# CHAPTER 6 – THE POWER OF WAVES: THE BLACK RIVER DELTA.

## 6.1 INTRODUCTION

The Black River coastal system differs from the proceeding systems as it classified as a delta rather than an estuary. The results of the aerial photograph analysis, sedimentological and hydrodynamic studies of the Black River Delta are presented and briefly discussed in this chapter. As with the Haughton and Elliot Estuaries, a more detailed discussion of the results follows in chapter seven. Contemporary and evolutionary patterns and processes of sand transfer are similarly inferred from the results and presented in a conceptual model. Comparisons are drawn with the results from the Haughton River Estuary (chapter four) and the Elliot River Estuary (chapter five).

## 6.2 GEOMORPHOLOGY

The Black River is located ~20 km west of Townsville see Figure 6.1. Table 6.1 summarises the physical characteristics of the system. The Black River is 42 km long and drains a catchment of 260 km$^2$, discharging into Halifax Bay. Similar to the Haughton, the Black River descends steeply until the estuarine section of the channel where the slope reduces by an order of magnitude (Fluvial reach: 0.019; Estuarine reach: 0.004). The Black River delta protrudes from the coastline, with sand spits forming across the river mouth. The delta is dominated by sandy sediments (see appendix H) (Hopley, 1970a). Closely spaced beach ridges to the north of the river are indicative of the large quantities of sand originating from weathered granites and diorites of the Hervey Range (Holmes, 1992).

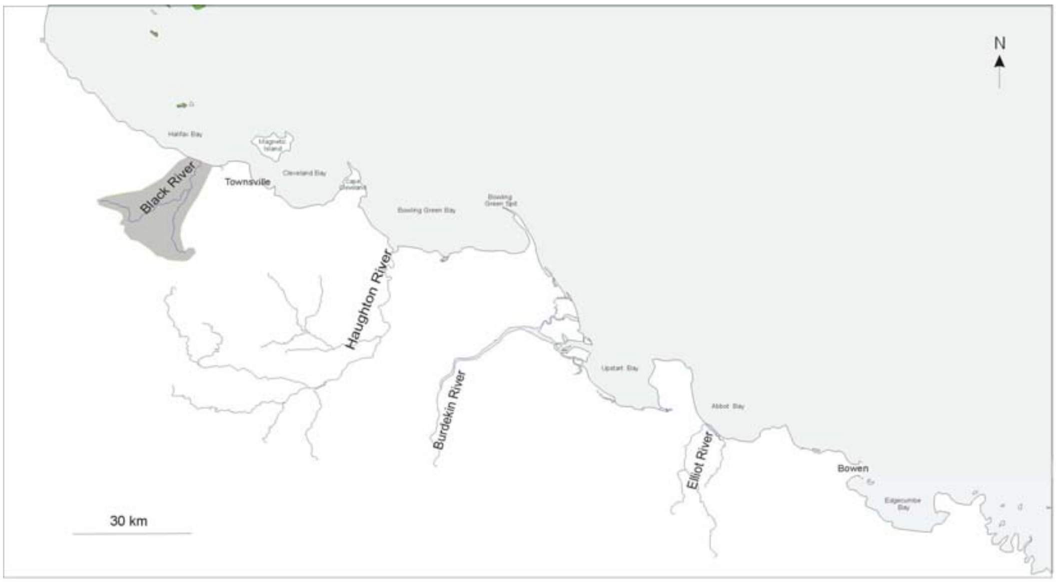


Figure 6.1. The Black River catchment.

## Table 6.1. Physical characteristics of the Black River Delta

| | |
|---|---|
| **Catchment area** | 260 km$^2$ |
| **Channel length** | 42 km |
| **Channel width** | 36-100 m |
| **Slope** | Fluvial reach: 0.019<br>Estuarine reach: 0.004 |
| **Sinuosity** | 1.7 |
| **Percentage of channel estuarine** | 3% |
| **Mean annual rainfall** | 1538 mm |
| **Modifications** | • 49% of catchment cleared for grazing and small areas of agriculture<br>• Sand extraction (>1,000,000 m$^3$ since 1972) |

## 6.3 SETTING

Figure 6.2 illustrates the marked intra and inter-annual variability of stream flow in the Black River (see table 6.2 for a summary of flood gauge data). Similar to the Haughton and Elliot Rivers, ~92% of total annual stream flow occurs between December and April. Discharge also varies between years, with 72% of annual stream discharge registering below a quarter of the maximum flow, with several years recording almost no flow at all. Episodic and flashy floods (see figure 6.3), results in over bank flooding or as observed in the 1998 flood (maximum instantaneous discharge of 2236 m.s$^{-1}$; estimated ARI 1:100 years) the diversion of the river mouth.

**Table 6.2. Summary of stream flow characteristics for the Black River Delta.**

| | |
|---|---|
| **Gauging station** | Bruce Highway |
| **Distance from stream mouth** | 8.9 km |
| **Catchment area at gauging station** | 256 km$^2$ |
| **Gauged area/catchment area** | 24% |
| **Available records** | 1973-2001 |
| **Maximum annual flow volume** | 395,000 ML in 1974 |
| **Minimum annual flow volume** | 46 ML in 1985 |
| **Maximum instant discharge** | 2236 m$^3$.s$^{-1}$ in January 1998 |
| **Maximum period of no flow** | 7 months in 1986/87 |

Similar to the Haughton River Estuary, waverider buoy data from off Cape Cleveland represents offshore wave energy for the Black River Delta. Modal significant wave height ranges from 0.2-0.4 m (BPA, 1996b), but for 66% of observations significant wave height ranged from 0.2-0.8 m (BPA, 1996b). Unlike the Haughton, the Black River Delta is not sheltered from south-easterly winds by Cape Bowling Green leaving it more exposed to south-easterly winds. The Delta experiences a diurnal tidal regime with a maximum spring tide range of 3.8 m (Queensland Transport, 2003).

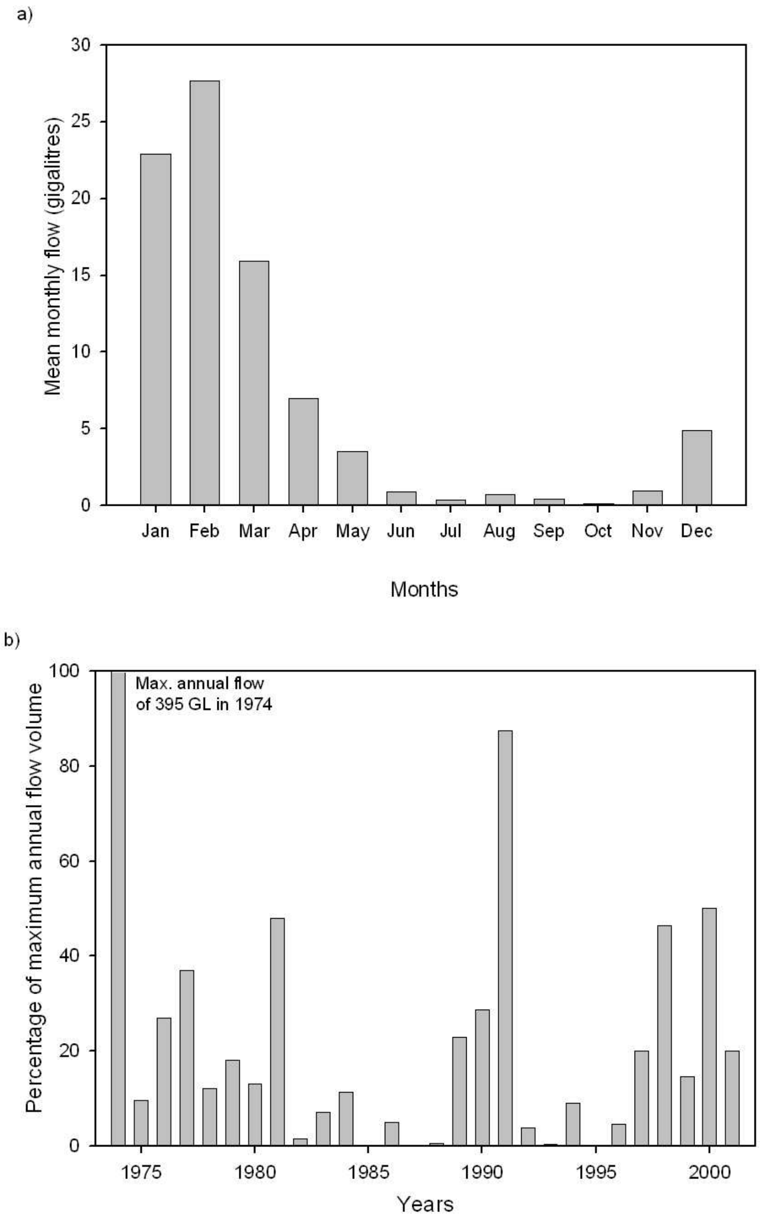


**Figure 6.2. Stream flow characteristics for the Black River recorded at the Bruce Highway gauge from 1974 -2001 (DNR, 2002), mean monthly flow volumes (a) and annual flow volumes shown as a percentage fo the maximum flow volume (b).**

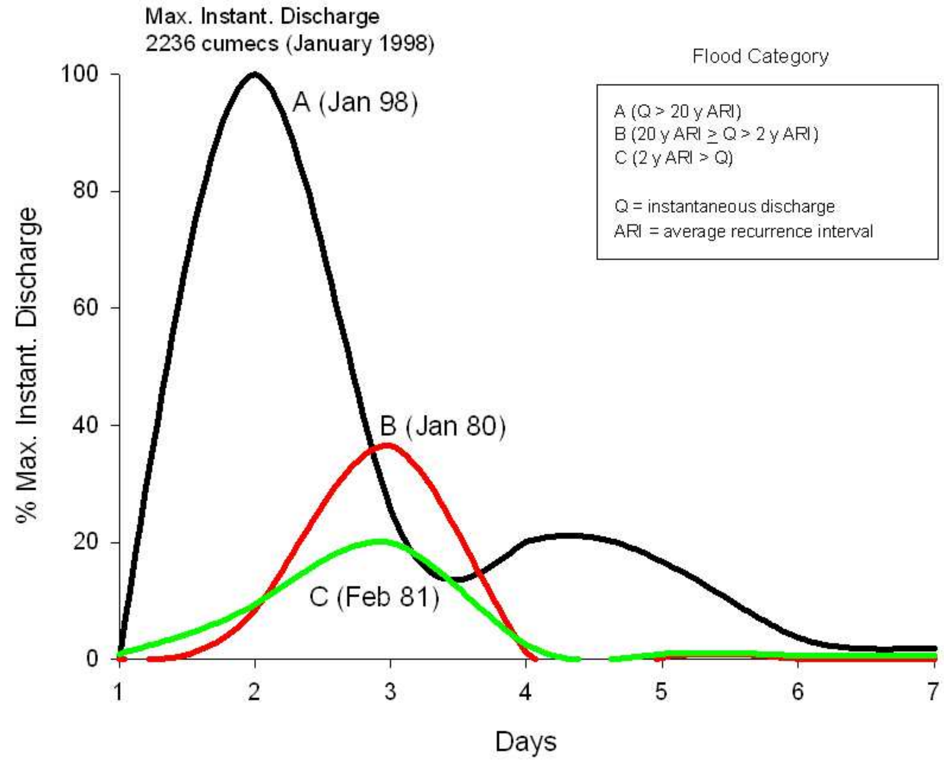


**Figure 6.3. Flood hydrograph for the Black River recorded at the Bruce Highway gauge.**

## 6.4 RESULTS

### 6.4.1 COASTAL CHANGE

Coastline position was recorded from aerial photographs of the Black River Delta from 1942, 1985 and 2000 (see chapter 3, section 3.4.1). The measurements of coastal change along each transect (see figure 6.4) from 1942 - 1983 and 1983 - 2000 are illustrated in Figure 6.5. Analysis of the coastline adjacent to the Black River north to Bluewater Creek revealed a general trend of progradation, with an average of 41 m or 1 m.y$^{-1}$ linear coastline advance between 1942-1983. Between 1983-2000 progradation continued close to the river mouth (2 km north along the coast) at a rate of 1 m.y$^{-1}$, with frequent occurrences of erosion (average of 18 m at each transect or at a rate of 1 m.y$^{-1}$) and some stability from 2.25 km – 5.25 km up the coast towards Bluewater and Althaus Creek.

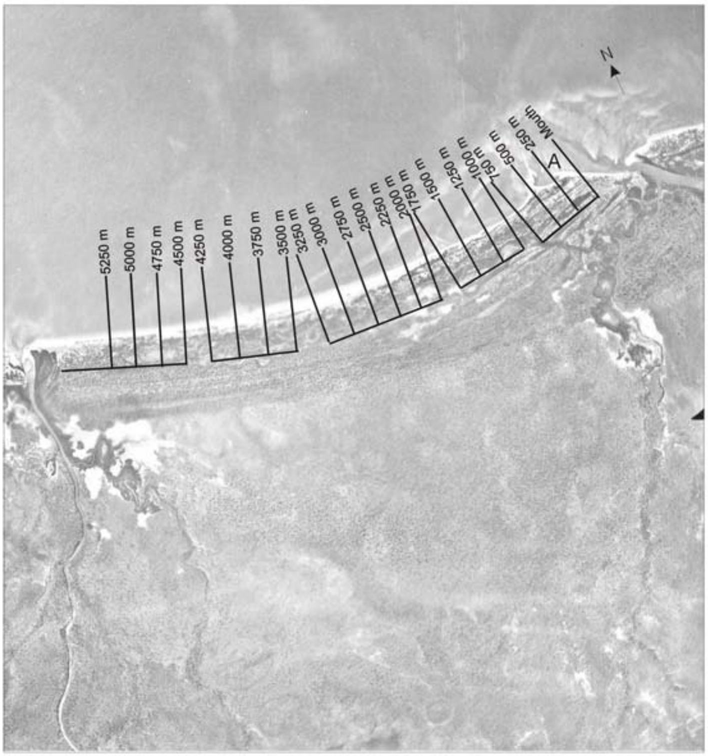


**Figure 6.4. Location of transects from which coastal change measurements were derived shown on the 1940 aerial photograph of the Black River Delta. 'A' indicates the location of bedforms shown in figure 6.8.**

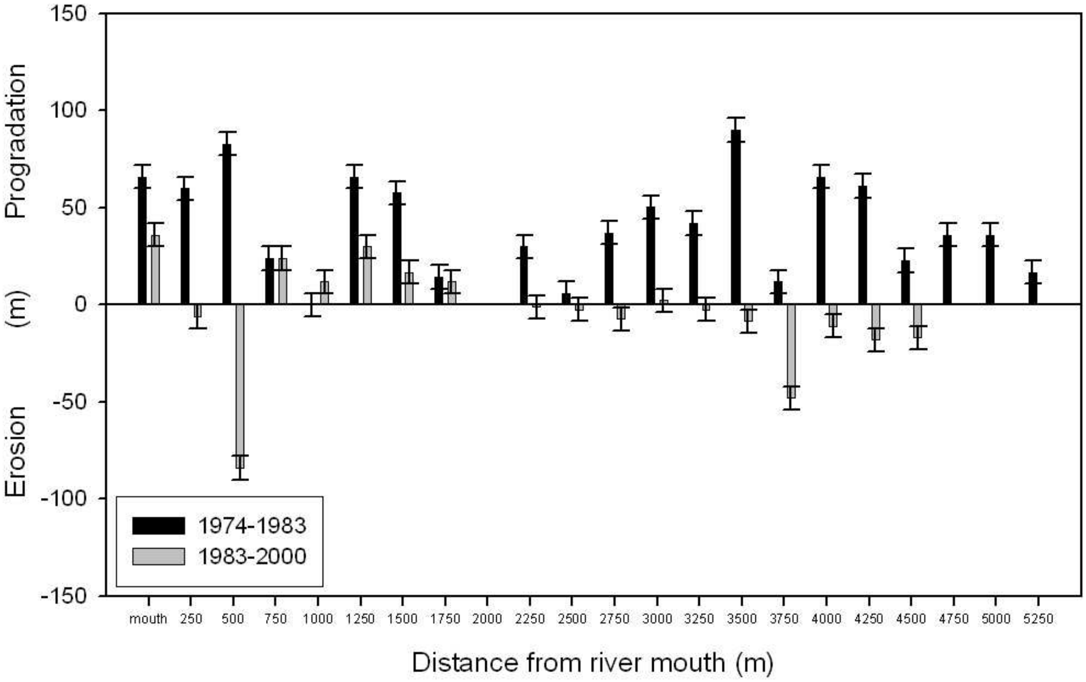


**Figure 6.5. Shoreline progradation and retreat along the Black River Delta measured from 1974 and 2000 aerial photographs. Standard error of measurement estimated at 6 m for 1:12,000 scale photography. (See figure 6.4 for locations of transects).**

The movement of sand bars explains much of the coastal change, due to a recurring pattern of moving close to shore and welding on to the shoreline and then detaching as described by Pringle (Pringle, 1984; Pringle, 2000) for the Burdekin Delta. For example along the transect 500 m north of the river mouth has prograded 84 m between 1942-1983 and then eroded 80 m in the subsequent 17 years to 2000. Analysis of intervening aerial photographs revealed that this progradation occurred rapidly over a period of five years between 1979-83. Along the 500 m transect there was only 8.4 m of progradation between 1942-1974, then a retreat of 4.8 m to 1979 followed by an advance of 80 m between 1979-1983. Over the following 8 years, this same section of coast retreated 66±6 m, eroding a further 16.8 m to 1995.

The dynamic nature of this coastline was first documented in 1880 (Coastal Engineering Solutions, 1998). The continual build up and erosion of the sand spit on the eastern side of the river mouth has been observed in the earliest surveys and in the most recent aerial photos, seemingly in response to major flood events. For example, the January 1998 flood (ARI 1:100) caused the erosion of the ~100 m long sand spit which extended across the delta mouth (Figure 6.6). A schematic model was produced from comparisons of aerial photos of the delta taken in 1995 and 2000 to illustrate the effect of the flood on its morphology (Figure 6.7).

