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Sediment transport along an artificial shoreline: "The Strand", Townsville, NE-Queensland, Australia

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Abstract

Construction measures to stabilise or spatially extend coastlines have become a routine measure in urbanised coastal zones. This study quantifies beach profile changes and sediment transport along an artificial beach in Townsville, NE-Queensland. The "Strand" was transformed from a single degraded shoreline into a shoreline with five embayments (or "pocket beaches") split by four artificial rocky headlands in 1998. The modified shoreline has had an impact on the local and regional northward long-shore sediment pathway, creating local shifts in sand. Sediment deposition and erosion occur at the same time at different parts of the pocket beaches. Collected offshore sediments show that little artificial sand is transported more than a few meters seaward in the south-eastern part of the Strand, while substantial and long-ranging export, i.e., tens to hundreds of meters, occurs in the north-western area. This is mainly the result of the breakwaters south of the Strand, which impacts the predominant northward long-shore sediment transport induced by the dominant south-easterly winds.

Keywords: foreshore; artificial beach; beach renourishment; sediment transport; long-shore current

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1. Introduction

About 70% of the world's sandy beaches experience erosion, and although this is normally on a scale of no more than about 1 m per year, it can be significant because most such beaches are only a few tens of meters wide (Leatherman et al., 2000). Beach erosion is often caused through a combination of factors such as sea level change, storminess, or human interference (Wong, 2003). Since the demand on coastal space is continuously rising, with almost half of the world's populations living in coastal environments (Haslett, 2001), mitigation of coastal erosion and stabilising shorelines through engineering techniques or sand renourishment programs has become a common routine for many highly urbanised coastal areas. Hence, research on coastal development with focus on coastal protection has evolved rapidly over the last decades. Some common coastal protection measures include the construction of seawalls, groins, or headlands, and sand renourishment programs. As a result, coastal research over the last few years has focused, for example, on (1) the impact of seawalls and shore parallel structures on coastal processes, such as wave dynamics (e.g. Dean, 1986; Miles et al., 2001); (2) the use of groins and artificial headlands as a measure to reduce the rate of sediment loss from beaches (Nordstrom, 2000); and (3) the potential benefits of sand replenishment programs to mitigate chronic erosion or to provide a buffer for beach protection (Work, 1993).

There are significant controversies about the impact of coastal developments on natural sediment transport mechanisms and on stabilising the modified coastlines. In many cases, headlands and groins have demonstrated to increase longevity of sand deposits up-drift, while seawalls have been documented to cause an increase in beach erosion in several coastal environments (Sherman et al., 1990; Kraus and McDougal, 1994). Groin/headland structures may locally

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stabilise beachfronts, however, they may also increase downdrift shoreline erosion (Nordstrom, 2000). With the occurrence of many engineering difficulties in coastal areas, several researchers have conclusively determined that beach renourishment is the most reliable mean in beach protection with the success of a renourishment project dependent on factors such as wave dynamics, sediment transport regime, and the presence of rigid structures (Work, 1993; Creed et al., 2000).

In Townsville, NE-Queensland (Fig. 1), the impact of tropical Cyclone Sid in 1998 left the city's shoreline in a dismal state, with severe erosion of the concrete seawall protecting the city. As a consequence, the 2.5 km Strand foreshore was redeveloped with four concrete and rock boulder headlands separating five pocket beaches filled with 400,000 tonnes of sand. Such drastic changes of a beach face can have major implications for existing wave and current patterns and can modify wave refraction patterns in such a way that it may cause major erosion along parts of the new beaches. Here, sedimentological investigations along the Strand that studied beach profile changes over an eight-month period in 2002 as well as the distribution pattern of offshore sediments are presented. The purpose of the study was to better understand the sediment movement patterns along the redeveloped Strand. The sediment transport model of the new Strand coastline is useful for future sand renourishment programs.

2. Geographic and historic setting

Townsville, a city on the coast of NE-Queensland at 146.5 °E and 19.15 °S (Fig. 1) is situated on Cleveland Bay that faces northeast towards the Coral Sea. It is bound to the east by Cape Cleveland, to the west by Cape Pallarenda, and to the north by Magnetic Island. The seabed of the bay generally slopes evenly away from the coast to a depth of about 15 m depth across Cleveland Bay (Fig. 1). Townsville experiences diurnal mesotides with a maximal range of 4 m. South-easterly winds are dominant that result in a northern long-shore drift. The area is part of the south Pacific cyclone zone, which frequently experiences strong winds during summer.

