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Monitoring the Coastal Sand Wedge Outbreak from the Stony River, Taranaki

A thesis submitted in partial fulfillment
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of

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in Earth and Ocean Sciences

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ABSTRACT

The Taranaki headland protrudes into a high energy wave climate system with a potential for strong littoral transport. This shoreline is typically comprised of a narrow cobble to boulder reflective beach, surmounting a rugged wave cut shore platform which is carved into lahar deposits from the nearby andesitic composite cone of Mount Taranaki. Historically along this coast, pocket sandy beaches have endured within embayments and adjacent to headland features; otherwise the the Taranaki littoral system is sand-starved. In 1998, persistent heavy rainfall resulted in the collapse of scoriaceous sand and gravel on the side of Mount Taranaki, leading to massive injection of sand and gravel directly into the Stony River, from which the adjacent coastal shoreline has experienced a continuous flux of dense 'black' titanomagnetite-rich volcanic sands. These sediments are rapidly transported to the north-east by the energetic wave climate, creating sandy beaches on what is normally a rocky boulder coast.

Coastline changes between Cape Egmont and New Plymouth were analysed by the comparison of aerial photographs dated 1995, 2001, and 2007. These photos illustrated a marked increase in sandy sediment in 2001 which has diminished rapidly by 2007. Sub-aerial beach profiles were undertaken, over the duration of this study, at 12 locations between Komene Road, just south of the Stony River mouth, and Back Beach in New Plymouth. The beaches including and south of Ahuahu Beach are characterised by dunes which reach greater elevations than those further north where the dune elevation decreases. This evidence along with visual observations suggest that the sediment derived from the Stony River sits on the upper beach forming a berm and high dunes.

Sediment textural analysis was conducted on samples collected at the 12 beach profiling locations. This analysis was undertaken every three months over the course of this study and showed (1) a decrease in mean grain size with distance north of the Stony River mouth; and (2) sorting generally improves with distance north-east in the direction of the dominant littoral drift. Mineralogical analysis illustrated that beach sediments are dominated by the heavy mineral titanomagnetite and the opaque minerals of augite, hornblende and plagioclase feldspar.

The longshore sediment transport flux between Rahotu Road, south of Cape Egmont) and Back Beach in New Plymouth was examined. Wave climate parameters were generated at 55 locations between 1998 and 2007 using the SWAN third generation numerical model. The CERC (1973) formula was used to calculate the potential longshore sediment transport flux, at each of these locations using the significant wave height and angle of incidence. Analysis of the wave data illustrate a wave energy gradient extends from the Cape toward New Plymouth, caused by: (1) the exposed nature of the coast near Cape Egmont to the dominant south-westerly swells; (2) the greater seabed gradient near Cape Egmont, and (3) the refraction shadowing that occurs with distance to the northeast of the Cape. The potential longshore sediment transport results indicate low potential sediment transport fluxes south of Cape Egmont, which increase,

reaching a maximum potential flux slightly south of the Stony River mouth. These potential longshore sediment transport fluxes then decrease towards Back Beach as a result of refraction in the vicinity of the Sugar Loaf Islands. The size of the 'slug' of sand derived from the headwaters of the Stony River is likely to have diminished in size substantially when it has been transported as far north as Back Beach, and these results indicate that there will be insufficient energy for any substantial volumes to be transported around the Paritutu Headland.

A sediment budget has been ascertained from the volume of sediment that has recently been eroded from the scarp on Little Pyramid on Mount Taranaki, and the volume of sediment that can be accounted for today on the beaches, and in the Stony River channel as aggradation deposits. Up to 14.4 M m^3 of sediment was estimated to have been deposited in the Stony River system directly from the scarp. Of this, $\sim 3.5 \text{ M m}^3$ has accumulated on the sub-aerial beach over a distance of 14 km to east from just south of the river mouth, and $\sim 3.3 \text{ M m}^3$ has been deposited along the Stony River channel. The remaining $\sim 7.6 \text{ M m}^3$ of sediment is likely to be deposited offshore, overlying the wave-swept boulder platform and in the interstitial space of the sediments that form these shore platforms. Significant quantities of this sediment are also likely to have been transported in the north-east directed littoral transport.

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CHAPTER ONE: INTRODUCTION

1.0 SEDIMENT ON A SAND STARVED COAST?

Prior to 1998, the high wave energy coastline extending from Cape Egmont to Oakura on the Taranaki Headland on the west coast of the North Island, New Zealand, comprised narrow cobble and boulder beaches (Figure 1.1) surmounting a rugged wave cut shore platform which was carved from lahar deposits that flowed from the nearby, andesitic volcano, Mount Taranaki.



Figure 1.1 Narrow boulder beach at the end of Stent Road (November 2008).

However, this predominantly rocky littoral system underwent dramatic change in 1998 when a scarp in the headwaters of the Hangatahua (Stony) River (Figure 1.2) collapsed, leading to massive input of sand and gravel down the river course, and subsequent injection into this coastal littoral system.



Figure 1.2 Scarp in Little Pyramid where the sediment is derived from (November 2008).

Since 1998, this influx of black sand and scoriaceous gravel, derived from Mount Taranaki, has been transported along the coast, driven by littoral drift to the northeast, resulting in beach sediment nourishment along the coastline so that it has fundamentally changed from cobble and boulder to sandy beaches.

Influx of sandy sediment into the coastal littoral system has many implications for down-shore beaches. As this ‘sand slug’ seeps around the Paritutu Headland and Sugar Loaf Islands (Hapuka Rock, Tokatapu, Motuotametea, Pararaki, Mataora, Wharemu, Tokomapuna, Motumahanga, Moturoa and Corinna Rocks), potential impacts include the effect on the Department of Conservation’s Sugar Loaf Islands Marine Protected Area (SLIMPA) and Tapuae Marine Reserve (Figure 1.3), the navigation approach channel to the port, which is regularly dredged, and down-drift beaches. Accordingly this thesis focuses upon the affect of this influx of sand on the Taranaki coastline from Stony River mouth to New Plymouth.

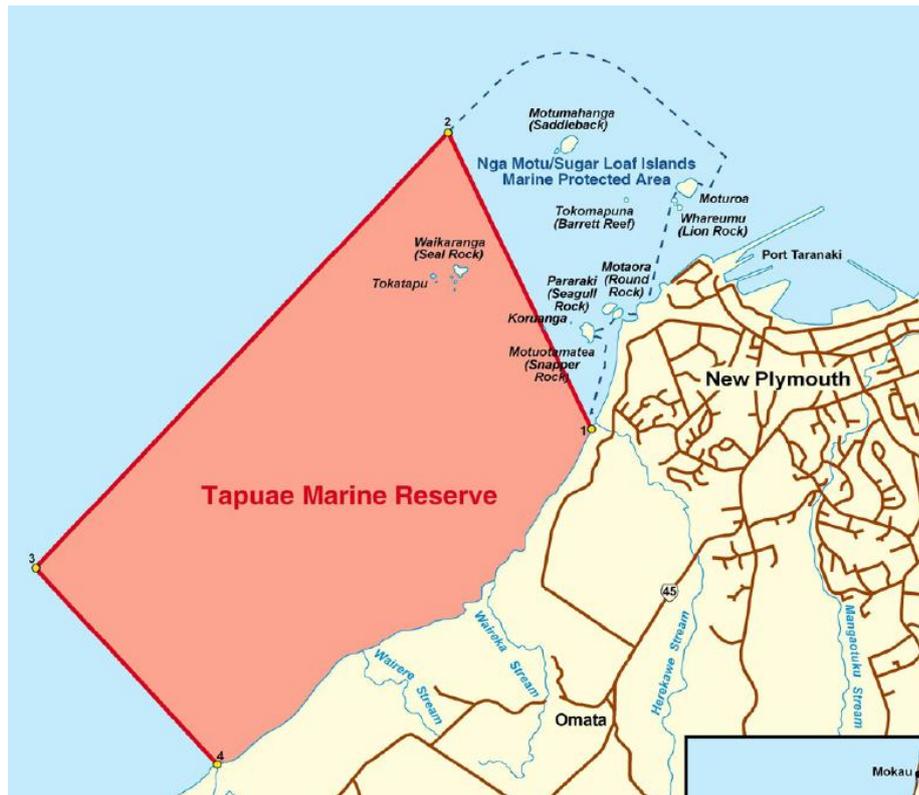


Figure 1.3 Tapuae Marine Reserve and Sugar Loaf Islands Marine Protected Area.
(Source: Department of Conservation, 2008).

There have been a number of reports, studies and management plans relating to near shore sediment transport along this coastal sector:

- Matthews (1977) studied the sand movement at Oakura, Werekino, Harriet beach, Oaonui beach, Okaweu beach and Opunake. He determined the sand budgets for littoral cells between Cape Egmont and New Plymouth and between Cape Egmont and Opunake. In the littoral cell, between Cape Egmont and New Plymouth he identified that stream and cliff erosion are the greatest input of sand into the littoral beach system on this coast, and the dominant sand components are rock fragments and plagioclase feldspar.
- Gibb (1979) studied late quaternary shoreline movements along New Zealand coasts including the longshore transport regime of the North Island's west coast.
- Kirk (1980) presented a study on the hydrological and sediment processes occurring around Port Taranaki. The study defined the regional shoreline

erosion problem and quantitatively evaluated shoreline protection and beach re-nourishment options through identifying sediment transport source, sinks and pathways.

- Kibblewhite, Bergquist and Gregory (1982) undertook a study on the Maui gas field environment, located 20 km west of Cape Egmont. The study included programmes in physical oceanography, coastal geology and marine biology, to assess the environment for the affect of the platform and pipeline operations and the impact of pollutants. This study included assessing the sand movements on five Taranaki beaches including Oakura, one of the beaches of interest in this study.
- McLennan (1982) analysed offshore sediment parameters and examined longshore models at Fitzroy Beach. This study determined that harbour maintenance dredging promotes down-drift sediment starvation and that the Caldwell (1956) longshore drift prediction model over-estimates sediment transport.
- Bartholomeusz (1985) analysed sediment samples from the New Plymouth harbour and beach areas, to determine the paths of net transport and concentrations of specific minerals. This was determined by undertaking solid density analysis, textural analysis and mineralogical examinations. From this analysis it was determined that the grains were derived from either inland Taranaki or from the sea cliffs around the Taranaki coast.
- McComb (2001) studied the wave dynamics, hydrodynamics and sediment dynamics along the Taranaki Coast. This study included wave, current and suspended sediment measurements; side scan sonar and hydrographic survey; sediment tracing and experimental dumping of dredged sand to observe the littoral transport.
- Swales, Hume, Hawken, Liefting and Gorman (2003) studied the changing mineral sizes and shape during parabolic (longshore) transport along the west coast of the North Island from Cape Egmont to Cape Reinga. This included grain analysis of beach sand collected 9 km north of the Stony River mouth.

1.1 RESEARCH AIMS AND OBJECTIVES

The general aim of this thesis is to investigate the extent of the sand injected into the littoral zone of the Taranaki high energy sand-starved rocky coast, and the potential down-drift impacts as the sediment seeps around Paritutu headland.

Specific objectives to be investigated include:

- to determine the changes to the sedimentary character prior to and after the 1998 influx of sediment along this coastal sector;
- to determine sediment textural characteristics at different locations along this coastal sector;
- estimating the relative potential longshore sediment transport rates along this coastal sector; and
- estimating the volumes of sediment eroded from the scarp in the headwaters of the Stony River.

1.2 THESIS OUTLINE

In order to achieve the specific objectives this thesis is organised as follows:

Chapter 2 presents aspects of the Taranaki coastal environment as background for the study. This includes a description of the geological setting, coastal geomorphology, sediment sources, sediment transport, rainfall and fluvial inputs along the coastal sector from Cape Egmont to New Plymouth.

Described in **Chapter 3** are the changes to the beach character both prior to, and after, the influx of sandy sediment into the littoral system via the Stony River. This is determined by the comparison of aerial photographs (both prior and after the 1998 sand outbreak) as well as analysing beach profiles (both prior and after the 1998 sand outbreak) and the estimation of the volume of sediment along this coastline. Findings from this chapter play a significant role in deriving the effect

this sediment injection has had on the littoral budgets along the central Taranaki Coast.

Presented in **Chapter 4** is the variation in the sediment characteristics along the Taranaki Coastal sector from the Stony River mouth to Paritutu Headland. The parameters of texture, roundness/sphericity and mineralogy indicate the variation along the coast and rates of change.

Chapter 5 evaluates the potential longshore sediment transport flux occurring between Cape Egmont and New Plymouth. Ten years of hindcast wave data from along the 5 m depth contour were applied to the CERC (1973) sediment transport equations to infer incremental potential fluxes at regular 1 km intervals along the coastal sector.

An episodic sediment budget is presented in **Chapter 6**. This incorporates an estimation of the volume of material eroded from the gully system in the headwaters of the Stony River as well as an estimate of the volume of sand currently deposited in the Stony River channel as aggradation deposits and along the sub-aerial beach between Komene Road and Ahuahu Beach.

The major findings of the study are presented in **Chapter 7**. Discussed are the implications these findings have to the many stakeholders and recommendations for future research is suggested.

1.3 STUDY AREA

The Taranaki Headland is located on the west coast of the North Island, New Zealand (Figure 1.4). This research focuses on the coastal sector between the Stony River mouth and the Sugar Loaf Islands where large reefs extend offshore between sandy channels (McComb et al., 1999a).

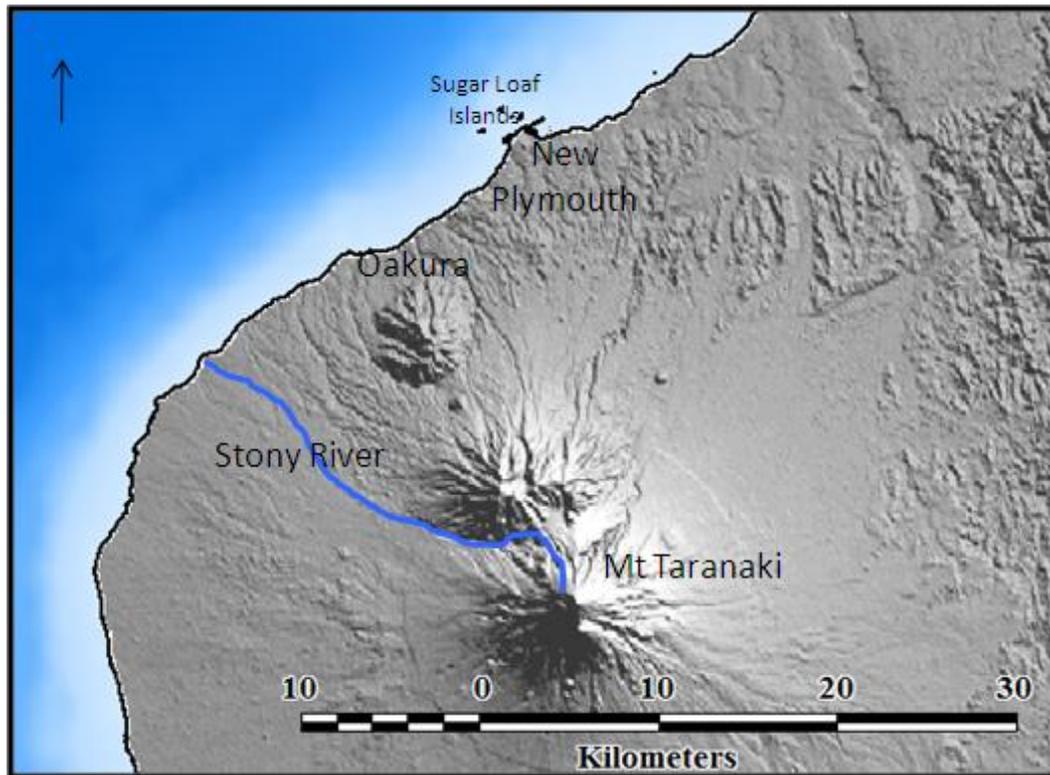


Figure 1.4 Location of the Taranaki Headland on the west coast of the North Island, New Zealand.

The Taranaki Region lies on the ring plain of an andesitic shield volcano, Mount Taranaki, otherwise known as Mount Egmont. Like all of New Zealand's west coast, it is exposed predominately to swells that are generated in the Tasman Sea and the Southern Ocean (Pickrill and Mitchell, 1979). This coastline is a high energy coastal environment (McComb, 2001) with erosion occurring at a number of locations, receiving minimal shelter from the westerly wind belt in the mid latitudes. The central Taranaki coastline is dominated by boulder beaches, lahar cliffs and offshore reefs, and various pyroclastic materials originating from nearby Mount Taranaki.

CHAPTER TWO: ENVIRONMENTAL BACKGROUND

2.0 INTRODUCTION

Knowledge of the environmental background of the Taranaki Peninsula is necessary to understanding the hydrodynamic and sedimentation processes occurring along the coastal sector between Cape Egmont and New Plymouth. Accordingly, this chapter describes a general description of the environmental background of the Taranaki coastline. This includes a discussion of the geological setting, coastal geomorphology, sediment sources, sediment transport factors, rainfall, and fluvial inputs which are fundamental to understanding the hydrodynamic and sedimentation processes of this coast.

2.1 GEOLOGICAL SETTING

The Taranaki Basin, covering approximately 100,000 km² is one of the largest sedimentary basins along the western margin of New Zealand. It formed during the late Cretaceous during the break-up of the palaeo-Pacific margin of Gondwana. Beneath this basin the Pacific plate dips at a northwestward direction (Muir et al., 2000). This basin is bound to the east by the Taranaki Fault (late Paleogene to Neogene reverse fault) and to the west it is bound by the Challenger Plateau. This large, mainly submerged, continental crust contains the Taranaki Peninsula, the largest onshore region of this basin. The Taranaki Peninsula (Figure 2.1) is dominated by the 2518 m high andesitic volcano, Mount Taranaki (previously known as Mount Egmont), a volcanic cone of lavas and breccias, the associated parasitic cones of Pouakai and Kaitake Ranges, and subsequent lava flows that have been built since the early Pleistocene. Mount Taranaki, the youngest and most southern of the Taranaki Quaternary volcanic succession (Neall et al., 1974), has been active for at least 130,000 years. Its cone is composed of alternating layers of pyroxene-andesite

and hornblende-andesite alternating layers and fragmental volcanic deposits (tephra fall units, pyroclastic flow deposits, block and ash deposits) (Procter, in press). Egmont andesites are a light or dark grey rock with a number of white speckles representing feldspar as well as patches of the dark green augite and black hornblende (Neall, 2003). Mineral assemblages (Matthews, 1977) and dispersal trends in iron sand concentrations (Fleming, 1946; Kear, 1965; Gow 1967; Christie, 1975; Carter; 1980) indicate that these Egmont andesites are the principle source of opaque minerals to the west coast of the North Island, with the Taupo Volcanic Zone being the secondary source (Gow, 1967).

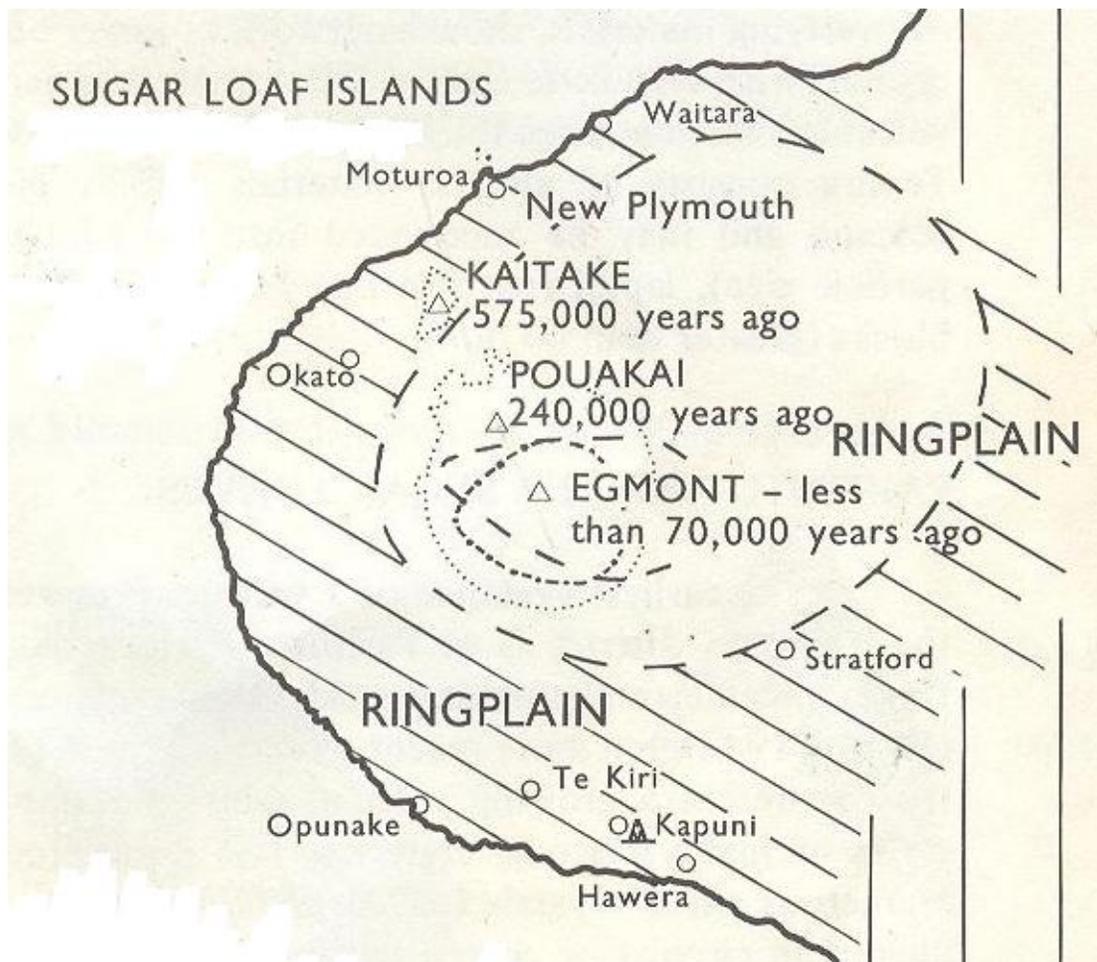


Figure 2.1 Taranaki Volcanic Succession
(Source: Neall, 1974).

The Sugar Loaf Islands (Ngā Motu) and Paritutu volcanic extrusions near New Plymouth are remnants from volcanic activity in the late Pliocene to early Pleistocene ages. Tectonic movement has been occurring since the late Miocene in relation to the plate boundary between the Australian and Pacific Plates, causing uplift of the Taranaki region. As a result a number of faults are present which strike in either the north or northeast directions (King and Thrasher, 1996).

A ring plain (Figure 2.1), built by several phases of pyroclastic lahar flows during the past 120,000 years, surrounds these volcanoes from the 900 m contour. It is composed predominately of laharc breccia flows, tephra deposits, alluvium, and dune sands that range from 2-3 m thick (Kibblewhite et al., 1982). On the southern and western parts of the Taranaki ring plain, debris avalanche deposits dominate featuring large conical hills/mounds separated by more confined lahar deposits (Procter, in press). Surrounding the Stony River Chanel is the Warea Formation which forms large flat surfaces dispersed around older debris avalanche deposits. The Warea Formation is scoria-rich containing volcanic bombs > 30 cm in diameter.