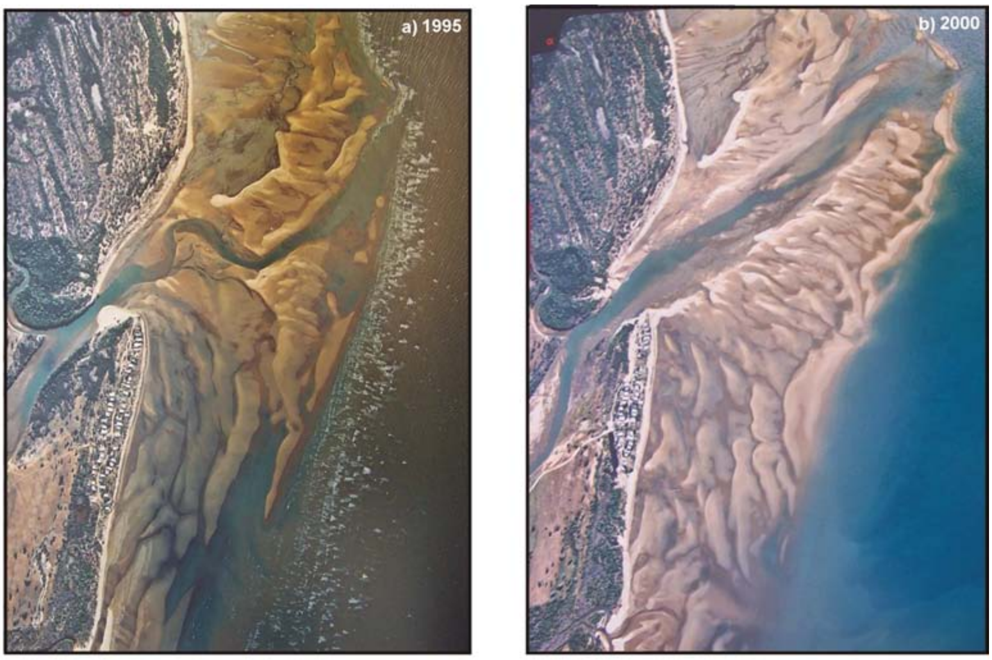


**Figure 6.6 a-b. Vertical aerial photographs of the Black River Delta which were used to develop figure 6.7 a-b. Copyright: The State of Queensland (Department of Natural Resources and Water) 1995 (a), 2000 (b).**

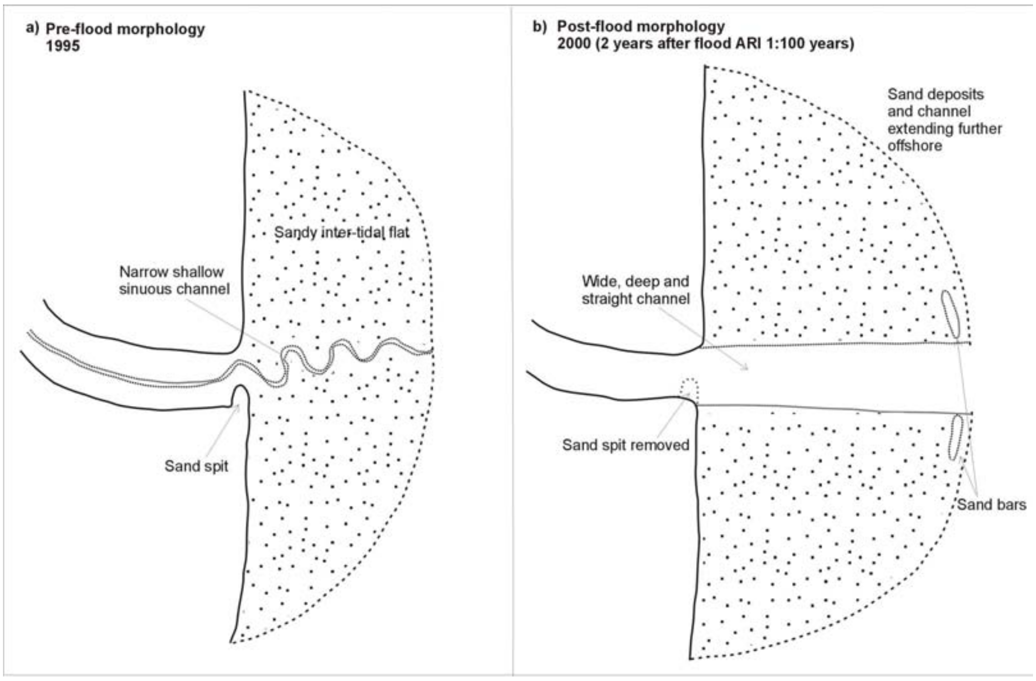


**Figure 6.7 a-b. A schematic model illustrating the impact of a ARI 1:100 year flood on the morphology of the Black River Delta.**

A comparison of the Black River pre-flood (1995) and post-flood (2000) photographs revealed distinct changes within the delta and adjacent coastline indicative of a major flood event. For example, the narrow (36±6 m) and sinuous main channel captured in the 1995 photograph had widened to 100±6 m, straightened and extended another 400±6 m offshore to 1.89 km, by the 2000 photograph (Figure 6.7). The tidal delta had also extended further offshore and the sand spit in the estuary mouth has been removed to leave a wider inlet in 2000. Tides and waves have started to move the sand bodies into the estuary and further along shore, however recovery to its pre-flood morphology is slow. A recent aerial survey (2003) revealed that the delta is still in the post-flood morphology yet to recover to the pre-flood state over five years after the event. Despite changes in the spatial arrangement of sand bodies within the delta, the flanking coastlines have remained stable from 1995-2000.

### 6.4.2 BEDFORMS

As noted in section 3.4.2, chapter 3, instantaneous patterns of sand transfer in estuaries can be inferred from studying bedforms. Small current ripples 1 cm in high with a 5 cm wave length, were observed at low spring tide orientated towards the sea (Figure 6.8). No megaripples were observed on the intertidal flats.

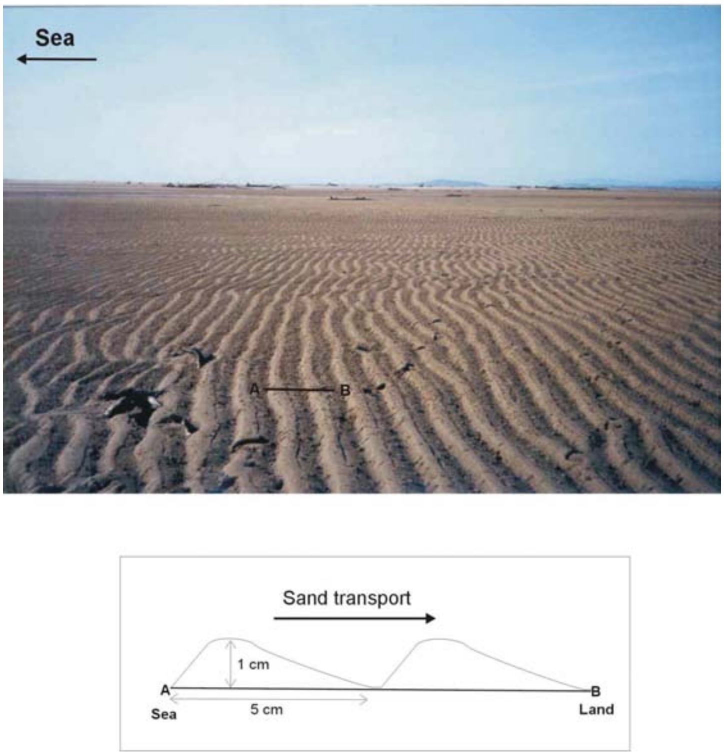


**Figure 6.8. Seaward orientated current ripples 1 cm high and 5 cm wavelength observed in the Black River Delta at low spring tide.**

### 6.4.3 SEDIMENTOLOGY

Unfortunately detailed pre-flood sedimentological surveys are not available for the study site. Post-flood fieldwork occurred in January 2001, three years after the January 1998 flood (ARI 1:100 year). Sixty-eight surficial sediment samples were collected from the Black River Delta and adjacent coastline (Figure 6.9). Figure 6.10 summaries the results of textural analysis of the surficial samples (see Appendix D) illustrating the spatial distribution of facies. The tidal reaches and mouth of the delta are dominated by moderately sorted coarse sand with some patches of medium sand. The intertidal areas encompass a broad range of sediment types from coarse silt (0.020 mm) to coarse sand (0.788 mm), moderately well sorted (0.001) to very poorly sorted (0.005), symmetrical (-0.015) to very finely skewed (-0.664). Beach sands also vary in grain size from fine (0.199 mm) to coarse sand (0.640 mm), but are all moderately well sorted (1.65) and symmetrical (-0.018) to coarsely skewed (0.339). Dune sands are generally finer ranging from fine (0.160 mm) to medium sand (0.347 mm) however two of the samples are coarse sand (0.507 mm and 0.550 mm). Further offshore from the delta the sediments become finer and more poorly sorted with mixtures of fine sand and coarse silt. Over half of Black River sediments have leptokurtic kurtosis values and are finely skewed. Coarse (0.510 mm) and moderately sorted (0.89), symmetrical (-0.09) with a feldspars content of 18% and low carbonate content (>1%) sand was interpreted as fluvial.

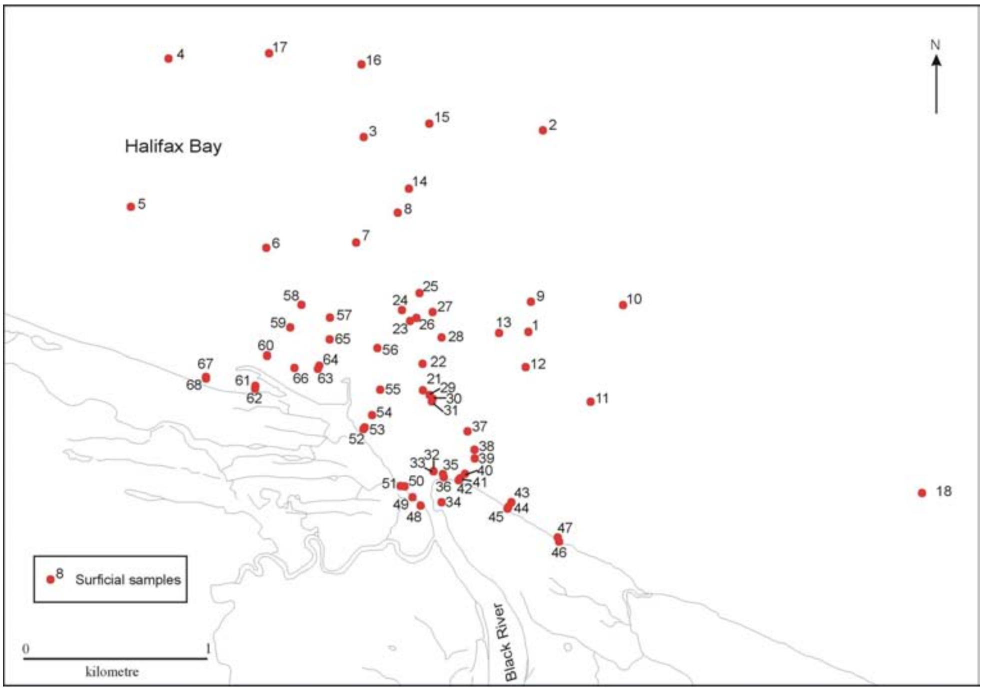


**Figure 6.9. Locations of surficial sediment samples taken at the Black River Delta. (See Appendix D for the results of the textural analysis of samples).**

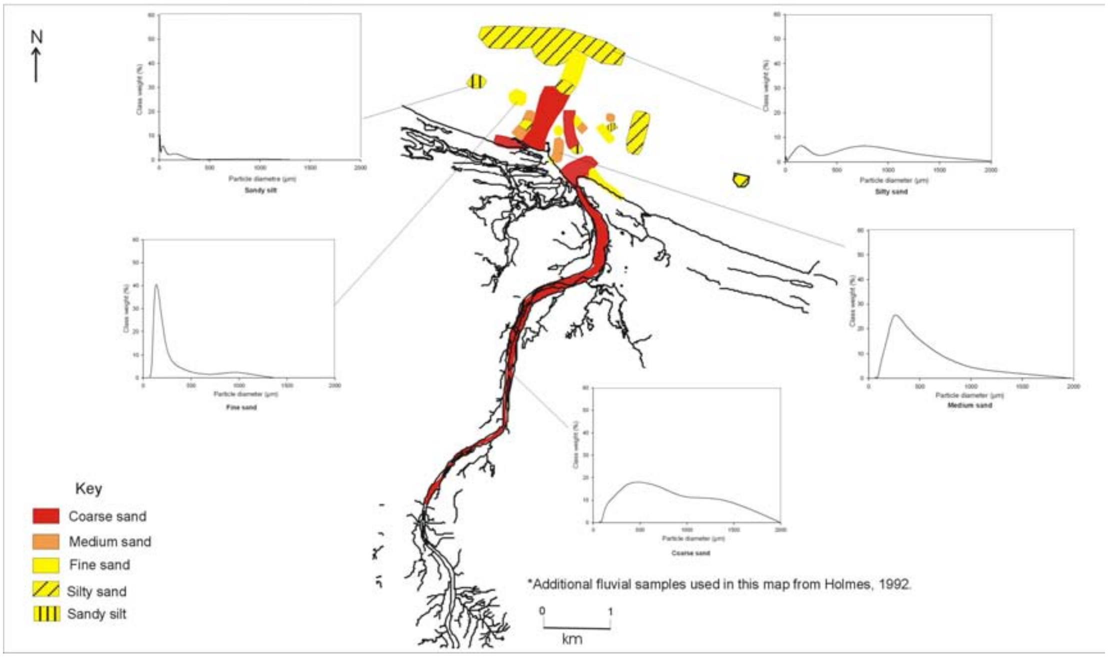


**Figure 6.10. Summary of the results of textural analysis of surficial samples from the Black River Delta. Histograms show the distribution of a typical example of each sediment class.**

Figure 6.11 part a-d compares the surficial samples according to mean grain size, sorting, skewness and kurtosis characteristics after Friedman (1961) (see section 3.4.3, chapter 3). In all graphs the samples are loosely correlated to their sampling location. The results of a discriminant analysis (Table 6.3) revealed that mean grain size (0.514 mm) was the most significant variable in the first function, with both sorting (0.814) and skewness (-0.638) most significant in the second. Plotted according to these functions (Figure 6.12) the samples loosely cluster according their environmental setting.

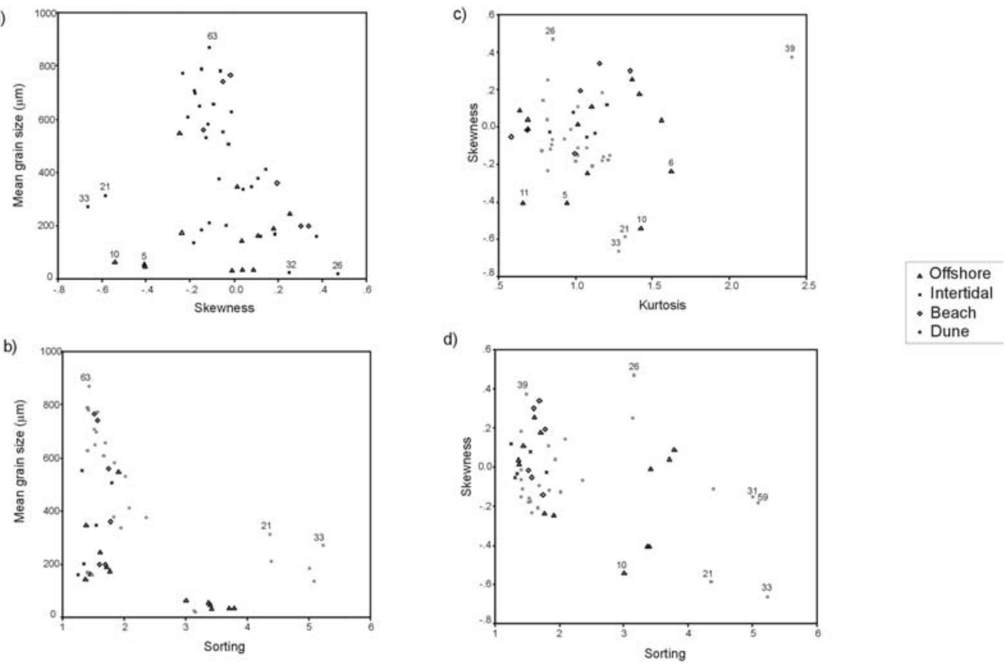


**Figure 6.11 a-d. A comparison of the surficial and subsurface sediment samples according to their mean grainsize, sorting, skewness and kurtosis characteristics for the Black River Delta after Friedman 1961.**

**Table 6.3. Structure matrix from the discriminant analysis for Black River Delta.**

| **Variables** | **Function** | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Sorting | 0.022 | 0.814* | 0.513 |
| Skewness | 0.037 | -0.638* | 0.593 |
| Mean grain size | 0.514 | -0.369 | 0.715* |
| Kurtosis | -0.052 | 0.231 | -0.325* |

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

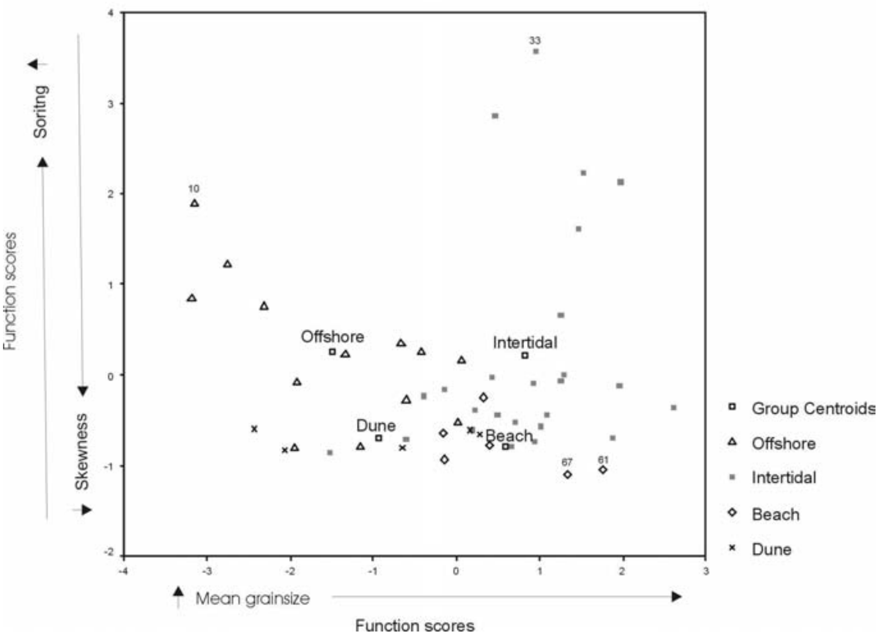


**Figure 6.12. Scatter plot showing the results of discriminant analysis using all descriptors for the Black River Delta.**

## 6.5 CONCLUSIONS

Aerial photographic, sedimentological and hydrodynamic data was used to develop a conceptual model of sand transfer in the Black River Estuary.

### 6.5.1 COASTAL CHANGE

Wave refraction around Magnetic Island probably contributes to the pattern of sand bar movement observed in the Black River Delta. Figures 6.13 a-c show wave refraction patterns for the most common wind directions south-easterly, easterly, and north-easterly. During south-easterly winds the resultant wave pattern indicates sand moving northwards up the coast and perhaps moving sand onshore. The easterly winds create a wave pattern, which targets the most dynamic section of coast (500 m adjacent to the river mouth) which may account for the erosion of the sand bar. Refraction of north-easterly waves creates an overlapping of wave trains on this section of coast directly adjacent to the river mouth. It is likely that this wave pattern would create erosion on the same section of coast and perhaps the movement of sand to the south.