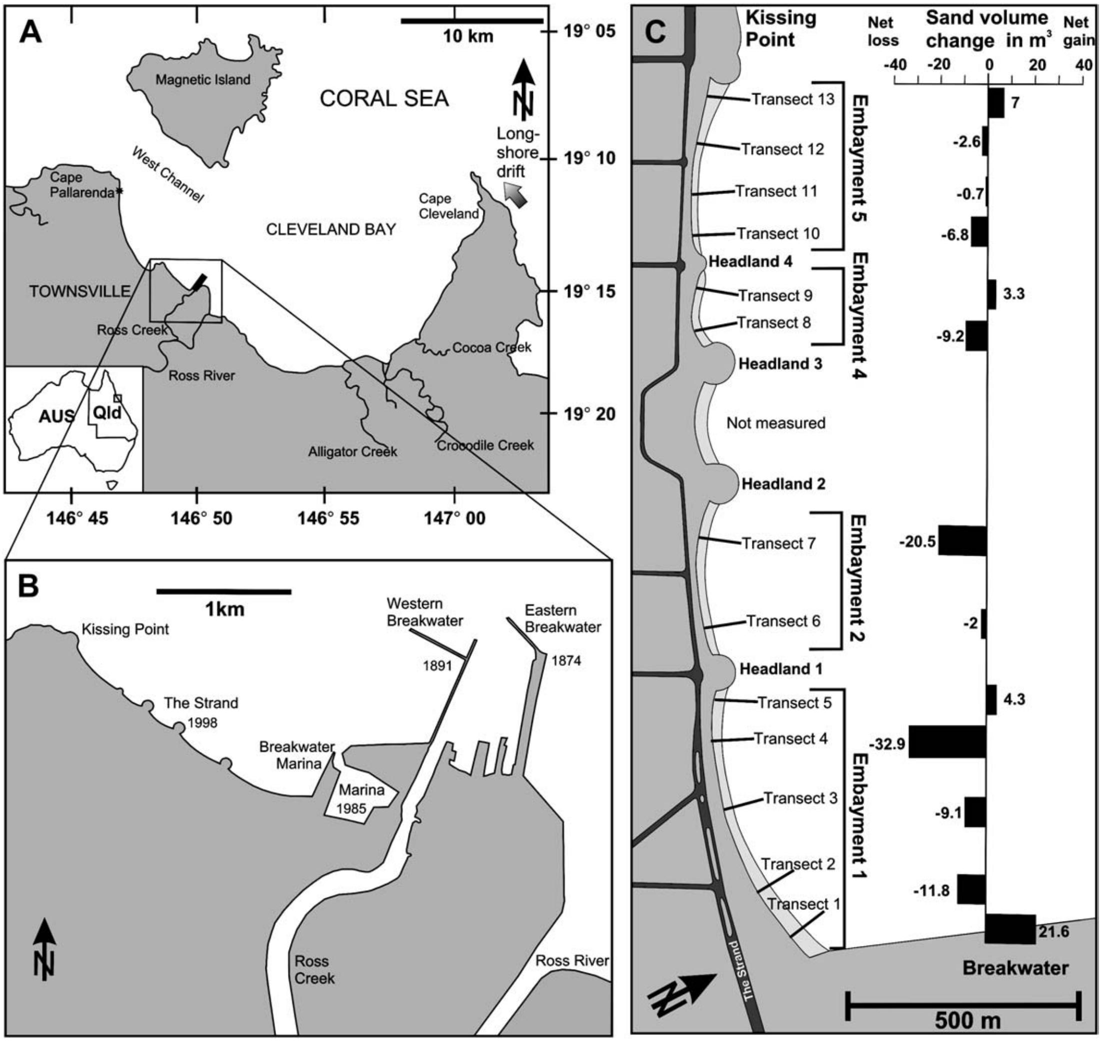

Fig. 1. (A) Map of the Townsville region including major rivers, breakwaters, and the dominant long-shore drift direction (*Pallarenda sediment sample). (B) Details of the Strand. (C) Locations of headlands, embayments (E) and beach transects (T) and their overall volume changes over the study period.