At the coast this ring plain terminates where sea cliffs expose predominately lahar deposits composed of graded andesitic rock fragments, ancient dune sands, tephra and occasionally peat (Figure 2.2).



Figure 2.2 Steep cliffs at Back Beach, New Plymouth composed of lahar deposits, ancient dune sands and tephra (November 2008).

At the base of the steep cliffs, high energy waves have cut shore platforms (Figure 2.3) into the lahar deposits, with remnant boulders extending 5-10 km offshore.



Figure 2.3 Shore cut platform at Stent Road, Cape Egmont (November 2008).

Prior to the 1998 outbreak of sediment from Little Pyramid in the headwaters of the Stony River, beaches exposing this shore platform were typical along the Taranaki Coast. However, after 1998, the lahar cut shore platform to the north of the Stony River (and slightly south) became covered with gravel and sand deposits which overlie these shore platforms, forming dynamic beaches. This sand and gravel sized beach sediment deposits are predominately andesitic with a great spatial variation in particle size which can be attributed to differing wave climates. The sands in this area well-sorted with an average density value of 2850 kgm^{-3} . Heavy minerals (augite, hypersthene, hornblende and opaques) make up 38% of the sand sized sediment while the remainder of this sand consists of the lighter minerals feldspar, quartz, shell and composites (Bartholomeusz, 1985).

2.2 COASTAL GEOMORPHOLOGY

The Taranaki coastline is irregular (Figure 2.4) dominated by the Paritutu headland in New Plymouth (Figure 2.5). It has a variable offshore topography made up of sand flats and rocky reefs (McComb, 2001).



*Figure 2.4 Irregular coastline looking south towards Cape Egmont.
(Source: davidwallphoto.com).*



*Figure 2.5 The Paritutu Headland in New Plymouth (left) with the Pararake, Matoroa and Motuotamatea Rocks in the foreground.
(Source: davidwallphoto.com).*

The rocky reefs are a dominant factor affecting the settlement of sediment on the seabed. Boundary layers are thicker on 'rougher' surfaces resulting in effects on sediment entrainment, sediment suspension and wave refraction (McComb, 2001).

The entire Taranaki coast from the Mohakatino River in the north to Wainui Beach in the South is eroding at a rate of between 0.05 m and 1.89 m annually (McComb et al., 1999a). This erosion is mainly due to cliffs collapsing as a result of wave undercutting. The greatest areas at danger from this erosion include Oakura due to the proximity of urban development to the eroding coast (Taranaki Regional Council, 2004).

2.3 SEDIMENT SOURCES

Mount Taranaki has suffered severe erosion, due to episodic heavy rainstorms. Over the past 400 years, unstable jointed lava flows and 11 debris flows have collapsed, a large proportion originating from the rim of the western crater (Neall, 1974). As a result sand and gravel has discharged into the littoral system via a series of rivers, the dominant ones being the Waitara, Waiwhakaiho, and Stony River (Bruce Wallace & Partners, 1981). At approximately 1500 A.D hot incandescent gas charged clouds flowed down the Stony River from Mount Taranaki's summit. Native bush on the northwestern slopes in the Stony River's catchment was destroyed and approximately 15 km² of land surrounding the river flooded (Neall, 1974). Approximately 17,000 years ago a pyroclastic flow plummeted down the Stony River and into the northwestern flanks of the Pouakai Range forming the Saunders Ash deposit. In 1974 Neall reported that the latest debris flow (prior to the 1998 Stony River outbreak) occurred about 100 years ago destroying all native bush from the Pyramid Stream to the National Park boundary. Deposits of these flows are evident in the thick gravel deposits of the Pyramid Stream (Figure 2.6) and Manganui Gorge (Neall, 2003).



*Figure 2.6 Exposure of Pyroclastic deposits in Pyramid Stream deposited approximately 8000 years ago. Note the figure with the white shorts for scale.
(Source: Neall, 2003).*

These sediments, derived from pyroclastic deposits, form a number of sandy beaches over this rocky Taranaki coastline. Normally the volume of sediment entering the coastal system is insufficient to maintain beaches under this high wave energy environment. As the upper slopes of Mount Taranaki have been regenerated with moss being converted to scrub the runoff has reduced and fine material has been restricted from entering the coastal littoral system (Bruce Wallace & Partners, 1981). In 1981, Bruce Wallace and Partners reported that small beaches are evident only at the mouths of streams and rivers, with the remainder of the foreshore having a rocky bed exposing the wave cut lahar shore platform.

Since 1998, the sandy sediment derived from the Stony River has been moving north as a thinning wedge of sediments extending as far as 16 km north of Stony River. Presently, the sediments provide a significant store of material in the upper shore, transported only during the high tides with energetic waves.

2.4 SEDIMENT TRANSPORT

Parabathic (longshore) sediment along this coastal sector has both north and south directed flows (Figure 2.7), as a result of westerly winds and waves converging at

Cape Egmont (Bruce Wallace & Partners, 1981). The net direction, north of Cape Egmont is towards the northeast (McComb, 2001). This littoral drift is reduced south of Cape Egmont due to the protection from the southerly swell provided by the South Island (Gibb, 1979). This longshore sediment transport results in iron sand derived from Mount Taranaki reaching as far north as Pandora's Bank and as far south as Paekakariki covering over 480 km (Kear, 1979). Diabathic (cross-shore) sediment transport has not yet been quantified, but offshore surveys (e.g. McComb et al., 2003) suggest that nearshore regions along the Taranaki coast (i.e. 20-30 m depth) are predominately rocky with sandy sediments persisting only within the bathymetric depressions. Studies by Kibblewhite et al. (1982) have indicated that while tides and waves are responsible for sediment transport on the inner and middle shelf most of the sediment transport occurs during storm periods where wave suspended sediment is transported by tidal and wind-driven circulation.



Figure 2.7 Littoral drift on the west coast of the North Island - the net direction towards the north.

(Adapted from Stokes, 1987).

Prior to the development of the Taranaki Port during the 1880s, sediment moved freely northeast along the Taranaki coast (Arron and Mitchell, 1984). In 1981 a breakwater was constructed, creating the Taranaki Harbour, interrupting this littoral transport resulting in the accumulation of sand. Further lengthening of the breakwater and the construction of a new breakwater resulted in the trapping efficiency of sand increasing. Consequently dredging is now undertaken regularly.

McComb et al. (1999a) estimated from the nearshore placement of dredged sand that the net littoral transport rate is greater than 220,000 m³yr⁻¹. Matthews (1977) estimated that in the coastal sector between Cape Egmont at New Plymouth, using a theory from the Hydraulics Research Station (1963), that three times as much sand moves to the northwest as does to the south. It was estimated that between 75,000 m³ and 180,000 m³ of material enters this coastal system (Table 2.1) and streams (principally the Stony River) are the major source of sediment, contributing 43% of the total inputs followed by cliff erosion.

Table 2.1 Approximate sand budget for the shore between Cape Egmont and New Plymouth. (Source: Matthews, 1977).

Cape Egmont to New Plymouth		
	Maximum Estimate (m ³ yr ⁻¹)	Minimum Estimate (m ³ yr ⁻¹)
Streams	55,000	36,000
Cliff Erosion	45,000	35,000
Pebble abrasion	10,000	Negligible
Biogenic	18,000	4,000
Continental Shelf	Negligible	Negligible
Wind	Negligible	Negligible
Net longshore movement out of cell	180,000	75,000

Holmes (1976) estimated the volume of sediment in the littoral drift to be between 350,000 m³ and 400,000 m³. Kirk (1980) stated that the medium and coarse sand fractions are transported northwards however when they reach the submarine ridge between Motorua Island and the breakwater (Figure 2.8), the medium and coarse sand

fractions continue to be transported northwards while the finer sands are worked into the harbour.

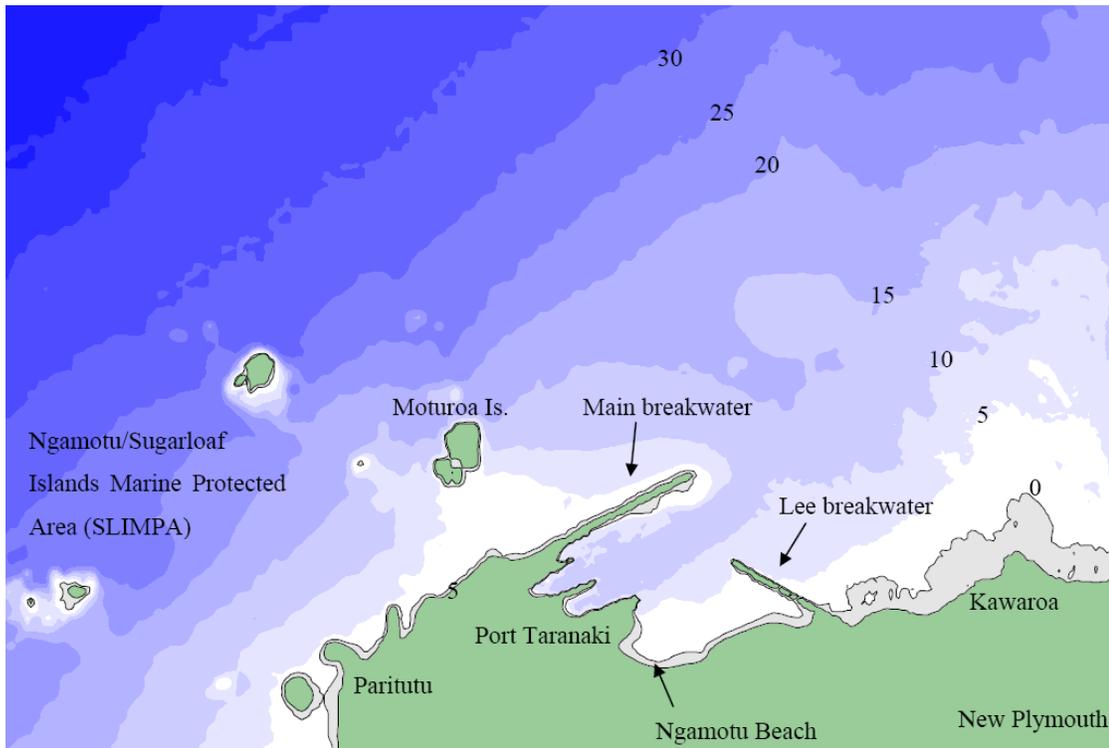


Figure 2.8 Bathymetric map (5 m isobaths) of the New Plymouth coast illustrating the submarine ridge between Moturoa Island and the main breakwater.
(Source: McComb, 2001).

Studies by Kibblewhite et al. (1982) have indicated that while tides and waves are responsible for sediment transport on the inner and middle shelf most of the sediment transport occurs during storm periods where wave-suspended sediment is transported by tidal-induced and storm-induced circulation.

Wind-driven and wave-driven currents are the main components that govern the near shore sediment transport along the Taranaki Coast.

2.4.1 Wind Climate

Winds blowing over the shore-face transfer energy to surface currents through the air/water interface and produce wind-driven shore-face currents. These currents can converge at the shoreline producing a set up of mean water set up against the shore or they can diverge at the shoreline creating a set down of the mean water surface

against the shore. This set up or set down results in pressure gradient forces that drive alongshore currents and therefore sediment transport (Niedoroda et al., 1985).

The wind rose from New Plymouth Airport between 1962 and 2008 and the wind rose from Kapoiaia at Cape Egmont (Figure 2.9) between 1998 and 2008 illustrates that the dominant wind direction is from the south west and south east (Figure 2.10; Figure 2.11). These winds originate in the Southern Ocean south of Australia between 45° and 55° south (Harris, 1990). The funneling affect Mount Taranaki has on this wind, however, results in the south-southeast wind being the dominant direction at the New Plymouth Airport. This short term data from Cape Egmont has a stronger northerly component than the longer term data.

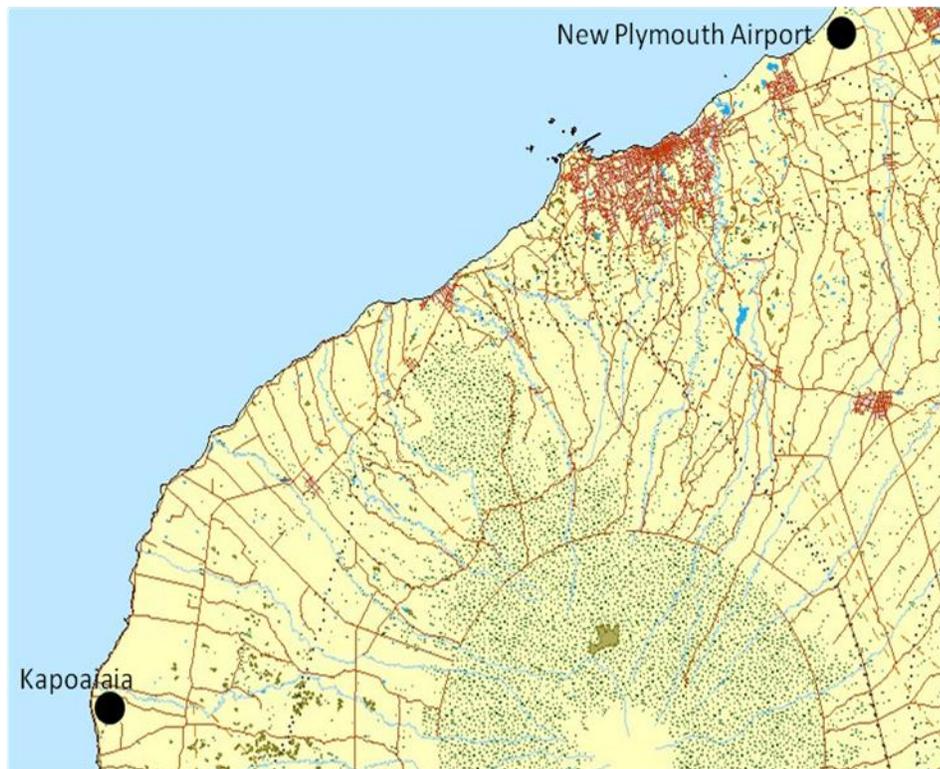


Figure 2.9 Location of the New Plymouth Airport.

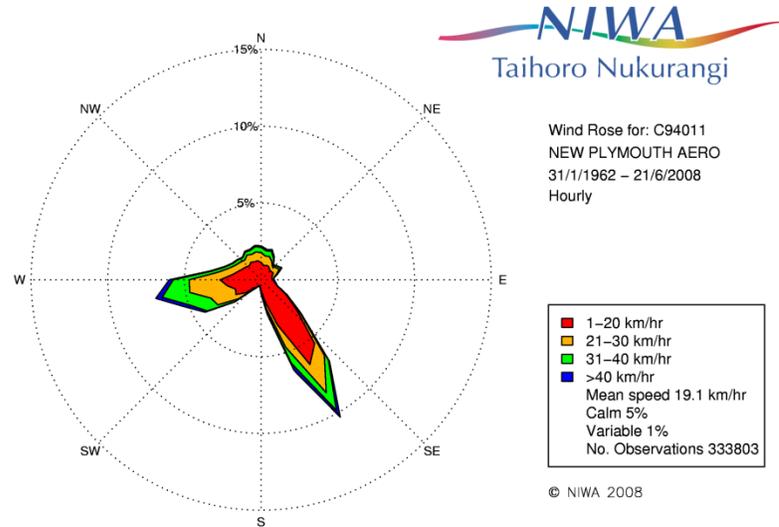


Figure 2.10 Wind Rose at New Plymouth Airport 1962-2008.
(Source: NIWA, 2008).

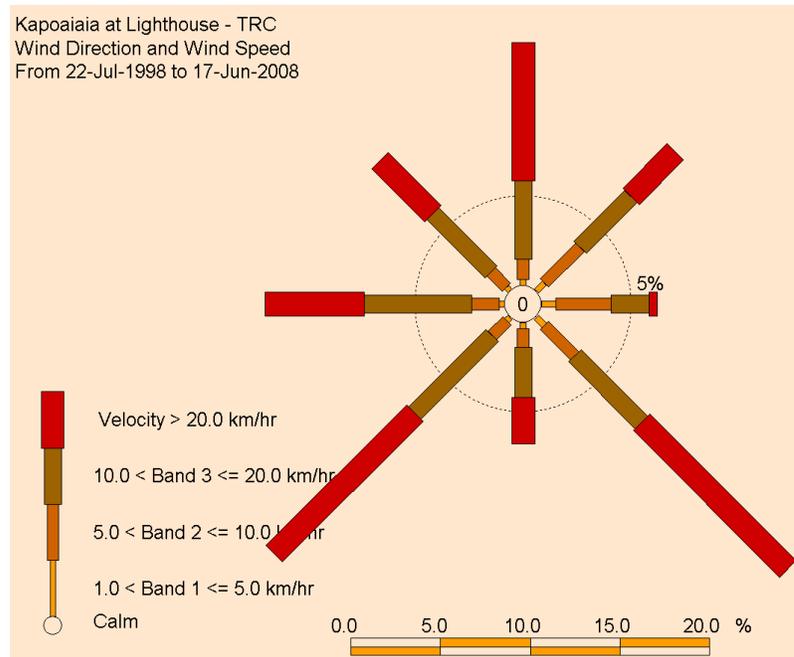


Figure 2.11 Wind Rose at Kapoiaia, Cape Egmont 1998-2008.
(Source: TRC, 2008).

The Taranaki coast is exposed to anticyclones migrating towards the east. They give the region settled conditions and are separated by low pressure troughs. The migration of these anticyclones occurs in five to seven day intervals separated by low pressure troughs occurring 25% of the time. The remainder of the time low pressure systems dominate, with the strongest winds occurring in the spring when the

anticyclones move more rapidly over New Zealand. During the summer and autumn months the anticyclones over New Zealand penetrate further south resulting in weaker winds in the Taranaki region (Matthews, 1977). Wind regimes are also affected by the circulation patterns and strengths of the Hadley and mid latitude cells (Black and Sokolov, 1993). During El Nino Southern Oscillation (ENSO) events, El Nino conditions result in more frequent west to southwest winds. When La Nina events occur the opposite occurs and there is an east to northeast wind dominant over normal conditions (McComb, 2001).

2.4.2 Wave Climate

Waves approaching the Taranaki coast from the west are dominated by long period swell waves and locally generated storm waves (McComb, 2001). The isolation of New Zealand in the South Pacific means that unlimited fetch conditions are available to generate waves promoting a high wave energy climate (Pickrill and Mitchell, 1979). The northeast to southwest shoreline orientation results in sheltering of the waves that approach from the south and southwest and a wave energy gradient is present from just south of Cape Egmont to New Plymouth (McComb, 2001). The steep Taranaki coastal shelf (the 30 m contour is approximately 1700 m offshore) results in there being little energy lost due to friction between the deep-water and shallow-water regions. Consequently the waves approaching this shoreline are large with wave heights ranging from 1- 6 m (McComb, 2001).

Data in 1991 show a seasonal variation in this wave height with the largest waves and waves with the lowest frequencies (less than 0.1 Hz), approaching the coast between the winter months of May and October (McComb, 2001). Studies by Ewens and Kibblewhite (1992) at the South Taranaki Maui oilfield demonstrate that there is a dominant swell coming from the south west (sources south of the Tasman Sea and in the Southern Ocean) with a long wave period of 12.4 s. Westerly and south-westerly wind components are an important role in the wave climate as well as waves generated in the northwest that occur frequently. The spectral levels of these waves however are lower than those winds coming from the west and south (Ewens & Kibblewhite, 1992).

2.4.2.1 Wave Refraction

Boulder reefs extend seaward from a number of small headlands along this coastal sector of interest (i.e. just south of Oakura (Figure 2.12)). As waves approach these small headlands, shallow water wave refraction aligns the wave crests with the isobaths and the angle between the wave crests and the bottom contour is reduced (Figure 2.13). The refraction spreads the wave energy over a long wave crest length and sand can accumulate (Coastal Engineering Centre, 1984). The low frequency swell waves refract more effectively in comparison with the shorter period sea waves ($T < 8$ s) (McComb, 2001).



*Figure 2.12 Refraction occurring to the north of the Stony River mouth.
(Source: TRC, 1995).*

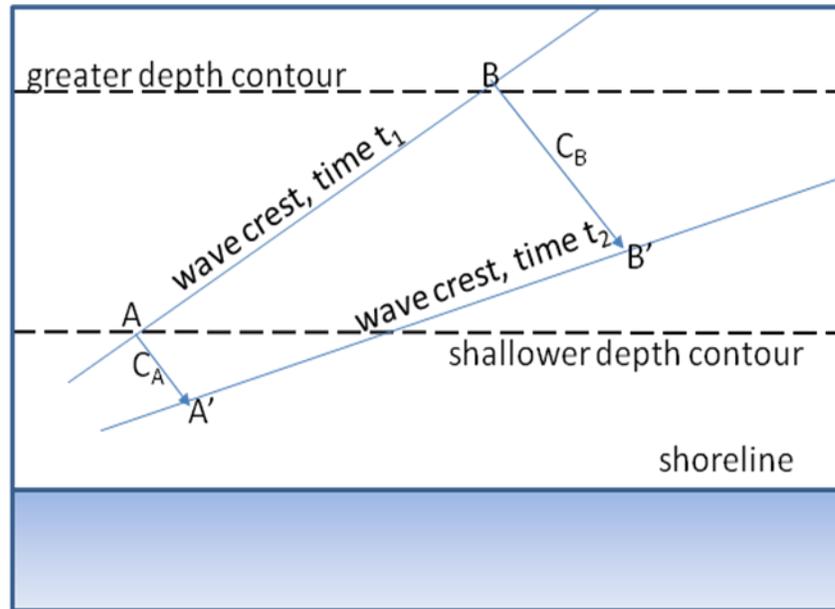


Figure 2.13 Wave refraction occurs due to waves in deeper water moving faster than waves in shallow water. Over a certain time interval the wave crest at point B will move further than the wave crest at point A resulting in the wave to swing around and become more shore parallel

2.5 RAINFALL

Rainfall data taken from the New Plymouth Airport (Figure 2.9) between 1941 and 1981 illustrates that rainfall varies seasonally with the majority occurring over June and July with less rainfall between December and March. The intensity of this rainfall also varies with most rain per event falling during the summer compared with the winter (Black and Sokolov, 1993). This rainfall pattern influences the rate at which sediment is delivered to the coast with higher intensity rainfall delivering sediment at a greater rate in comparison with lower intensity rainfall. Topography affects this rainfall with higher areas of Mount Taranaki receiving $> 25,000 \text{ mmy}^{-1}$ and coastal areas receiving $\sim 10,000 \text{ mmy}^{-1}$ (Black and Sokolov, 1993).