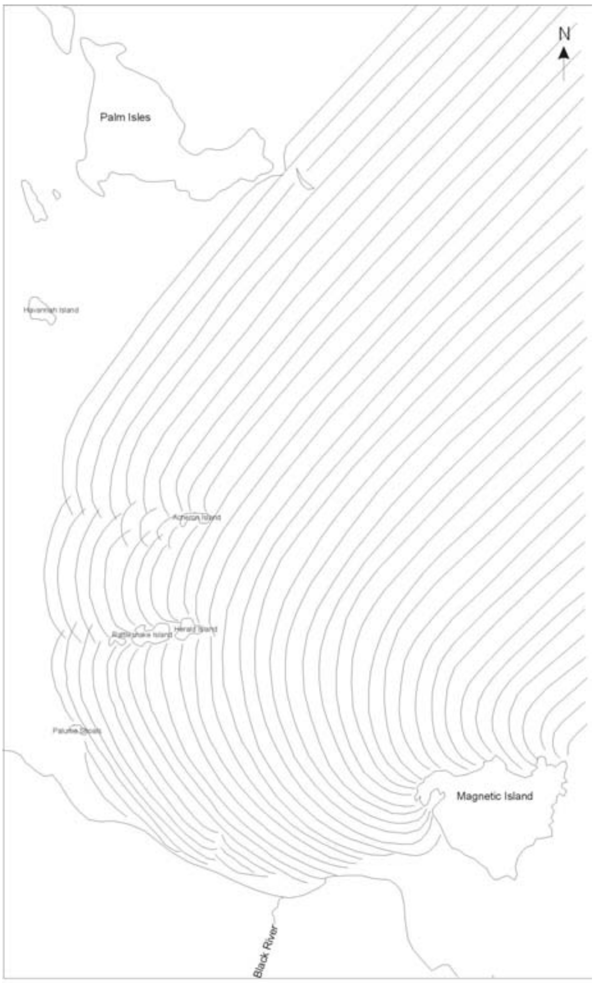


**Figure 6.13 a. Wave refraction pattern for 5 second wave intervals and 20 wave crest spacing generated by south easterly winds.**

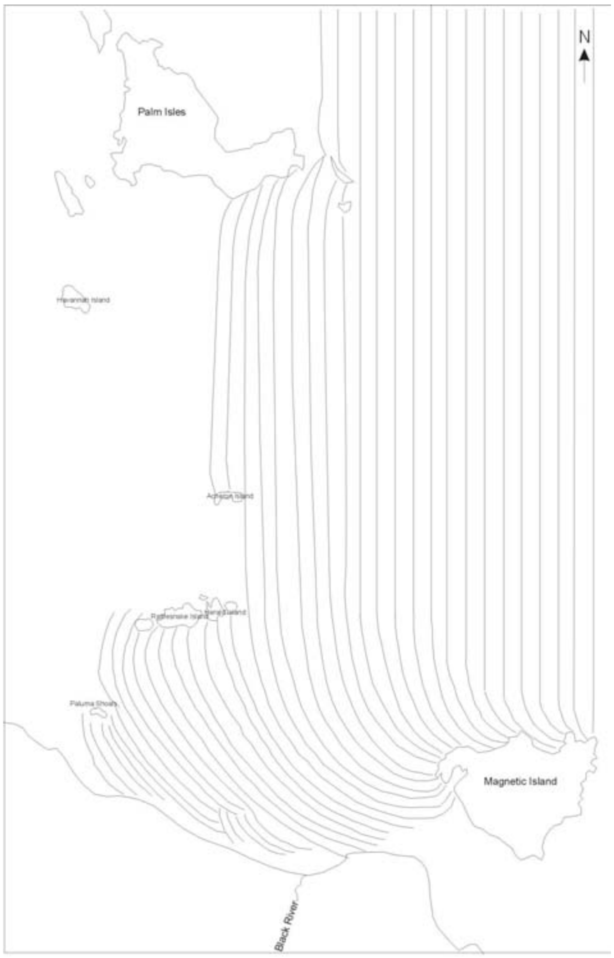


**Figure 6.13 b. Wave refraction pattern for 5 second wave intervals and 20 wave crest spacing generated by easterly winds.**

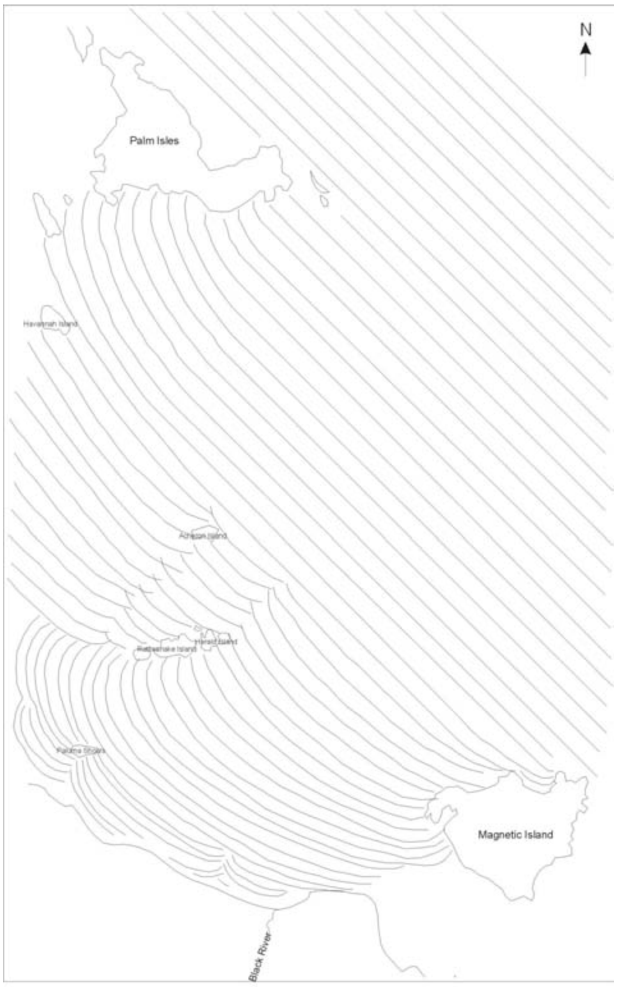


**Figure 6.13 c. Wave refraction pattern for 5 second wave intervals and 20 wave crest spacing generated by north easterly winds.**

Wind data analysis for Townsville has revealed a significant (both $R^2$ = 0.47) increase the frequency of south-easterly and easterly winds at all speeds since 1950 (Figures 6.14 and 6.15). This may have increased the movement of sand to the north west – indicated by spits orientated to the north west. There is also a marked increase in the frequency of south-easterly and easterly winds <21 km.h$^{-1}$ from 1980-1984 which decreased again from 1985-1989. The frequency of north-easterly winds has dropped off significantly ($R^2$ = 0.59) between 1965 and 1985 (Figure 6.16). The frequency of north-easterly winds has increased again in the subsequent 15 years, which may account for recent coastal erosion.

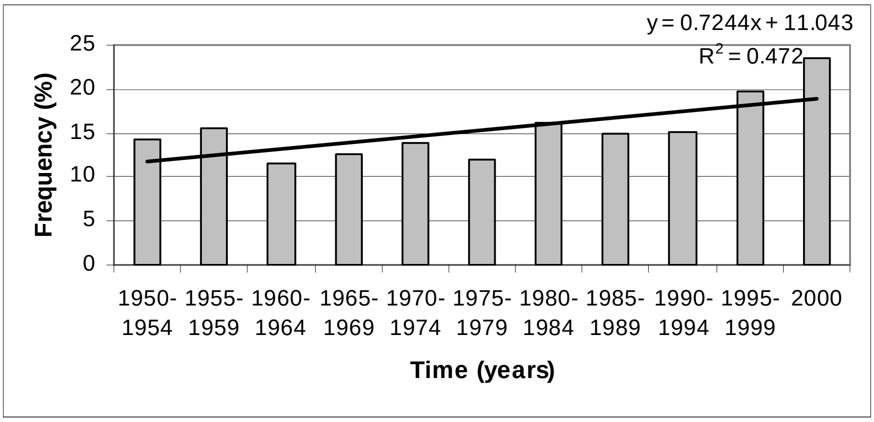


**Figure 6.14. The frequency of south easterly winds at all speeds has increased from 1950-2000. Townsville wind data from the Bureau of Meteorology.**

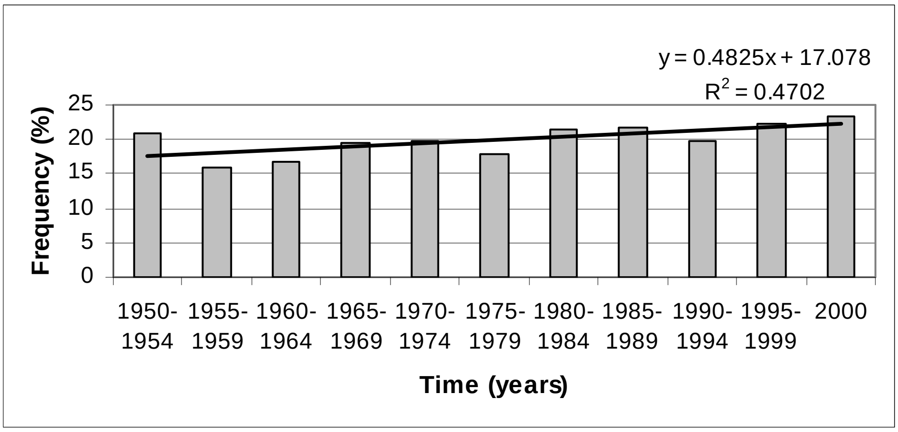


**Figure 6.15. The frequency of easterly winds at all speeds has increased from 1950-2000. Townsville wind data from the Bureau of Meteorology.**

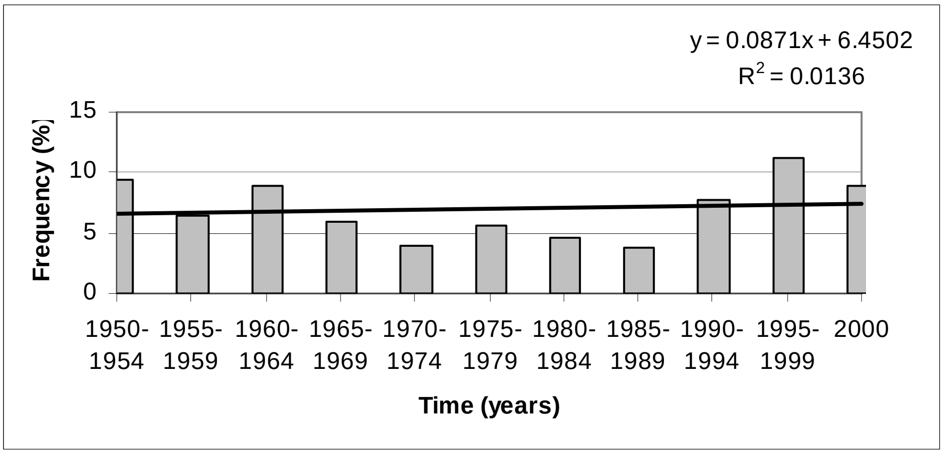


**Figure 6.16. The frequency of north easterly winds over 21 km.h-1 has dropped off between 1965-1985. Townsville wind data from the Bureau of Meteorology.**

The increase of south-easterly and easterly winds during 1980-84 correlated with the movement of the sand bar onshore 500 m from the mouth and the massive 80 m progradation of the shoreline. An increase in the frequency of north-easterly winds post-1985 is correlated with the sand bar moving offshore again.

### 6.5.2 BEDFORMS

The lack of larger bedforms (megaripples) suggests that tidal currents are short in duration and weak in the Black River Delta. This is because the size of the estuary is smaller compared to the Haughton and the Elliot River Estuaries. With a maximum bed velocity of 0.2 $m.s^{-1}$ during spring tidal currents (Kinhill, 1998) both ebb and flood currents are insufficient to transport bed material larger than fine sand (0.02 mm) in or out of the delta. Small ebb tide current ripples were observed on the intertidal flat indicating the seawards movement of sand.

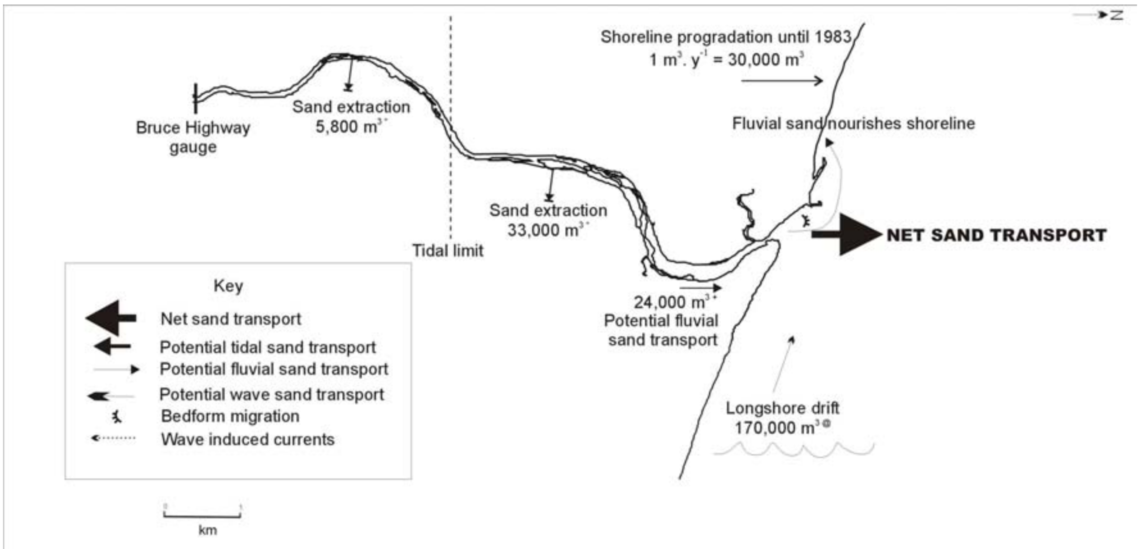
### 6.5.3 SEDIMENTOLOGY

Many of the intertidal and offshore samples from the delta are bimodal, trimodal and even polymodal, therefore interpretations from the statistics must be made with caution. Sediments close to their source are characteristically leptokurtic and finely skewed (Folk and Ward, 1957). Over half of the samples from all locations within the delta are leptokurtic and finely skewed which suggests they are close to their source, which is most likely, the Black River. River and delta mouth sediments are angular and poorly sorted and interpreted as immature fluvial sands. Beach and dune sands are slightly more rounded (sub-angular to sub-rounded) and better sorted however still in the same size range. The angularity of the grains, relatively high feldspars content and low carbonate content (12-24%) suggests that the delta is composed of Black River sands. The presence of magnetite in both fluvial sediment from the Black and sand on the adjacent coast supports the conclusion that the Black River supplies significant volumes of sand to the coast today and in the past.

The Black River delta protrudes from the coastline. The river cuts through approximately 1 km of closely spaced beach ridges from 1 to 4 m in height, which have developed over the last 6,000 years. The most likely source of this sediment is the Black River (Hopley, 1970a) (Holmes, 1992). Belperio (1978) assumed that the original source of this sand was from the Burdekin when it was positioned at the Barrattas, as the tombolo to Cape Cleveland was yet to be completed and sand moved between the compartments. Holmes (1992) tried to establish a definite link between the Black River sediments and adjacent coast deposits by the presence of magnetite. However, magnetite has been found in sand accumulations around the Whitsunday Islands (Heap *et al.*, 2002) therefore cannot be linked exclusively to the Black River.

### 6.5.4 CONCEPTUAL MODEL

The results of the aerial photograph, sedimentological and hydrodynamic investigations suggest that the Black is a wave-dominated delta. The Delta is a net exporter of sediment, which is in contrast to the Haughton and the Elliot River coastal systems which were classified as estuaries, and are net importers of sediment (chapter 2, section 2.2). The contemporary processes of sand transfer occurring in the Delta are illustrated in figure 6.17.



[#] Tidal current data from Kinhill, 1998

[*] Total sand extraction estimated as over 1,000,000 m3 since 1972 (Maunsel, 2001)

[+] Fluvial yield figures from Kinhill, Cameron and McNarmara, 1993

[@] Longshore drift estimates from ACES software

**Figure 6.17. Summary diagram of net sand transport trends at the Black River Delta as indicated by bedform orientations, grain size patterns and dominant current directions. Fluvial energy and wave-induced currents are the most dominant, hence net sand transport direction is seawards.**

Coastal change can be attributed to the movement of sand spits and bars in association with changes in wave action due to cycles of wind speed, frequency and direction. However, the aerial photograph analysis revealed the impact of flooding on the morphology and spatial arrangement of sand bodies within the delta (section 6.4.1). Modelling suggests that the Black River has the potential to deliver an average of 24,000 m$^3$ of bedload to the coast every year (Kinhill *et al.*, 1993) (section 7.3, in the following chapter for a discussion of the assumptions associated with modelling fluvial sediment yield). As in the Haughton, reference to yearly estimates of fluvial supply in this highly variable discharge system is not ideal, however it is all that is available. Also similar to the Haughton and the Elliot short duration of high discharge events in the Black River is not conducive to large amounts of sand transfer. However the shorter estuary, i.e. only 3% of the channel is under tidal influence creates a different situation in the Black, and despite geomorphically ineffective flooding (Costa and O'Connor, 1995) (see chapter 2, section 2.4.1) fluvial sediment is still delivered to the coast.

Holmes (1992) identified the Black River Delta as the source of sediment for the adjacent coast. Aerial photograph analysis (see section 6.4.1) reveals that this coast has continued to prograde at a rate of 1 m per year in recent years (1942-1983). Strong longshore currents driven by dominant south-easterly waves act as a mechanism to transport sand at the delta mouth to the adjacent coast and also provide additional sand imported into the system from further south. Modelling using ACES (Leenknecht *et al.*, 1992) (chapter 3, section 3.4.4.1, Appendix C) suggests that longshore currents have the potential to transport 170,000 $m^3$ of sand north per year. While large-scale coastal progradation has been linked to changes in wind patterns, erosion along the adjacent coast indicated from analysis of the most recent 20 years of aerial photographs (section 6.4.1 and 6.5.1) implies a reduction in the supply of sand. Reduction in sand availability in the delta possibly due to The extraction of over 1,000,000 $m^3$ of sand from the Black River channel for commercial purposes (Kinhill, 1998) (equivalent to ~30 years of average sediment delivery to the coast) may be a contributing factor to reduced sand availability in the delta.

# CHAPTER 7 – HOLOCENE SAND BUDGET FOR THE SWT COAST

## 7.1 INTRODUCTION

The results of aerial photograph, sedimentological and hydrodynamic investigations at the Haughton River Estuary, Elliot River Estuary and the Black River Delta (see chapters 4, 5 and 6) suggest that SWT streams have not been delivering the volume of sand to the coast predicted by recent modelling e.g. Prosser *et al.*, (2001a) who support an average of 400,000 $m^3.y^{-1}$. These findings must be interpreted within a Holocene context to incorporate multi-cyclic processes of coastal evolution. This chapter presents a Holocene sand budget for the SWT coast. Sand stored onshore and on the inner shelf within the SWT is quantified and compared with modelled estimates of sand delivery to the coast extrapolated over the last 7 ka. The spatial extent of sand that has contributed to the modern SWT coast is largely restricted to sand deposits on the present inner shelf, which at -5 m sea level (~7 ka BP) could have been reworked by waves and transported on shore.

