h^{-1} from 1969-1998. Bowen wind data 1969-1998 from the Bureau of Meteorology.

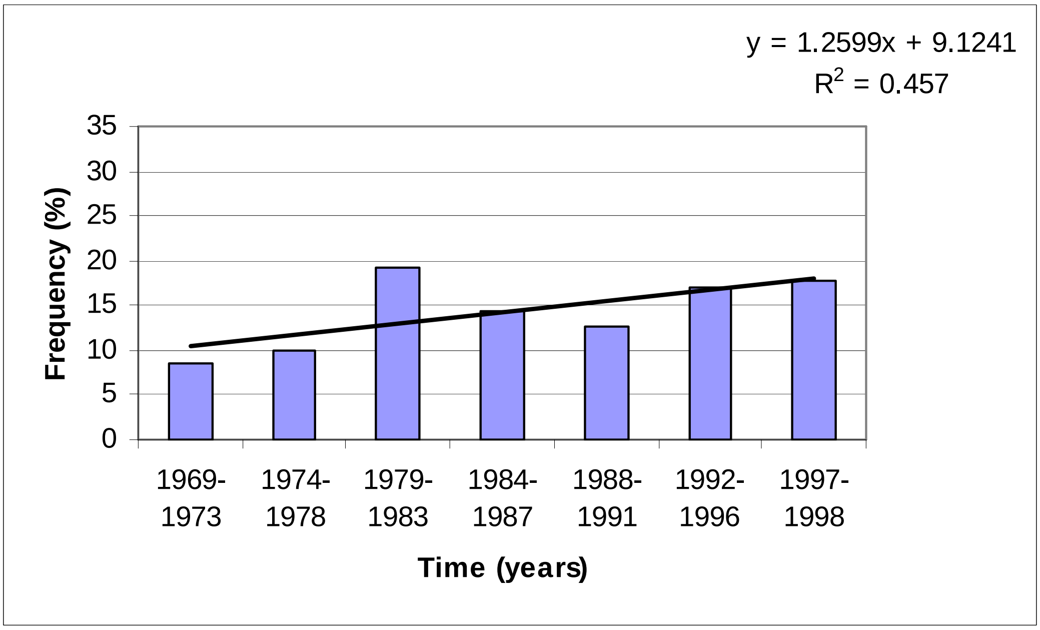


Figure 5.21. Significant increases in the velocity of easterly winds over 21 km.h^{-1} from 1969-1998. Bowen wind data 1969-1998 from the Bureau of Meteorology.

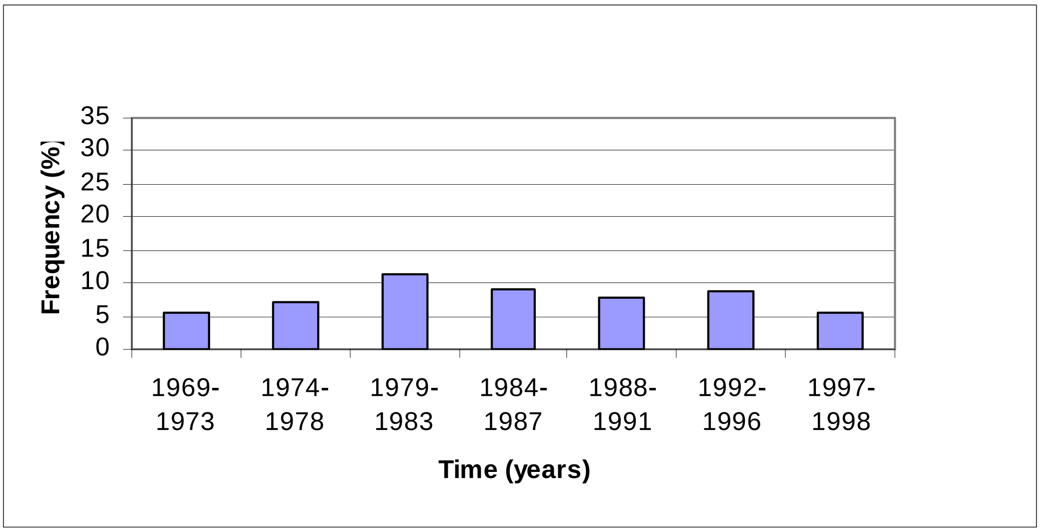


Figure 5.22. The frequency of strong north-easterly winds over 21 km.h^{-1} have increased by up to 5% in 1979-83 and then decreased again by 1998. Bowen wind data 1969-1998 from the Bureau of Meteorology.