2.6 FLUVIAL INPUTS

Within the Taranaki Region there are over 500 rivers from 286 main catchments (Taranaki Regional Council, 2001). The 25 largest catchments in the Taranaki region each have a mean annual flow of 150 l/s (Taranaki Regional Council, 2005). The

stretch of coast between Cape Egmont and Back Beach in New Plymouth contains four of these 286 main catchments, the Oakura, Timaru, Kaihihi and Stony catchments.

2.6.1 Oakura River

The most northern of these catchments is the Oakura catchment. The Oakura River drains the northern slopes of the Pouakai Ranges and the southern slopes of the Kaitake Ranges meandering its way through the Egmont National Park and farmland on the volcanic ring plan before it enters the Tasman Sea at Oakura. The median flow (occurring 50% of the time) of this 44 km² catchment is 1,730 l/s and its mean annual low flow is 565 l/s (Taranaki Regional Council, 2005).

2.6.2 Timaru Stream

The Timaru Stream drains the southern and western slopes of the Kaitake Ranges and the north-western slopes of the Pouakai Ranges. This small stream's catchment area is just 31 km², and its estimated median flow is 1,110 l/s with its mean annual low flow being 420 l/s (Taranaki Regional Council, 2005).

2.6.3 Kaihihi River

The Kaihihi River and tributaries drain a catchment of 39 km². This catchment drains the lower western slopes of Mount Taranaki through Okato and into the Tasman Sea. Its median flow is estimated at 700 l/s, with its mean annual low flow of 300 l/s at the stream mouth (Taranaki Regional Council, 2005).

2.6.4 Stony River

The Stony River, to the west of Egmont Natural Park (Figure 2.14) drains a 51 km² area of the western flank of Mount Taranaki, and is the most southern catchment of the coastal sector this research focuses on. The Stony River, one of the largest rivers flowing from Mount Taranaki, sources from unconsolidated volcanic detritus. The head of the catchment is in the rocky slopes near the summit of Mount Taranaki. Before entering the Tasman Sea, this 25 km river and its tributaries meander through the Egmont National Park, into farmland on the mountain's ring plan (north of

Rahotu) where the catchment becomes narrow and receives little water from the farmland surrounding (Taranaki Regional Council, 2005). Above 750 m in elevation it has a steep river bed gradient (4-14°), with high rainfall which results into it cutting into the lava flows and lahar deposits (Swales et al., 2003). The Stony River's median flow is 3,860 l/s with a mean annual low flow of 2,730 l/s (Taranaki Regional Council, 2005). This is the largest catchment along this stretch of coast with the river having significantly greater flows than all the other catchments. The Stony River bed is unstable as a result of continuous active erosion at its headwaters and aggradations downstream (Neall, 1999).

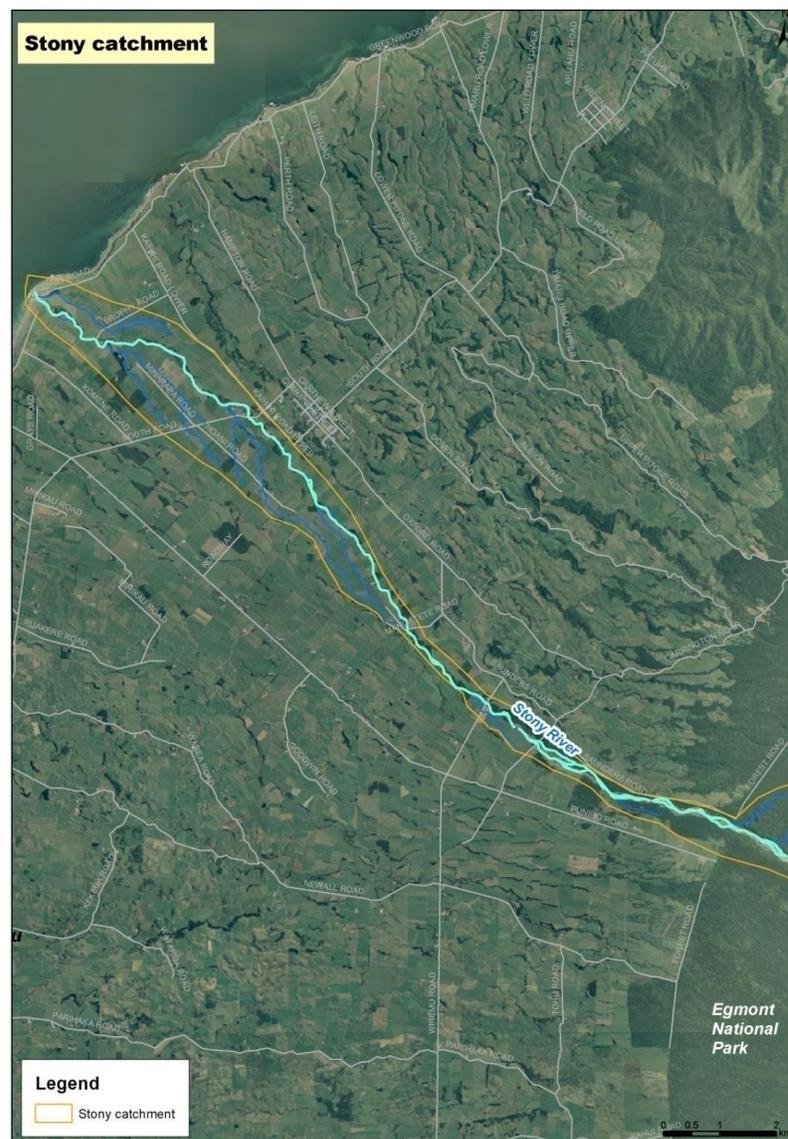


Figure 2.14 Stony Catchment
(Source: TRC, 2005).

2.7 SUMMARY

The significant environmental factors that need to be taken into account when understanding the hydrodynamic and sedimentation process on the southern Taranaki Coast include:

1. The Taranaki peninsula ring plain terminates at the coast exposing sea cliffs of lahar flows made up of andesitic pebbles and boulders derived from Mount Taranaki. These flows overly raised beaches of gravels and dune sands and retreating sea-cliffs are flanked by intensive intertidal wave-cut shore platforms.
2. The eroding Taranaki coastline is irregular with a sea-bed composed of sand flats and rocky reefs.
3. The Taranaki coastline has a high wave energy climate with a net flux to the east. This parabathic sediment transport has both north and south directed flows due to the convergence of westerly winds at Cape Egmont. Long period waves ($T > 12$ s) from the Southern Ocean and Lower Tasman Sea dominate as well as shorter period ($T < 10$ s) wind waves from local storms.
4. Four main rivers supply sediment to the coastal sector of interest, the Stony River being the most significant in terms of catchment size, discharge and mean annual flow.

These factors all play an important part in the hydrodynamic and sedimentation processes as will be discussed in subsequent chapters.

CHAPTER THREE: COASTLINE CHANGES

3.0 INTRODUCTION

Beaches are the most dynamic physical systems on the earth's surface (Short, 1999). The overall morphology of a coastal sector is a reflection of the sediment characteristics along with other physical processes acting on the beach including waves, currents, and sediment transport processes (Komar, 1998). The processes responsible for shoreline change vary in temporal scale such as sea-level rise, an increase/decrease in sediment supply (from land), storm activity, longshore variations in wave energy, seasonally changing profiles and anthropogenic factors (Fenster and Dolan, 1993).

Beach profiles, natural features of the intertidal environment, are governed by waves, tides and beach sediments. They cause waves to break and lose their energy. Beach profiles vary with time and through their measurement, along transects running perpendicular to the shoreline, changes in beach morphology can be identified (Komar, 1998). Beach profiles were surveyed in three monthly intervals between June 2008 and May 2009 at 12 locations between Komene Road, just north of Cape Egmont, and Back Beach in New Plymouth. Beach profiles undertaken at Oakura were compared with Matthews (1977) beach profile data measured in 1975 and 1976, as well as with data obtained from McComb et al. (2005). The beach profile data obtained in 2008 was presented at the International Coastal Symposium 2009 conference in Lisbon, Portugal and a proceedings paper (Appendix A) is published as:

Cowie, N.A., Healy, T. R., and McComb, P. J., 2009. Sediment Flux on the High Energy Taranaki Coast, New Zealand. *Journal of Coastal Research*, SI 56 (Proceedings of the 10th International Coastal Symposium), Lisbon, Portugal, pp.703-707.

By combining the measured 2008/2009 beach profile data and using aerial photographs taken in 2007, an estimate of the current volume of sediment along this coastal sector, originating from the Stony River, was determined. This was presented along with data calculating the volume of material that has eroded from

the gully at the headwaters of the Stony River, at the 2009 Coasts and Ports Conference in Wellington and a proceedings paper (Appendix A) is published as:

Cowie, N.A., Healy, T. R., and McComb, P. J., 2009. Sediment Budget for an Episodic Injection on a High Energy Coast, Paper 17.

This chapter describes the coastline changes along the southern Taranaki coastal sector of interest. Comparisons of aerial photographs, sub-aerial beach profiles and beach volume estimates are made prior to, and after the Stony River outbreak.

3.1 PREVIOUS ANALYSIS OF COASTLINE CHANGES

The following studies have analysed coastline changes at some of the sites between Komene Road and Back Beach, the coastal sector this study focuses on.

- Matthews (1977) undertook beach profiles on six beaches in the Taranaki Region. These included Oakura and Werekino Beaches near the entrance of the Stony River. These profiles indicated that the weekly volume of sand that accreted during January and February 1977 ranged between 2,000 m³ to 15,000 m³. Between February and May 40,000 m³ was lost at Werekino while 25,000 m³ was added to Oakura Beach.
- Gibb (1978) determined coastline changes at various locations around New Zealand including at Stent Road, Leith Road, Ahuahu Road, Oakura Beach and at the Herekawe Stream at the southern end of Back Beach. The coastal erosion and accretion rates at these Taranaki locations were determined using cadastral plans from the Department of Lands and Survey New Plymouth. At Stent Road the net accretion rate between 1881 and 1953 ranged from 14-28 m.yr⁻¹ while between 1892 and 1975 there was no net accretion or erosion at Leith Road. Between 1865 and 1961 there was a net accretion rate of 0.21 m.yr⁻¹ at Ahuahu Road and accretion at Oakura Beach with a net rate between 33 and 67 m.yr⁻¹. At the Herekawe Stream, at the southern end of Back Beach, there was no accretion or erosion between 1925 and 1975.
- The Taranaki Catchment Commission (1978) investigated possible long term erosion and accretion cycles along the Oakura Beach coastline. From

literature and personal communication with residents, the Harbour Board and the Wellington Meteorological Office it seemed likely that a cycle pattern exists however the time period of this cycle was not determined. Between 1960 and 1975 Oakura Beach had undergone two accretion and erosive phases, while aerial photograph analysis of the camp area detected erosion between 1969/1975 and 1975/1977.

- McComb et al. (2005) undertook onshore profiles at Oakura Beach to identify long term management options for the western beach in front of the Holiday Park. These surveys, undertaken by laser scanning, incorporated the ~ 130 m wide beach and a 475 m alongshore length. These surveys identified a narrow intertidal zone (minimum distance between the MLWS and MHWS is 70 m) along the western side of the camping ground, while identifying an intertidal distance at central Oakura beach approximately twice as wide (maximum distance between the MLWS and MHWS is 60 m).

3.2 METHODS

3.2.1 Aerial Photo Comparison

Aerial photographs of the coastal sector between Cape Egmont and Back Beach in New Plymouth, were obtained from 1995, prior to the Stony River outbreak, and after the outbreak in 2001 and 2007. Initially, these photographs were geo-referenced, using Arc GIS software, to NZMG. Polygons were overlaid on areas identified as beach sediment as shown by the example in Figure 3.1. Using Arc GIS, the areas of the polygons were determined.

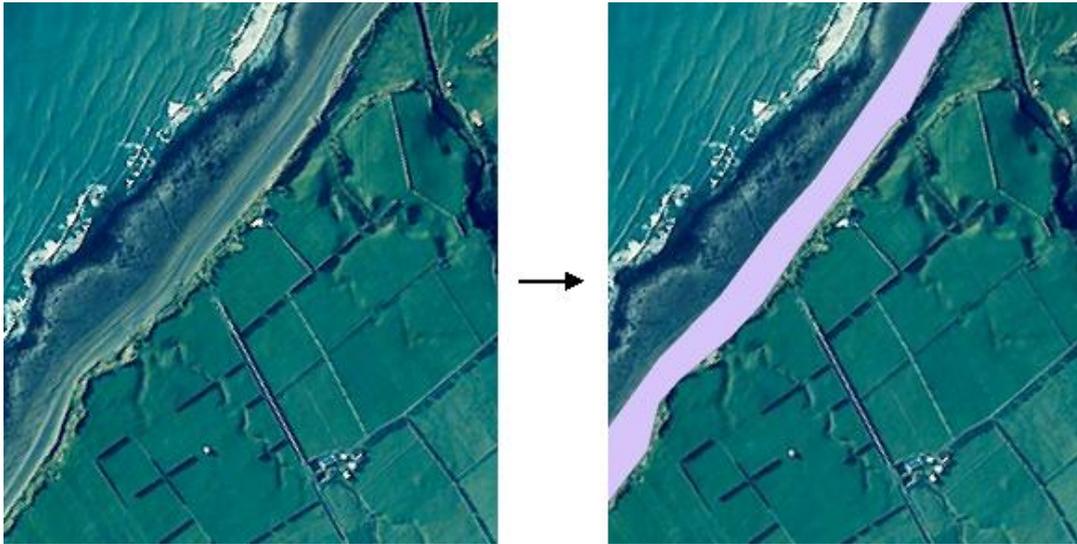


Figure 3.1 Section of Kaihihi Surf Beach (2007) with sand covering the rocky boulder coast. Picture on the right shows a polygon overlaid on the sand in this image.

Errors associated with using aerial photographs include:

- Varying tidal conditions. The photos taken in 1995 were taken approximately one hour after high tide. The photos taken in 2007 were taken at close to low tide. In the case of the 2001 photos, the tide height is unknown, but visual estimation suggests that the photo was taken near high tide. This high tide may result in the area of sand being underestimated.
- The resolution of the photos taken in 2001(1:25,000) is poor (2.5 m x 2.5 m) compared with the resolution of the photos taken in 1995 (1:27,500) and 2007 (1:20,000). Lower resolution photographs decrease the accuracy of sediment extent estimation.

For comparative purposes, the photographs have been de-lineated along the coastal sector into four unequal segments namely Komene Road, Kaihihi Surf Beach, Fort St. George and Ahuahu Beach.

3.2.2 Beach Profiles

To undertake beach profiling the Emery (1961) rapid survey method was used. This method requires two rods, each held vertically by two people, and a measuring tape, which is extended between the two rods. One person (the observer) holds the landward rod and aligns their eye with the horizon, measuring where on the seaward rod (held by the second person) the horizon intersects. The seaward rod moves down the beach at predefined intervals, with smaller intervals used at locations of significant morphological change. Profiles were surveyed as close to low tide as possible (~ 1.5 hours either side) to maximise survey distance, however, adjustments after calculations were made to determine the tide height at any particular time. This was calculated using the following formulae:

$$h = h_1 + (h_2 - h_1) \frac{(\cos A + 1)}{2}$$

Equation 3.1

$$A = \pi \frac{(t - t_1)}{(t_2 - t_1)} + 1 \text{ radians}$$

Equation 3.2

where t_1 and h_1 are the time and height of the tide immediately preceding time t , and t_2 and h_2 are the time and height of the tide immediately following time t . Note t , t_1 and t_2 are in decimal hours (LINZ, 2009).

3.2.2.1 Profile Locations

Twelve profiles between Cape Egmont (at the end of Komene Road) and Back Beach in New Plymouth (Figure 3.2) were surveyed on the 12th and 13th of June 2008, the 25th and 26th of September 2008, the 17th and 21st of November 2008, the 2nd and 3rd of February 2009, and the 21st and 22nd of May 2009.

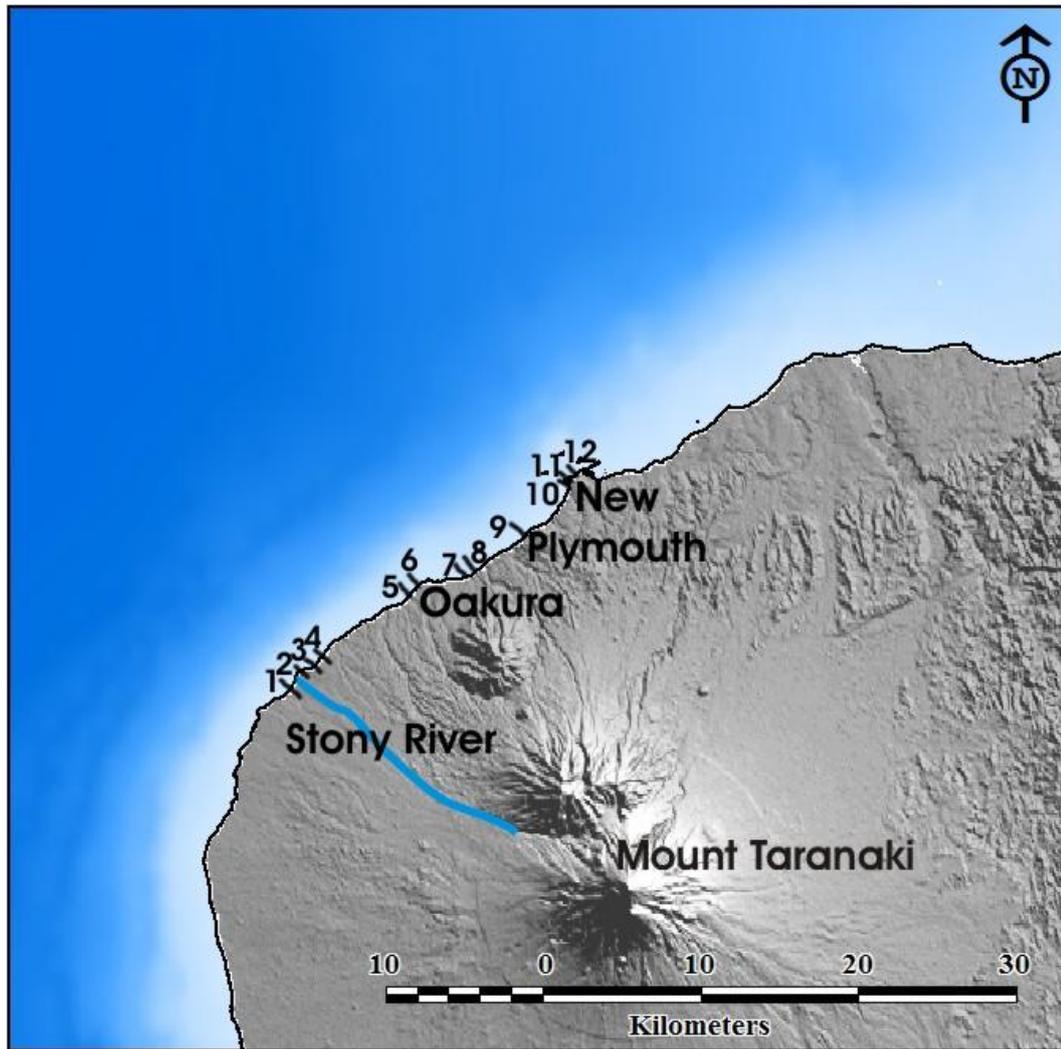


Figure 3.2 Locations of the 12 profiles.

Profile 1 - South of Stony River: Profile 1 was taken at the end of Komene Road, south of the Stony River mouth. This location lies between the Werekino Stream mouth and the Stony River mouth (Figure 3.5).

Profile 2 – Immediately North of Stony River: Profile 2 was the measuring location nearest to the Stony River mouth located at what is known to the locals as the ‘Kumara Patch’ (Figure 3.3 and Figure 3.4). Located just north of the Stony River mouth, this location undergoes great sediment quantity fluctuations between sampling times. Prior to 1998 this coast comprised a narrow cobble to boulder reflective boulder beach as shown in Figure 3.4. This site was inundated with coarse sand after the 1998 collapse resulting in a berm 5 m high and 22 m wide (Figure 3.4). This headland (the Kumara Patch) causes wave refraction, which results in sediment accumulation on either side.



*Figure 3.3 Kaihihi Surf Beach on 14th March 1976. The Stony River mouth is 30 m to the left of this picture.
(Source: Doug Hislop).*



*Figure 3.4 'The Kumara Patch' (east of the Stony River mouth) which was inundated with millions of cubic metres of sand after the 1998 Stony River outbreak.
(Source: McComb et al., 2005).*

Profile 3 – Kaihihi Surf Beach ~ 3 km North of Stony River: Profile 3 was taken mid-way along the Kaihihi Surf Beach (Figure 3.5).

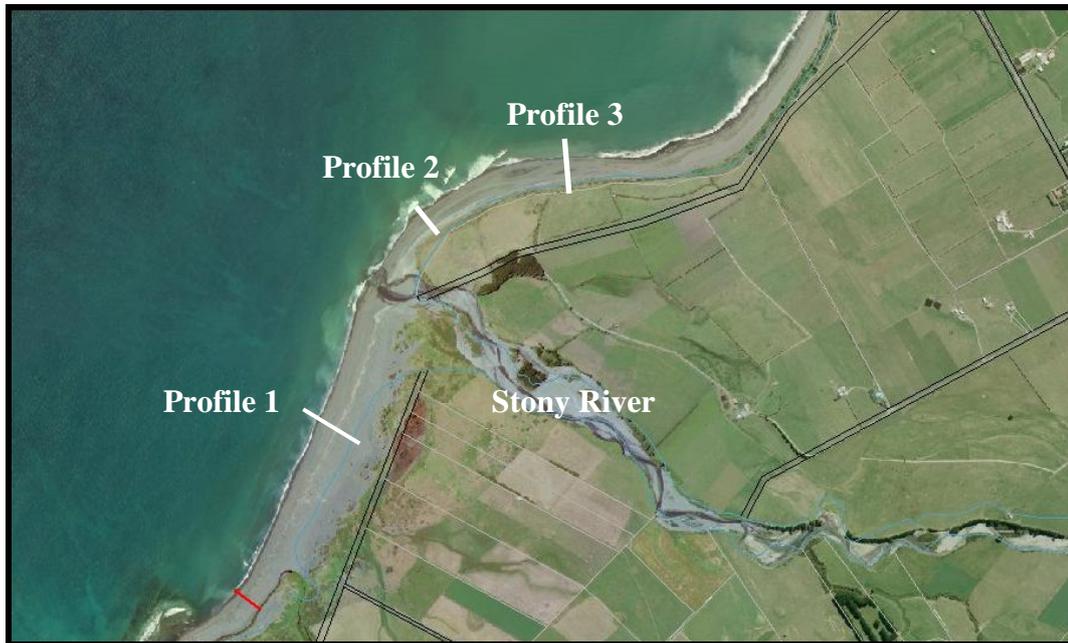


Figure 3.5 Location of beach profiles 1-3.

Profile 4 – Immediately North of Kaihihi River: Profile 4 is located just north of the Kaihihi Stream (Figure 3.6). During the course of this study, the wave-cut shore platform became exposed at approximately mid-tide level (Figure 3.7).