## 7.2 ESTIMATING THE VOLUME OF SAND IN THE COASTAL ZONE

The SWT coast is dominated by sand with extensive beach ridge plains, sand-choked inlets and sandy nearshore deposits (Figure 7.1). Sedimentological, stratigraphic and seismic investigations were reviewed to quantify the volumes of sand deposited on the SWT coast (4 m to L.A.T.), nearshore (subtidal) (0 to -5 m L.A.T.) and continental shelf (inner shelf -5 to -20 m L.A.T.) during the Holocene. Sand deposits were quantified using the following equation:

$$\mathbf{x = (a \times t)\ s}$$

*where*

**x** = the volume of sand contained in a deposit

**a** = area of deposit

**t** = estimated or established thickness

**s** = the proportion of sand-sized material in the deposit.

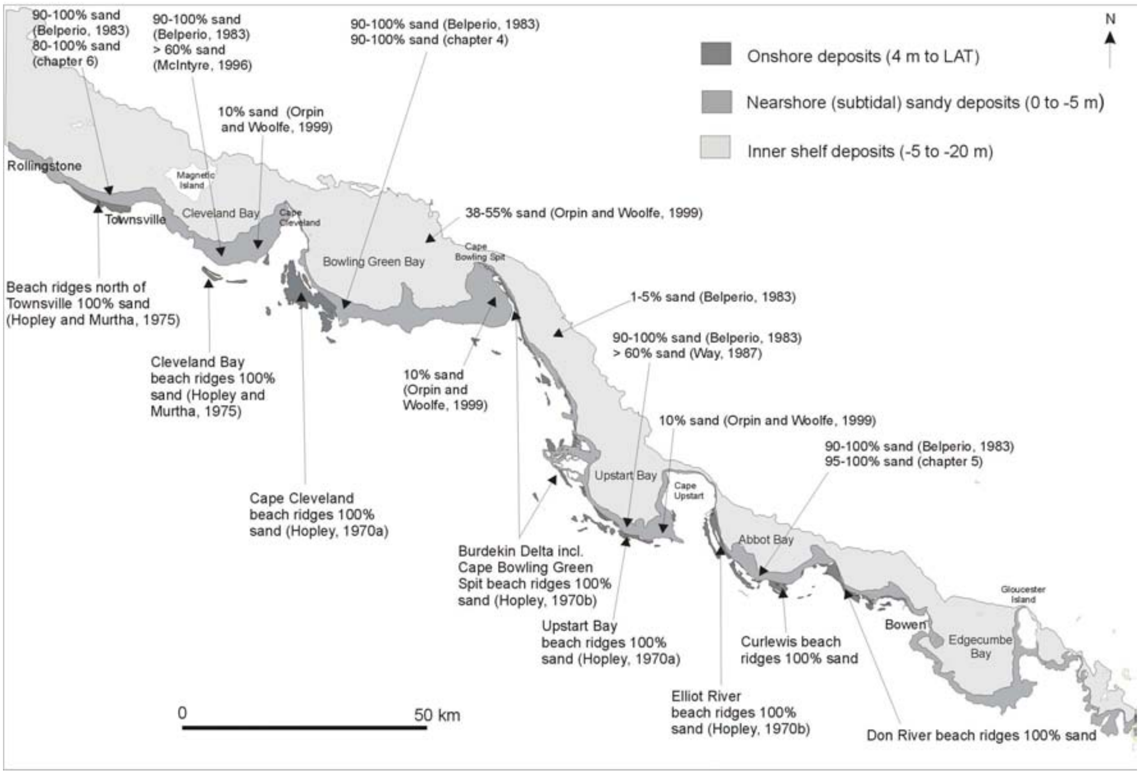


**Figure 7.1. Location of onshore, nearshore and inner shelf deposits for the SWT coastal zone and the percentage of sand reported in the literature.**

### 7.2.1 ONSHORE DEPOSITS

Hopley (1970a) and Hopley and Murtha's (1975) detailed studies established that the SWT coastal plain is dominated by sand. Extensive beach ridge complexes of both Pleistocene and Holocene age have been identified and mapped (Hopley, 1970a). The Cape Cleveland beach ridge complex has been most intensively studied and is the largest complex in the region, with over 100 individual ridges covering an area of 15.3 km$^2$ (Hopley, 1970a). The ridges range from 2.6 m to over 10 m in height and are entirely composed of sand (Hopley, 1970a). Fourteen cores taken in the swales of the Cape Cleveland beach ridge plain revealed a sand thickness of 0.9 m – 3 m (McIntyre and Associates, 1985). Bird's (1973) method was used to calculate the volume of sand stored in the Cape Cleveland beach ridge plain. Bird's (1973) method was considered most appropriate as it accounts for the topographic highs (crests) and lows (swales) characteristic of beach ridge plains unlike other methods (e.g. Holmes, 1992). It was assumed from topographic survey data (McIntyre and Associates, 1985) that 50% of the area is comprised of the ridge crests with an average height of 6 m above L.A.T (Hopley, 1970a) and that 50% of the area is comprised of swales with sand to an average depth of 1.95 m beneath. Using this approach it was calculated that the Cape Cleveland beach ridges contain approximately 6.1 × $10^7$ $m^3$ of sand.

This methodology was applied to quantify the volume of sand contained in onshore deposits along the entire SWT (Table 7.1). Typically, these coastal deposits comprise a beach foredune and beach ridge plain or open coast and a chenier plain on more sheltered north facing bays (see chapter 2, section 2.5) (Hopley and Murtha, 1975). Previous attempts by Holmes (1992) have overestimated the amount of sand stored onshore by failing to take into account swales in calculations of sand stored in beach ridge plains in the Townsville region, (termed collectively in on figure 7.1 as 'north of Townville beach ridges'). Bird's (1973) method is more realistic as it assumes that 50% of the area is comprised of ridge crests at an average of 4 m above L.A.T. and 50% of the area is swales with sand thickness taken as a minimum thickness of 0.9 m based on the Cape Cleveland cores (McIntyre, 1996). Cheniers are storm deposits and are not commonly homogenous sand deposits like beach ridges (see chapter 2, section 2.5 for more details). Cheniers will be considered separately in the calculations. Chenier ridges, adjacent to the Bohle River, are 1.8 m in height, composed of between 68 and 87% sand and occupy an area of 1.27 $km^2$ (Hopley and Murtha, 1975). The sum of estimates from individual onshore deposits indicates that ~1.28 × $10^8$ $m^3$ of sand is stored in onshore deposits on the SWT coast (Table 7.1).

### 7.2.2 NEARSHORE (SUBTIDAL) DEPOSITS

Sandy nearshore (subtidal) deposits extend out from the SWT coast to a depth of about 5 m below L.A.T. (Johnson and Searle, 1984) and cover ~750 $km^2$ (Figure 7.1). Seismic investigations reveal an average thickness of Holocene nearshore sediment of 2 m along the SWT coast usually overlying Pleistocene clay (Searle *et al.*, 1981; Johnson *et al.*, 1982; Johnson and Searle, 1984). Textural analyses indicate that sand comprises 60-100% of most of the surficial sediments collected from the nearshore zone along the SWT coast (Table 7.2), however in more sheltered bays such as Bowling Green Bay, sampled sediments may contain only 6-14% sand (Orpin and Woolfe, 1999). Orpin and Woolfe (1999) suggest that the increased deposition of fine fraction muds and silts in northward facing bays is due to generally lower ambient hydrodynamic energy as a result of sheltering from south easterly waves and northerly currents. Therefore the volume of sand in the sheltered areas of the northward facing bays: Cleveland Bay (73 $km^2$); Bowling Green Bay (72 $km^2$); Upstart Bay (38 $km^2$) were calculated separately with an average thickness of 2 m and an estimated proportion of 10% sand (see Table 7.3). A total of $3.7 \times 10^7$ $m^3$ (Cleveland Bay $1.5 \times 10^7$ $m^3$; Bowling Green Bay $1.4 \times 10^7$ $m^3$; Upstart Bay $7.7 \times 10^6$ $m^3$) of sand contained in sheltered areas of the bays.

The remaining nearshore deposits cover an area of 567 $km^2$ with an average thickness of 2 m. The volume of sand ranges from $2.3 \times 10^8$ $m^3$ at 60% sand to $1.1 \text{ x } 10^9$ $m^3$ at 100%. It was conservatively estimated that the remaining majority of nearshore sand deposits would contain approximately 70% sand - slightly above the minimum result from sampling (Table 7.2). These figures provide an estimate of $7.9 \times 10^8$ $m^3$ of sand. With an additional $3.7 \times 10^7$ $m^3$ of sand contained in the sheltered areas of the bays, this approximates $8.3 \times 10^8$ $m^3$ of sand deposited in the nearshore (subtidal) areas during the Holocene.

# Table 7.1 Estimated volume of sand stored in SWT onshore deposits.

| **Onshore deposit** | **Area km$^2$ (source)** | **Height of deposit m (source)** | **Average thickness of sand (m)** | **Percent sand (source)** | **Estimated volume of sand (m$^3$)** |
|---|---|---|---|---|---|
| Rollingstone Creek beach ridges* | 0.65 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 1,592,500 |
| Saltwater Creek beach ridges* | 0.08 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 196,000 |
| Leichhardt Creek beach ridges* | 0.53 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 1,298,500 |
| Sleeper Log Creek beach ridges* | 0.46 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 1,127,000 |
| Bluewater Creek beach ridges* | 0.45 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 1,102,500 |
| Black River beach ridges* | 1.20 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 2,940,000 |
| Bohle River chenier ridges | 1.27 (Hopley and Murtha, 1975) | 1.80 (Hopley and Murtha, 1975) | 1.8 | 77% (Hopley and Murtha, 1975) | 1,760,220 |
| Shelly Beach ridges | 0.37 (Hopley and Murtha, 1975) | 3.50 (Hopley and Murtha, 1975) | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 899,150 |
| Many Peaks Range beach ridges | 2.70 (Hopley and Murtha, 1975) | 6.86 (Hopley and Murtha, 1975) | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 6,165,000 |
| Cleveland Bay beach ridges | 1.82 (Hopley and Murtha, 1975) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley and Murtha, 1975) | 4,459,000 |
| Cape Cleveland beach ridge plain | 15.3 (Hopley, 1970a) | 2.6- 10.3 (Hopley, 1970a) | 3.98 | 100% (Hopley, 1970a) | 60,894,000 |
| Burdekin Delta incl. Bowling Green Spit | 4.60 (geology maps) | | 2.45 (50% 4 m; 50 % 0.9 m) | 100% (Hopley, 1970b) | 11,270,000 |
| Upstart Bay (RM point) | 2.53 (Hopley, 1970a) | | 2.45 (50 % 4 m; 50 % 0.9 m) | 100% (Hopley, 1970a) | 6,198,500 |
| Elliot River beach ridges<br>Barrier spit | 3.85 (Hopley, 1970b)<br>0.34 (see chapter 5) | 4.57 (Hopley, 1970b)<br>2.00 (see chapter 5) | 2.45 (50 % 4 m; 50 % 0.9 m)<br>2.00 | 100% (Hopley, 1970b) | 9,432,500<br>686,000 |
| Curlewis Bay beach ridges | 2.37 (geology maps) | | 2.45 (50% 4 m; 50 % 0.9 m) | | 5,806,500 |
| Don River beach ridges | 4.80 (geology maps) | | 2.45 (50% 4 m; 50 % 0.9 m) | | 11,760,000 |
| **TOTAL** | **43.32** | | | | **127,587,370** |

* these individual deposits appear grouped on figure 7.1 and are referred to as 'North of Townsville' beach ridges.

### Table 7.2 Estimated volume of sand stored in SWT nearshore deposits (0 to –5 m L.A.T.)

| **Sampling Location** | **Area km$^2$** | **Average thickness (m)** | **Percent sand (source)** | **Maximum (100% sand) volume of sand (m$^3$)** | **Minimum (60% sand) volume of sand (m$^3$)** | **Conservative (70% sand) volume of sand (m$^3$)** |
|---|---|---|---|---|---|---|
| Halifax Bay | 59 | 2 | 80-100 (this study see chapter 5)<br>90-100 (Belperio, 1983) | 118,000,000 | 70,800,000 | 82,600,000 |
| Cleveland Bay | 106 | 2 | > 60 (McIntyre, 1996)<br>90-100 (Belperio, 1983) | 212,000,000 | 127,200,000 | 148,400,000 |
| Bowling Green Bay | 198 | 2 | 90-100 (this study see chapter 4)<br>90-100 (Belperio, 1983) | 396,000,000 | 237,600,000 | 277,000,000 |
| Upstart Bay | 89 | 2 | > 60 (Way, 1987)<br>90-100 (Belperio, 1983) | 178,000,000 | 106,800,000 | 124,600,000 |
| Abbot Bay | 115 | 2 | 95-100 (this study see chapter 5)<br>90-100 (Belperio, 1983) | 230,000,000 | 138,000,000 | 161,000,000 |
| **TOTAL** | **567** | | | **1,134,000,000** | **680,400,000** | **793,600,000** |

### Table 7.3. Estimated volume of sand stored in SWT nearshore deposits (0 to –5 m L.A.T.) on the leeward side of northward facing bays.

| **Sampling Location** | **Area km$^2$** | **Average thickness (m)** | **Percent sand (source)** | **Conservative (10% sand) volume of sand (m$^3$)** |
|---|---|---|---|---|
| Leeward side of Cleveland Bay | 73 | 2 | 10 (Orpin, 1999) | 15,000,000 |
| Leeward side of Bowling Green Bay | 72 | 2 | 10 (Orpin, 1999) | 14,000,000 |
| Leeward side of Upstart Bay | 38 | 2 | 10 (Orpin, 1999) | 7,700,000 |
| **TOTAL** | **183** | | | **36,700,000** |

### 7.2.3 INNER SHELF

The inner shelf extends from the 5 m isobath to the 20 m isobath (Figure 7.1) and covers an area of approximately 2922 km$^2$ offshore of the SWT coast. During the 1970’s and early 1980’s the Queensland Geological Survey conducted an extensive program of Continuous Seismic Profiling (CSP) of the sea bed along the continental shelf between Cairns and Bowen (reviewed in Searle *et al.*, 1981). These seismic records together with later offshore sedimentological studies (e.g. Belperio, 1983; Way, 1987; McIntyre, 1996; Orpin and Woolfe, 1999; Dunbar *et al.*, 2000; Lambeck and Woolfe, 2000; Heap *et al.*, 2002) identified the extent of Holocene sand deposits on much of the inner continental shelf.

Constraining the inputs and outputs of sand on the inner shelf over the Holocene is complicated by rising sea levels altering the position of the coast and varying rates of sea-level rise due to shelf topography. The onset of sea-level rise and the subsequent flooding of the inner shelf (~9 ka) almost certainly caused the onshore movement of sand stored on the shelf (Hopley, 1970a; Thom and Roy, 1985). However the sources of the sand that moved onshore with the marine transgression must be determined to constrain the inputs of this sand budget. Dunbar *et al*. (2000) and Heap *et al*. (2002) suggest that early Holocene sediment deposits have remained on the mid-shelf and were not moved onshore with the transgression. Rather Dunbar *et al.* (2000) found increased rates of deposition of siliciclastic sediments into the Queensland trough during the transgression and Heap *et al.* (2002) found that mid-shelf siliciclastic sediments have been accumulating around the Whitsunday Islands for the last 10 ka. This occurrence can be explained by the altered capacity for the onshore transport of sand as rates of sea-level rise varied with shelf topography. Sea level reached the mid-shelf at ~12 ka rapidly flooding the low gradient shelf at a rate of ~10 m. ka$^{-1}$ or a shoreline change rate of as much as 250 m.y$^{-1}$ (Hopley, 1970a; 1984). The capacity of sand to be moved onshore would have been reduced by rapid flooding of the shelf. However once sea level reached the steeper slope of the inner shelf at around 9 ka the rate of sea-level rise halved to ~5 m.ka$^{-1}$ or a shoreline movement of 125 m.y$^{-1}$. Flooding of the inner shelf coincided with the ‘open window’ phase of the Holocene ‘high energy window’ and it is likely that sand deposits were reworked and pushed shorewards (Hopley, 1984). This was investigated by Graham (1993) to explain the large sand ridge sequence at Cowley Beach in the wet tropics 100 km north of the study area. Graham’s (1993) results were inconclusive but in this analysis the Holocene sand budget includes deposits on the inner shelf and excludes deposits stranded by rapid inundation on the mid and outer shelf due to submergence below the active wave transport zone.

The veneer of Holocene sediment on the inner shelf has been estimated at between 0.5 m (Belperio, 1983) and 1 m (Johnson and Searle, 1984) thick. Sedimentological investigations off the Burdekin Delta have found that muddy deposits on the inner shelf contain minimum values of 1-5% sand (Belperio, 1983). More recent sampling by Orpin and Woolfe (1999) in Cleveland, Bowling Green and Upstart Bay suggests much sandier inner shelf deposits with proportions of sand ranging from 38-55%. The range of estimated volumes of sand on the inner shelf using sand proportions from Belperio (1983) and Orpin and Woolfe (1999) and thickness from Belperio (1983) and Johnson and Searle (1984) are compared in table 7.4. The marked variation of sand content may be explained by sampling locations. Orpin and Woolfe's (1999) sampling regime was concentrated within the bays while Belperio's (1983) sampling regime incorporated more areas of the inner shelf. Therefore there is a high potential to over estimate the amount of sand contained on the entire inner shelf by using Orpin and Woolfe's (1999) results for sampling within the bays. Inner shelf deposits are assumed to be an average of 0.75 m thick given Belperio's (1983) estimate of 0.5 m thick and Johnson and Searle's (Johnson and Searle, 1984) estimate of 1 m thick. Applying a proportion of sand of 5% from Belperio's (1983) comprehensive sampling regime of the SWT inner shelf, yields a conservative and best available estimate of 1.1 × $10^8$ $m^3$ of sand contained on the inner shelf.

**Table 7.4. Estimated volume of sand stored in SWT inner shelf deposits from Rollingstone to Bowen (-5 m to -20 m L.A.T.)**

| **Area $km^2$ of inner shelf** | **Average thickness (source)** | **Percent sand (source)** | **Estimated volume of sand ($m^3$) (38-55% sand @ 1 m thick)** | **Estimated volume of sand ($m^3$) (1-5% sand @ 0.5 m thick)** | **Conservative (5% sand @ 0.75 m thick) volume of sand ($m^3$)** |
|---|---|---|---|---|---|
| 2,921 | 0.5 m (Belperio, 1983)<br>1 m (Johnson and Searle, 1984) | 1-5% (Belperio, 1983)<br>38-55% (Oprin and Woolfe, 1999) | 1,110,217,500 – 1,606,893,750 | 14,608,125 – 73,040,625 | 109,560,938 |

Sediment deposits trapped in definable palaeochannels on the inner shelf are also included. The longest Burdekin palaeochannel extends 25 km over the inner shelf, is greater than 1000 m wide and contains 5.5 - 14 m thick sediment deposits (Fielding *et al.*, 2003). An average thickness of 9.75 m over the area of the channel (25 $km^2$) is sufficient for this quantification and equals ~2.4 × $10^8$ $m^3$ of sediment. Fielding *et al*. (2003) describe the channel fill as mud-dominated therefore applying a conservative estimate of 5% sand (Belperio, 1983) equates to 1.2 × $10^7$ $m^3$ of sand contained in the Burdekin palaeochannel on the inner shelf. Adding the palaeochannel sand deposits (1.2 × $10^7$ $m^3$) with the above estimate of sand deposited on the rest of the inner shelf (1.1 × $10^8$ $m^3$) gives a total of ~1.2 × $10^8$ $m^3$ of sand.