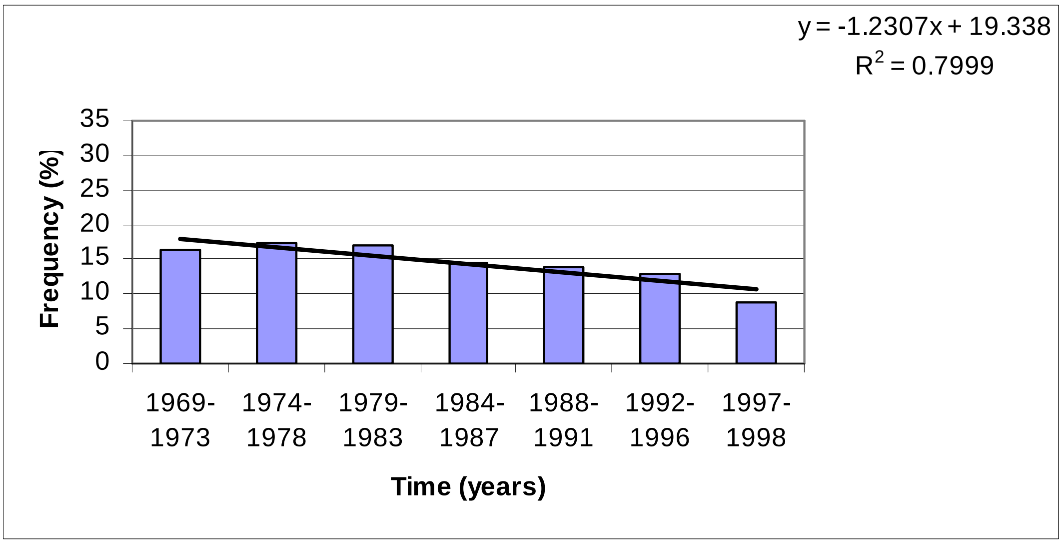


Figure 5.23. The frequency of north-easterly winds of all speeds has decreased significantly from 1969-1998. Bowen wind data 1969-1998 from the Bureau of Meteorology.

It can be seen from Figures 5.14, that wave refraction around Camp Island will direct wave energy at the mainland coastline, with the area of concentration responding sensitively according to wind direction i.e. moving south when winds are more northerly and moving north when winds are more southerly. This adds to the dynamic nature of this section of coast and is superimposed upon the more general south to north movement of sediments along the beach. Figures 5.14 show the different patterns of wave refraction that are formed by the three most common wind directions south easterly, easterly and north-easterly. During south-east winds wave energy is concentrated along the coastline, which may bring sediment on to the shore. Easterly winds produce a more dispersed pattern of wave energy on the shore, however wave energy is still concentrated on the mid sections of the coastline. North-easterly winds create a convergence of wave energy along the coast causing the transfer of sand towards the estuary mouth. Modelling using Automated Coastal Engineering Software (ACES) (Leenknecht *et al.*, 1992)(see chapter 3, section 3.4.4.1) suggests that north-easterly waves (approaching at 10° angle and occurring for 5% of year) can transport ~4,900 m^3 of sand south per year, which explains the build-up of sand on the northern bank of the estuary. This may result in erosion along the coastline and accretion near the river mouth. If the trend shown in the 1969 - 1978 wind data is representative of the previous 25 years, it is possible that the wind regime was weaker from 1942 - 1978, which may account for the widespread coastal progradation between 1942 - 1974. Subsequent erosion around the middle of the coastline and continued progradation at the northern and southern ends from 1974 - 1998 may reflect the strengthening of winds during this period.