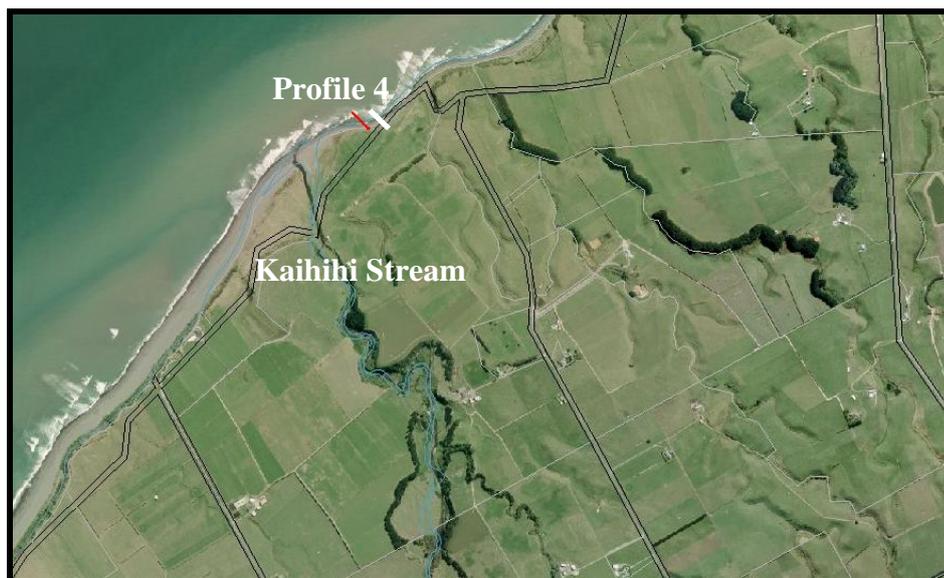


Figure 3.6 Location of profile 4.



Figure 3.7 The exposed wave-cut shore platform present at the site of profile 4.

Profile 5: Profile 5 is taken at the end of Timaru Road, at Fort St. George, and taken just to the north of the Timaru Stream mouth (Figure 3.8).



Figure 3.8 Location of profile 5.

Profile 6 – Ahuahu Beach: Profile 6 was taken at the end of Ahuahu Road (Figure 3.9). The beach at the end of Ahuahu Road suffers from the down-coast effects of sediment pulses, resulting in large variations in sand volume at the intertidal and sub-tidal areas (McComb et al., 2005).



Figure 3.9 Location of profile 6.

Illustrated in Figure 3.10 is Ahuahu Beach in the 1930s as a rocky embayment, with a steep coarse grained beach face, in contrast to today's beach where the centre has been filled with sand, most likely as a result of the 1998 Stony River flood (McComb et al., 2005).



*Figure 3.10 Ahuahu Beach in the 1930s (top image) and in 2007 (bottom image).
(Source: McComb et al., 2005).*

Profile 7 – Oakura Beach (South): Like Ahuahu Beach, Oakura Beach (Figure 3.11) is influenced by the headland/reef at the southern end of the beach, affecting the local wave climate. Oakura Beach is orientated obliquely to the wind and wave direction (Patchett, 1978). During the last 54 years, this shoreline has exhibited episodic erosion and accretion periods (McComb et al., 2005). Since 1970, the shoreline to the west of the Holiday Park has been retreating at an average rate of 0.1 m annually (McComb et al., 2005). Directly in front of the Holiday Park the erosion rate is 0.4 m/yr, with accretion occurring between 1981

and 1986, and erosion occurring episodically since then (McComb et al., 2005). Further north at central Oakura Beach approximately 10 m of retreat occurred between 1950 and 1981, with accretion occurring between 1981 and 1986 (McComb et al., 2005). Profile 7 was taken at the southern end of Oakura Surf Beach (Figure 3.11).

Profile 8 – Oakura Beach (North): Profile 8 was taken further north along Oakura surf beach directly in front of the surf life saving club (Figure 3.11).



Figure 3.11 Location of profiles 7 & 8 at Oakura Beach.

Profile 9 – Tapuae Beach: Profile 9 was taken just the north of the Tapuae Stream (Figure 3.12). Public access is limited at this beach due to a private housing development directly on the shore front.



Figure 3.12 Location of profile 9.

Profiles 10, 11 and 12 (Southern, Central and Northern Back Beach): Profiles 10, 11 and 12 were undertaken at Back Beach in New Plymouth (Figure 3.13). Approximately 22 km north of the Stony River, a long sandy beach has formed in the lee of the Sugar Loaf Islands. Sediment characteristics and geomorphology of this beach are altered frequently due to the eroding cliff situated landward of this beach. These cliffs expose lahar deposits composed of graded andesitic rock fragments, ancient dune sands, tephra and occasionally peat (see Figure 2.2 in Chapter Two).



Figure 3.13 Location of profile sites 10, 11 & 12.

3.2.2.2 Survey Errors

It is estimated that the vertical accuracy of the Emery (1961) method is ± 0.05 m; however, the horizontal error is thought to be approximately ± 0.15 m (Matthews, 1977). Benchmarks with a known elevation and GPS position were marked with orange pegs. However, problems were encountered when they were overtopped with sand or moved by the public. The angle of the profile was projected from the bench mark also poses an error. Where possible, a landmark such as a boulder or offshore structure was used to give direction to the profile or it was lined up with a feature inland such as a tree or building. A GPS was used to minimise these errors.

3.2.3 Estimation of Beach Volumes

Beach volumes are widely used to quantify beach changes. Beach profile data obtained from this study over 2008 and 2009 at the twelve sites from Komene Road to Back Beach (Table 3.1) and geo-referenced aerial photographs were used to estimate sediment volumes along the coastal sector between the Stony River and Ahuahu Beach, which has been affected by sediment derived from the Stony River. Firstly, the coast was divided into six segments and using Arc GIS, and polygons were created covering the sand area, as shown in Section 3.2.1.

Combining the dimensions of these polygons and the beach profile data, beach sediment volumes were estimated along these six coastal segments. It is important to note that these six segments are not equal lengths so cannot be directly compared to each other. When combining the beach profile data with the areas derived from aerial photos, it was assumed that the wave-cut shore platform has a slope of 1:100.

3.3 RESULTS

3.3.1 Aerial Photo Comparisons

Table 3.1 and illustrate the surficial sand coverage identified from aerial photographs. It is important to note that the coastal sectors are different lengths so are not comparable and are just indicative of temporal change at that particular location. Komene Road is located immediately to the south of the Stony River mouth while Kaihihi Surf Beach, Fort St. George and Ahuahu Beach are located to the north.

Table 3.1 Area of beach sediment calculated from aerial photographs (m²).

Location	1995	2001	2007
Komene Road	73,043	170,507	233,697
Kaihihi Surf Beach	-	2,361,641	329,145
Fort St. George	16,302	168,622	158,619
Ahuahu Beach	-	23,742	126,887
TOTAL	89,345	2,724,512	848,348

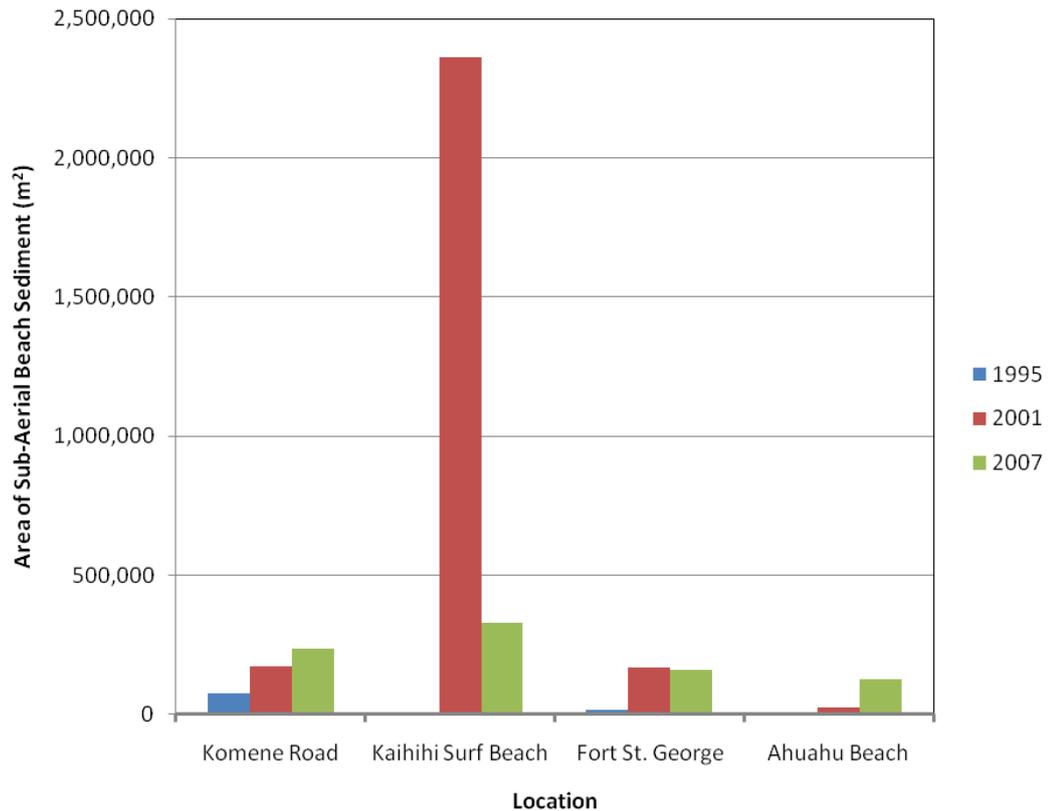


Figure 3.14 Area of sand calculated from aerial photographs (m^2)

It was hypothesised that the three sites north of the Stony River (in the direction of the net littoral drift) will contain the least amount of sand in 1995 (prior to the Stony River outbreak) and the greatest amount following the outbreak in 2001 and 2007. The amount of sand was not determined in 1995 along the Kaihihi Surf Beach and Ahuahu Beach coastal sectors as the tide was too high when the imagery was taken. Clearly, the greatest amount of sediment present in this system in 2001 is along the Kaihihi Surf Beach (Table 3.1 and Figure 3.14). By 2007, this sediment coverage had reduced significantly by $\sim 2,030,000 m^2$, most likely due to removal by longshore sediment transport processes. South of the Stony River, at the end of Komene Road, there has been a small increase in surficial sand, likely to be produced by the locally directed littoral transport to the south and the diffusion of sediment from the Stony River mouth.

3.3.2 Beach Profiles

Beach profiles respond to changing wave climates. Typically the Taranaki Coast is in an erosive state where energetic short steep waves have transported any

beach sediment present in the area and exposed the wave-cut shore platform. However, since the 1998 influx of sediment transported to the coast via the Stony River, the morphology of the beaches north of the Stony River mouth has altered significantly.

Wind data measured at New Plymouth Aero, to the north of New Plymouth (Figure 3.), was obtained from NIWA’s National Climate Database (Cliflo), prior to when surveying was undertaken to explain beach morphology changes. Table 3.2 summaries the wind direction and speed for each of the surveys.



Figure 3.15 Location of New Plymouth Aero where the wind data was measured. (Source: Google Earth, 2009).

Table 3.2 Wind direction and speed data measured at New Plymouth Aero. (Source: NIWA, 2009)

Surveying Time	Direction (°)	Speed (ms ⁻¹)
June 2008 (2/6/08-11/6/08)	204	5.3
September 2008 (15/9/08-24/9/08)	171	4.0
November 2008 (8/11/08-21/11/08)	178	5.0
February 2009 (23/1/09-1/2/08)	171	3.24
May 2009 (11/5/09-20/5/09)	263	7.84

The following illustrates the differing morphologies of beach profiles taken during 2008/2009 and the comparison with previous beach profile data from Oakura Beach. Terminology to describe the beach profiles is defined in Figure 3.16.

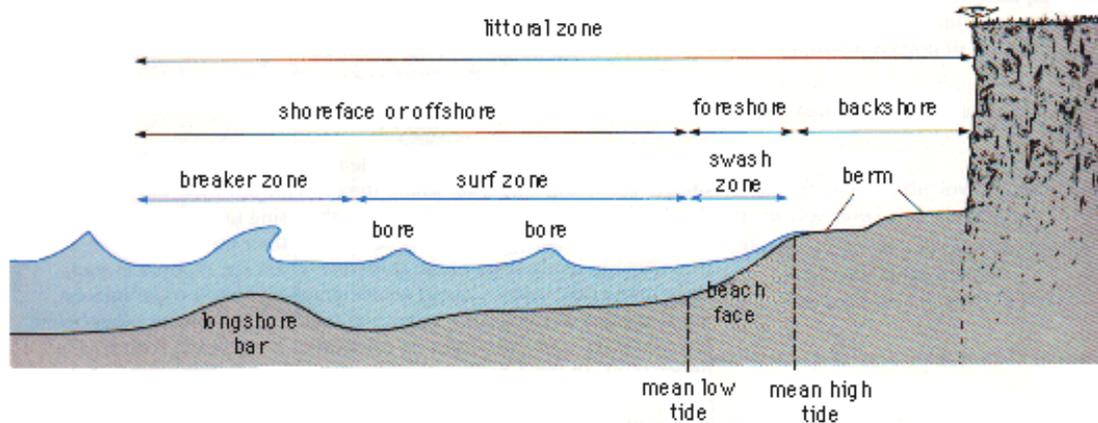


Figure 3.16 Terminology used to describe the beach morphology.
(Source: Thai Marine Ecological Center, date unknown).

3.3.2.1 2008/2009 Beach Profile Data

Profile 1: South of the Stony River

At the site of Profile 1, south of the Stony River mouth, there was little change in the beach profile morphology between September 2008 and November 2008 while in June 2008 the upper beach had an extra $180 \text{ m}^3 \text{ m}^{-1}$ of sediment and two berms (Figure 3.17). In February 2009, the profile (up to 60 m from the fixed land point) had $\sim 2 \text{ m}$ elevation in comparison with profiles undertaken in September 2008 and November 2008. A possible explanation for this increase in sediment in February 2009 may be due to less intense winds resulting in sediment transport onto the beach (Table 3.2). In June 2008 and February 2009 the beach face was significantly steeper in comparison with the other survey periods.

Profile 2: Immediately north of the Stony River

Immediately north of the Stony River the beach profiles exhibit large fluctuations in morphology (Figure 3.17). The profile taken in June 2008 had a much steeper dune, while the September 2008, November 2008 and February 2009 profiles exhibited two berms. The profile measured in June 2008 had lost $\sim 170 \text{ m}^3 \text{ m}^{-1}$ of sediment compared with the other profiles. There is little difference in morphology between the September 2008 and November 2008 profiles. Two

distinct berms were present in the May 2009 profile which has the most sediment ($\sim 550 \text{ m}^3 \text{ m}^{-1}$), some $\sim 110 \text{ m}^3 \text{ m}^{-1}$ greater than the next highest profile surveyed in November 2008.

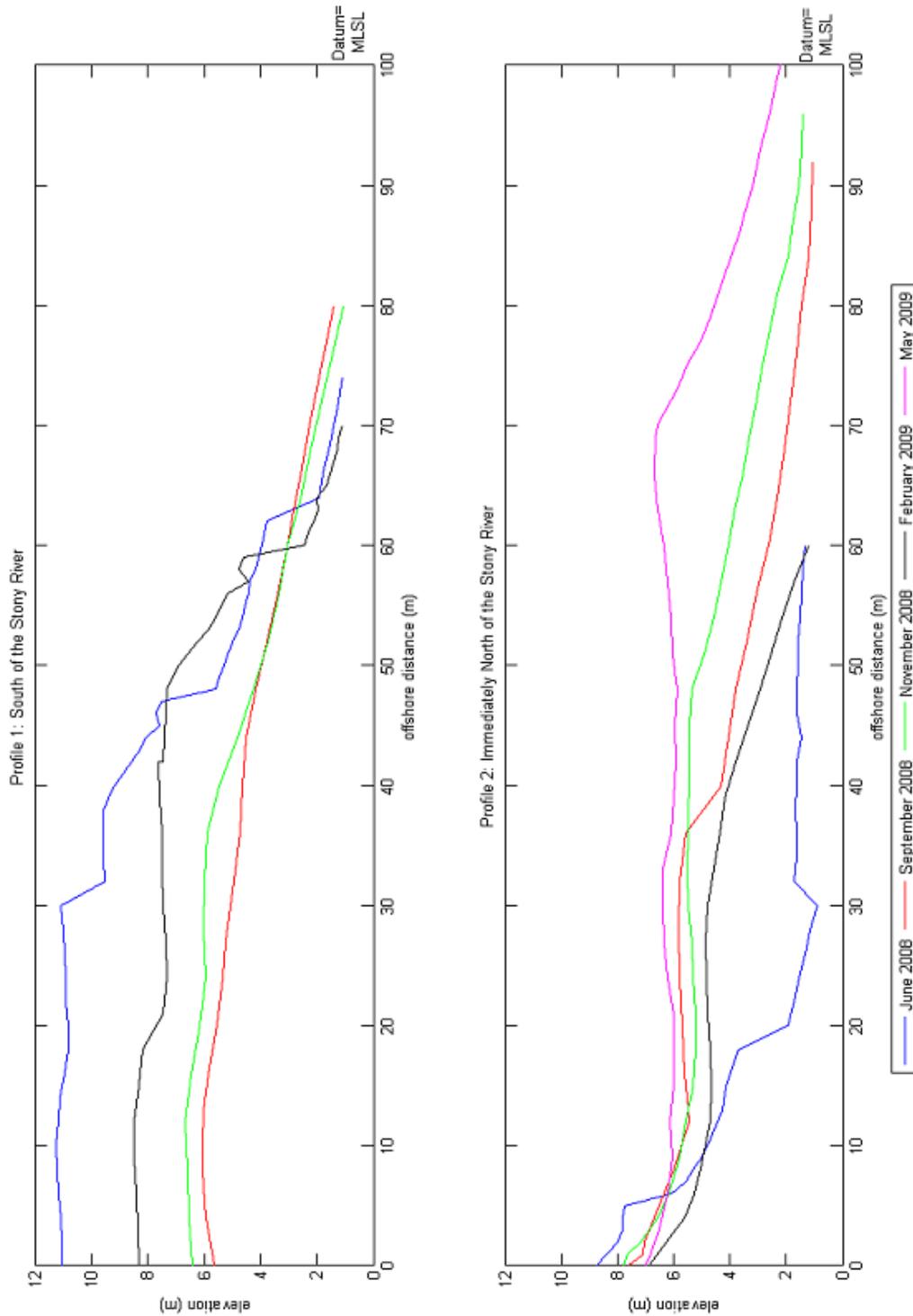


Figure 3.17 Onshore and sub-aerial beach profiles surveyed south of the Stony River (Profile 1) and immediately north of the Stony River (Profile 2).

Profile 3: Kaihihi Surf Beach

The widest beach along the stretch of coast, 3 km north of the Stony River mouth, had an average width of 150 m over this survey period (Figure 3.18). Over the course of this surveying, Kaihihi Surf Beach had two berms and a steep beach face with the morphology remaining relatively consistent over the eleven months these beaches were monitored. The profile measured in November 2008 had an extra 2 m elevation compared to later profiles. A significantly eroded profile, with $\sim 130 \text{ m}^3\text{m}^{-1}$ of sediment, was surveyed in May 2009, likely to be as a result of greater wind speeds coming from the south-west (Table 3.2).

Profile 4: Immediately north of Kaihihi River

In September 2008, November 2008 and February 2009 the morphology just north of the Kaihihi River varies little (Figure 3.18). This may be due to the small headland formed at the Kaihihi River mouth providing shelter from the net SW wind direction. A significant berm was present in June 2008 approximately 30 m seaward of the fixed land point which added $\sim 40 \text{ m}^3\text{m}^{-1}$ to the profile. Like all the other profiles undertaken in November 2008 the profile was elevated by approximately 2 m.

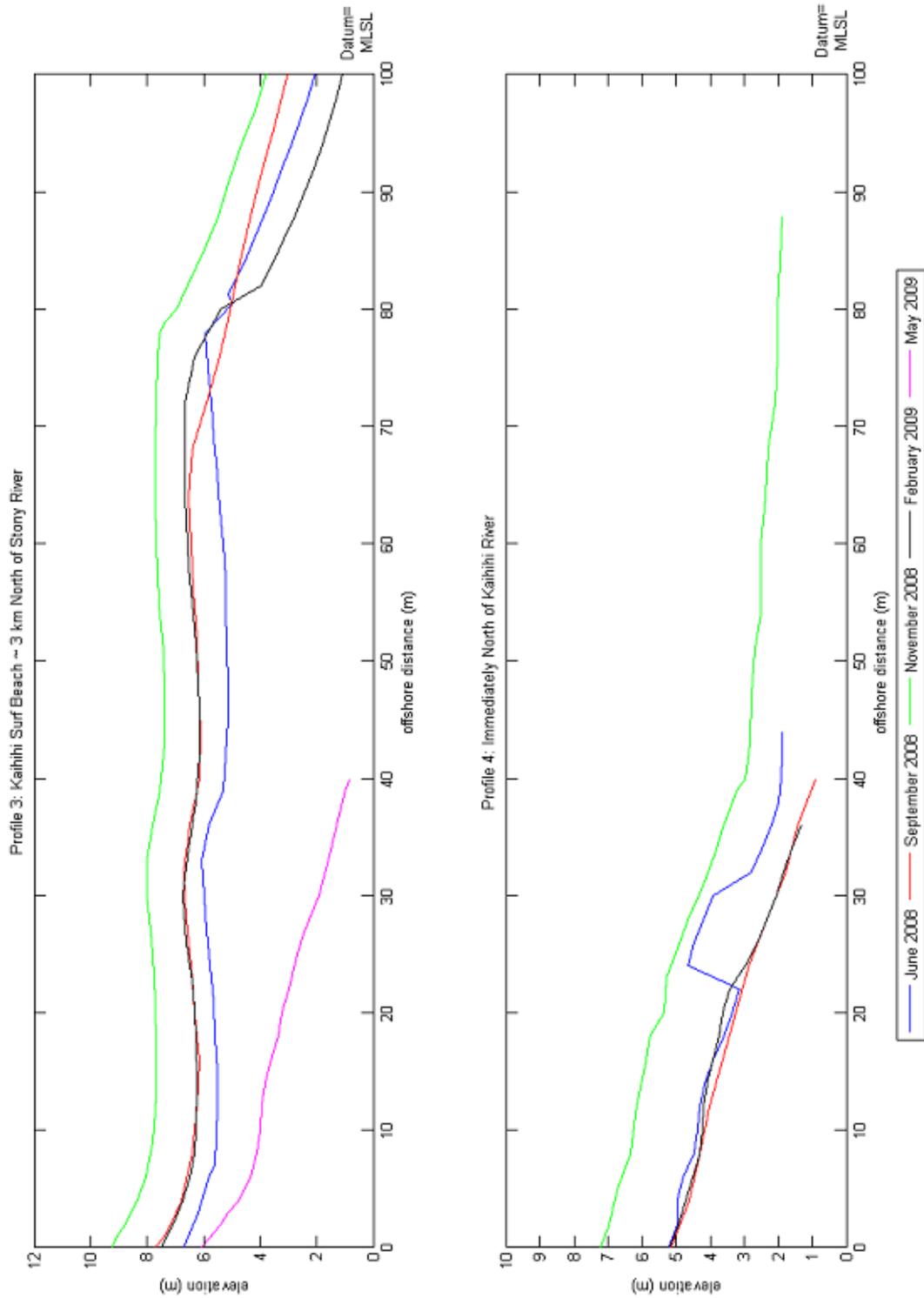


Figure 3.18 Onshore sub-aerial beach profiles surveyed at Kaihihi Surf Beach (Profile 3) and immediately North of Kaihihi River (Profile 4).