2.1. History of human impact on the dynamics of sedimentation in Cleveland Bay

European settlement in Townsville began in 1864 and the first 120 m long breakwater was constructed for the Port of Townsville in 1874. In 1884, the 850 m eastern breakwater was constructed (Mabin, pers. comm.). During the early 20th century, three weirs were constructed along the Ross River (Fig. 1) to supplement the region's growing water demand. These structures have interrupted the natural balance of deposition and erosion along Townsville's northern beaches (Berwick, pers. comm.). In particular the natural northern long-shore sediment transport and the sediment supply to Cleveland Bay were disturbed. Today it is unlikely that the beaches north of the breakwater receive any significant sediment formerly supplied by Ross River, Ross Creek, and long-shore drift in Cleveland Bay. Reducing the natural sediment supply to the Strand, erosion of the city's beach has been a longstanding issue. In the early 1940s, sloped concrete seawalls were built along the Strand to mitigate erosion and in 1972, following Cyclone Althea, a rock wall was constructed (Kapitzke, pers. comm.). In March 1997, Cyclone Justin caused persistent wave action that undermined the central portion of the Strand seawall. On January 10th and 11th, 1998, another severe storm, ex-Cyclone Sid, coincided with a period of high spring tides that further damaged Townsville's foreshore. At this time the Strand consisted of a severely damaged seawall, fallen blocks from the rock wall, and a coarse sand lag.

Following Cyclone Sid, Townsville City Council redeveloped the Strand foreshore at a total cost exceeding AUS$ 30 million. The 2.5 km foreshore, extending from Tobruk Pool near the Breakwater Marina to the Rock Pool near Kissing Point, was transformed from a single beach into a foreshore with several pocket- or micro-beaches separated by headlands (Fig. 1). The seawall was reconstructed and moved approximately 30 m seawards. The headlands and pathways were constructed with 390,000 tonnes of rock fill, with the headlands extending approximately 50–80 m (up to 10 m high) seaward. The headlands are expected to prevent loss of sand from one embayment to another and extend storm water outlets from street drainage. The five embayments along the Strand were filled with 400,000 tonnes of coarse and poorly sorted fluvial sand. Since October 1998, when the Strand was opened to the public, several beach sections have required sediment renourishing, none of which occurred during this study period.

3. Methods

Thirteen beach profiles perpendicular to the shoreline were established in four embayments (E1, E2, E4 and E5) (Fig. 1C). Beach profiles were surveyed monthly for eight months in 2002 and topographic profiles were constructed. The data were used to reconstruct changes along the beach profiles and to calculate sand loss or gain (volumetric change of the profiles). The volume data of each transect (T) collected during the first measurements were used as reference data to calculate subsequent volume changes (per 1 m width) which are expressed as relative "net loss" or "net gain" compared to the volume of the first measurements. Four representative transects, T1 and T4 from E1, T6 from E2, and T11 from E5, are discussed in detail. The study was terminated in August 2002 because the City Council modified the foreshore with heavy equipment in several areas after development of terraces following strong wave actions.

To map offshore sediment movements, offshore sediment samples were collected with a Van Veen grab sampler along a line approximately 100 m parallel to the shore. Sediments were analysed for grain size, lithological composition, and grain shape. Samples were wet or dry sieved depending on clay content. Dry sieving was done on samples dried at 40 °C for 24 h according to the method of Gee and Bauder (1986). Sieve sizes were 2 mm (granules), 1 mm (very coarse sand), 250 μm (coarse/medium sand) and 62.5 μm (fine/very fine sand). The pan collected everything <62.5 μm. The percentage of sediments >250 μm and >1 mm from each of the offshore grab samples were used to plot maps of the grain size distribution. The results are expressed in percentage of the total sample weight. For comparison, sample material was collected from both artificially replenished beach at the Strand and natural beach at Cape Pallarenda, north of the Strand (Fig. 1A).

Reed and Wells (2000) previously determined that artificial renourishment sand can be distinguished from natural beach sand by grain size analyses. The fluvial sand used to fill the pocket beaches on the Strand was obtained from the upper Burdekin River west of Townsville. The fill is conspicuous because it is composed of 49% of grains $>$ 1 mm and 98% of grains $>$ 250 μm. Natural sand from the beach at Pallarenda (Fig. 1A) is composed of 25% of grains $>$ 1 mm and 71% of grains $>$ 250 μm. Hence, the renourished sand is clearly coarser than the natural beach sand of Pallarenda.