The shift from a constructional phase (1942-1974) to an erosional phase (1974-1998) suggests a 30-year cycle of progradation and retreat along the coastline adjacent to the Elliot River. If this is occurring, it is likely that erosion would continue at the same pace (0.9 $m.y^{-1}$) for the next few years and then perhaps a recovery of ~1.5 $m.y^{-1}$ over the next few decades. This cyclic pattern is probably related to changes in the dominant wave pattern, in response to changes in the dominant wind direction. For example, in the Torres Strait Rasmussen & Hopley (1997) have documented a significant change in wind patterns in the late 1970's. Greater predominance of southerly winds over the last 20 years has changed patterns of sand transfer leading to greater erosion along the southern beach of Warraber Island (Rasmussen and Hopley, 1997). A 20 - 30 year wind cycle has also been reported in the southern Great Barrier Reef by Flood (1986) where a change from dominant south-south-easterly winds in the early 1960's to dominant east-south-easterly winds in the late 1970's, has reversed patterns of sand transfer around Heron Island. Therefore the patterns of sand movement in Abbot Bay, including longshore drift, may well reflect changes in wind patterns.

Dominant south-easterly winds produce ambient wave conditions averaging significant wave heights of 0.5 m (BPA, 1996a). Modelling using ACES (Leenknecht *et al.*, 1992) (chapter 3, section 3.4.4.1, Appendix C) suggests that these south-easterly waves, which occur for 38% of the year and approach shore at an 80° angle, produce a potential longshore drift of 100,000 m^3 of sand per year to the north. Similar rates of longshore drift are predicted to occur to the south suggesting that sand from the Don River may be transported into the Elliot River system. Aerial surveys in 2000 and 2003 revealed sand bodies aligned northwards along shore from the Don River to the Elliot (Figures 5.24-5.27). The Don River is estimated to contribute an average of 40,900 m^3 of sand to the coast per year (Horn *et al.*, 1998). The recent construction of a coal loading jetty off Abbot Point may interrupt this movement of sand. However large subaqueous sand waves observed northwards of Abbot Point and orientated northwards suggest sand is still moving towards the Elliot River Estuary via longshore drift and that the jetty is essentially transparent to sand movement.

Figure 5.24. Northward facing sand bars at the Don River looking south towards Bowen. Photograph taken at low tide May 2003.

Figure 5.25. Northward facing sand bars at the mouth of the Don River. Photograph taken at low tide May 2003.

Figure 5.26. Subaqueous sand waves in Abbot Bay orientated north towards the Elliot River. Photograph taken at low tide May 2003.

Figure 5.27. Northward facing sand bars just south of the Elliot River Estuary. Photograph taken at low tide May 2003.

5.5.2 BEDFORMS

A flood tide delta has formed at the river mouth and an equivalent ebb tidal delta is present at the southern opening behind the barrier. Well-formed megaripples were observed on these tidal deltas and indicate strong tidal currents capable of transporting bed material. Surface current velocities to a maximum of 0.7 $m.y^{-1}$ have been recorded at the river mouth during flood phases of spring tides (Sinclair Knight Merz, unpublished data). However the strength of tidal currents is likely to be enhanced due to constriction at the mouth. The south-east facing megaripples observed along the inner side of the barrier suggest strong ebb tidal currents capable of transporting bed material out of the estuary. The orientation of bedforms and tidal deltas suggests an exclusive flood tide inlet at the estuary mouth and ebb outlet at the end of the barrier spit.

5.5.3 SEDIMENTOLOGY

The northward fining of sand deposits suggests the alongshore transport of sand from the mouth of the estuary to the adjacent coast. The presence of coarse sand offshore from the medium to fine sand onshore deposits may be 'lag' winnowed by the removal of finer sediments. Most sub-surface and many of the other intertidal and offshore samples were bimodal compromising the reliability of the descriptive statistics (Blott and Pye, 2001). Like the results from the Haughton (see chapter 4, section 4.3.3) there is a lack of consistent separation of samples according to their environmental setting. A discriminant analysis of the sediment characteristics and sampling location revealed that only 39.5% of original grouped cases (35.1% of cross-validated) were correctly classified. Unlike the Haughton this result is not due to a lack of variation in textural characteristics of sediments throughout the estuary. Rather, it is that the distribution of the broad range of sediments within the Elliot, are unrelated to their setting indicated by the significant kurtosis value in the discriminant analysis (Table 5.3).

Similar to the Haughton (see section 4.3.3, chapter 4) there was a lack of sediment interpreted as immature fluvial deposits in either the surficial or sub-surface samples. Even samples from the fluvial reaches of the channel were very similar to the very coarse – to coarse, sub-angular to sub-rounded sands that dominate the estuarine reaches on the surface and up to 3 m below AHD. However fine-medium sands are found on the adjacent coast with coarse to very coarse deposits found in the nearshore areas. Interpretation of these results in the context of previous investigations on the system suggest complex scenarios of sand transfer in the Elliot River Estuary over Holocene and contemporary timescales.