Profile 5: Fort St. George

In comparison with other sites there have been small changes in morphology during the course of this study at Fort St. George (Figure 3.19). The profiles

undertaken in September 2008 and November 2008 have very similar morphologies with the November 2008 profile having ~ 1 m extra elevation compared to the other profiles. The profiles surveyed in February 2009 and June 2008 displayed similar gradients, however, they each possessed a similar sized berm at different widths across on the shore. The profile of June 2008 had a berm between 5 and 20 m from the landward profile starting mark, while in February 2009, a berm was present between 20 and 40 m, giving these profiles an extra ~ 10-20 m³m⁻¹ of sediment. The profile surveyed in May 2009 had a similar gradient to the profile surveyed in June 2008 however the berm that is present ~ 15 m from the landward start of the profile is not present in May 2009. The absence of this berm is likely to be due to high speed south-westerly wind climate (7.84 ms⁻¹) resulting in sand transport off the beach (Table 3.2).

Profile 6: Ahuahu Beach

As is the case with the profile surveyed immediately north of the Kaihihi River, in June 2008 a significant berm is present ~ 2 m greater elevation than the remainder of the profiles at Ahuahu Beach (Figure 3.19). The profiles of September 2008 and November 2008 had similar morphologies and prior to being surveyed this coast experienced similar wind directions and speeds at these times (Table 3.2). The profile surveyed in February 2009 had two berms present, the first ~ 20 from the landward start of the profile and the second ~ 40 m from the start of the profile. These berms bring an extra ~ 1 m elevation on the profile (Figure 3.19) and are most likely due to the calmer wind conditions this coast experienced prior to the February 2009 surveying (Table 3.2). By May 2009 these berms had been cut down and infilling has taken place at the base of the dunes. This berm erosion is due to the high speed wind climate this coast experienced prior to surveying (Table 3.2).

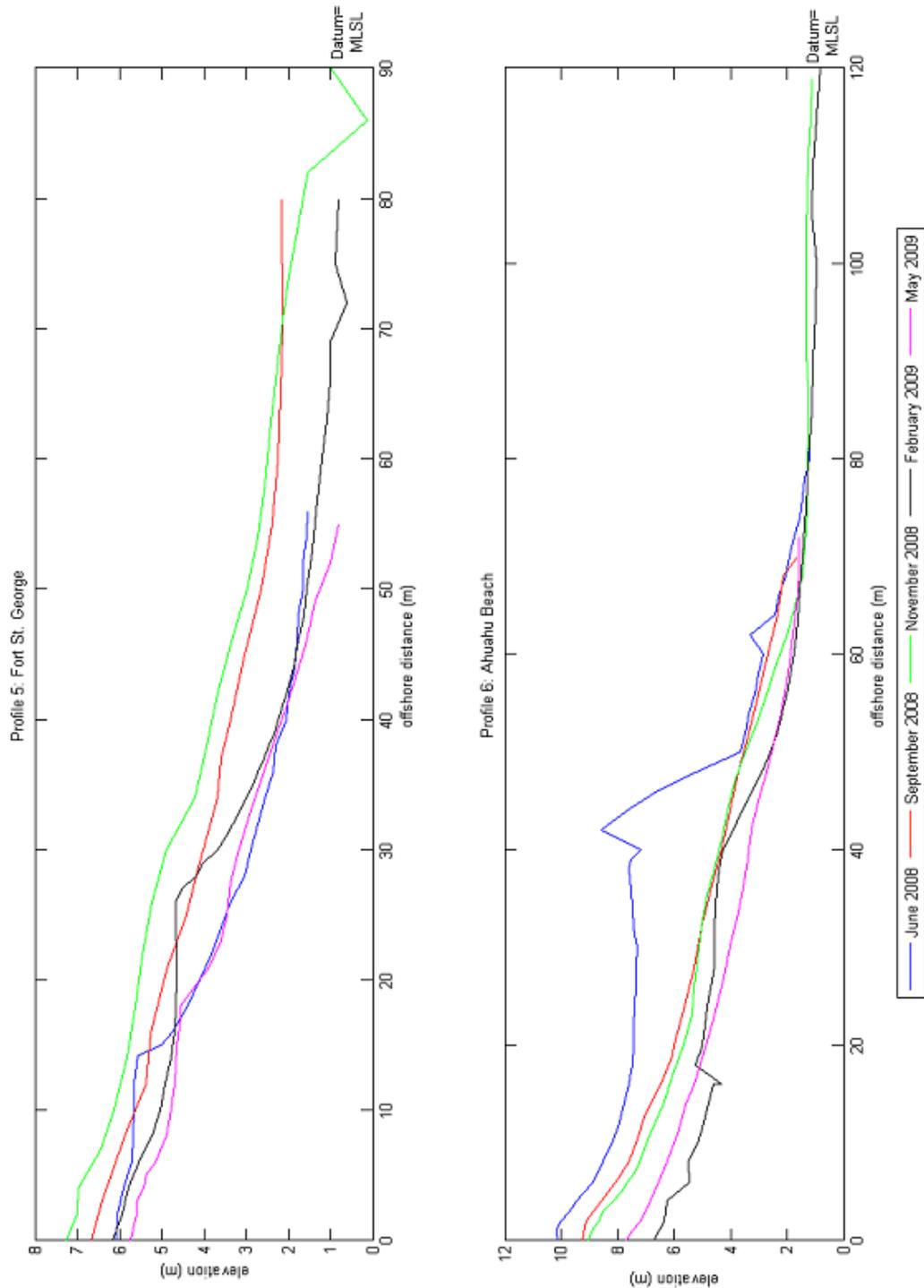


Figure 3.19 Onshore sub-aerial beach profiles at Fort St. George (Profile 5) and Ahuahu Beach (Profile 6).

Profile 7: Oakura Beach (South)

The profiles surveyed in September 2008 and November 2008, at Oakura Beach (South), displayed very similar morphologies as did the profiles surveyed in June 2008 and February 2009 (Figure 3.23). The profile surveyed in November 2008

is ~ 1 m higher than the profile surveyed in September 2008. The profile undertaken in June 2008 is ~ 1.5 m higher than the profile surveyed in February 2009. The February 2009 profile shows a decreased elevation at ~15 m from the landward point (at the base of the dunes). By May 2009, sediment had accumulated resulting in a berm building the profile ~ 1.5-2 m greater at this spot (15 m from the landward point) compared with profile of February 2009. There appears to be a discrepancy between the wind conditions this beach is exposed to and the beach profiles shape surveyed. This discrepancy could be a result of:

- the headland/reef to the left of the surveying location altering the local wave climate and injecting sediment in ‘pulses’ to Oakura; and
- the Waimoku Stream discharges in front of the camping ground. Over this study period it regularly changes course therefore altering the geomorphology and sediment volume present at Oakura. Figures 3.20, 3.21 and 3.22 each show the Waimoku Stream following a different course in April 2008, September 2008 and February 2009.



Figure 3.20 Oakura Beach (South) looking E (April 2008). Note the Waimoku Stream channel orientated parallel to the Oakura Coast.



Figure 3.21 Oakura Beach (South) looking SE (September 2008). Note the Waimoku Stream orientated parallel to the coast before sharply changing course and flowing perpendicular to the coast.



Figure 3.22 Oakura Beach (South) looking SW (February 2009). Note the Waimoku Stream orientated parallel to the Oakura Coast as in Figure 3.20 but located close to the mid tide mark, rather than the high tide mark as shown in Figure 3.20.

Profile 8: Oakura Beach (North)

Over the course of this study there has been little variability in the heights of the profiles obtained at Oakura Beach (Figure 3.23). In each profile at least two berms are present. The beach is relatively flat in comparison with the other profiles measured during the course of this study at other locations. A berm in June 2008 is more elevated and closer to land in comparison with the berms of other profiles at this location. The profile surveyed in May 2009 is much steeper

in comparison with the other profiles and exhibited a ‘step-like’ shape as a result of the relatively high speed (7.84 ms^{-1}) with climate this beach was exposed to prior to the May 2009 surveying taking place (Table 3.2).

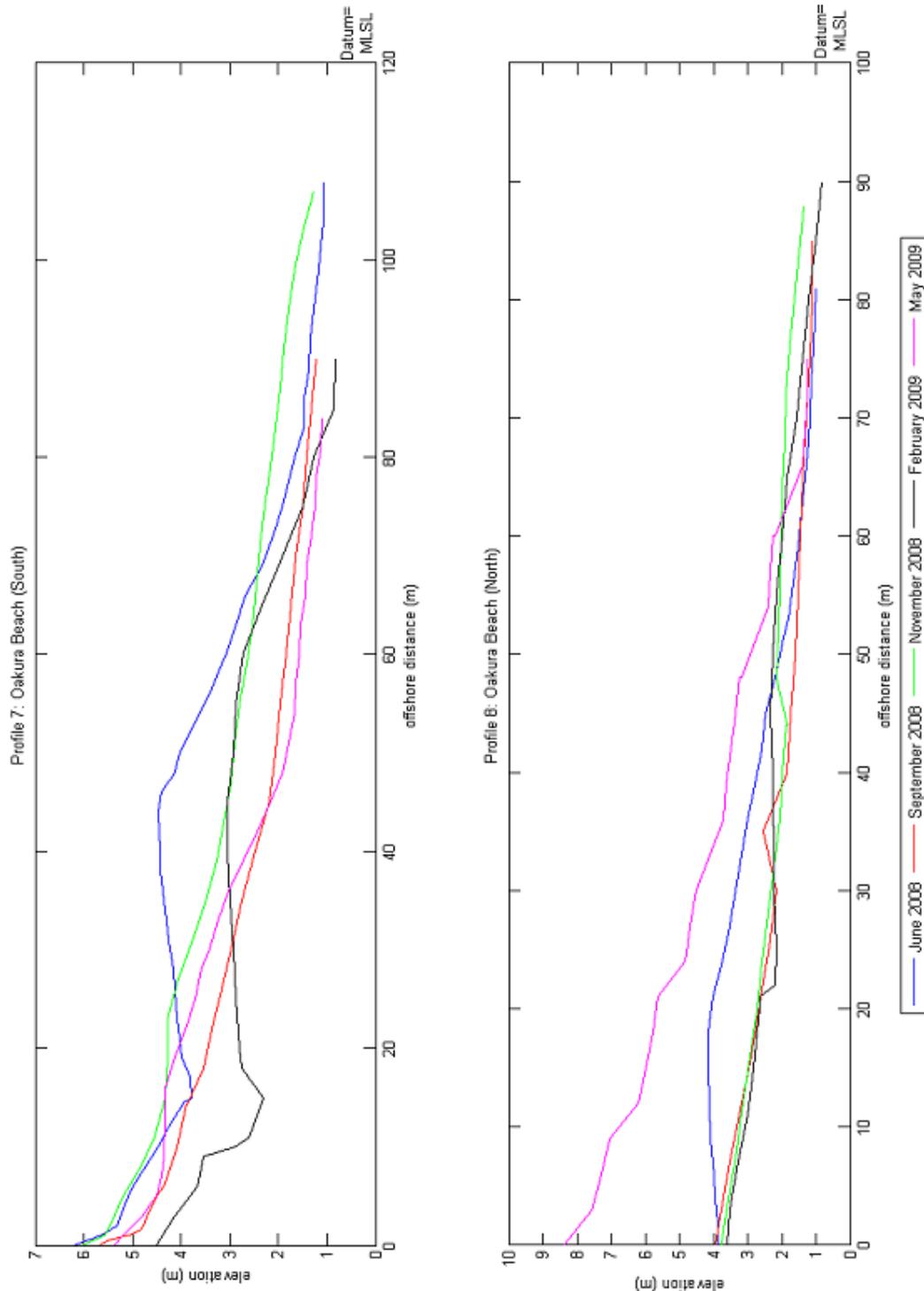


Figure 3.23 Onshore sub-aerial beach profiles surveyed at Oakura Beach (South) (Profile 7) and Oakura Beach North (Profile 8).

Profile 9: Tapuae Beach

The morphologies of the profiles surveyed at Tapuae Beach measured in September 2008 and November 2008 and May 2009 were similar in the backshore until ~ 60 m from the marked onshore point where the profile measured in September 2008 was steeper (Figure 3.24). The profile surveyed in June 2008 had a reduced elevation ~ 2 m lower compared to the other profiles surveyed while the profile surveyed in May 2009 was ~ 0.5 m greater than the other profiles. The accretion and erosion of this beach is different to what would be expected from the wind climate (Table 3.2). The likely reason for this is the close proximity this beach is to the Tapuae Stream which is located ~ 200 m to the south of where this profile was surveyed. A small headland has built up at the Tapuae Stream mouth (Figure 3.12), which provides protection from the south-westerly wind climate.

Profile 10: Southern Back Beach

All the profiles surveyed during the course of this study, at the southern location of Back Beach, apart from June 2008, had similar morphologies (Figure 3.24). There is little difference between the profiles undertaken in February 2009 and November 2008. The profile surveyed in November 2008 had ~ 1.5 m greater elevation compared with the other profiles. Prior to the November 2008 surveying, from the 8th to 20th of November, this coast was exposed to winds with an average angle of 178° (Table 3.2). However, six days prior to surveying, the average wind direction was 265°. It is likely that this change in wind direction immediately prior to surveying is responsible for this ~ 1.5 m increase in elevation. The profile measured in May 2009 was ~ 1 m lower than the other profiles however had similar morphologies to the profiles surveyed in September 2008 and February 2009. This reduction of sediment in May 2009 is likely to be a result of the increased wind speeds this coast was exposed to prior to the surveying (Table 3.2).

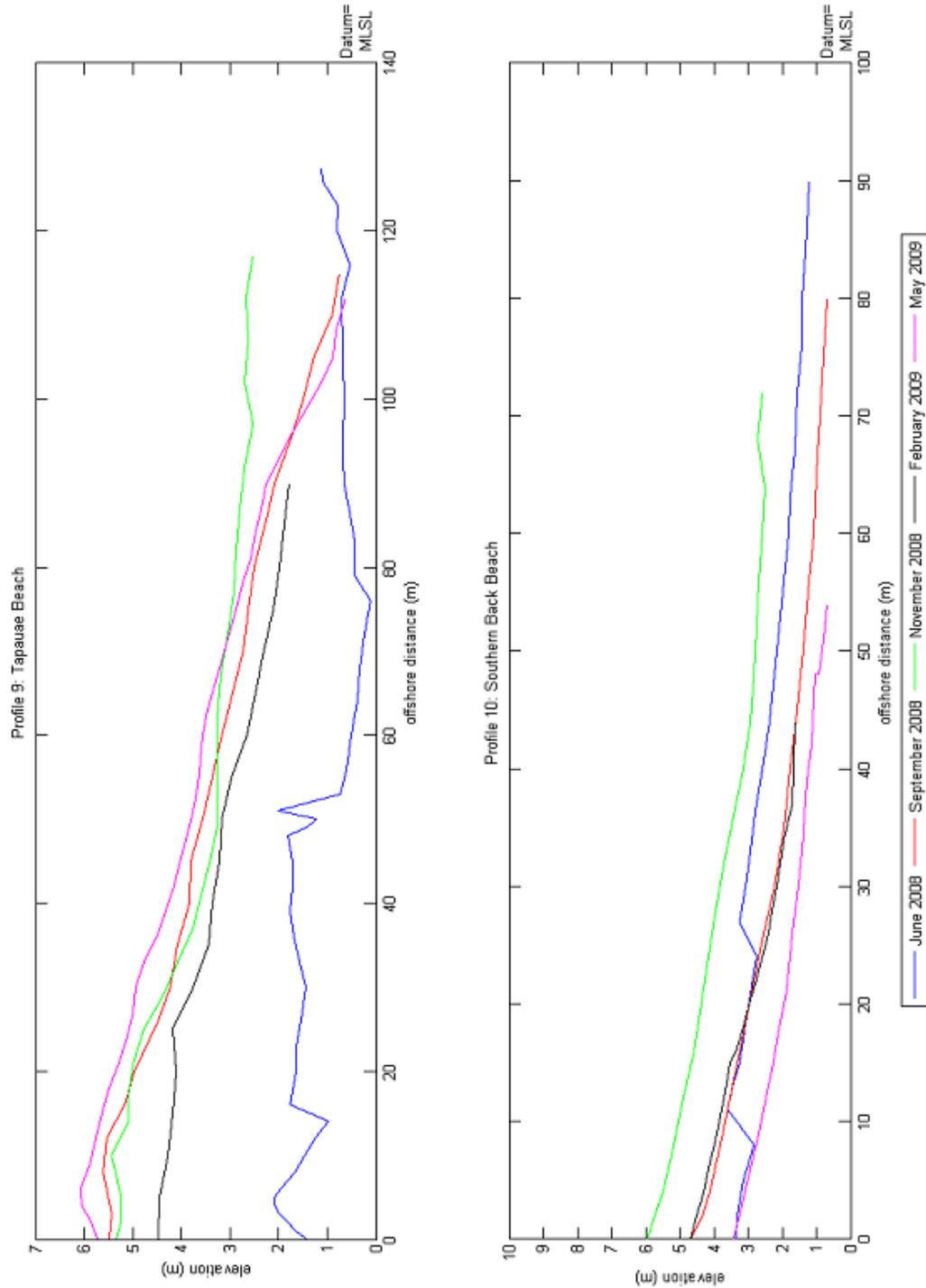


Figure 3.24 Onshore sub-aerial beach profiles surveyed at Tapuae Beach (Profile 9) and Southern Back Beach (Profile 10).

Profile 11: Central Back Beach

The profiles surveyed in June 2008, September 2008 and February 2009 all display similar shapes with a distinct berm ~ 25 m from the landward start of the profile (Figure 3.25). This berm is not obvious in the profile measured in

February 2009. In November 2008, the profile displayed similar characteristics to the other profiles surveyed, however, at ~ 30 m from the landward mark, there is a sharp rise in the gradient indicative of a berm, which increases the elevation of the remainder of the beach by at least 1.5 m over the other beach profiles.

Profile 12: Northern Back Beach

The profiles undertaken in September 2008 and November 2008 display similar shapes with the profile undertaken in November 2008 profile having ~ 1 m greater elevation than the profile measured in September 2008 (Figure 3.25). The slightly greater average wind speed in prior to the surveying in November 2008 compared with the wind speed in September 2008 may be responsible for this. A distinct berm was surveyed in June 2008 ~ 30 m from the landward mark. There is a very distinct beach face high in the profile which is obvious in the profiles measured in June 2008 and February 2009.

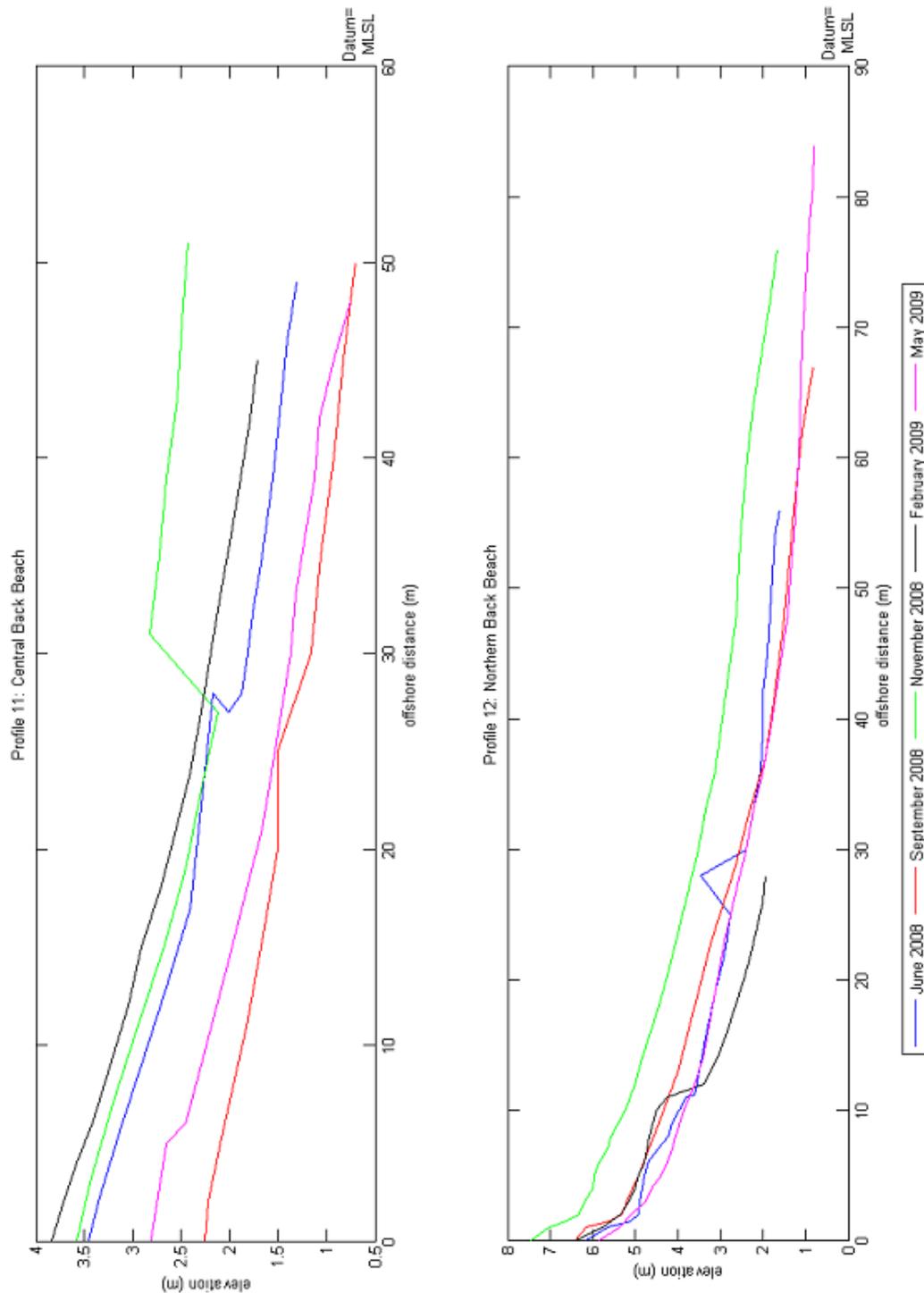


Figure 3.25 Onshore sub-aerial beach profiles on Central Back Beach (Profile 11) and Northern Back Beach (Profile 12).