4. Results

4.1. Beach transects

The individual transects illustrate how dynamic sandy beaches act under the influence of tides, storms and natural coastal currents. T1 (Fig. 2), located in E1 (Fig. 1C), shows steady accretion over the study period. The changes to this beach profile are recorded over the whole beach face; however, the greatest positive and negative changes occur in the lower half of the inter-tidal zone.

T4 (Fig. 2) in E1 shows also greatest change in the inter-tidal zone. A large increase or net sand gain occurs between January and February, followed by a substantial loss between February and April. After April, the beach section remains fairly stable to the end of the study period. The changes in T1 and T4, both located in E1, show that changes occur at different rates and in different locations and different times.

T6 (Fig. 2) in E2 shows two significant changes during February and May. In February, significant sand is lost across the entire profile, while during May, substantial gain to the beach in the upper inter-tidal zone is observed. The upper inter-tidal section of this transect is where most changes take place,

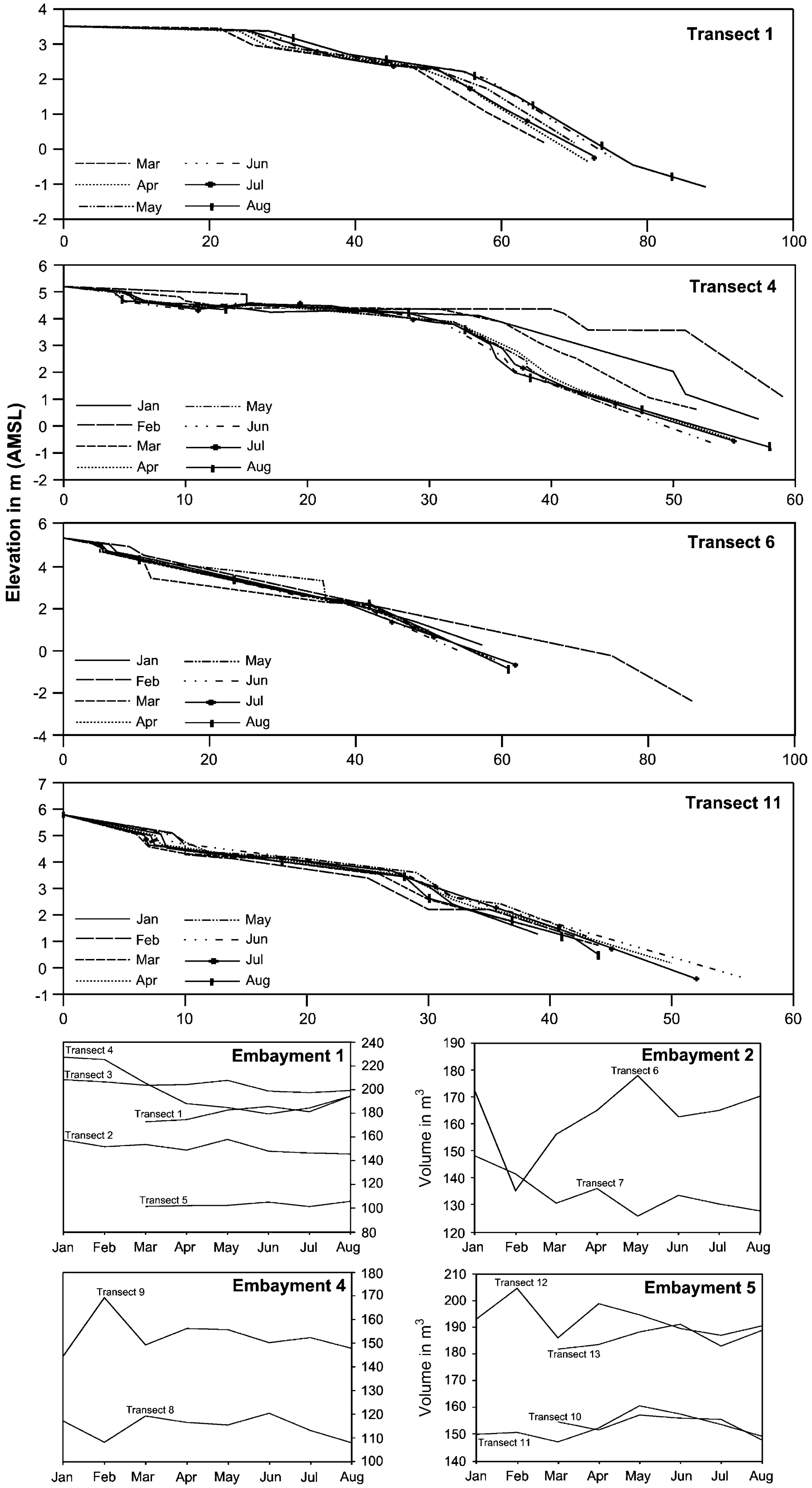

Fig. 2. (Top) Four representative beach profiles (T1, T4, T6, T11) from the Strand beach showing cross sectional changes over the study period. AMSL = Australian Mean Sea Level. (Bottom) Volume plots for each transect studied in 2002 assuming 1 m transect width.

whereas in T1 and T4 most changes are associated with the lower inter-tidal area.

T11 (Fig. 2) of E5 had a major loss of sand between January and February that affected the entire shore face. The subsequent changes were mainly accumulative and again over the entire profile. Overall, the changes in this transect appear to be less dramatic than changes observed in T1, T4 and T6.