The total volume of sand contained on the SWT coast as onshore deposits (~1.3 × $10^8$ $m^3$), in the nearshore area (~8.3 × $10^8$ $m^3$) and the inner shelf (~1.2 × $10^8$ $m^3$) is ~1.1 × $10^9$ $m^3$. If this amount of sand was supplied to the coast by SWT fluvial systems over the last 7 ka, this equates to an average annual delivery rate from all SWT catchments of 156,625 $m^3$ of sand to the coast.

## 7.3 ESTIMATING FLUVIAL INPUTS OVER THE LAST 7 KA

Quantifying fluvial inputs of SWT streams during the Holocene relies heavily on numerical models estimating current sand delivery rates to the coast. Two methods have been used to model bedload delivered to the coast by streams: 1) calculating the volume according to the energy available, for example, Ackers and White formula (Ackers and White, 1973) which assumes sediment is available to be transported; and 2) estimating erosion rates for the catchment based on the standardised estimates such as the Revised Universal Soil Loss Equation (RUSLE) or the Fournier curve (Stoddart, 1969) which assumes that energy is available to transport the sediment to the coast. The second assumption is particularly relevant to this analysis that SWT streams have highly variable intra and inter annual discharges which has varied markedly throughout the Holocene evidenced by coral records (Isdale *et al.*, 1998) (see section 7.4.2.1). Table 7.3 summarises and compares previous estimates of fluvial bedload inputs for SWT streams between the Don River and Rollingstone Creek.

Streams in the SWT have highly variable stream flow (chapter 2). Therefore the estimates used in this study are based on bedload delivery rates according to energy availability and suggest a potential of 424,525 $m^3.y^{-1}$ supplied to the SWT coast. Application of the Fournier curve method (Belperio, 1978) yields bedload delivery rates of 8.5 × $10^6$ – 1.7 × $10^7$ $m^3.y^{-1}$, which is

20 to 40 times larger than those derived using the RUSLE equation and its derivatives. While reliance on modelled estimates is still problematic, they are the best figures available. For example, contention exists over Belperio's (1978) estimate of average annual bedload yield from the Burdekin River of 281,000 $m^3$. Neil *et al.* (2002) suggest that Belperio's use of mean monthly flow rather than daily flow results in the underestimation of sediment yield for the Burdekin by a factor of two. However as bedload transport is not just influenced by the magnitude of the flood but also the duration (see chapter 2 section, 2.4), Belperio's (1978) figures are still considered to be the most accurate. Therefore Belperio's (1978) estimate for the Burdekin and estimates for the other SWT streams also derived using the Ackers and White (1973) formula is used to quantify fluvial inputs in the SWT over the last 7 ka. Assuming fluvial sand supply to the SWT coast has averaged 424,525 $m^3.y^{-1}$ over the last 7 ka gives a total of ~2.95 × $10^9$ $m^3$. However as previously mentioned, stream discharge and other environmental conditions have varied throughout the Holocene which may have impacted on sand delivery rates to the coast over the last 7 ka and will be discussed in the following sections. As indicated in section 7.2.3, only the inner shelf sediment deposits are included in the sand budget for the present coast. At the beginning of the Holocene transgression sea level was at ~-20 m and began to inundate the continental shelf off the SWT at ~9 ka (Thom and Chappell, 1975; Thom and Roy, 1985). At about 7 ka sea level had reached –5 m below present and the sand deposited on the inner shelf is still within the active wave zone and able to be transported onshore (Hopley, 1984). Therefore inner shelf deposits, which are most likely fluvial deposits from previous low sea level stands (Johnson *et al.*, 1982), are also incorporated into the coastal sand budget.

## 7.4 THE SAND BUDGET

Comparison of mid-late Holocene fluvial sand inputs (2.95 × $10^9$ $m^3$) with the volume of sand contained in onshore deposits, nearshore areas and the inner shelf (1.1 × $10^9$ $m^3$), suggests that there should be 62% (1.85 × $10^9$ $m^3$) more sand deposited within the SWT coastal zone. While this may be the product of inaccurate models, there are other possible explanations for the apparent deficit of sand.

### 7.4.1 OTHER EXPLANATIONS FOR THE APPARENT DEFICIT OF SAND

Other possible explanations for the apparent deficit that must be considered include:

1. Fluvial sediment supply has varied in the past, perhaps due to climate change, and in the shorter term, the influence of anthropogenic activities such as land use change, sand extraction, and flow regulation;

2. Fluvial sediment supply has also varied spatially, as river mouth locations have changed, creating variations and/or lags between reserves and processes;

3. Longshore drift has lead to net gains or losses of sand to various parts of the SWT coast, with net sediment possibly varying though time.

### 7.4.2 CHANGE IN FLUVIAL SAND SUPPLY COMPARED TO MODERN DAY RATES

Environmental conditions have varied throughout the Holocene which are likely to have affected sand delivery rates to the coast over the last 7 ka. Factors that may have influenced sand yield from streams in the SWT during the Holocene include:

- Late Quaternary climate changes - variations in rainfall, vegetation cover and stream flow;

- Anthropogenic activities such as land use change, sand extraction and river regulation.

#### 7.4.2.1 Climate change

The Australian climate has exhibited humid and arid phases during the Late Quaternary period (Nott *et al.*, 2001). As indicated in section 7.2.3 fluvial deposition to the inner shelf began ~9 ka, hence variations of climate since 9 ka are most relevant when predicting variations in supply rate to the inner shelf. Figure 7.2 compares records of climate change derived specifically from within the north Queensland region with records from around Australia and Papua New Guinea dating back to 9 ka BP. The record for north Queensland is compiled from three main data sources: 1. Pollen record of vegetation changes from Lynches Crater, north Queensland (Kershaw, 1975; 1978; 1985; 1986); 2. Slack water and boulder deposits in the Burdekin River

Gorge (Wohl, 1992); and, 3. Burdekin River flood discharges reconstructed from records of freshwater influx preserved in coral skeletons including luminescent bands (Isdale *et al.*, 1998).

Kershaw's record of Quaternary climate change in north-east Queensland is derived from the analysis of 60 m of sediment cores from Lynch's Crater on the Atherton Tablelands (Kershaw, 1985). Palaeoclimatic information was derived from the cores and a best estimate precipitation curve was established, though Kershaw (1985) concedes other important climatic variables (that would influence vegetation distributions) such as seasonality and the degree of cloud cover were not considered in this interpretation. Kershaw's (1985) interpretation suggests that annual precipitation on the Tablelands increased from ~800 to 3000 mm after 18 ka particularly between 11 and 7 ka. The apparent increase in precipitation coincides with the late transgression (11 – 7 ka) which reduced the distance from the Atherton Tablelands to the coast allowing moisture bearing south-easterly trade winds to influence the area (Ash, 1981). Wohl's (1992) investigation of boulder deposits in the Burdekin River Gorge reveal that seven floods have occurred over the last 1.2 ka with sufficient discharge and duration to transport boulders much larger than recent floods. Corals from the Great Barrier Reef suggest that overall the last century was generally drier than the seventeenth and eighteenth century (Isdale *et al.*, 1998). Despite being drier overall, three major flood events in the Burdekin have occurred over the last century (Wohl, 1992).

Inferring the probable effect of such climate variations on fluvial bedload yield and delivery to the coast is difficult (Thomas *et al.*, 2001). Figure 7.2 is a schematic representation of the relationships between fluvial sand supply, fluvial sand transport potential and climate change during the Holocene. There is debate in the literature over the impact of palaeoclimate variations on fluvial bedload yields and delivery to the coast. For delivery to occur sand must be available and streams must be capable of transporting this sand to the sea (Thomas, 2003). Increases in average annual rainfall (e.g. over 2000 mm between 11 – 7 ka in the Atherton Tablelands (Kershaw, 1985) have previously been associated with elevated rates of fluvial sand delivery to the coast in other tropical rivers in the early Holocene (Goodbred and Kuehl, 2000). Higher rainfall increased the streams ability to transport bedload sands. However Neil *et al.* (Neil and Yu, 1996a) argue that for north east Australia higher rainfall is likely to increase vegetation cover reducing sand availability. Conversely drier periods would have reduced vegetation cover increasing sand availability; however lower rainfall may have limited the stream’s capacity to delivery the sand to the coast (see figure 7.2). Nott (2001) reported an increased period of alluvial fan development between 27 – 14 ka in the wet tropics region of north Queensland (Cairns). Dry conditions (rainfall less than 800 mm (Kershaw, 1985)), lead to sparse vegetation cover on slopes allowing the liberation of sand to stream network (Nott *et al.*, 2001). Lower rainfall also reduced the capacity of the streams to transport this sand to the coast resulting in the accumulation of extensive alluvial fans (Nott *et al.*, 2001). Page *et al.* (2003) claim the onset of wetter conditions between 11 and 7 ka (based on Kershaw’s record (Kershaw, 1985) led to north Queensland streams actively depositing sand out to the shelf, despite higher rainfall improving vegetation cover and thus limiting sand available from the slopes. Page *et al*. (2003) argue that during this period (11-7 ka) streams with increased capacity to transport sand incised into previously deposited alluvial fans as described by Nott *et al*. (2001), delivering sand out to the shelf. While climate change has almost certainly impacted fluvial sand delivery to the coast, given that regional vegetation change may lag shifts in rainfall by up to 1 ka (Thomas, 2003), the direct links between climate change and sand flux to the coast are still contentious.

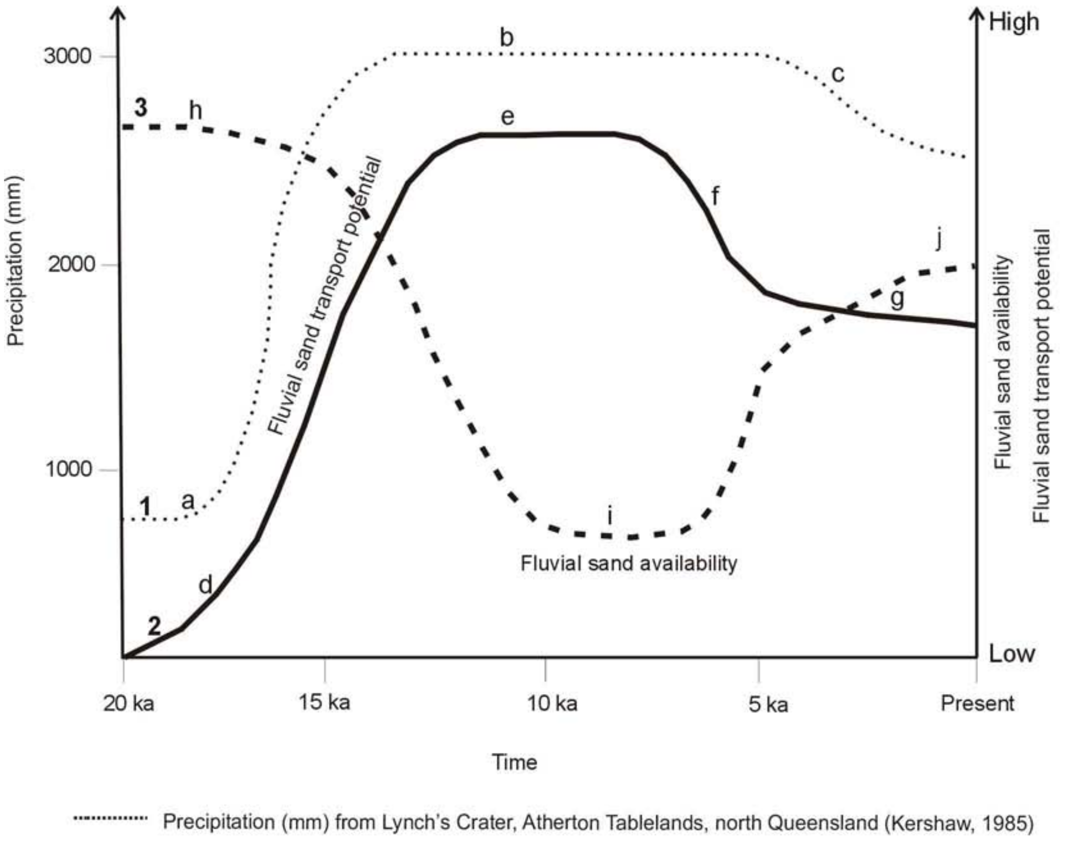


**Figure 7.2 This figure portrays the presumed broad relationship between the amount of sand available in the catchments (3) and the stream's ability to transport sand to the coast (2) inferred from variations in precipitation (1) over the last 20 ka**. Kershaw (1985) interpreted precipitation levels from pollen samples from Lynch's Crater in north Queensland. From ~20 ka (LGM) until ~14 ka BP was a very dry period, average annual rainfall is estimated at less than 800 mm (1a) (Kershaw, 1985) and would have most likely limited the capacity of stream's to deliver sand to the coast (2d) (Page *et al.*, 2003). The dry conditions from (~20 ka to ~14 ka BP) may have led to sparse vegetation cover in the catchment, consequently a relatively high amount of sand would have been available (3h). The onset of wetter conditions between 11 and 7 ka (1b) (Kershaw, 1985) is likely to have promoted denser vegetation cover in catchments and reduced sand availability (3i) (Neil and Yu, 1996), while higher rainfalls may have increased the stream's ability to transport sand (2e). After 7 ka precipitation reduced slightly to present day levels (~2,500 mm) (1c) (Kershaw, 1985). Drier conditions after 7 ka may have led to sparser catchment vegetation cover, therefore increasing sand availability (3j). Lower precipitation levels may have reduced the potential of streams to deliver sand to the coast after 7 ka (2f) and has remained stable for the last 3 ka (2g).

#### 7.4.2.2 Land use change

While modelling estimates to determine the impact of land use change on SWT catchments are available (see GBRMPA, 2001), the only data derived from actual field experiments is from Wet Tropics catchments. Early work by Douglas (1966) and Gilmour (1971; 1977) to more recent work by Pringle (1991) and Neil *et al.* (2002) have reported four to ten fold increases in suspended sediment concentrations in Wet Tropics rivers after land has been cleared of natural vegetation. Douglas (1967) noted increased erosion rates in the upper Barron catchment after forest clearances from plot experiments. This conclusion was later supported and strengthened by Gilmour's (1971; 1977) findings that logging produced a two-three fold increase and complete clearing up to ten fold increase of suspended sediment loads in Freshwater Creek (a sub-catchment of the Barron River). Clearing for sugarcane and dairy farms in the Barron catchment has been associated with a two to four fold increase in suspended sediment discharged by the Barron River (Pringle, 1991). Vegetation clearing has also been associated with an increase in sand yield from the Barron catchment, empirical models predicting an increase from almost zero in 1916 to 180,000 $m^3.y^{-1}$ in 1979 (Pringle, 1991).

Neil *et al.*'s (2002) review of anthropogenic changes to fluvial sediment yield to the Great Barrier Reef concluded that total sediment delivery to the coast from SWT streams has increased by a factor of four. Vegetation clearing has caused the greatest increases in SWT catchments compared to humid catchments due to the episodic and erosivity of rainfall (Neil *et al.*, 2002). Analysis of Ba/Ca ratios in Great Barrier Reef corals support this theory in part indicating a five to ten fold increase in the delivery of suspended sediments to the inner Great Barrier Reef since European settlement ~1870 (McCulloch *et al.*, 2003).

However, to understand the downstream impacts of land use change, especially sand delivery to the coast, requires information on rates of sediment transfer from catchments to streams rather than rates of erosion on plots, or catchments. Plot-scale experiments give measures of erosion but lack data on the distance the sediment travels which flume experiments have shown may only be a few metres (Wasson *et al.*, 1996). Wasson *et al.* (1996) estimates that sediment yields from Australia streams have only doubled in the last 200 years despite a reported 100-fold increase in hillslope erosion. Indeed it is also thought to be rare for sand-sized sediment eroded due to anthropogenic influences to reach the coast (Roy and Crawford, 1977). The SEDNET model (Prosser *et al.*, 2001a; 2001b) uses the models such as the RUSLE (Revised Universal Soil Loss Equation) which is based on plots measures of erosion. However assumes that there is no input of coarse sediment to the stream from the hillslopes, only 5-10% of the sheet wash and rill erosion and 90% of sediment is trapped in reservoirs. As noted, increased sand yield from cleared catchments is usually inferred from empirical models however the actual delivery of sand to the coast is a complex process (see section 7.6 this chapter). While many authors report strong links between clearing of natural vegetation in catchments and increases in suspended sediment yield to the coast (Brodie, 1996; Isdale *et al.*, 1998; McCulloch *et al.*, 2003; Radlke, 2003), land use change cannot be easily correlated to increased rates of fluvial bedload sediment delivery to the coast (Pringle, 1991; Neil *et al.*, 2002) given that human activities such as dam building and sand extraction may also reduce sand supplies (Pringle, 1986; 1991).

#### 7.4.2.3 Sand extraction and river regulation

Anthropogenic impacts may reduce or interrupt the natural delivery of some sediment fractions to the coast. Reduced sand and gravel delivery to the coast is often attributed to anthropogenic impacts such as sand extraction and dam construction (Kinhill *et al.*, 1993). In the past no limits were imposed on sand extraction from SWT streams and records were not kept, so the total amount of sand that has been removed from the river systems in north Queensland is unknown. Approximately 5,000,000 $m^3$ of sand is documented to have been extracted from SWT coastal systems since 1972 (Table 7.5).

**Table 7.5. Amounts of sand extracted from SWT coastal systems since 1972.**

| **River (Source)** | **Sand extracted from non-tidal reaches ($m^3$)** | **Sand extracted from tidal reaches ($m^3$)** |
|---|---|---|
| Black River (Kinhill, 1998) | 100,000 | 1,000,000 |
| Ross River (Townsville Port Authority, 2002) | 1,790,000 | 4,285,796 of sediment unknown proportion of sand |
| Haughton River (Kinhill *et al.*, 1996) | 560,000 | 100,000 (since 2001) |
| Burdekin River (Kinhill *et al.*, 1993) | 1,000,000 | Figures not available |
| Don River (Kinhill *et al.*, 1993) | 1,000,000 | Figures not available |

Regulating river flows may diminish the capacity of a river to transport sediment, especially bedload (Pringle, 1986). The Ross River for example, is one of the most highly regulated rivers in the SWT with a dam and three weirs. Coarse sediments are trapped in the upper reaches of the river upstream of the dam (Persson, 1997). Flood frequency analysis based on peak discharges recorded along Ross River shows that the 1 in 10 year flood peak flow rate decreased after dam construction by 89% from 2200 $m^3.s^{-1}$ to 240 $m^3.s^{-1}$ (Persson, 1997), which may reduce the capacity of the river to transport bedload sediments downstream.