Despite the locations along the coast having localised factors that influence the profile geomorphologies (e.g. headlands and streams) it can be concluded that the sub-aerial beach profiles surveyed (Figures 3.17 to 3.25) indicate:

- an increase in sediment in November 2008 due to SE directed winds immediately before the profile surveying;
- a decrease in sediment on the sub-aerial beach in February 2009 due to decreased wind speeds; and
- a decrease in sediment in May 2009 north of Oakura Beach.

3.3.2.2 Comparison with Historical Beach Profile Data

Matthews (1977) undertook beach profiles at Oakura Beach in 1976 and 1977 at five locations from western, central, and eastern Oakura Beach. The methodology to determine the beach profiles was similar to that used in this present study, using hand-held rods. The profiles obtained in 1976, illustrated in Figure 3.26, have an extremely steep frontal dune with two distinct berms. When compared with the 2008/2009 beach profile data, Matthews' profiles have significantly greater volumes of sediment (at least $136 \text{ m}^3 \text{ m}^{-1}$ (Table 3.3)). This reduction in volume is in agreement with the report of McComb et al. (2005), which stated that Oakura Beach's foreshore eroded between 1950 and 1981 by ~ 10 m, followed by accretion between 1981 and 1986. Since 1986, Oakura Beach has remained relatively stable.

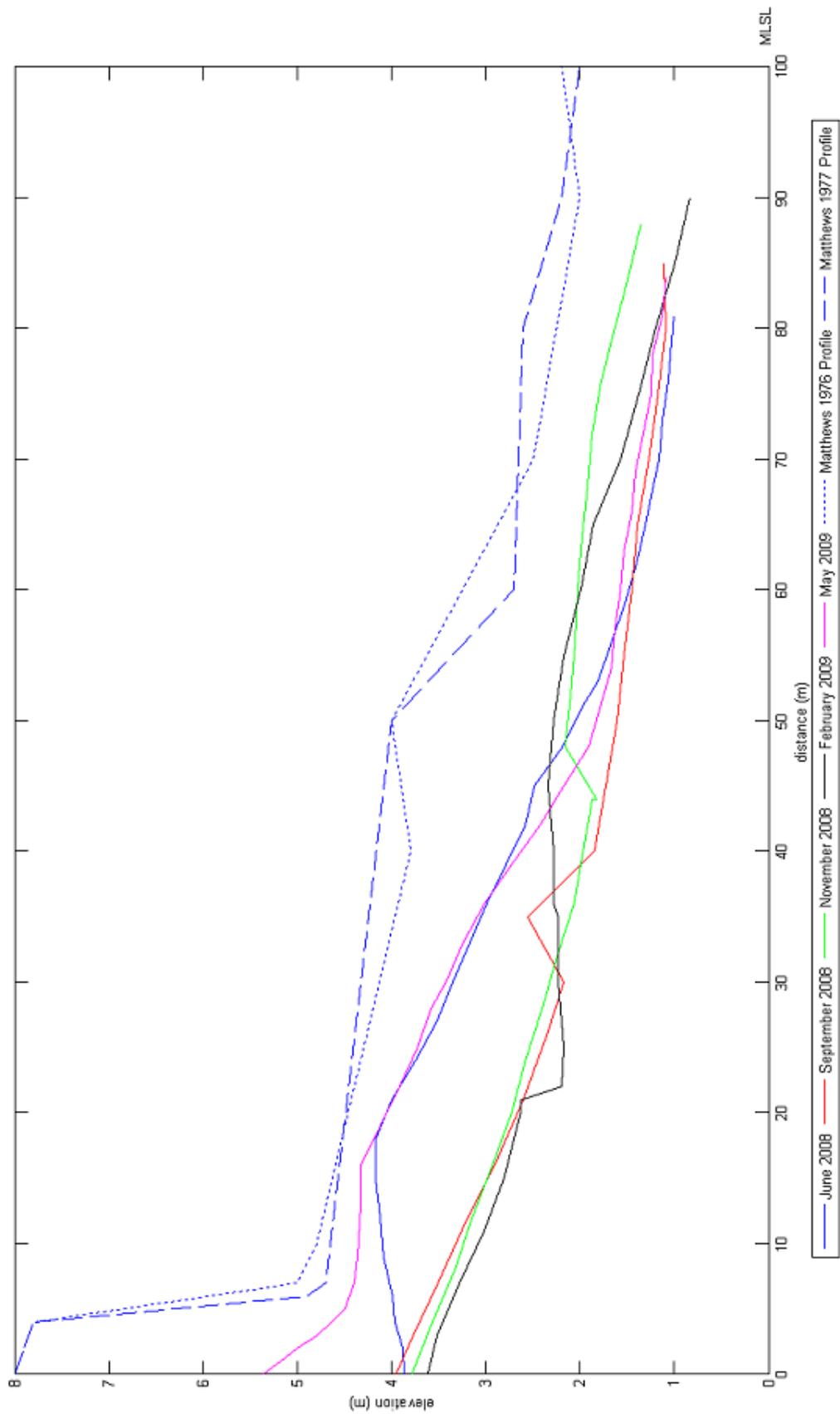


Figure 3.26 Onshore beach profiles of Oakura Beach surveyed during 2008/2009 along with Matthew's profiles surveyed in 1976/1977.
(Adapted from Matthews, 1977)

Table 3.3 Volume of sub-aerial beach sediment calculated from beach profiles over 2008/2009 and 1976/1977 at Oakura Beach.

Profile	Volume (m ³)
June 2008	202
September 2008	163
November 2008	185
February 2009	163
May 2009	197
Matthews 1977	338
Matthews 1976	403

McComb et al. (2005) undertook eight beach profiles on the intertidal sector of the beach at Oakura in front of the holiday park on the 10th of February 2005 at low tide. The total area surveyed covered the 130 m intertidal beach with an alongshore extent of 475 m (Figure 3.27).

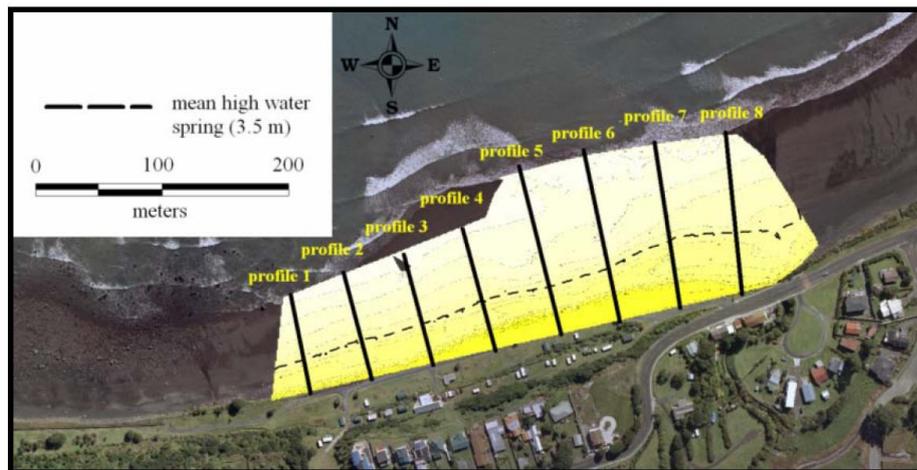


Figure 3.27 Location of beach profiles 1-8 in the McComb et al.(2005) report on Oakura Beach.

(Source: McComb et al., 2005).

These beach profiles were undertaken using Laser scanning using the following:

- Leica HDS 3000 3D Laser Scanner
- Compaq Portable PC Pentium 4
- Cyclone topographic

While these beach profiles were undertaken at the southern end of Oakura Beach and using a different method, it can be concluded that the beach elevation was much higher in 2005, compared with the recent 2008/2009 beach profile data.

The McComb et al. (2005) beach profile data illustrates dunes ~ 7.5 m high in comparison to the dunes ~ 4 m with height, which were measured in 2008/2009 (Figure 3.28). The sub-aerial beach profile area in 2005 is between 47 m³m⁻¹ and 212 m³m⁻¹ greater in comparison with the volumes measured in 2008/2009 (Table 3.4). A retaining wall is present at Oakura Beach. The surveys conducted in 2008/2009 started at the base of the vegetation on the retaining wall. Differing vegetation growth between 2008/2009 and 2005 may result in the 2005 profiled dunes to be significantly greater in elevation. The dominant berm present ~ 40 m from the landward start of the 2005 beach profiles is significantly higher than the berms measured in 2008/2009 which are ~ 1 m elevated in comparison to the rest of the profiles.

Table 3.4 Volume of sub-aerial beach sediment calculated from beach profiles over 2008/2009 and 1976/1977 at Oakura Beach.

Profile	Volume (m³m⁻¹)
June 2008	202
September 2008	163
November 2008	185
February 2009	163
May 2009	197
Mc Comb et al. (2005) Profile 1	210
Mc Comb et al. (2005) Profile 2	232
Mc Comb et al. (2005) Profile 3	252
Mc Comb et al. (2005) Profile 4	317
Mc Comb et al. (2005) Profile 5	354
Mc Comb et al. (2005) Profile 6	365
Mc Comb et al. (2005) Profile 7	375
Mc Comb et al. (2005) Profile 8	337

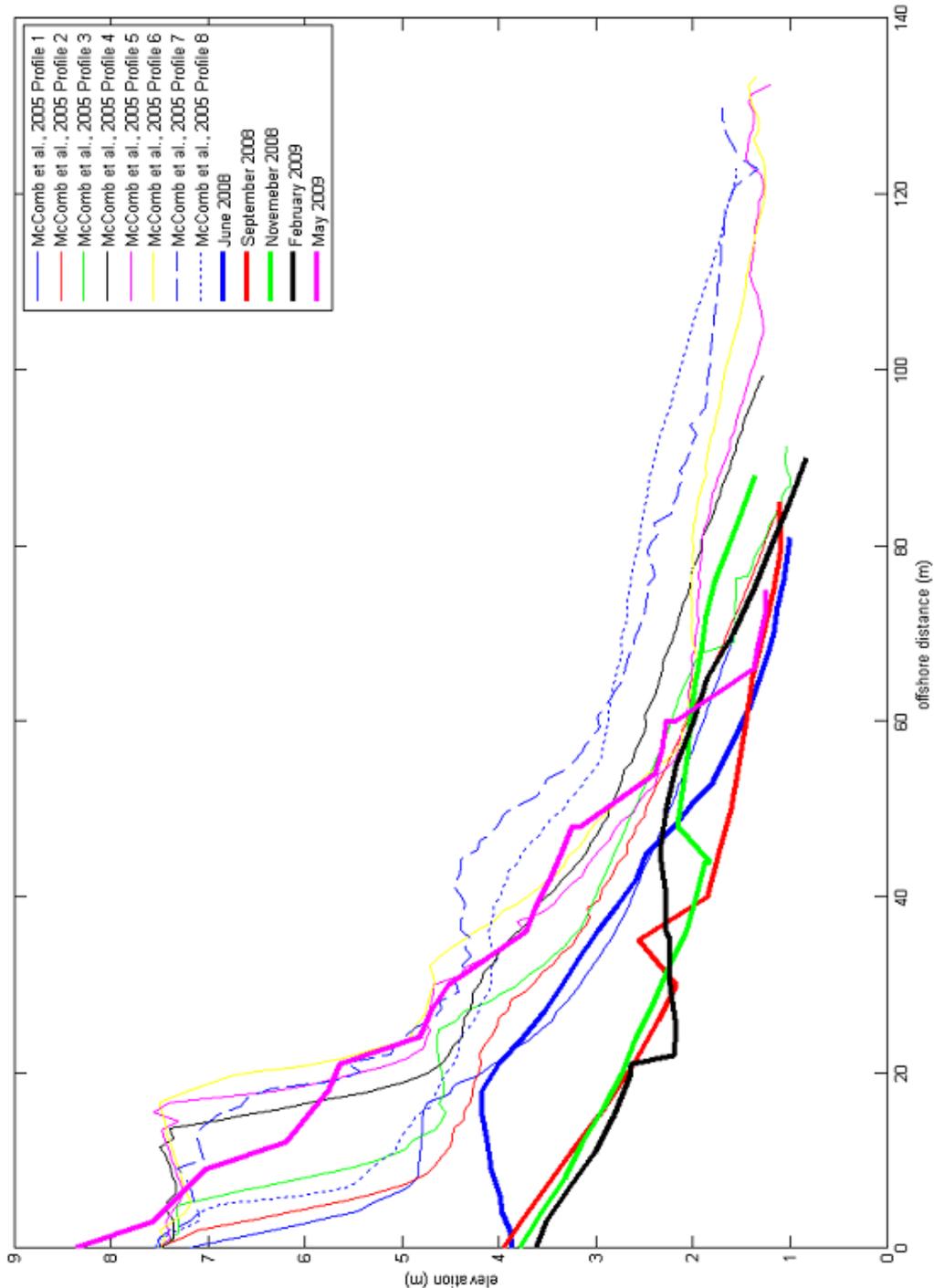


Figure 3.28 Beach profiles 1-8 surveyed and published in the McComb et al. (2005) report on Oakura Beach.
(Source: McComb et al., 2005).

3.3.3 Beach Volume Estimates

Using beach profile data and aerial photographs the total volume of sediment along the coastal sector between the Stony River and Ahuahu Beach was calculated to be approximately 3,472,000 m³ (Table 3.5 and Figure 3.29).

Table 3.5 Volume of sediment (from the Stony River) calculated from aerial photographs dated 2007 and beach profiles undertaken in 2008/2009.

<i>Volume of sediment in sub-aerial beach profile (above MLSL)</i>							
	<i>Sediment Volume along each profile transect (m³ m⁻¹)</i>						<i>Total Volume (m³)</i>
Location	<i>June 2008</i>	<i>September 2008</i>	<i>November 2008</i>	<i>February 2009</i>	<i>May 2009</i>	Average Sediment Volume	
Ahuahu Beach	360	246	292	227	174	259.8	273,000
Fort St. George	96	194	232	128	82	146.4	436,000
North of Kaihihi River	110	75	276	64	-	131	786,000
Kaihihi Surf Beach (Northern Profile)	429	627	674	469	24	444.6	1,060,000
Kaihihi Surf Beach (Southern Profile)	68	258	319	149	447	254.2	390,000
Komene Road	496	163	291	380	-	332.5	527,000
Total Volume of Sediment							3,472,000

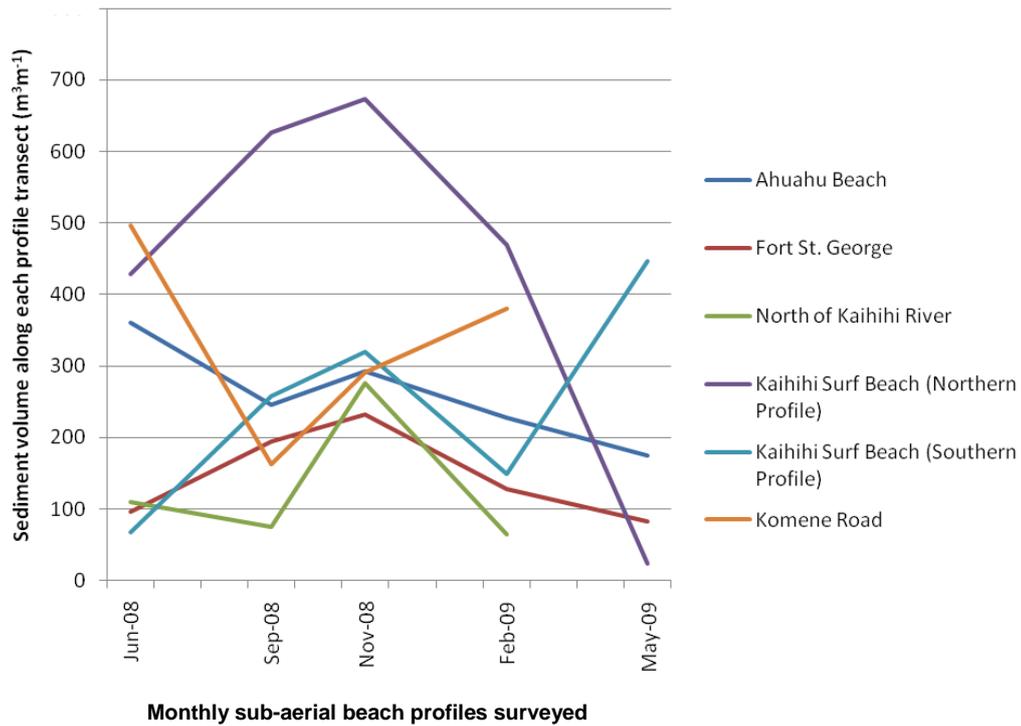


Figure 3.29 Volume of sediment calculated for beach profiles undertaken in 2008/2009.

Ahuahu Beach (Figure 3.30), the most northern site where the outbreak is thought to have reached, has a relatively large volume of sediment compared to the nearby beaches at Fort St. George, the beach north of Kaihihi River, and Oakura Beach. This greater sediment volume at Ahuahu Beach may be attributed to the small headland as shown in Figure 3.30 which intercepts the sediment travelling in the net northward directed littoral transport resulting in the deposition and formation of Ahuahu Beach.

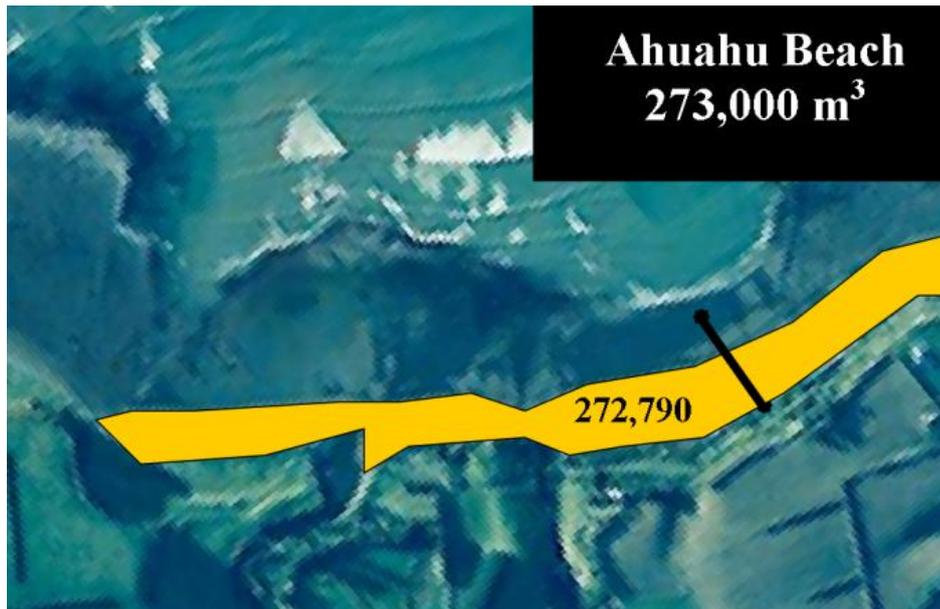


Figure 3.30 Sediment coverage at Ahuahu Beach. The black line shows the location of where the profile was surveyed.

To the south of Ahuahu Beach, just north of the Timaru Stream, is Fort St. George (Figure 3.31). The profiles surveyed over the course of this study have been used to estimate $\sim 436,000 \text{ m}^3$ of sediment is situated along this coastal sector.

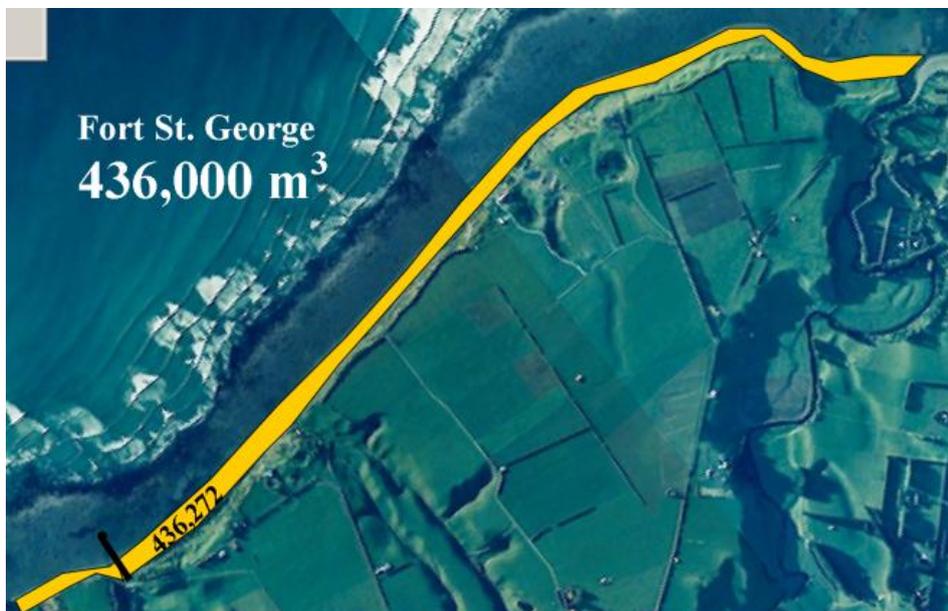


Figure 3.31 Sediment coverage at Fort St. George. The black line shows the location of where the profile was surveyed.

To the north of Kaihihi River the wave-cut shore platform is exposed from approximately the mid-tide level. The profiles surveyed along this narrow stretch of coast contain the smallest volume of sediment ($\sim 131 \text{ m}^3 \text{ m}^{-1}$) in comparison

with other sections along this coast. The total volume along this 4.78 km stretch of coast, situated on the sub-aerial beach is $\sim 785,000 \text{ m}^3$ (Table 3.3 and Figure 3.32).



Figure 3.32 Sediment coverage north of the Kaihihi River. The black line shows the location of where the profile was surveyed.

Immediately north of the Stony River, Kaihihi Surf Beach, is the largest reservoir of sediment along this stretch of coast studied (Figure 3.33). Over each tidal cycle substantial volumes of sediment are transported exposing the wave-cut shore platform. This fluctuating sediment volume is shown in the sediment volumes obtained from beach profiling (Table 3.3). Between the Stony River mouth it is estimated that $\sim 1,450,000 \text{ m}^3$ of sediment is deposited along the Kaihihi Surf Beach, most likely to be the largest depository of sediment along the Taranaki Coast.

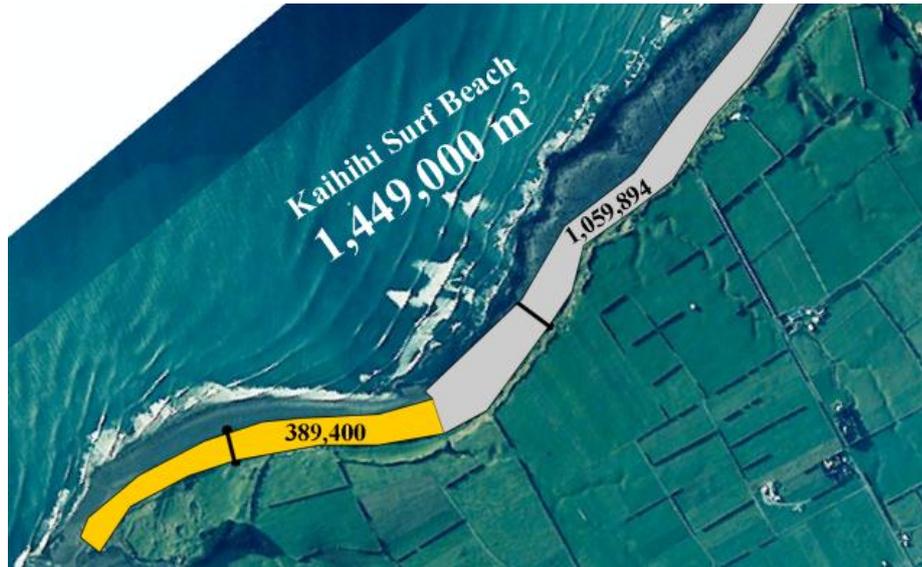


Figure 3.33 Sediment coverage along Kaihihi Surf Beach to the north of the Stony River. The black lines show the location of where the profile was surveyed.