The beach transects (Fig. 2) show that some areas (e.g. T1 and T11) have steady changes in beach loss and/or accumulation over the eight-month period, whilst other transects, such as T6 and T4 have punctuated major sediment losses and/or gains. In addition, some transects (e.g. T1 and T11) have a more or less even change over their entire beach profile, while other transects show major changes either in the upper (T6) or lower part of the profile (T4).

4.2. Volumetric changes of the beach profiles

The volume changes of each transect for all embayments (Fig. 2) illustrate also the complexity of sediment movements along the Strand. E1 shows variable sand losses and gains. T1 had a constant gain through to August, which resulted in a net sediment gain of 21.6 m^3 (Fig. 1C), while a large sediment loss (32.9 m^3) occurred in T4 from February through to April. The transects within this embayment recorded smaller net sediment changes. T2 had a net loss of 11.8 m^3, T3 a net loss of 9.1 m^3 and T5 a net gain of 4.3 m^3 (Fig. 1C). The greatest changes of sand volume occurred during February and April (Fig. 2). Most of the volume changes were moderate (loss or gain) except during May when markedly sand gains were recorded.

In E2 (Fig. 2), T6 had marked sediment loss from January to February, but rapidly gained sand from February through to May, which resulted in a net sediment gain. Then, other erosive events during May followed by accretion of sediment resulted in a net sediment loss of 2 m^3 (Fig. 1C). Interestingly, when T6 recorded a loss, for example in May and June, T7 showed a gain. The total changes over the study period are, however, different from T6. While T6 had a total loss of 2 m^3, T7 recorded a net sediment loss of 20.5 m^3 (Fig. 1C).