Hopley (1970a) suggested that the Elliot River supplied sand to the double barrier system, Pleistocene aged inner barrier and Holocene aged outer barrier, that link the granitic outcrop of Cape Upstart to the mainland. However these barriers are composed of medium sand (0.375 mm) (Hopley, 1970a) while very coarse to coarse sand dominates the estuary up to 3 m below AHD. The only medium sand found in the estuary was at 3.2 m below AHD at the bottom of ERVC 1. The volumes of sand in the Holocene barrier and barrier spit is approximately 8.39 x 10^6 m^3 of sand so over 6.5 ka that the Elliot would have supplied an average of ~1,300 m^3 of sand per year (assuming no losses or gains to the system). Hopley (1970a) observed erosion on the adjacent coast and attributed it to diminishing fluvial sediment supply from the Elliot. However from the aerial photograph record (see section 5.4.1) the coastline adjacent to the Elliot has been relatively stable since 1942. Further investigation suggests the coastal change that has occurred is more likely the result of varying wind patterns and wave refraction than changes in fluvial sediment supply. However, given the significance of sand waves in wave-dominated coasts further south (Short, 1999), these are likely to influence patterns of coastal change in the Elliot River Estuary. Also the lack of immature fluvial sands in the estuary up to

3.2 m below AHD suggest that the modern Elliot is not contributing significant amounts of sand to the coast. Indeed, considering that the Pleistocene and Holocene barriers are composed of medium sand, and the Elliot River Estuary is dominated by very coarse sands, prompts doubt that the Elliot River supplied the sand for these barriers in the past. However it is possible that the medium sand has been preferentially transported south via longshore currents and the coarse sand remains as a lag deposit (Bird, 2000). It is common for armouring to occur on beds subject to high velocity in fluvial settings (Knighton, 1984). Therefore it is likely that armouring could also occur in high velocity coastal settings and when armoured beds are disturbed, for example by a storm event, a reserve of finer sand is available beneath.

The sand for the outer barriers and the large spit off the mouth of the estuary and adjacent coast may have been supplied, via longshore drift, from the larger Don River (see section 5.5.1). However, even if the Don River was not the sole supplier of sediment for the barriers in the past, the influx of sand via longshore drift would explain the presence of medium to fine well sorted sand in the estuary today.

Similarly the low kurtosis value of the sediment indicates that part of the sediment achieved its sorting in a higher wave-energy environment and that it was transported with its size characteristics unmodified, into another environment where it is mixed with other material (Folk and Ward, 1957; Taylor and Stone, 1996). This suggests the Pleistocene barrier was formed by the onshore movement of marine sediment when sea level rose at 125 ka BP. The truncation of the Pleistocene barrier (2.4 km from the Elliot River) and Holocene alluvial deposits at the end of the barrier, suggest the river channel migrated over the low relief flood plain eroding the end of the Pleistocene barrier. Finer sediments have since been transported out sea and deposited onto the adjacent coast contributing to the Holocene barrier, with the coarse sand remaining in river channel. Additional sand from the Don River may have contributed to the coastline and barrier spit.

5.5.4 CONCEPTUAL MODEL

The interpretation of aerial photographs, sedimentological and hydrodynamic investigations in the Elliot River Estuary are summarised in a conceptual model of contemporary sand transfer processes (Figure 5.28). The Elliot is a mixed estuary, with relatively strong wave and tide processes dominating sand transfer patterns during ambient conditions.