Pringle (1986) reports that dams in other north Queensland rivers are trapping coarse sediment. For example the Tinaroo Falls Dam in the Atherton Tablelands, has prevented the downstream movement of all sand-sized sediment. The Burdekin River, the largest river in the SWT region, was dammed in 1986. Pringle suggests (Pringle, 1986) over the longer term (100 years) intertidal and submarine deltas will dwindle and fail to maintain sediment supply to spits and barrier islands further north. This may lead to the destruction of Bowling Green Spit which would alter the hydrodynamics of Bowling Green Bay (Goh, 1992) More recently Pringle (Pringle, 2000) attributed the cessation of the 1 km seaward extension of the northern most spit, Alva Spit observed in 1940-1980 to the impact of the dam. However in the short to medium term, impacts near the contemporary river mouth are likely to be delayed as enhanced erosion of the lower section of the Burdekin River compensates for reduced sand supply (GHD, 2000). Also, the Burdekin Falls Dam is located on the northern tributaries which are draining largely basaltic low sand yielding catchments and make up only one third of the extent of the Burdekin catchment (40,093 $km^2$). It is the southern tributaries draining mainly sedimentary rocks which produce the most sand-sized sediment, suggesting that impact of the dam on reducing sand supply to the coast has been largely overstated.

The regular release of water from dams for irrigation purposes also has the potential to impact coarse sediment availability in SWT streams. This practice creates elevated dry season base flows which may encourage the growth of instream vegetation and enhance the stability of instream bars (Smithers, 2002). Thus anthropogenic impacts such as sand extraction and river regulation may have contributed to the lack of fluvial sand delivery to the coast, in terms of availability at least in the last 200 years. However from the results of this study it appears that availability of sand is not the restricting factor, rather the competency of SWT streams to deliver this sand to the coast.

### 7.4.3 CHANGES IN GEOMORPHOLOGY

#### 7.4.3.1 Locations of stream mouths

SWT streams have evolved during the rising sea levels of the Holocene transgression, taking different courses and discharging at different locations (Hopley, 1970b). These variations have affected the spatial distribution of fluvial input over the last 7 ka. For example the Ross and Bohle Rivers were joined at lower sea levels (Hopley, 1970a). The Ross once discharged into Rowes Bay until meander migrations caused it to enter the sea at Ross Creek, and then migrating further south to its present mouth (Hopley, 1970a). The Black and Bohle Rivers used to discharge into a bay that is now the Town Common (Hopley, 1985). The location of the Burdekin River mouth has also varied with changes in sea level (see chapter 8, section 8.4.2). However, the overall effect on sand delivery is purely local and does not affect regional budgets.

#### 7.4.3.2 Pleistocene inheritance

Despite the sand budget for the SWT calculated over the Holocene it is not assumed that all sand contained in Holocene deposits is of Holocene age. Modern landforms are inherited from earlier forms particularly from the last interglacial shorelines which were only a few metres above present sea level (Hopley, 1985). For example, Thom *et al*. (1981) attributed the initial phase of Holocene barrier development in NSW with the landwards movement of sand on the shelf during the post-glacial transgression. This shelf-derived sand almost certainly included material from Pleistocene interglacial barriers (Hopley, 1970a; Belperio, 1978; Pringle, 1983; 2000).

### 7.4.4 MOVEMENT OF SAND IN AND OUT OF THE SWT

The occurrence of northward extending spits, bars and tombolos along the SWT coast (Hopley, 1970a; Belperio, 1978; Pringle, 1991; 2000) provide geomorphic evidence of the northward movement of sand via longshore currents. Sand movement is restricted in the nearshore to depths of about 5 m as a result of hydrodynamic controls (depth of active wave base). Finer sediments (mud and clay) carried in suspension can be transported further with less energy and the northward transport of these fractions is not restricted by depth like sand (Belperio, 1978; Pringle, 1991). Prevailing south-easterly trade winds promote strong littoral currents ($0.25\ m.s^{-1}$) along the SWT coast capable of transporting sand-sized sediment north (Orpin *et al.*, 1999).

Cyclones also cause wind-driven north-directed middle shelf flows (> 130 $cm.s^{-1}$) which erode the sea bed, concentrate the sparse mobile sediment into sand ribbons, and advect suspended load onto the outer part of the nearshore terrigenous sediment prism (Larcombe and Carter, 2004).

In order to quantify the inputs and outputs in a coastal system, Davis (1974) proposed the concept of a coastal sediment compartment. Davies (1974) applied the concept to a hierarchy of compartments of varying size and degrees of exclusiveness. The SWT coastal system can be described as a 'maxi compartment' (Davies, 1974:471) encompassing smaller coastal sediment compartments within it and where the southern limit of the compartment is Gloucester Island and the northern limit in Rollingstone Creek (Figure 7.3). Figure 7.4 is a conceptual model of sand transfer within the SWT maxi compartment. The deeper water (>8 m) around the Whitsunday Islands, Conway Coast, Cape Gloucester and Gloucester Island just south of Bowen, impede sand transfer by longshore drift currents from the south east. Therefore north of Bowen is the start of a partially enclosed sand compartment (Davies, 1974) with net sand movement north of Bowen (see figure 7.3). The presence of northward orientated spits and subtidal sand waves (see chapters 5 and 6) supports sand transport figures derived from models. Longshore drift calculations using ACES (Leenknecht *et al.*, 1992) (chapter 3, section 3.4.4.1; Appendix C) suggest that 100,000 $m^3.y^{-1}$ of sand is potentially driven north from Bowen by south easterly winds to Guthalungra. However, water depths averaging 8 m (below the active sand transport zone) off the granite headland of Cape Upstart impedes the movement of sand further north. Therefore while sand derived from the Don River coastal system could be transported by longshore currents into Abbot Bay it is unlikely to be transported any further north. The low energy wave conditions in Bowling Green Bay produce lower rates of northward sand transfer. However, water depths of over 7 m off Cape Cleveland (Figure 7.5) prevent the transport of sand into Cleveland Bay. Extensive sand bars off Cape Pallarenda (Figure 7.6) indicate the movement of sand northward out of Cleveland Bay. ACES models suggest that 170,000 $m^3.y^{-1}$ of sand could be potentially transported along the coast north of Townsville via longshore currents past Rollingstone Creek and without any impediment until Hinchinbrook Island. This may be producing a potential loss to the SWT system of 170,000 $m^3$ of sand northwards each year. Indeed continued erosion along the Strand foreshore, Cleveland Bay has lead to the artificial re-nourishment of the foreshore with 400,000 tonnes of sand sourced mainly from the upper reaches of SWT rivers (Kettle *et al*., 2001).

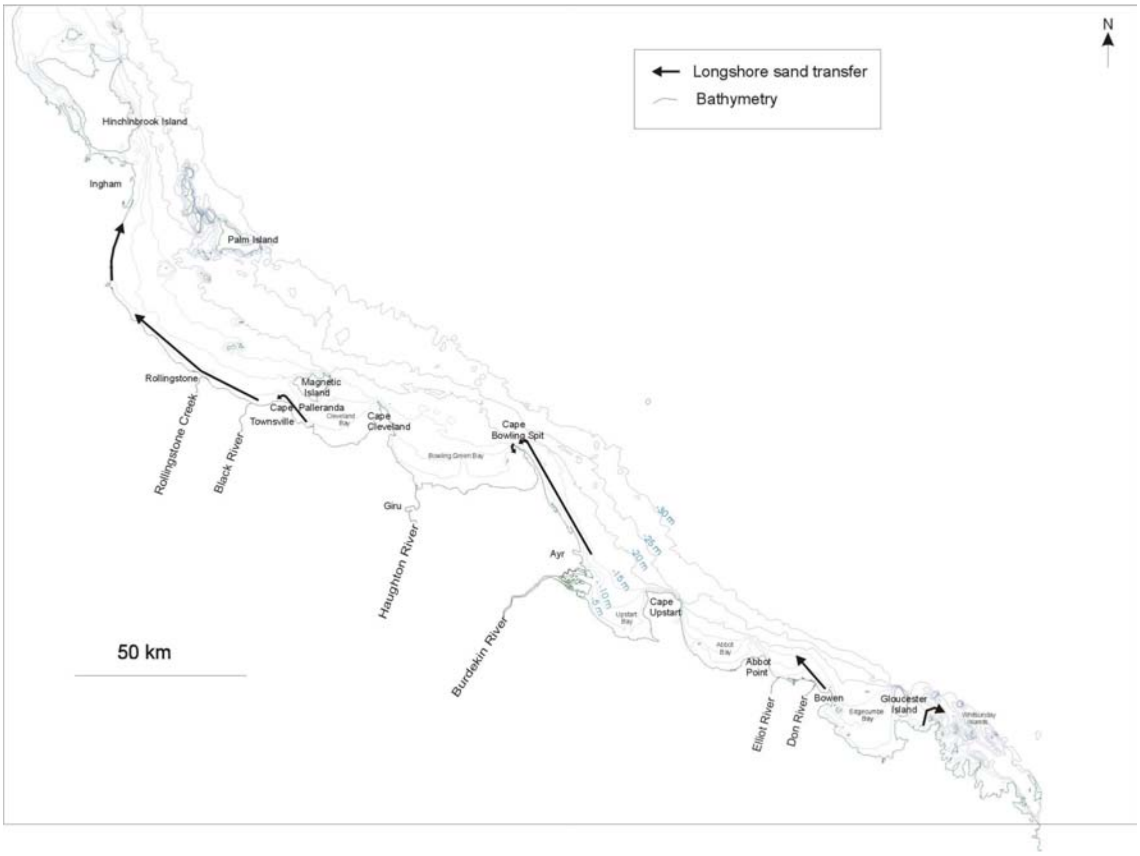


**Figure 7.3. The SWT maxi-compartment.**

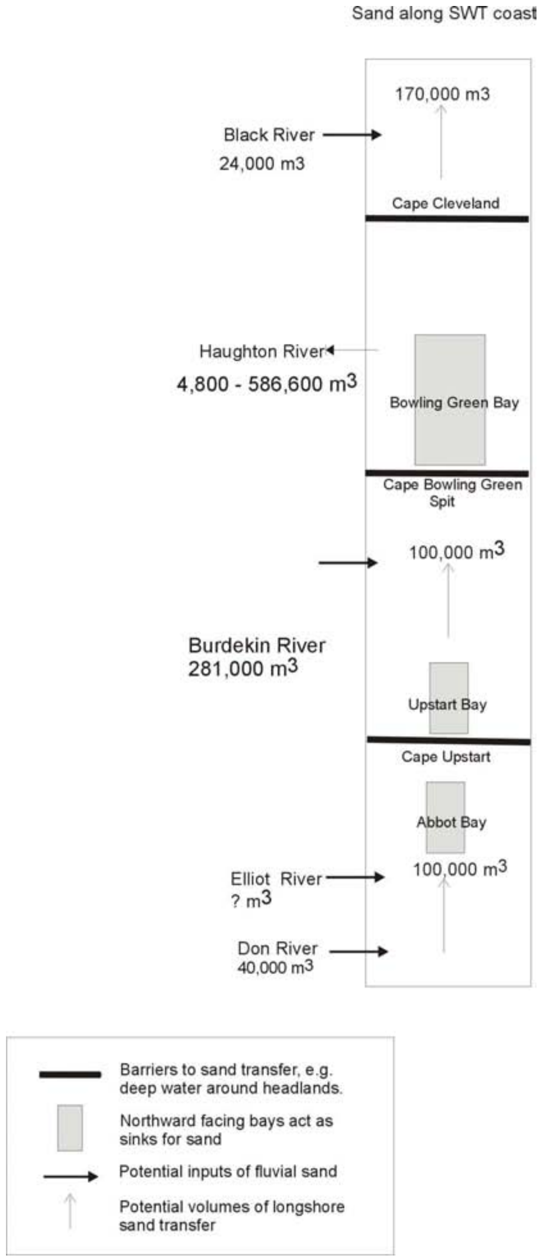


**Figure 7.4. Conceptual model of sand transfer in the SWT maxi-compartment (refer to figure 7.3)**

**Figure 7.5. Oblique aerial photograph of Cape Cleveland. Note the lack of sandy nearshore deposits around the tip of the Cape. (Photograph taken 16/05/03).**

**Figure 7.6. Oblique aerial photograph of Cape Palleranda. Note the continuation of nearshore (subtidal) sandy deposits around the Cape. (Photograph taken 16/05/03).**

The Burdekin Delta is often referred to as the major point source of fluvial sediment to the SWT coast (Belperio, 1978). While this statement is true for the past (see chapter 8, section 8.4), at present suspended sediments from the Burdekin may reach Cleveland Bay, but the northward limit of sand transport is Bowling Green Bay (Belperio, 1978). Northward extending sand spits along the eastern coast of the delta accreted northward at a maximum rate of 375 $m^3.y^{-1}$ in 1991-1993 (Pringle, 2000). The Bowling Green Bay compartment is bounded by Bowling Green Spit to the east and south and Cape Cleveland to the west and north and like other northward facing embayments, is a sink for northward moving sediment (Orpin, 1999). Approximately 76-93% of sediment from the Burdekin is transported north into Bowling Green Bay with only 5-10% retained in Upstart Bay (Orpin, 1999). Way (1987) estimated that 2 x $10^5$ t of sediment is retained in Upstart Bay which equates to 12,500 $m^3$ of sand (assuming 10% bedload after Belperio, 1978). It is feasible that 95,000 – 232,500 $m^3.y^{-1}$ of Burdekin River sand is transported into Bowling Green Bay, either from recent fluvial supply or erosion of the delta. Indeed seismic investigations revealed asymmetrical sand waves approximately 3 m in height and 750 m across along the eastern side of Cape Bowling Green, indicating strong northward movement of sand (Orpin, 1999). From Cleveland Bay north along the SWT coast, sand can be transported northwards with few impediments, until Hinchinbrook Island.

## 7.5 CONCLUSIONS ON LONG-TERM SAND BUDGETS

Fluvial sediment supply has almost certainly varied during the Holocene in response to climate change, sediment availability, sea level variations and anthropogenic impacts. The onset of wetter conditions (11-7 ka) enabled SWT streams to actively deposit sediment onto the shelf from incision into previously deposited alluvial fans and the erosion of sparsely vegetated slopes (Nott *et al.*, 2001; Page *et al.*, 2003). It is likely that fluvial sand deposited during the late transgression and earlier was pushed shoreward by the strong wave conditions associated with the ‘Holocene High-Energy Window’ (Hopley, 1984). The impact of anthropogenic activities on fluvial sediment yield in more recent times will not affect this quantification as it is difficult to make direct links between increased erosion in catchments and increased delivery of sand to the coast. Results from investigations in the Haughton, Elliot and Black Rivers (see chapters 4, 5, and 6) suggest that SWT streams have not been major contributors of sand to the coast during the late Holocene.

The spatial variability of fluvial sediment discharge due to the changing locations of river mouths along the coast, has little impact on the quantification as the SWT coastal region was treated as a whole. The potential degree of Pleistocene inheritance material in the Holocene deposits does little to explain the sand deficit, in fact it suggests that even larger quantities of sand should be deposited in the coastal zone. However, the loss of a potential 170,000 $m^3$ of sand northward from the SWT coastal compartment via longshore drift does account for 65% ($1.2 \times 10^9$ $m^3$) of the apparent deficit assuming there is no replenishment from the south. However, it still does not account for the rest of the sand - $2.95 \times 10^9$ $m^3$ predicted to have been delivered to the SWT coast by empirical models over the last 7 ka. The answer may lie in the model calculations.

## 7.6 THE ‘SAND DELIVERY PROBLEM’

There is a strong possibility that fluvial sediment delivery models are overestimating the volumes of sand delivered to the coast, especially when applied to SWT streams. Walling (1983) describes the difficulties associated with linking rates of erosion within a catchment to the sediment yield at the catchment outlet as ‘the sediment delivery problem.’

Variations in storm magnitude and frequency effect the generation and movement of sediment slugs downstream (Nicholas *et al.*, 1995), making them especially relevant to sediment transfer in the SWT. For example, the sand delivery estimate used from Belperio (1978) for the Burdekin was the average yield 0.45 MT. However, further modelling (Belperio, 1979) shows the substantial variation in delivery rates between flood years (1957/58) estimated yield 3.07 MT and drought years (1968/69) estimated yield of 0.001 MT. The bulk of bedload is thought to be transported through the catchment or delivered to the coast during high magnitude flood events, induced by tropical cyclones. However this is often not the case (refer to chapter 2, section 2.4). The hydrograph from the Black River (see chapter 6, figure 6.3) shows that despite reaching a high maximum instantaneous discharge estimated as having an ARI of 1:100 years the duration of the maximum discharge was less than one day allowing little time for high rates of bedload transport (Costa and O'Connor, 1995)

While globally Australia has high rates of soil erosion, sediment delivery to the coast by streams is inefficient due to the arid, low lying and flat nature of the continent (Wasson *et al.*, 1996). Wasson *et al.* (1996) estimates that the proportion of eroded sediment actually delivered to the coast by streams at 3% in Australia which is a relatively low sediment delivery ratio by global standards. Indeed, Wasson (1997) warns that sediment delivery models like that of Belperio (1983) often result in an overestimation of sediment volumes actually reaching the coast because they rely on measurements of stream discharge and sediment loading collected inland from the coast. The influence of stream power on sediment transport diminishes when it reaches the estuary (Dalrymple *et al.*, 1992; Heap *et al.*, 2001), therefore these estimates must be taken as maximum potential delivery volumes.

Prosser *et al.*'s (2001a) SEDNET quantified sediment storage in river networks including: water reservoir sediment storage; floodplain storage of suspended material; in-channel storage of bedload; and transient in-channel storage. Floodplains are the areas of greatest potential for deposition of both suspended and bedload sediments (Wasson, 1997; Prosser *et al.*, 2001b), particularly in the SWT where streams have downstream decreasing channel capacities (Kapitzke *et al.*, 1998). The channel capacity of the Haughton River decreases by over 90% in the lower 27 km of channel. (Kapitzke *et al.*, 1998) (see chapter 3). Flooding of the Haughton River causes overbank flow and sand remains in-channel rather than being transported to the coast (Kapitzke *et al.*, 1998). In addition, the reduction in channel gradient along the lower reaches in SWT streams results in in-stream storage of sediment common to streams which are transport limited rather than supply limited (Prosser *et al.*, 2001b). The steep descent of streams down the Great Escarpment ends abruptly with the gently sloping coastal plain reducing the capacity of the stream to transport bedload out to the coast, which results in abundant alluvial stores of sand and gravel within the middle fluvial reaches of coastal streams in the region (Hopley and Murtha, 1975). Therefore while the catchment yield modelling may rate SWT streams as having high sediment yielding catchments due to sparse vegetation cover (Neil and Yu, 1996b), the actual sediment delivery ratio is estimated at between 9 and 34% according to the SEDNET model (Prosser *et al.*, 2001a). Even with these refinements the SEDNET model (Prosser *et al.*, 2001a) is still likely to overestimate the rates of sand delivery to the coast because it does not account for the sand that is delivered to the lower reaches of the stream but remains as in channel storage. The lack of recent fluvial sand identified seaward of estuaries from detailed sedimentological investigations in the Haughton, Elliot and Black River Estuaries (see chapters 4, 5 & 6) support this theory.