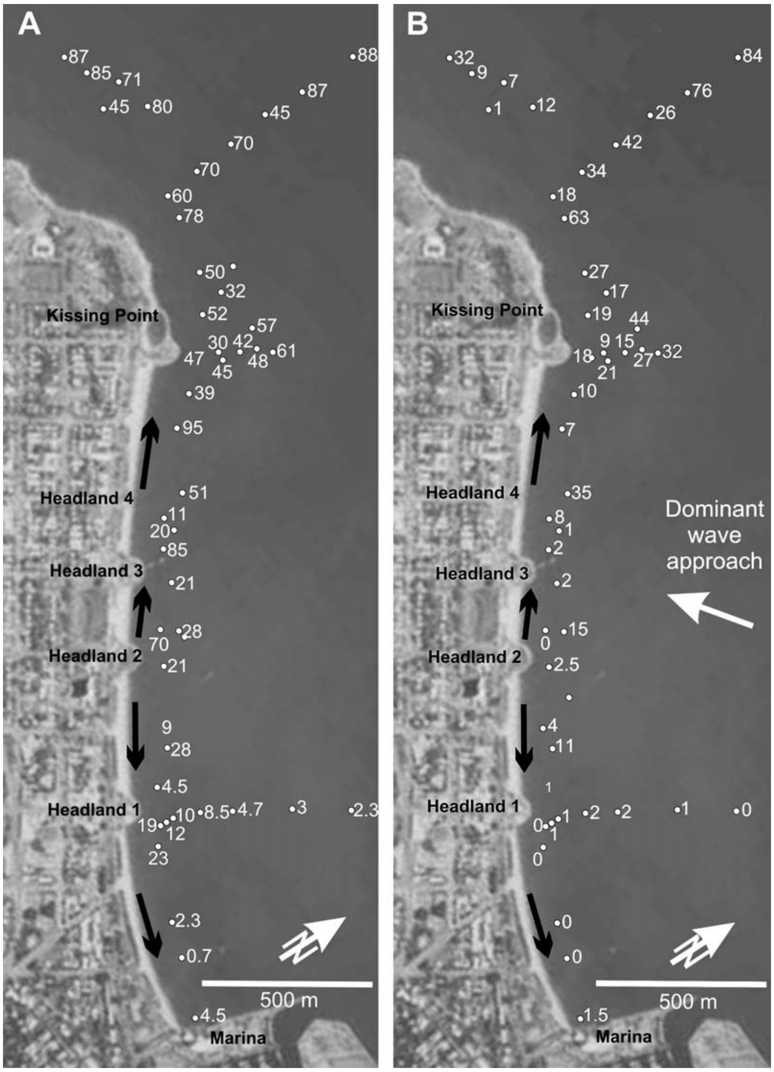

Fig. 3. (A, B) Aerial photos showing superimposed offshore sample sites with sediment weight-percentage of the fractions >250 μm (A) and >1 mm (B) in order to map sediment movements along the Strand. Black arrows display interpreted dominant long-shore drift direction based on the sediment volume changes.

The beach transects of E4 (Fig. 2), like E2, showed also sediment gain and loss through the study period. The sediment volume of T8 and T9 remained fairly constant, except for large changes recorded during February, when T8 lost 8 m^3 and T9 gained 25 m^3 of sediment. During the following months, however, the sediment budget was levelled and the overall changes during the study period were a loss of 9.2 m^3 for T8 and a gain of 3.3 m^3 for T9 (Fig. 1C).

Volume changes in E5 show a similar picture as the other embayments (Fig. 2). The volume changes of all transects over the study period are, however, small and < 10 m^3 (Fig. 1C), despite a large net loss of sand (20 m^3) in T12 between February and March and a further loss between May and July. T12 gained sediment during April and August. The north-westernmost transect, T13, recorded an almost constant gain with a total net gain of 7 m^3 (Fig. 1C), while the south-eastern transects (T10, T11 and T12) of this embayment recorded a net loss of 6.8 m^3, 0.7 m^3, and 2.6 m^3, respectively.

4.3. Offshore grab samples

Grain size analysis of the offshore samples shows that the percentage of medium-coarse grained sands varies strongly (Fig. 3). The offshore sediments at the southern end of E1 are predominately composed of mud with about 4.5% of grains > 250 μm (Fig. 3A) and 1.5% of grains > 1 mm (Fig. 3B). E2 was also composed of fine sediments with 5–30% of grains > 250 μm and 1–10% of grains > 1 mm. Coarser sediments are located around Headland 2, where 20% of grains > 250 μm, with the coarse fraction increasing north-westwards. At the southward side of E3, 70% of grains is > 250 μm and these sandy deposits continue around Headland 3 where a small area has 80% of grains > 250 μm. High percentages of sediments > 250 μm and > 1 mm are located also offshore from E4. E5 has offshore sediments composed of 11–95% of grains > 250 μm and coarse sediments continue around Kissing Point where also a greater percentage (1–35%) of material > 1 mm occurs.

5. Discussion

This study has measured changes along beach transects of the Strand. Transect results illustrate that sediment movements along the foreshore are common and do not occur uniform along the embayments. A complex pattern of sediment movements, with periodic large losses and gains of sand, was observed but the net loss/gain over the entire study period was maximum 33 m^3.

5.1. Sedimentological/hydrographical effects of the altered Strand foreshore

The beach profile study has several important findings. The location of transects within an embayment as well as the position of the embayments affected whether sand changes occur in the lower inter-tidal zone (T4, Fig. 3) or near to the high-tide mark (T6). Also, sediment changes within an embayment do not occur simultaneously and sediment loss can occur in one transect with a gain in the nearby transect (e.g. E4, Fig. 2). Storm events can also result in major changes. Both transect and volume plots (Fig. 2) suggest greatest changes during January and February coinciding with Townsville's most severe weather event in 2002. Cyclone Claudia developed in the central Coral Sea around 11th February and Townsville experienced high rainfall (200–400 mm) and strong winds (61 km/h) for approximately three weeks (Bureau of Meteorology, http://www.bom.gov.au).