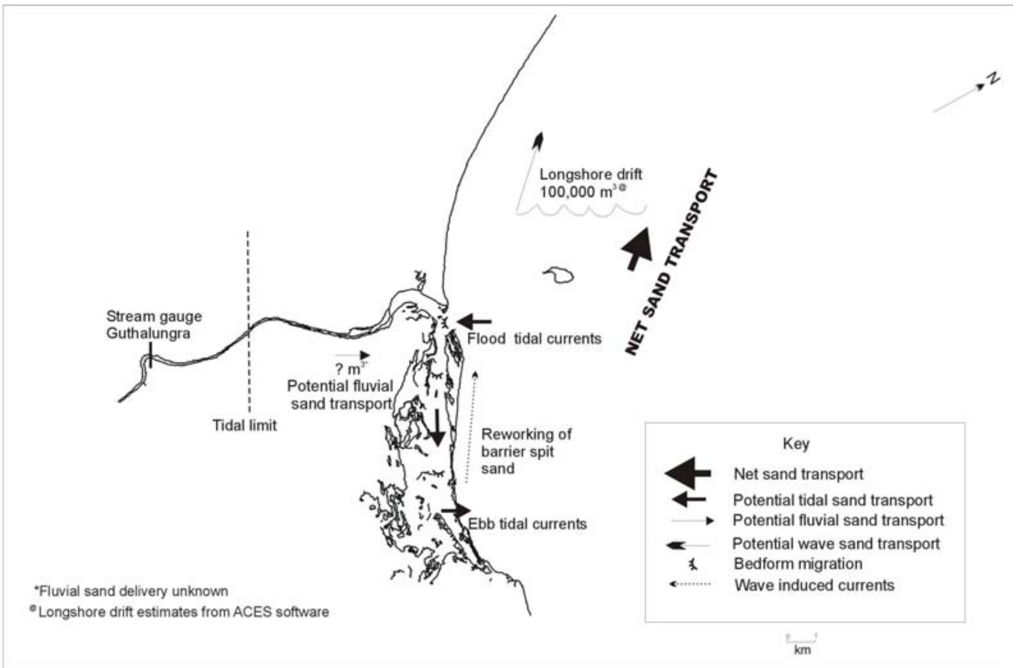


Figure 5.28. Summary diagram of net sand transport trends at the Elliot River Estuary as indicated by bedform orientations, grainsize patterns and dominant current directions. Tide and wave-induced currents are the most dominant, hence net estuarine sand transport direction is north west along the shore.

The most dynamic coastal feature is the barrier spit at the mouth of the Elliot River estuary. Initiated by a major flood event strong ebb tidal currents have led to the rapid erosion of the barrier spit and dominant south easterly wave action combined with strong flood tidal current have lead to subsequent accretion of similar volumes of sand at the northern end of the barrier spit. Strong longshore drift currents in the estuary have the potential to transport 100,000 m^3 of sand northwards alongshore every year into the Elliot system provided it is available. Seismic data offshore from Bowen reveal incisions in the pre-Holocene surface that are infilled with deltaic gravel, sand and mud up to 17 m below sea level (Johnson *et al.*, 1982). These deposits may indicate palaeochannels of the larger Don River to the south of the Elliot River and are a reservoir of marine sand that may be transported northwards.

Before the breach in the barrier inlet strong tidal currents would have been transporting sand into and out the mouth of the estuary and this may have lead to a removal of finer material and lag coarse material in the lower reaches the estuary. Dominant south-easterly wave action would have transported this finer material northwards long the coast. The wind, sedimentological and historical coastal change analysis presented in this chapter suggest that while large-scale coastal change may be initiated by flooding events in some cases (e.g. breach of the barrier spit), sand transfer is dominated by everyday wave action and tidal currents.

The lack of sediments that could be interpreted as immature fluvial sand and the bimodal nature of many of the sediments suggest the coarse – very coarse sand found in the estuary comes from the reworking of the truncated Pleistocene dune and the finer fraction of the deposit (fine – medium sands) have been removed by high discharge events and tidal currents. Therefore, this suggests that the modern Elliot River is not a significant contributor of sand to the coast. Despite significant effort it was not possible to obtain quality and quantity data required to calculate the average volume of sand that could be delivered to the coast by the Elliot River, and unlike the Haughton and the Black Rivers previous estimates were not available. However the relatively coarse sand in the fluvial and estuarine reaches compared to Haughton and the Black suggest relatively high amounts of energy would be need to transport this sand to the coast. The duration of fluvial flooding is brief (see figure 5.3 hydrograph), which is not conducive to transporting large volumes of very coarse sand downstream. Therefore like the Haughton River (see chapter 4, section 4.6), the modern Elliot is not contributing significant amounts of sand to the coast. Wave and tide processes dominate sand transfer throughout the system and the sources of sand are most likely the reworking of previously deposited sediments and the influx of sand via longshore drift.