## 7.7 CONCLUSIONS

Calculations used in this study have revealed an apparent deficit of sand in the SWT coast budget. The inputs do not equal the outputs with a discrepancy of $0.65 \times 10^9$ $m^3$ of sand, most likely due to an overestimation of the inputs rather than an underestimation of the outputs. Overestimation of the inputs is probably a result of variations in fluvial sediment supply due to:

- climate change, and
- anthropogenic influences including land use change,
- sand extraction and river regulation.

However, the most important factor contributing to the overestimation of sand inputs to the SWT coast is that the morphology of SWT streams is not conducive to delivering the predicted rates of sand to the coast. Detailed investigations on the Haughton, Elliot and Black coastal systems (see chapters 4, 5 & 6) confirm, that these streams have not been delivering predicted quantities of sand to the coast in the recent past and, in the case of the Haughton, for at least the last 1 ka (see chapter 4). The results of the Holocene sand budget suggest an apparent deficit of $\sim 0.65 \times 10^9$ $m^3$ of sand (including loss to the system via longshore drift) suggesting that SWT streams have not been delivering predicted volumes of sand to the coast for at least the last 1.6 ka. Similar conclusions have been drawn in coastal systems in other SWT areas of Australia. For instance, Bryce *et al.* (1998) concluded that the Normanby River is not a significant contributor of sand to the coast despite modelling that suggests it delivers over 100,000 $m^3$ of sand to the coast per year (Prosser *et al.*, 2001a). Indeed stratigraphic evidence revealed that sand has been trapped in the estuary and has been accumulating over the last 6 ka.

Therefore supposing that the SWT streams have not supplied current estimates of sand at least for the last 1.6 ka, the most likely source for the beach ridges, sand choked inlets and nearshore sediment wedge, characteristic of the SWT coast is the onshore movement of marine sand. The most likely mechanism for placement of the substantial sand deposits that dominate the SWT system is the Holocene transgression (Hopley, 1970a). The slowed rate of sea-level rise when it reached the steeper gradient of the inner shelf at about 9 ka, would have provided ideal conditions for the landward transport of marine sand. The stabilisation of sea level over the last 6.5 ka has then allowed the build up of sand derived landforms on the mainland coast. Thom and Roy (Thom and Roy, 1985) have similarly linked the mass landwards transport of earlier coastal sand deposits in south-east Australia to the Holocene transgression and subsequent stillstand period.

Sedimentological studies in the Haughton Estuary (chapter 4) revealed that the sand-sized sediments that have accumulated in the estuary have very similar characteristics to adjacent beach ridge sands. The well sorted, rounded grains with low feldspar content in the majority of sand sampled from the estuarine and coastal parts of the Haughton system indicate mature marine sands derived from offshore (chapter 4). Orpin and Woolfe (1999) found that the terrigenous component of the inner shelf sand off Bowling Green Bay is quartzose, with only minor feldspar and also concluded they were mature sediments. Similar findings in the Elliot and the Black (chapter 5) further support the theory that the beach ridge plains, sand choked estuaries and thick nearshore sand wedge present in the SWT coastal system are composed of relict sand deposits with little direct input from modern fluvial systems. Contrary to earlier suggestions (e.g. Hopley, 1970a), the sand derived landforms that dominate the SWT coast are the result of multi-cyclic processes – initiated by the landward movement of marine sand during the Holocene transgression.

## 7.8 IMPACT OF THE HOLOCENE MARINE TRANSGRESSION ON THE COAST

The most recognisable and dominant feature of the SWT coast are the beach ridges. Investigation of these landforms provides an indication of coastal evolution over the Holocene. While it is accepted that the marine transgression between 11-7 ka BP instigated their development (Taylor and Stone, 1996; Otvos, 2000), the dominant source of sand supply to the ridges is debated in the literature. With the exception of the Shoalhaven Delta (Wright, 1970; Young *et al.*, 1996; Umitsu *et al.,* 2001), the majority of research on southern east coast beach ridges and barrier concludes that they were supplied by the onshore movement of marine sand with low sediment yielding rivers having little influence on coastal development (Thom *et al.*, 1981; Bird, 1978). Consistent with literature suggesting SWT region produce high sand yielding streams (Fournier, 1960; Stoddart, 1969), Hopley (1970a) suggested that the beach ridges were formed from sand directly supplied by adjacent streams. However new evidence presented in this thesis suggests that SWT streams have contributed little sand to the coast in the recent past prompting a revision of this theory.

The maturity of the Cape Cleveland beach ridge sands and the recession of the ridges led Hopley (1970a) to consider the possibility that these beach ridges developed in a similar way to those in southern Queensland and New South Wales. The Haughton River was not considered capable of supplying the vast quantities of sand stored in the adjacent beach ridge complex. However there may have been adequate supplies offshore in Bowling Green Bay from the time when the Burdekin discharged there prior to 6 ka BP. Considering that beach ridges form where an abundance of sediment exists and the offshore gradient is low (Taylor and Stone, 1996) waves would have transported marine sand reserves landward when sea level transgressed over the inner shelf. The final part of the transgression and the subsequent stillstand period after ~ 6.5 ka would have seen the rapid progradation of the coast. However this progradation ceased ~3 ka BP and like the rest of the SWT coast the beach ridges are presently eroding. For example the uncovering of mangrove peat on Cape Bowling Green Spit indicates retreating shorelines (chapter 2, section 2.1) (Hopley, 1970a). This suggests that the coast has not been actively supplied with sand in the recent past and implies either a reduction in sand supply or that the mechanism of transporting sand to the beach ridges is no longer occurring. Despite little fluvial sand currently being delivered to the SWT coast, estuaries are continuing to infill with sediment from the landward side and the nearshore and inner shelf are dominated by sand (chapter 7, section 7.2). Thus if the supply of sand is still available it suggests that the mechanism which originally instigated the formation of the beach ridges is no longer occurring or that redistribution has increased. This was a transgressing sea level rising over previously deposited sand. Where and how this sand was deposited as inshore marine, deltaic, estuarine or even lower riverine locations, is irrelevant as once it has been reworked and transported onto the inner shelf the sand becomes part of the coastal sand budget. The onshore movement of marine sand during the transgression has been identified as a major source of sand in other parts of the world, for example the Kennebec River, USA (FitzGerald *et al.*, 2000), and in northern France between the Somme Estuary and Belgium (Anthony, 2000).

The variation in sediment textural characteristics locally between beach ridges along the SWT coast lends some support to the original theory that they were directly supplied by adjacent streams, especially in the Black River where Holmes (1992) established a mineralogical link between Black River fluvial sediments and adjacent beach ridge sediments. However initial origin of the sand is not disputed; the process of delivery is the distinguishing factor. Sand stored in the lower estuarine channels at lower sea levels could be reworked and moved onshore as it was transgressed by rising sea levels. For example sand at the mouth of the Burdekin is very well sorted due to strong longshore currents and wave action. Fine sediments have been dispersed to leave only sand-sized sediment that waves could transport onshore as the shelf is transgressed.

# CHAPTER 8 – CONCLUSIONS

## 8.1 INTRODUCTION

This study set out to 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 were 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.

To achieve this aim detailed sedimentological, stratigraphic and hydrodynamic investigations were conducted in the Haughton and Elliot River Estuaries and the Black River Delta to develop a conceptual model of contemporary sand transfer to the coast from both streams and onshore. The second part of the investigation developed a Holocene sand budget for the SWT to interpret the relative volumes of contemporary sand transfer over Holocene time scales. Detailed studies were not conducted in the Burdekin River Delta however its influence was considered in the sand budget for the SWT (see section 8.4). This chapter outlines the main findings of the preceding chapters and discusses these findings within the context of broader issues, that were beyond the direct scope of this study but which have been highlighted by the results. Finally, an alternative scenario of evolution for the SWT coast is proposed, which downplays the direct influence of high sand yielding streams. Predictions of the future evolution of SWT estuaries and coast are discussed in view of potential sea-level rise.

## 8.2 CONCLUSIONS

### 8.2.1 CONTEMPORARY SAND TRANSFER PROCESSES IN SWT ESTUARIES

- The modern Haughton is a tide-dominated estuary and the direction of net sand transfer is landward into the estuary. The river has not delivered predicted volumes of sand to the coast for at least the last 1 ka, if at all (chapter 4);

- The modern Elliot is a mixed estuary and the main sand transfer process is the reworking shoreward and alongshore of previously deposited coastal sand by waves and tides, rather than the contribution of fluvial sand to the coast (chapter 5);

- The modern Black River is a wave-dominated delta and while it may deliver predicted volumes of sand to the coast (average of 25,000 $m^3.y^{-1}$) this does not have a major influence on coastal development (chapter 6).

### 8.2.2 HOLOCENE SAND BUDGET FOR THE SWT

The Holocene sand budget for the SWT is in deficit (chapter 7), in that the volumes of sand identified in the coastal zone as mid-late Holocene are less than models of fluvial input over this same period would suggest that SWT streams do not appear to have been significant contributors of sand to the coast in the past. Cyclone-induced flooding is thought to control fluvial sediment delivery to the SWT (Larcombe *et al.*, 1996a; Larcombe and Carter, 2004). However delivery of the sand fraction to the coast is limited no matter the severity of the cyclone due to:

1. The morphology of SWT streams. Downstream decreasing channel capacities cause overbank flows during floods so the fines are deposited over bank while the coarse sediment (sand) remains in channel rather than transported to the coast.

2. Flooding characteristics of SWT streams. While streams may reach high maximum instantaneous discharges, the duration is short (usually less than one day) limiting the amount of time available to do geomorphic work, in this case transport bedload downstream.

However the strong winds associated cyclones generate high-energy wave conditions which influence coastal sand transfer by reworking previously deposited coastal sand (see chapter 5). The sand derived landforms that dominate the SWT coast today are the result of multi-cyclic processes. Cyclones and flooding can have destructive and constructive impacts over yearly or decadal timeframes while sea-level change has impacted the SWT coast over the Holocene. The Holocene marine transgression is considered to be the most likely mechanism to initiate the onshore movement of marine nearshore sand to the east coast of southern Australia and the subsequent stillstand period allowed the accumulation of marine sand on the coast (Thom and Roy, 1985).

### 8.2.3 CONCEPTUAL MODEL OF THE HOLOCENE EVOLUTION OF THE SWT COAST

From the findings of this thesis a conceptual model of the Holocene evolution of the SWT coast is proposed (Figure 8.1). Figure 8.1 illustrates the relationship between variations in fluvial and marine sediment supply to the accretion of the SWT coast over the last 10 ka. Marked variations in fluvial sediment supply and transport potential in response to climate change during the Holocene (see chapter 7 section 7.4.2.1) have still resulted in an overall sand deficit for the SWT. Coastal accretion in the SWT during the Holocene has been inextricably linked to fluctuations in marine sediment supply largely controlled by changes in sea level. This process is described in detail later in this chapter (see section 8.5). Cyclones impact the SWT coast over decadal timeframes and could not be depicted in this conceptual model. The influence of low-frequency high-magnitude events is discussed in the following section.

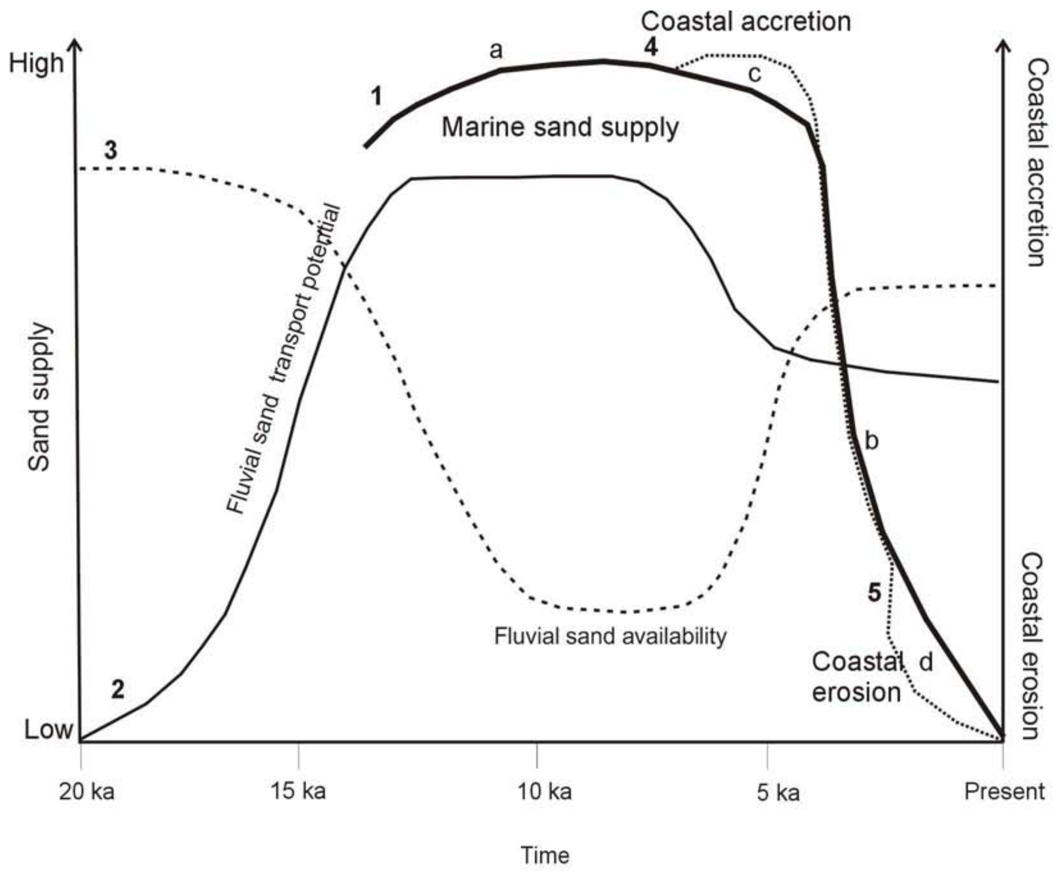


**Figure 8.1. Following on from figure 7.2, which illustrated the relationship between amount of sand available in the catchments (3) and the stream's ability to transport sand to the coast (2), this figure includes broad trends of coastal erosion (5) and accretion (4) over the last 20 ka.** While sand availability and transport potential fluctuated according to changes in precipitation, the marine sand supply curve (1) and phases coastal accretion (4) and erosion (5) were seemingly unaffected by the interplay between (2) and (3). Rather marine sand supply (1) was linked to sea level change (Thom and Roy, 1985). Marine sand supply would have increased with rapid sea-level rise between ~11 and 7 ka BP (1a) as waves would have transported marine sand landwards as sea level transgressed over the inner shelf. The final phase of the transgression and subsequent stillstand period after ~6.5 ka was associated with the rapid progradation of the coast (4c). Coastal progradation ceased at ~3ka BP, most likely due to a decrease in the shoreward movement of marine sand after sea level stabilised (1b). The SWT coast is presently in an erosional phase (5d) despite fluvial sand supply and fluvial sand transport potential available. Coastal accretion was at the highest levels when fluvial transport potential was high but there was limited sand available to transport, which suggests that patterns of coastal accretion in the SWT are linked to sea level changes and marine sand supply rather than fluvial sand supply and transport potential.

## 8.3 IMPACT OF LOW-FREQUENCY HIGH-MAGNITUDE EVENTS ON COASTAL SAND TRANSFER

SWT streams have not been delivering predicted volumes of sand to the coast even during low-frequency high-magnitude flooding events which are often induced by cyclones (see chapters 4,5,6,7). However as indicated in chapter two, section 2.4, cyclones do influence coastal sand transfer through direct marine impacts such as storm surge and high-energy waves (Hopley, 1974), which may cause the erosion of previously deposited coastal features. Pringle's (1991) study of the impacts of cyclone induced flooding on the Burdekin River Delta describes both erosive and constructive effects at a local scale (~ 30 km). Major flooding in the Burdekin (maximum instantaneous discharges > 19,000 $m^3.s^{-1}$ recorded at the Home Hill and Clare gauging stations, Queensland Department of Natural Resources and Mines) caused considerable erosion of spits, bars and barrier islands, while the deposition of sand close to the delta front (mainly in subtidal deltas) allows the accretion of spits and the delta (Pringle, 1991). Cyclone Althea (December 1971) also caused erosion along the SWT coast with up to 10 m of erosion at the eastern side of the Burdekin Delta and the south side of Cape Cleveland, between 11.6 and 15.8 m of recession between Rowes Bay and Pallarenda and 10.9 and 12.2 m of erosion at Black River and Saunders Beach, respectively (Hopley, 1974). However within the vicinity (~100m) of the river mouths the overall effect was aggradation – especially on parts of the Burdekin Delta and streams between the Bohle River and Crystal Creek (Hopley, 1974). Hopley (1974) reported an initial accretion of 20 m on the northern end of spits at Alva Beach, east coast of the Burdekin Delta (Figure 8.2). In the subsequent ten months after the cyclone the spits had grown by 200-400 m. However it is not clear whether this is due to the longshore movement of recently delivered fluvial sediment or the redistribution of recently eroded coastal sediments (Hopley, 1974).

**Figure 8.2. The Burdekin Delta location map.**

Storms and cyclones may be the most important factor controlling short-term (<10 years) coastal change (Morton *et al.*, 1995) (see chapter 2, section 2.4.2) but low-frequency high-magnitude events appear to have a relatively minor impact on large-scale coastal sand transfer and the long-term evolution of the SWT coast. The strong influence of south easterly wind generated waves over coastal sand transport is demonstrated in an analysis of wave data for the central region of the SWT coast. Modelling using ACES (chapter 3, section 3.4.4.1, Appendix C) (Leenknecht *et al.*, 1992) shows that despite relatively low ambient wave energy in north Queensland there is still the potential to move substantial volumes (>100,000 $m^3.y^{-1}$) of sand provided it is available. A waverider buoy located in deep water off Cape Cleveland has recorded modal significant wave height of 0.2 - 0.4 m for the Townsville region (BPA, 1996b). Longshore drift rates were estimated at 812,293 $m^3.y^{-1}$ using the ACES equations, for easterly wind waves approaching the shore at a 70° angle. As easterly winds prevail for 21% of the year (based on records from 1950 to 2001 taken at the Townsville Airport, station 32040) (Bureau of Meteorology, 2003), it is estimated that 170,588 $m^3.y^{-1}$ of sand is potentially moved north (21% of 812,293 $m^3.y^{-1}$). Cyclone Joy (23 December, 1990) produced the highest significant wave heights since 1975 at 2.96 m. North-easterly deep water waves at 2.96 m at a 10° angle to the coast for one day can move 23,000 $m^3$ of sand alongshore, in this case south. Wind waves associated with Cyclone Joy are estimated to have transported 14% of the amount of sand moved by easterly winds every year. Indeed, while the January 1998 floods associated with Cyclone Sid (estimated ARI of 1:100 years in the Black River see chapter 6) may have delivered sand to the delta it was quickly redistributed along the adjacent coast by ambient wave conditions. Aerial photograph analysis of the Haughton River Estuary failed to show any impact from cyclone or flooding events on the estuarine morphology, and additional stratigraphic analysis also failed to identify any immature fluvial sediments being deposited at the lower estuary for at least the last 1 ka. Modelling of the competency of bedload transport in the Haughton River estuary, further illustrates this point. A flood over ARI 1:3 years with duration over 24 hours has the potential to transport a maximum of 2,000 tonnes of sand into the estuary (Kinhill *et al.*, 1996). This is equivalent to between 2 weeks and 3 months net influx of sand by tidal currents into the lower estuary using Gadd *et al.'s* (1978) and Hardisty's (1983) equations respectively (see chapter 4). Thus the relatively high rates of sand transfer which occur under ambient wave and tidal processes may overshadow the impact of cyclones on coastal sand transfer in SWT estuaries.