Immediately south of the Stony River at Komene Road, surveyed sub-aerial beach profiles indicate that at least 403,000 m³ of sediment is deposited along this beach. The profiles undertaken during this study have been extrapolated in the lower and upper shore (left and right polygons shown on Figure 3.34) to determine the total volume of sediment along this coastal section (527,000 m³). The presence of sediment deposited south of the Stony River mouth, is due to sediment diffusing from the river mouth and southwards directed littoral transport.

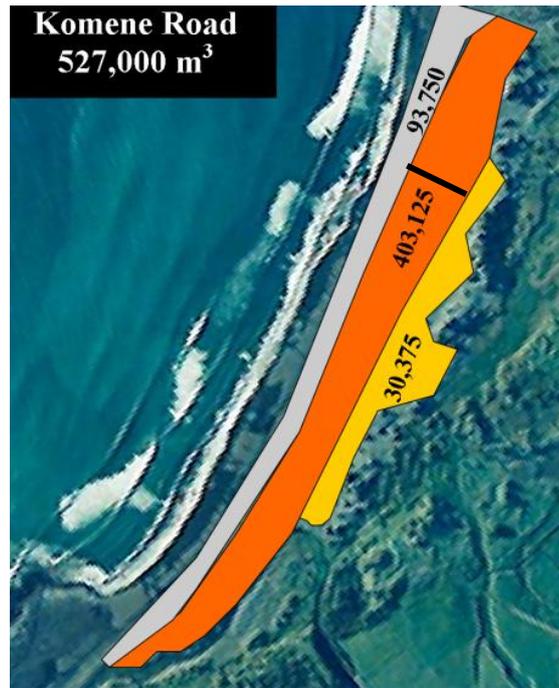


Figure 3.34 Sediment coverage along Komene Road, south of the Stony River. The black line shows the location of where the profile was surveyed.

3.5 SUMMARY

Analysis of coastline changes, through the comparison of aerial photos, beach profiles, and estimating beach volumes, along the coastal sector between Komene Road and Back Beach are indicative of a highly dynamic coastal system.

Aerial photos dated 1995, 2001 and 2007, both prior to and after the 1998 Stony River outbreak, were used to determine the area of visual sand on the backshore. The coastal sector which was thought to have been inundated with sediment derived from the Stony River was divided into four areas namely Komene Road, Kaihihi Surf Beach, Fort St. George, and Ahuahu Beach. These photos illustrate a marked increase in sand in 2001 which has diminished rapidly by 2007. Ahuahu Beach, the most northern coastal sector analysed, did not have a significant increase in sand until 2007, suggesting that alongshore transport is moving the sand outbreak to the NE.

Sub-aerial beach profiles were undertaken in June 2008, September 2008, November 2008, February 2009 and May 2009 at twelve sites along the coastal sector between Komene Road, just south of the Stony River and Back Beach in New Plymouth. These profiles along with visual observations are indicative of an

extremely dynamic coastline. Beaches including and south of Ahuahu Beach are characterised by dunes which reach greater elevations than those further north up the coast north of Ahuahu Beach. In many instances, these dunes reach elevations close to 10 m, however south of Ahuahu Beach these elevations decrease to closer to ~ 5 m elevation. This evidence along with visual observations indicate that the sediment derived from the 1998 Stony River outbreak sits on the upper portion of the beach forming berms and high dunes in the backshore segment of the shoreline. This beach sediment is transported only during storms and at high tides where there is sufficient energy to remove this dense sediment.

Beach profile data obtained in 2008/2009 was compared to data by Matthews (1977) and McComb et al. (2005). The data obtained by Matthews (1977) and McComb et al. (2005) show profiles with greater volumes of sand with average volumes of $371 \text{ m}^3\text{m}^{-1}$ and $305 \text{ m}^3\text{m}^{-1}$ respectively. Oakura beach has reportedly undergone significant erosion since 1976. However, there is no evidence in surrounding beach infrastructure that 3 - 4 m of erosion has occurred since 2005. McComb et al. (2005) used a different method as well as different start points. These variations may be responsible for the above noted survey discrepancy.

Combining the beach profile data and aerial photographs it was determined that $3,472,000 \text{ m}^3$ of sediment is present in the sub-aerial beach between Komene Road and Ahuahu Beach. Significant quantities of sediment derived from the scarp up Mount Taranaki may have been transported further north of Ahuahu Beach in the north-east directed littoral transport. Significant volumes of sediment may also be present offshore (see Section 4.4.3 in Chapter Four) and along the Stony River channel (see Chapter Five: Longshore Sediment Transport).

CHAPTER FOUR: SEDIMENT CHARACTERISTICS

4.0 INTRODUCTION

Size distribution of a sediment sample can reflect the source rock as well as the resistance the sediment has to weathering, erosion, transport and deposition processes (de Lange et al., 1997). The three dominant factors that are responsible for the mean grain size are the sediment source and the wave energy level (Komar, 1998).

The mineralogical composition of sedimentary deposits is a reflection of:

- a) the character of the sources rocks from which the detrital grains are derived from;
- b) the diagenetic influences that have affected the sedimentary rock; and
- c) sorting and transport in the environment of deposition (Laurent, 2000).

The black sands on the west coast of the North Island have a high iron sand content which is principally magnetite (Fe_3O_4), titanomagnetite (Fe_2TiO_3), and ilmenite (FeTiO_3). Most of these iron-rich minerals are derived from the Mount Taranaki andesitic rocks also containing hornblende, augite, and plagioclase feldspar (Gow, 1967). As this sand is transported and abraded, it becomes smaller and less angular. Different minerals possess different hardness, density and crystal form characteristics and, therefore, abrade at different rates. These characteristics influence how the sediment is entrained dispersed and thus how it is transported along the coast (Swales et al., 2003).

Since the 1998 influx of sand to the coast via the Stony River, there have been obvious changes to the aerial beach along the Taranaki coast. This chapter will describe textural and mineralogical characteristics of the sediments found at 12 sites along the coastal sector between Komene Road, just south of the Stony River mouth, to Back Beach in New Plymouth.

The textural analysis data of sediment collected in 2008 was presented at the International Coastal Symposium 2009 conference in Lisbon, Portugal and a proceedings paper (Appendix A) was published as:

Cowie, N.A., Healy, T. R., and McComb, P. J., 2009. Sediment Flux on the High Energy Taranaki Coast, New Zealand. *Journal of Coastal Research*, SI 56 (Proceedings of the 10th International Coastal Symposium), Lisbon, Portugal, pp.703-707.

4.1 PREVIOUS ANALYSIS OF SEDIMENTS

The following studies have undertaken sediment analysis on samples collected from locations along the Taranaki coast.

- Gow (1967) studied the mineralogy of beach sands at Hawera in south Taranaki. Methodology included using standard sieves attached to a Rotap vibrator to determine textural characteristics, while microscopic analysis on sand samples mounted on Canada balsam enabled mineral counts to be undertaken. He found that the heavy minerals are concentrated on the upper beach by swash processes, however there are no real diagnostic differences in the sorting, size, and mineralogy between the beach and dune sands. It was determined that most sands along the Hawera coast are fine grained and well sorted. On the beach, the sand is sorted in the direction of the wave energy transmission which affects the size, shape and the mineralogy of the sediments. His study identified different compositions of sands at different parts of the beach with the dominant minerals at the top to the bottom of the beach being titanomagnetite, augite, hornblende, and light minerals. The minerals in Hawera are derived from the erosion of the Rapanui Formation exposed in sea-cliffs, as well as from streams that drain the slopes of Mount Taranaki.
- Matthews (1977) undertook textural and mineralogical analysis on sediment from six beaches in the Taranaki Region. These included Oakura Beach and Werekino near the entrance of the Stony River. The methodology of this study included grain counts, using gravity to separate the heavy and light fractions, and the removal of carbonate. This study

identified that the most abundant constituent of the sand-sized sediment is fragmented andesite, followed in order by plagioclase feldspar, augite, titanomagnetite, and hornblende (which is found in high concentrations at Oakura). These heavy minerals were concentrated on the upper beach, especially during the stormy winter months when the beach is typically in an erosive state. His research identified that the sediment exhibit polymodal grain sizes, controlled by the heavy mineral content. However, at the lower beach sections, gravel and pebbles dominate, resulting in a coarsening of the mean grain size. Sorting and mean grain sizes were inversely proportional, and the beach gradient is influenced by mean grain size with the beach face slope increasing with grain size. Typically greater grain sizes are more permeable, thus the swash carried onto the upper beach as waves break is absorbed and swash-piled sediments are deposited at relatively steep gradients. Other important factors influencing the beach gradient include wave exposure, the position of the water table, sorting, and the heavy mineral content.

- Gibb (1977 & 1979) investigated longshore drift around New Zealand (including this research area) obtaining evidence from direct measurements, and sedimentary evidence including gravel tracers, heavy mineral tracers, changing mineral concentrations, textural differences of beach sediment, and geomorphic evidence. These studies found that from Paraparaumu to Cape Egmont heavy minerals increased in abundance from ~ 20% to ~ 90%, and from Cape Egmont northwards there is a decrease in heavy mineral abundance from ~ 90% to ~ 7% at Cape Reinga. This was identified using the tracer lamprobolite (basaltic hornblende). Distinctive pebble tracers were identified 55 km north of Cape Egmont at the Awakino River. This research indicated that the Egmont Volcanic Region is the major heavy mineral source of the west coast of the North Island.
- The Taranaki Catchment Commission (1978) undertook a study of the coastal processes in the Cape Egmont to New Plymouth littoral cell which included sand budgets, wave and wind climates, along with an investigation of erosion rates and trends at Oakura Beach. Grain size

analysis was conducted at the Stony River, Oakura, Ahuahu Road, Lower Pitone Road, and the Oakura River Mouth. This investigation did not produce any conclusive evidence for trends in direction of net sand movement. However, it was found that grain size does relate to beach slope.

- Laurent (2000) determined the dispersal and origin of beach sediments along the west coast of the North Island from the Waitotara River in South Taranaki to the North Cape in Northland. Sediments were analysed using petrographic methods which included studies on the mineralogy, point counting, and X-Ray Diffraction analysis. Results obtained by Laurent (2000) identified that pebble to sand-sized rock fragments dominated beaches nearest the Taranaki Volcanic Complex and these sediments decreased in size to the north and south, with increased proportions of individual crystals and a decrease in rock fragments.
- Swales et al. (2003) analysed sediment from Mount Taranaki to Cape Reinga, using a stream-scanning time-of-transition laser sizer and image-analysis system to determine longshore changes in particle size and shape. This research concluded that most changes to the easily abraded titanomagnetite sediments occur within 20 km of the source while the abrasion of the hard plagioclase sediments occurs much more slowly, over hundreds of kilometres. Hornblende was found to be relatively resistant to erosion processes as it was transported along the shore. His results also illustrated that the longshore dispersal rate of titanomagnetite is lower than other minerals commonly found in black sand due to its high sphericity, high specific density and magnetism which results in the sediments aggregating and lagging behind forming placer deposits. These placer deposits are evident at many locations along the Taranaki Coast.

Since the 1998 collapse of the gully in the headwaters of the Stony River there has been no research investigating the impact of this influx of sediment on the sediment characteristics of the Taranaki coast.

4.2 METHODS

4.2.1 Sediment Sample Collection

In order to determine the longshore trends in sediment characteristics along the coast adjacent and down-drift from the Stony River mouth (Figure 4.1), samples were collected at three monthly intervals from the same position at each locality. The beach samples were collected on five separate occasions, as close to low tide as possible, in June 2008, September 2008, November 2008, February 2009 and May 2009.

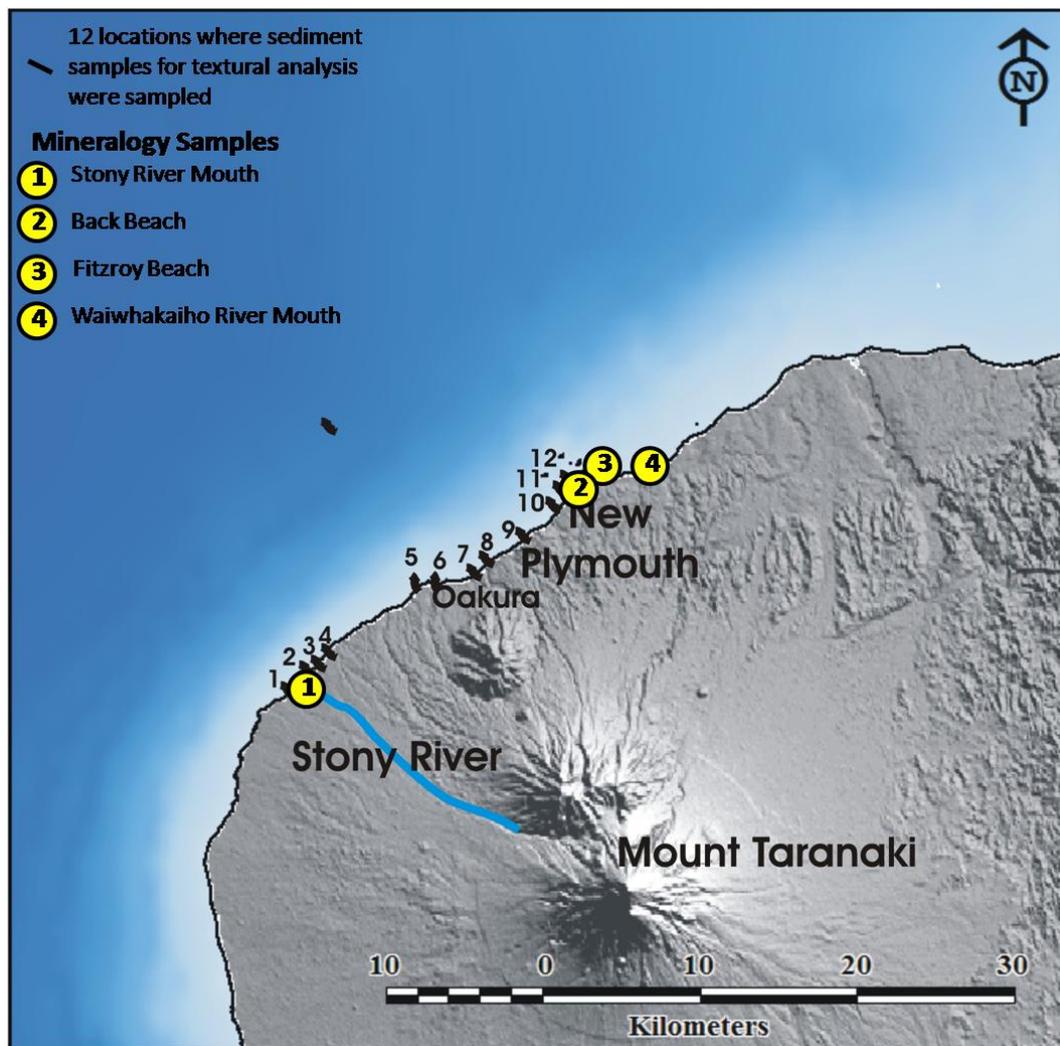


Figure 4.1 Locations where sediment samples were taken along the Taranaki coast at low, mid, and high tide levels during 2008/2009 and where the samples were collected for mineralogical analysis (see section 4.2.3).

In the field, samples were collected from the top 15 cm of sand at the low, mid, and high tide levels at each of the 12 sites. In the laboratory, samples were initially wet sieved, firstly on a -2.00 phi (4 mm) sieve to remove the coarse fraction. The samples were then sieved through the 4.00 phi (0.063 mm) sieve removing any silt, clays or precipitated salts (de Lange et al., 1997) leaving behind the medium fraction. Of all the samples collected there was no sediment less than 4.00 phi (0.063 mm). The samples were then dried for 48 hours at 50 °C and analysed using the Rapid Sediment Analyser (RSA) at the University of Waikato. This methodology is illustrated in Figure 4.2.

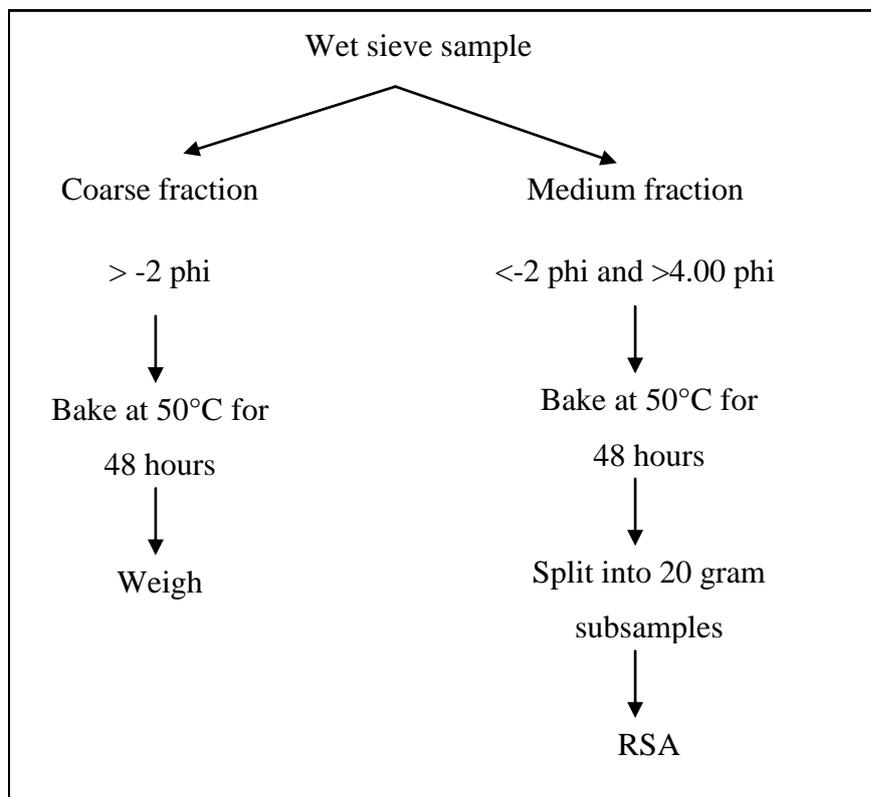


Figure 4.2 Methodology for preparing samples for sediment analysis.

4.2.2 Grain Size Analysis

4.2.2.1 Rapid Sediment Analyser (RSA)

The RSA system at The University of Waikato processes sand sized sediments and measures grain size distributions of sediments between -2.00 phi (4 mm) and 4.00 phi (0.063 mm) equivalent quartz sphere diameters. RSA analysis was undertaken on each sediment sample twice and the values were averaged.

The RSA consists of a 2 m long settling tube (composed of two tubes, the outer tube providing a thermal jacket to minimise temperature fluctuations and for additional strength) (Figure 4.3). The sample (approximately 20 grams) is released into the tube, and the mass arriving on the pan is linked to an electronic balance detected by the computer.



Figure 4.3 The top of the RSA (Rapid Sediment Analyser) at the University of Waikato. (Source: Anais Wille).

The sediment grain size and settling velocity is calculated by using Stokes Law:

$$\omega = \frac{1}{18} \frac{(\rho_s - \rho_f) g D^2}{\mu}$$

Equation 4.1

where ω is settling velocity (ms^{-1}), ρ_s is the density of sediment (kgm^{-3}), ρ_f is the density of the fluid inside the RSA (kgm^{-3}), g is the gravitational acceleration ($9.81 \text{ m}^{-1}\text{s}^{-2}$), D is the sediment diameter (mm) and μ is the viscosity of the fluid (m^2s^{-1}). The density of the sediment used was 2850 kgm^{-3} as used in the research of McComb (2001).

Grain size is then automatically calculated from the settling velocity using the following equation:

$$r = \frac{0.055804V^2\rho + \sqrt{0.003114V^2\rho + [g(\rho_s - \rho)](4.5\eta V + 0.008705V^2\rho)}}{[g(\rho_s - \rho)]}$$

Equation 4.2

where V is the velocity (cms^{-1}), g is the gravitational acceleration, η is the dynamic viscosity (poise), ρ is the density of the fluid (gcm^{-3}), ρ_s is the density of a sphere (gcm^{-3}) and r is the sphere radius (cm).

The presence of rock and shell fragments in some samples may be a potential source of experimental error altering the density, thus the hydraulic grain size of the beach sediments. As the samples all contained different proportions of titanomagnetite the proportions were taken into account when analysing the data. A magnet was used to separate titanomagnetite particles from the samples. By weighing the samples before and after separation, the proportion of titanomagnetite present was determined.

The advantage of using the RSA rather than standard mechanical sieve techniques is that data is based on the hydraulic equivalent behaviour of sediments, which is useful in determining the direction of littoral drift. Output results from the RSA are normal and frequency curves of particle size results and are given in both graphical and moment method parameters. In this study, moment method parameters are used as they are believed to be more sensitive to environmental processes compared with graphical methods (Friedman and Saunders, 1978). The moment measures used to determine mean grain size, sorting and skewness are presented in Appendix B.

4.2.3 Mineralogical Analysis

Heavy minerals along a beach can be indicative of longshore sediment transport processes. Eroded regions are associated with fine-grained sands which are rich in heavy minerals, while zones of accretion are associated with coarser sized sediment poor in heavy minerals. This indicates that longshore transport processes preferentially remove the lighter, lower density minerals and they are deposited further alongshore in the direction of net littoral transport (Frihy and Lotfy, 1994).

The mineralogical composition of sediment is a function of the independent variables namely, provenance, transportation mechanisms, the depositional environment, and post-deposition effects. The provenance controls the initial mineral composition while the transportation and depositional environments further modify the sediment composition by winnowing out minerals as a result of variable specific gravities and their resistance to disintegration (Laurent, 2000).

Placer deposits are the resulting formation of a number of processes. These include beach erosion (Rao, 1957; Komar and Wang, 1984; Komar, 1989; Frihy and Komar, 1991; Frihy and Lotfy, 1994), storm events (Woolsey et al., 1975), rhythmic beach topography (Bogdanov et al., 1986), seasonally changing wave conditions (Peterson et al., 1986), rips currents (Marra, 1987), and longshore currents (Komar, 1989).

Mineralogical analysis was undertaken on sediment derived from four locations namely, the Stony River mouth, Back Beach, Fitzroy Beach and the Waiwhakaiho River mouth (Figure 4.1) in February 2009 at the high tide mark.