Transect studies illustrate that each embayment operates separately in terms of beach processes, i.e., each embayment acts as a micro-beach, although some embayments may feed off other ones. The southern embayments (E1 and E2) undergo processes of erosion at their north-western end, whilst sediments build up at the south-eastern end (Fig. 1C). In the north-western embayments (E4 and E5), however, the process of erosion occurs at the south-eastern ends, whilst the sand builds up at the north-western ends. These sediment shifts could indicate a southern littoral drift in E1 and E2 and a northern littoral drift in E4 and E5 (Fig. 3). Wave diffraction around the Townsville breakwaters combined with the obstructions along the Strand may have created two different directions of littoral drift along the newly developed Strand shoreline (Fig. 3). Current meters deployed along the Strand would contribute valuable information regarding the viability of our model.

The new headlands and the extensions of the Kissing Point Headland were assumed to ensure the longevity of sand within the foreshore area by preventing or reducing sediment leakage from one embayment to another. The results of this study show that this is probably the case and that sediment movements along the Strand shoreline are suppressed as a result of the headlands. The results show that the Strand pocket beaches may not have reached equilibrium yet.

5.2. Offshore sediments

Williams (1994) documented that if breakwaters and headlands are built, the driving force for the currents is intercepted by the artificial structures along the shoreline. As a result, the prevailing long-shore current, unless maintained by its inertia, will slow or stop when it moves into the sheltered area behind the breakwater. Woolfe and Larcombe (2001) noted that northward facing beaches along the Queensland coast are primary sites for fine-grained sediment accumulation because those sites are protected from the dominant south-easterly winds. The interpretation of the offshore sediment data has to be treated with caution. The new beaches have been built 30 m further into the sea from its original position and the fluvial sands overly the bay muds. Therefore offshore sand particles along the Strand are exclusively derived from the new sediment.

Along the Strand foreshore with four new headlands, fine-grained sediments accumulate in the southernmost end of E1, which has maximum protection from dominant south-easterly winds by the Townsville and Marina breakwaters (Figs. 1

and 3A). Therefore, wave energy is insufficient to maintain particles in suspension and flushing is insufficient to remove resuspended material so that only 10–20% of sediments are $>250\ \mu m$ and an insignificant amount of >1 mm are transported around Headland 1 (Fig. 3).

It is possible that Headland 2 marks the onset of a predominant northwestward long-shore drift because sediments become increasingly coarser from Headland 2 (20% $>250\ \mu m$) to the southern side of E3 and around Headland 3 (Fig. 3). Water movements between E3 and E4 must be dynamic enough to transport coarse particles, such as the artificially replenished sand. The percentage of the coarser fraction (>1 mm) is still small (maximum 15%) indicating that currents are strong enough to move the medium fraction, but not so much the coarse fraction.

Sediments composed of between 11–80% $>250\ \mu m$ and 1–35% >1 mm were found off Kissing Point, indicating that currents must be strong enough to transport coarse material around this point despite the fact that the Kissing Point Headland was extended during the Strand redevelopment to ensure that all of the replenishment sand be kept on the Strand foreshore. Because Kissing Point was also under similar current conditions before the redesign of the Strand, it is possible that some of that sandy material derived from the original degraded foreshore.

6. Conclusions

The conclusions of this beach profile and offshore sediment study along the redeveloped Strand of Townsville are the following:

(1) Changes of beaches within new artificial embayments are dynamic and large gains and/or losses of sediments can occur on a regular basis. The highest changes over the study period occurred in transects T1, T4, and T7, showing loss or gain $> 20\ m^3$, but most transects showed balanced gains/losses over the study period.
(2) The dominant currents induced by prevailing SE trade winds usually transport sand in a northward direction. The coastal constructions in Townsville have altered wave refraction. In the south-eastern end of the Strand, breakwaters and headlands induce a southward sediment drift (E1, E2) which trap a dominant muddy fraction. In the north-western part of the Strand (E4, E5), sediment drift is northward with coarse sediments (up to >1 mm) located offshore Kissing Point.
(3) Currents are transporting Strand sand off the beach and around Kissing Point into Rowes Bay and future renourishment activities will be a necessity in order to keep the Strand in its current state. However, as predicted by the engineers of the headlands, the four headlands greatly reduce the sediment transport along this part of the coastline, without which sediment loss would be much greater.

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