The geomorphological impacts of low-frequency high-magnitude events on the SWT coast can persist over longer time frames. Chenier ridges are examples of cyclone/storm deposits which can be found along the SWT coast (Hopley, 1974; Chappell and Grindrod, 1984)(see Chapter 2, section 2.5). More recently, subtidal storm features have been discovered. Shelly gravel megaripples up to 2.5 m high (-8 m AHD) present in Halifax Bay are interpreted as cyclone generated and have been radio-carbon dated at ~2,600±170 y (Kirsch and Larcombe, 1999; Larcombe and Carter, 2004). Heap *et al.'s* (1999) sedimentological study of the Nara Inlet, Whitsunday Islands revealed that bed sediments are too coarse to be remobilised by ambient waves and tides suggesting that bedload sediment transport thresholds are only exceeded in the inlet during cyclones.

Larcombe and Carter (2004) suggest that cyclones are a major control on the supply of sediment to the SWT coast not only by the delivery of terrigenous sediment by river flooding, but by the erosion of the middle shelf seafloor. Their concept of 'The Cyclone Pump' proposes that water motions induced during the passage of a major cyclone introduce 'new' sediment from the middle shelf to the inner shelf (Larcombe and Carter, 2004). This new theory does not discount assumptions made in the 'Holocene sand budget for the SWT coast' (chapter 7) which includes only the inner shelf, as 'cyclone pumping' only results in the finer fraction (mud) being transported northwards and advected towards the coast (Larcombe and Carter, 2004).

## 8.4 THE BURDEKIN AS A MAJOR POINT SOURCE OF FLUVIAL SAND TO THE COAST

Belperio (1978) identified the Burdekin River as the major point source of fluvial sediment to the SWT coast; modelling suggests it delivers over 70% of the total sand supply (Prosser *et al.*, 2001a). The purpose of this section is to evaluate the Burdekin River's influence on coastal evolution over contemporary and Holocene time scales, especially in relation to sand-sized sediments.

### 8.4.1 CONTEMPORARY TIME SCALES

Suspended fine sediments discharged from the Burdekin can be dispersed as far north as Cleveland Bay in flood plumes (Orpin and Ridd, 1996; Devlin *et al.*, 2001), however, sands are only deposited over a relatively discrete area between the Burdekin River mouth north to Bowling Green Spit and perhaps some into Bowling Green Bay at contemporary time scales (Belperio, 1978; Pringle, 1983; 1984).

The vertical accretion of 30 m high dunes at the Delta, indicate an alternative sink for fine sand delivered to the coast. Also like other SWT streams, the hydrology of the Burdekin Delta limits the amount of sand actually delivered to the coast. Only a small proportion of flow discharges via the present mouth, with the smaller distributaries with limited sand carrying capacity such as Kalamia Creek dissipating flood waters. Thus floods produce mainly floodplain flow over the Barrattas plain (Queensland Water Resources Commission, 1980) with sand remaining in channel and not delivered to the coast. Therefore, under contemporary time scales, even the Burdekin River is not a major contributor of sand to the SWT coast.

### 8.4.2 HOLOCENE TIME SCALES

Figure 8.3 a-c is a summary of the previous positions of the Burdekin River channel and an interpretation of the spatial variation of sand supply to the coast during the Holocene after (Hopley, 1970a). Figure 8.2 shows that the Burdekin River would have indirectly supplied sand to a much larger part of the SWT coast in the past influencing the development of the coast. Lambeck and Woolfe (2000) provide evidence of relict sand reserves along the 10 m isobath off the SWT coast with maximum concentrations of sand off Bowling Green Bay and the Burdekin

Delta. This research supports Hopley's (1970a; 1970b) earlier conclusion that large reserves of sand were deposited offshore in Bowling Green Bay when the Burdekin discharged from ~11 to 8 ka.

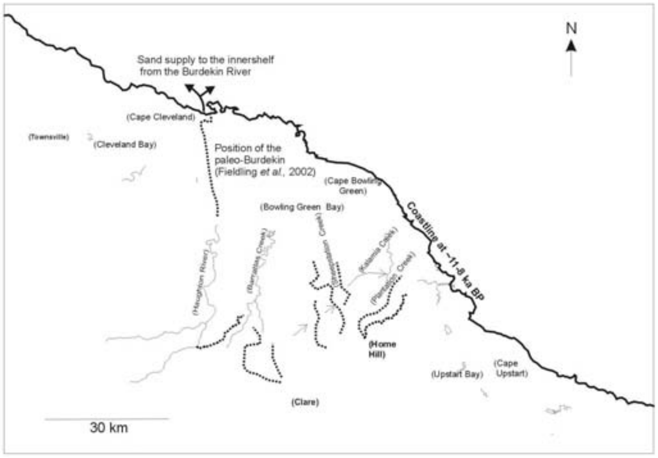


**Figure 8.3 a. The influence of the Burdekin River on the SWT coast during the Holocene Transgression (11-8 ka BP).**
Sea level was 20 m below present levels. The present coastline position is also shown on this map and the present feature names are in brackets. The Burdekin River channel originally discharged offshore of the modern location of Bowling Green Bay (Fielding et al., 2002). The Burdekin migrated south occupying several positions where Barrattas, Sheepstation, and Plantation Creeks are located today (Hopley, 1970).

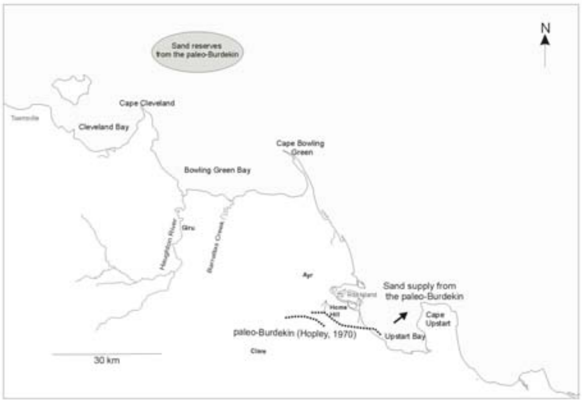


**Figure 8.3 b. The influence of the Burdekin River on the SWT coast during the Middle Holocene (8-6 ka BP).**
Sea level has reached present levels. The Burdekin River channel is diverted east of the present mouth (Hopley, 1970). Burdekin sand would have been deposited into Upstart Bay. This stage may be the one which found or initiated the large dune ridges found on Rita Island.

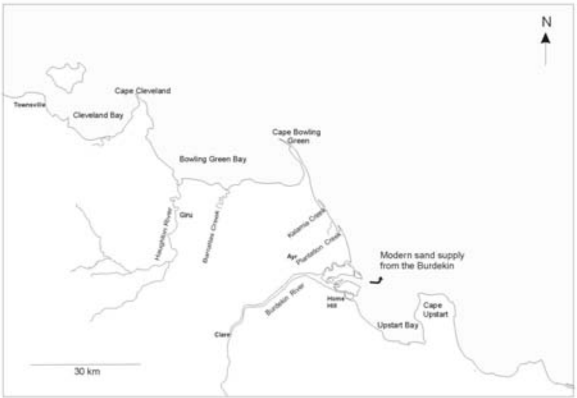


**Figure 8.3c. The influence of the Burdekin River on the SWT coast during Late Holocene (6 ka BP - present).**
The Burdekin River channel is diverted to its present location. Fluvial sand is only supplied to the east coast of the delta. The rate of delta progradation has slowed compared to the previous 4 ka. Vertical accretion of dunes at the delta mouth suggest an alternative sink for sand supplied to the coast.

## 8.5 FUTURE EVOLUTION OF SWT COAST AND ESTUARIES

From the evidence presented in this thesis it is apparent that the SWT coast is currently in an erosional phase with little nourishment from modern streams or marine reserves. Figure 8.1 illustrates the relationship between marine sediment supply and sea level change – suggesting that changing sea level has had the greatest influence over coastal accretion in the SWT during the Holocene. The following section will extrapolate these findings to predict the future evolution of the SWT coast under two scenarios: a stable sea level and a rising sea level.

### 8.5.1 STABLE SEA LEVEL

If sea level and climate remain stable the estuaries that are presently infilling with marine sand, namely the Haughton and the Elliot will continue to infill, while the Black River Delta should retain its present morphology. The Haughton River Estuary is likely to completely infill and become a tide-dominated delta (refer to chapter 2, figure 2.1). The present mouth of the Elliot River Estuary is also likely to be closed off by the continued accretion of the barrier. The lagoon behind the barrier will continue to fill with marine sediment eventually forming a wave-dominated delta (see chapter 2, figure 2.1). There is the potential that once these estuaries become completely infilled, fluvial sand may be delivered to the coast by tidal processes like in the Shoalhaven Delta, NSW (Wright, 1970; Young *et al.*, 1996). However this seems unlikely to occur in the Haughton and the Elliot considering the current deposition of fluvial sands is well above the tidal limit. A more likely scenario, is that complete infilling of these estuaries will reduce tidal currents which may result in increased northward sand transfer via longshore drift. However despite some localised progradation when the former estuaries become deltas, the rest of the SWT coastline will continue to erode.

Graham’s (1993) theory of the developing ‘maturity’ of wet tropical coasts further north could also apply to the SWT. As described in chapter 7 (Figure 7.3), the northward transfer of sand in the SWT is restricted by headlands such as Cape Upstart and Cape Cleveland creating discrete compartments within the region. Progradation in some areas may lead to headlands no longer blocking longshore drift. If this situation was to occur, increasing leakage of sand from the SWT coastal system into other compartments is possible.

### 8.5.2 IMPACT OF FUTURE SEA-LEVEL RISE ON SWT COAST

The Intergovernmental Panel on Climate Change predict a globally averaged rise in sea level of 0.09-0.88 m by 2070 (2001). The range between the maximum and minium prediction prevents a detailed forecast of the future, however modelling has been conducted and the impacts from most recent sea-level rise may be extrapolated. Wolanski and Chappell (1996) conducted hydrodynamic modelling on the South Alligator River, Northern Territory, the Norman River, and north-west Queensland to predict the impact of a future sea-level rise of 0.1 - 0.5 m. Like the Haughton and Elliot, and the Norman River estuaries are flood-dominated, meso-tidal estuaries. Wolanski and Chappell (1996) predicted that a rise in sea level is likely to enhance the strength of ebb tidal currents in these estuaries. Thus it is likely that a rise in sea level would also increase the strength of ebb tidal currents in the Haughton and Elliot creating more symmetrical tidal currents (rather than flood-dominated) or even reversing the current pattern in the estuary to create an ebb-dominated setting. Further modelling (Wolanski and Chappell, 1996) in the Norman River Estuary predicts an overall increase in tidal current velocities and may cause increased bank erosion which may lead to a widening of the upper estuary channel – a scenario that also seems likely in the Haughton and Elliot estuaries. The direction of net sand transfer is likely to be reversed with more sand being transported seawards than into the estuary. Sea-level rise may increase the tidal prism in the Black producing an overall increase in tidal velocities and tidal range, which may lead to increased erosion and channel widening in the upper estuarine channel like in the Haughton and Elliot. Potential for increased erosion is exacerbated by increased wave set up and storm surge during cyclone events. Increased erosion of stored sand may lead to an increase of sand delivered to the coast.

A sea-level rise of 0.09-0.88 m is likely to accelerate erosion on the SWT coast rather than produce rapid progradation like the rises of 140 m experienced during the Holocene transgression. Submergence will deepen nearshore water allowing larger waves to break upon the shore (Bird, 1993). As the SWT coast is dominated by beach-ridge plains formed as a result of Holocene progradation, a rise in sea level is likely to initiate or accelerate erosion on their seawards margins (Bird, 1993). The Bruun Rule (Bruun, 1962) is a widely used to quantify the impact of sea-level rise on sandy coasts. Bruun (1962) suggests that erosion of the upper beach occurs with removal of this sand to the nearshore zone to restore the previous transverse profile. Erosion of the coast would cease once sea level stabilised at the new higher level (Bruun, 1962). Thus the Bruun Rule predicts that the coastline will retreat 50 – 100 fold the dimensions of the rise in sea level, for example a 9 cm rise (min IPCC) would cause coastal retreat of 4.5 - 9 m while a 88 cm rise (max IPCC) would cause a retreat of 44 – 88 m. Recent studies have evaluated the accuracy of the Bruun Rule predictions (see Kench and Cowell, 2001; Cooper and Pickley, 2004) and have found it tends to overestimate erosion rates in response to sea-level rise, and Bruun (1988) himself warns of the need to apply the ‘rule’ within its’ limitations. However it is clear that if sea level does rise over the next 100 years most sandy coastlines will retreat substantially (in the absence of protective structures and artificial nourishment), (Bird, 1993). However if a rise in sea level also causes estuaries to change from net importers of sand to net exporters perhaps the increased sand delivery to the coast may locally reduce shoreline retreat to some extent. Given that SWT have a maximum tidal range of 4 m an overall sea-level rise of 0.09 – 0.88 m is not likely to have a major impact. For a return to the rapid delivery of sand to the coast and subsequent progradation, a much more substantial rise in sea level would be needed. Only a rise of 10 m or more at a rate of 5-10 $m.ka^{-1}$ would reproduce the early-mid Holocene scenario of transgression over sand deposits of the present coastal plain and the delivery to a newly located coast as 'marine' sediments.

## 8.6 IMPLICATIONS FOR MANAGEMENT

### 8.6.1 MANAGEMENT OF SAND RESOURCE

Anthropogenic impacts that reduce the potential amount of fluvial sand reaching the coast, for example sand extraction or river regulation are often linked with coastal erosion (Pringle, 1989; 2000). However in SWT streams the extraction of sand and construction of dams has not altered the delivery of sand to the coast. This research has shown that in SWT streams, namely the Haughton, Elliot and Black Rivers, little sand reaches the coast even under essentially natural conditions. For example investigations revealed that the Haughton River has not delivered significant amounts of sand to the coast for at least the last 1 ka while the weirs have only been in place in the last 27 years (see chapter 4). Therefore artificial reductions in the amount of sand available to transport is not likely to impact the coast, if conditions remain constant. While extraction of sand from the river channel will not cause erosion at the coast, if conducted unsustainably it will have localised impacts on the stability of the river channel most likely accelerating bank erosion as the river attempts to compensate for the missing sediment.

A reduction of sand from the fluvial channel and estuary may have no immediate effect on the adjacent coast, which in the case of the SWT is in a natural erosional phase. However in the longer term the reduction of sand stored in the estuary or river channel may influence coastal evolution. This is especially relevant if there is a substantial rise in sea level. The sand stored in the estuary and river channel is likely to be reworked by marine processes and brought onshore. Reworked river derived 'marine' sand has been a major source of sand for coastal accretion in the SWT in the past (see figure 8.1). Under management timeframes and in terms of determining sustainable rates of sand extraction, the focus should be shifted from the maintenance of coastal sand supply to ensuring the integrity and stability of the river channel.

### 8.6.2 COASTAL COMMUNITIES

The SWT coast is eroding, and though this erosion may be exacerbated by anthropogenic activities, the process is a natural phase in the coast's evolution. Shoreline retreat is of major concern to residents of coastal communities notably Cungulla (at the mouth of Haughton River), Guthalungra (at the mouth of the Elliot River), Black River and Bushland Beach. Hopley and Rasmussen (1995) were commissioned by the Townsville City Council to review beach erosion in the Cungulla area. Hopley and Rasmussen (1995) concluded that the erosion was a natural processes and it was recommended that the council should adopt the 'do nothing' approach as engineering works would be ineffective and may even exacerbate erosion. Without major engineering works and artificial nourishment like has occurred on Townsville's main beach, The Strand, at a cost of ~$30 million, the SWT coastline will continue to recede impacting the aforementioned coastal communities. Despite the fact that some loss of property would occur, the recession of the coast is a natural process and there is little management agencies can do to prevent it. Large scale engineering works may offer some protection, however the cost is likely to outweigh the value of the property and they are likely to make it far less attractive to residents.

Perhaps more emphasis should be on preventing this unfortunate situation from occurring in the future by incorporating geomorphological timeframes into management decisions, especially with regard to town planning. For example appropriate set-back lines for coastal development need to be established to provide a buffer for the natural dynamism of the coast. These should be in the order of 100-150 m given that Cungulla shoreline has retreated 100 m over the last 60 years (see chapter 4). Planning for coastal change is especially relevant for future development given the predictions of increased rates of erosion under rising sea levels (see section 8.5.2 this chapter). Rising sea levels are also predicted to increase the rate of infilling of SWT estuaries which will impact the Townsville Port, located on the mouth of Ross River. The port is regularly dredged to prevent the infilling, however if the rate of infill increases, an up scaled and more expensive dredging effort will be required by the Townville Port Authority to maintain the channel.

## 8.7 RECOMMENDATIONS FOR FUTURE RESEARCH

- The fieldwork for this thesis represents an invaluable source of baseline/pre-flood data for SWT estuaries. If a catastrophic flood did occur in the future a similar surficial sampling regime could be undertaken in these systems to test inferences made in this study. For example that sand transfer to the coast in SWT streams is restricted by morphological factors and will be limited irrespective of the magnitude of the flood.

- The impact of cyclones and high magnitude events on sand transfer processes could be investigated further if nearshore wave conditions were monitored during cyclone and storm events.

- The lack of organic material preserved in SWT estuarine deposits limited the detail of the chronology of sedimentation by radiocarbon dating techniques. Application of high resolution Optical Sensor Luminescence (OSL) dating on deeper sand deposits would refine the chronology of sedimentation however the technique would of limited use for reworked surficial sediments. OSL combined with seismic or other techniques such as c-section coring or probing to locate and identify samples for OSL dating could be a better approach.

- This research has reported similar findings to Bryce *et al.'s* (1998) study of the Normanby River Estuary, in a SWT region in far north Queensland, suggesting that other SWT streams may not deliver substantial amounts of sand to the coast Application of the methods used in this study to other SWT regions for example South Africa would provide greater insight into the impact of the SWT climate on fluvial sand supply to the coast.