Firstly a grain mount was made on a slide, covered with four to five drops of Clove Oil and lastly a cover slip. The abundances of each mineral was determined using an Olympus petrographic microscope and a swift point counter. The minerals and rock proportions were identified using standard petrographic techniques on the first 200 grains encountered which was considered to be a sufficient number of grains to represent the sediment at that particular location (Briggs, R. 2009, pers. comm.).

4.3 RESULTS

4.3.1 Grain Size

4.3.1.1 Introduction

Mean grain size, sorting, skewness and kurtosis are output parameters from undertaking RSA on the sediment samples. Raw grain size data obtained from the RSA is provided in Appendix C.

4.3.1.2 Mean Grain Size (M_z)

Mean grain size is the most important parameter measured and is defined as the weight force that must be balanced by a stress for sediment transport to occur (Leeder, 1982). Grain size is measured using the Phi scale which is a logarithmic transformation of the Udden-Wentworth scale (Table 4.1). The mean size of a sediment sample is a function of the size range of the sediment supplied to a morphodynamic system and the energy that the deposit is subjected to. Providing the sediments on a beach are of similar density, then typically sediments become finer in the direction of transport as a result of selective sorting, with smaller particles winnowing out and being transported preferentially to the larger particles in the down current direction (Folk, 1968).

Illustrated in Figure 4.4 are the variations in the mean grain size of sediment collected at the 12 locations between Komene Road and Back Beach in New Plymouth at the low tide, mid tide and the high tide water marks.

The mean grain sizes collected over the sampling period (June 2008 to May 2009) ranged from 0.72 mm (collected at mid tide location at the Kumara Patch in November 2008) to 0.16 mm (collected at the mid tide location at Fort St. George in May 2009) (Figure 4.4). The alongshore variation in grain size at each cross-shore location where samples were collected (low tide, mid tide or high tide) illustrates a general trend of greater grain sizes near the mouth of the Stony River that decrease with distance north-east along the Taranaki coast towards Back Beach in New Plymouth (Figure 4.4). This is normally indicative of the direction of littoral drift (Komar, 1998).

Table 4.1 The Udden-Wentworth Scale.
(Folk, 1968).

Millimeters	μm	Phi (ϕ)	Wentworth size class	
4096		-20		
1024		-12	Boulder (-8 to -12 ϕ)	
256		-10		
64		-8	Pebble (-6 to -8 ϕ)	
16		-6		
4		-4	Pebble (-2 to -6 ϕ)	
3.36		-2		
2.83		-1.75		Gravel
2.38		-1.50	Gravel	
2.00	2000	-1.25		
1.68		-1.00		
1.41		-0.75		
1.19		-0.50	Very coarse sand	
1.00	1000	-0.25		
0.84		0.00		
0.71		0.25		
0.59		0.50	Coarse sand	
1/2	500	0.75		
0.42	420	1.00		Sand
0.35	350	1.25		
0.30	300	1.50	Medium sand	
1/4	250	1.75		
0.25	250	2.00		
0.210	210	2.25		
0.177	177	2.50	Fine sand	
0.149	149	2.75		
1/8	125	3.00		
0.125	125	3.25		
0.105	105	3.50	Very fine sand	
0.088	88	3.75		
0.074	74	4.00		
1/16	63	4.25		
0.0625	63	4.50	Coarse silt	
0.0530	53	4.75		
0.0440	44	5		
0.0370	37	6	Medium silt	
1/32	31	7	Fine silt	
0.0310	31	8	Very fine silt	
1/64	15.6	9		Mud
1/128	7.8	10		
0.0078	7.8	11		
1/256	3.9	12		
0.0039	3.9	13		
0.0020	2.0	14		
0.00098	0.98		Clay	
0.00049	0.49			
0.00024	0.24			
0.00012	0.12			
0.00006	0.06			

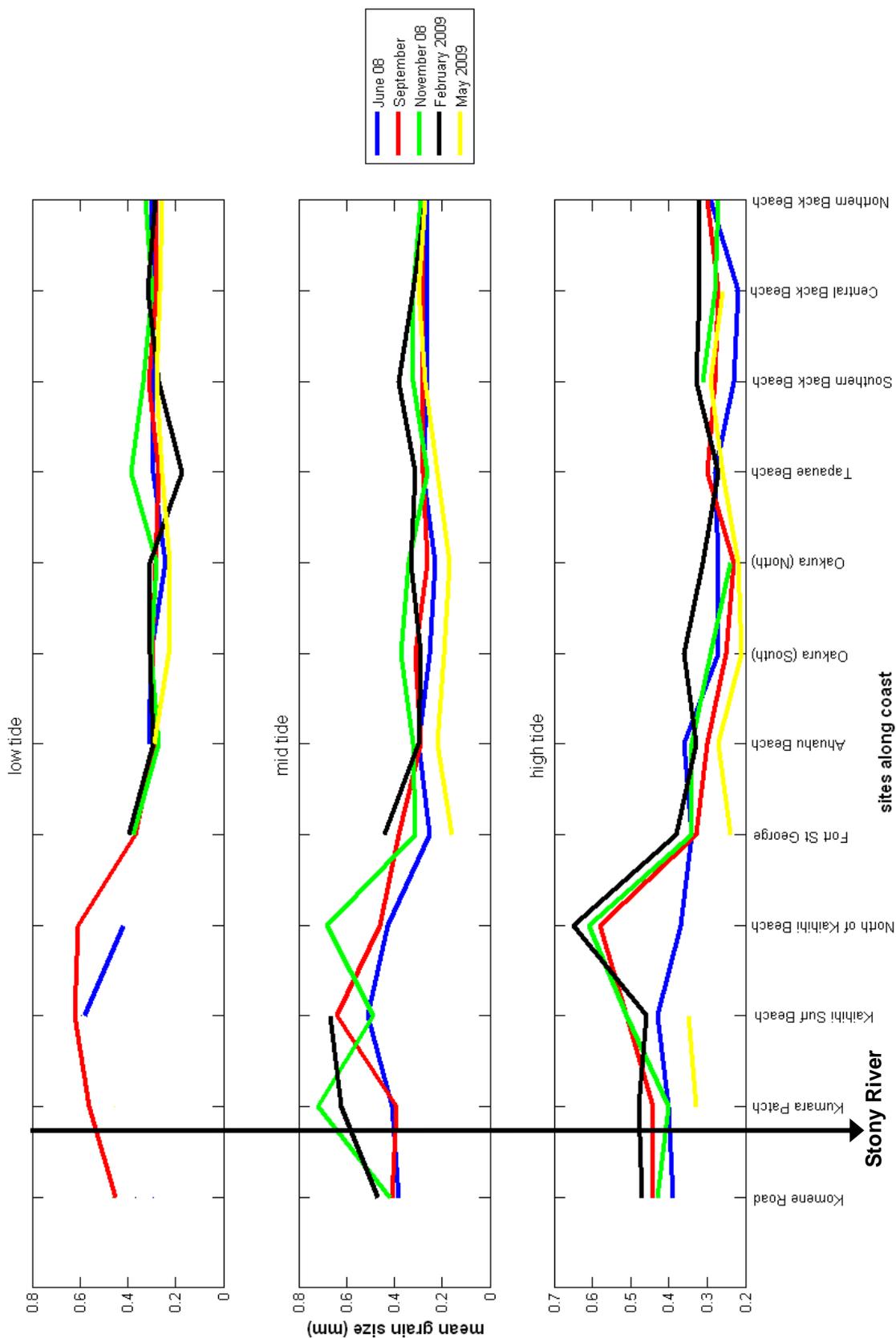


Figure 4.4 Alongshore variation in mean grain size for sub-aerial beach sediments at low, mid and high tide locations collected at 12 sampling sites along the Taranaki coast over 2008/2009 and analysed using the RSA.

As mentioned previously, the variable densities of different rock components greatly influence the fall velocity of sediment clasts, and thus the apparent mean grain size obtained from the RSA. Illustrated in Figure 4.5 is the proportion (by weight) of heavy minerals in the samples collected in June 2008 at the low, mid and high tide locations, tested using a magnet and averaged over 3 samples.

Figure 4.5 illustrates a reduction in heavy mineral content with distance between Komene Road and Back Beach. This reduction in titanomagnetite has a gradient of -0.8526% per km along this coastal segment samples were obtained from. Greater quantities of the denser heavy minerals near the mouth of the Stony River result in a larger fall velocity than samples composed of the less dense minerals of augite, hornblende or plagioclase feldspar. The grain size is therefore over-calculated especially near the mouth of the Stony River. Visually the sediment samples derived from near the Stony River mouth are significantly larger than those further up the coast and between the Kaihihi River (approximately 4 km north of Komene Road) and Northern Back Beach (~ 24 km north of Komene Road).

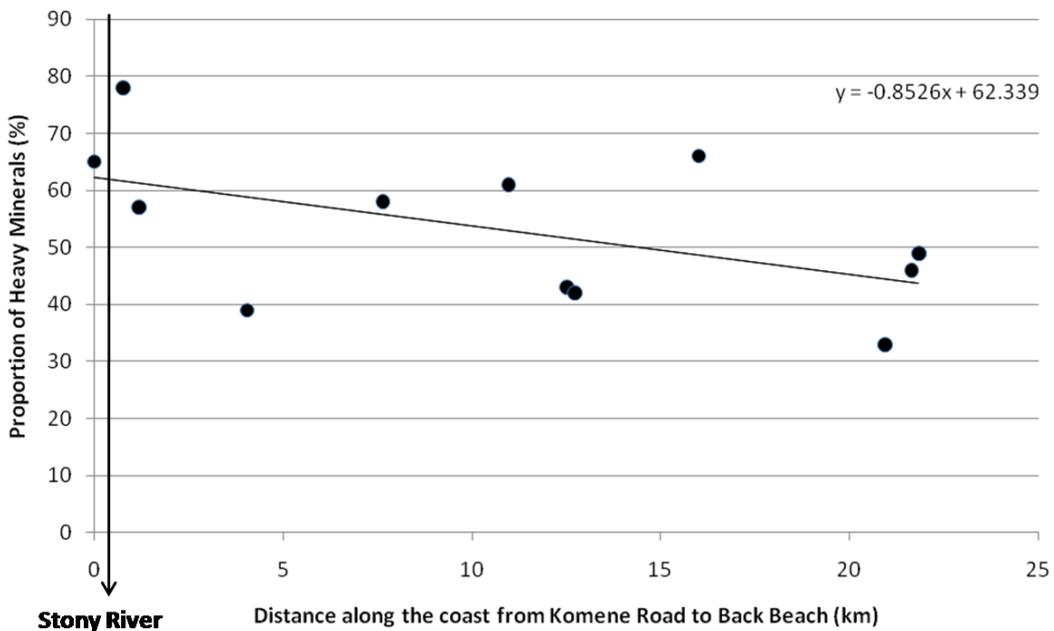


Figure 4.5 Alongshore variations in the proportion of heavy minerals along the sub-aerial beach from Komene Road to Back Beach.

4.3.1.3 Mode (M_d)

The mode, the measure of the most abundant grain size, allows more precision in determining the size distribution characteristics. The mode is strongly influenced by the source rock and is used to indicate provenance (Friedman and Saunders, 1978). This data (see Appendix C: Sediment Textural Results) indicated that the samples collected are uni-modal, where the majority of the sediment between Komene Road and Ahuahu Beach has been derived from Little Pyramid in the headwaters of the Stony River.

4.3.1.4 Sorting (σ)

The sorting parameter can be defined as the standard deviation of the grain size distribution. The sorting characteristics a sediment sample possesses is dependent on the size range of the material supplied to the environment, the type of deposition, time, and the current characteristics. Currents of constant strength (not really weak or really strong) have better sorting than currents with varying strengths while the best sorting is derived from currents with intermediate, constant strengths. Sorting is extremely dependent on grain size, where more sorted sediments are typically fine sands (2.00 to 3.00 phi) and less sorted sediment is typically coarser (0 to 1.00 phi). However, sorting is generally improved for gravels (-3.00 to 5.00 phi). Sand to coarse silt sized sediments from weathered granular rocks grain sizes correspond to the size of the crystal units in the original parent rocks (Folk, 1968). Beach sands derived from cliffs are generally more poorly sorted because supply is continuous. Dune sands have better sorting than beaches and nearshore sediment (Folk, 1968). Sediment transport typically improves sorting, making sorting an important factor in determining transport pathways (Komar, 1998). Komar (1998) states that there are at least four ways in which longshore sorting variations are produced:

1. by the parallel variation in wave energy;
2. by selective transport rates (fine grains are generally transported further than coarse grains);
3. by selective removal of the finer grains resulting in the coarse grains remaining and forming lag deposits; and

4. through wave energy variations (direction and energy level).

The classification of sediment sorting is shown in Table 4.2.

*Table 4.2 Classification for sediment sorting
(Source: Folk, 1968).*

Sorting (phi)		Sorting classification
phi	mm	
0.00-0.35	1-0.78	Very well sorted
0.35-0.50	0.75-0.71	Well sorted
0.50-0.71	0.71-0.61	Moderately well sorted
0.71-1.00	0.61-0.5	Moderately sorted
1.00-2.00	0.5-0.25	Poorly sorted
2.00-4.00	0.25-0.0625	Very poorly sorted
> 4.00	> 0.0625	Extremely poorly sorted

The sorting of the sediments collected over the sampling period (June 2008 to May 2009) ranged from poorly sorted at 0.41 mm (collected at Fort St. George at the mid tide water mark in May 2009) to very well sorted at 0.82 mm (collected at Kaihihi Surf Beach and Fort St. George at the mid water tide mark in September 2008) (Table 4.2 and Figure 4.6).

The sediment collected at low tide from June 2008 to February 2009 each displayed an increase of sorting with distance from Komene Road (Figure 4.6). Sediment collected in June 2008 and November 2008 had similar levels of increased sorting while the strongest trend in sorting with distance was in February 2009. There was a decrease in sediment sorting for samples collected in September 2008 and in May 2009.

All the sediment obtained in June 2008, September 2008, November 2008, and May 2009, at the mid tide location possessed sorting values that increased with the distance from Komene Road (Figure 4.6). The sediment collected in February 2009 had sorting values that increased slightly with distance north of Stony River.

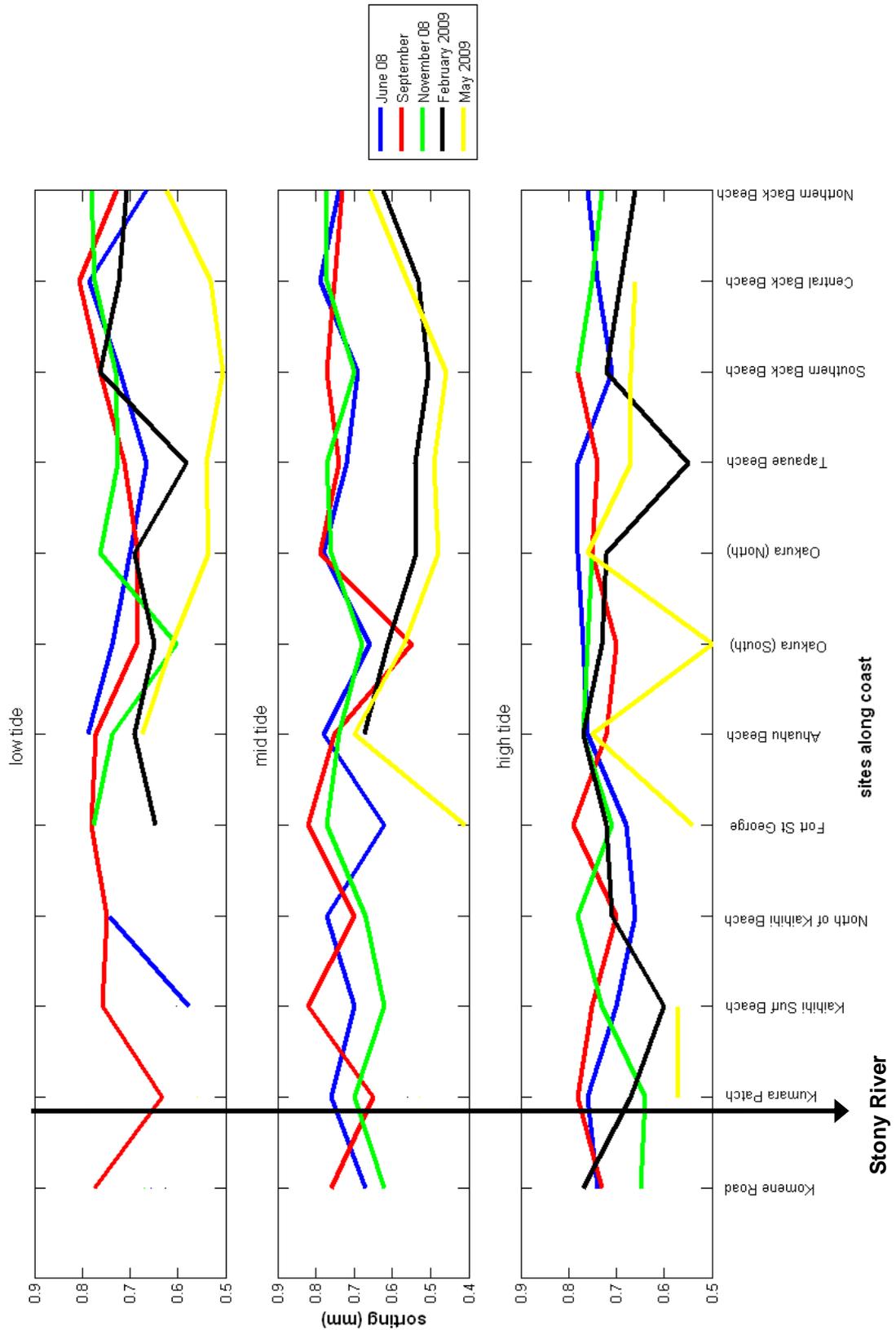


Figure 4.6 Alongshore variation in sediment sorting for sub-aerial beach sediments at low, mid and high tide locations collected at 12 sampling sites along the Taranaki coast over 2008/2009 and analysed using the RSA.

4.3.1.5 Skewness

Sediment skewness (Table 4.3) is a measure of how closely the grain size distribution is to a normal Gaussian probability curve i.e. a measure of the asymmetry of the frequency distribution curves. It is a ratio and is therefore dimensionless. Sediments derived from one source tend to have normally distributed curves, while those derived from a number of sources have pronounced skewness values (Folk, 1968). Generally samples collected offshore and on the beach are coarse skewed as waves remove the finer portions. Samples collected from the dune areas tend to be fine skewed (has a lower value than the mean) due to fines derived from aeolian transportation processes (Friedman and Sanders, 1978).

The samples collected over the course of this study were fine or strongly fine skewed, having skewness values slightly lower than the mean. There is no apparent trend in the skewness values with distance north from the Stony River mouth.

*Table 4.3 Classification for sediment skewness.
(Source: Folk, 1968).*

Skewness	Description
0.30-1.00	Strongly fine skewed
0.10-0.30	Fine skewed
-0.10-0.10	Near symmetrical
-0.10—0.30	Coarse skewed
-0.30—1.00	Strongly coarse skewed

4.3.2 Mineralogy

Peterographic analysis on samples collected at four locations (Stony River, Back Beach, Fitzroy Beach and the Waiwhakaiho River Mouth (Figure 4.1)) indicate that both heavy and light minerals were found in the sediment. These will be described in the following section.

4.3.2.1 Titanomagnetite

Titanomagnetite ($\text{Fe}_0(\text{FeTi})_2\text{O}_3$) grains reflect a blue-black colour and are strongly magnetic. Titanomagnetite is the dominant mineral (60%) that makes up ironsand (Lawton and Hochstein, 1993). Coarse titanomagnetite grains are generally of a sub-rounded shape, while the finer grains are more angular (Gow, 1967). Under the microscope they can be identified as having an opaque colour with an isometric crystal shape (Figure 4.7 and Figure 4.8).

4.3.2.2 Augite

Gow (1967) determined that diopsidic augite is the dominant mineral in the beach and dune sands (not placer deposits) near Hawera. The coarse fractions are commonly sub-rounded euhedral grains, however as this grain size decreases towards the finer particles an anhedral crystal shape dominates (Figure 4.7 and Figure 4.8). Augite can be identified under the microscope by its dark green colour, which remains constant as the microscope stage is rotated.

4.3.2.3 Hornblende

Hornblende can be identified under the microscope as a brown mineral that changes colour when the microscopic stage is rotated. Additionally, it can be identified as an elongated rectangle shape (Figure 4.7 and Figure 4.8).

4.3.2.4 Plagioclase Feldspar

A light mineral, plagioclase feldspar is a colourless grain that is often tabular shape, subhedral and surface-altered, which often exhibits twinning (Figure 4.7 and Figure 4.8). Plagioclase minerals have rings on the outside indicating zoning as the composition of mineral changes from the core to the outside.

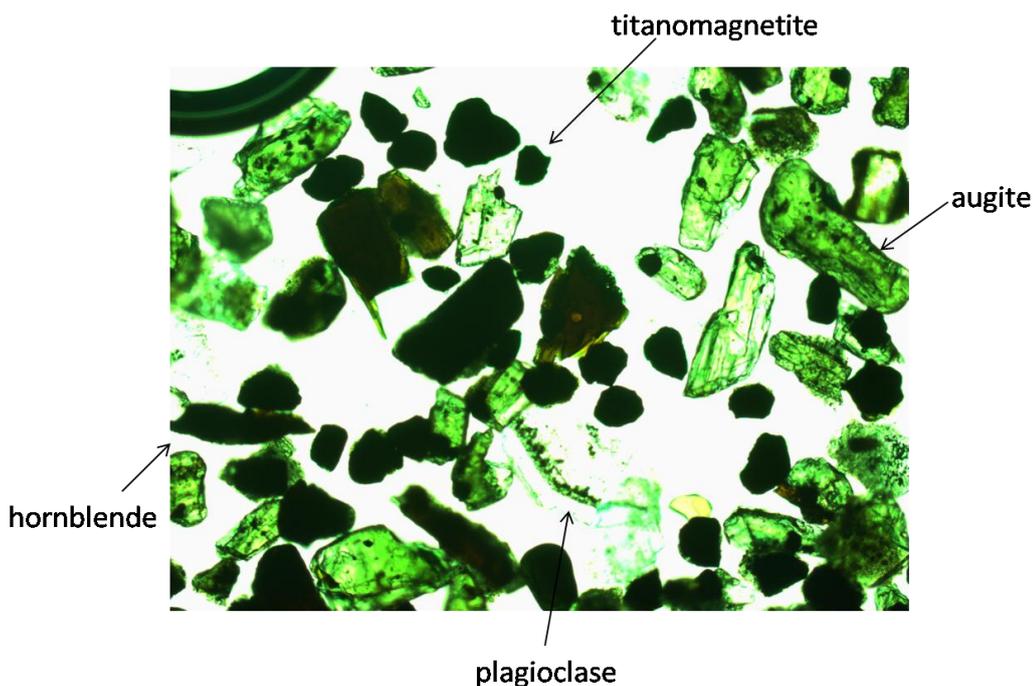


Figure 4.7 Microscopic view of minerals found along the southern Taranaki Coast.

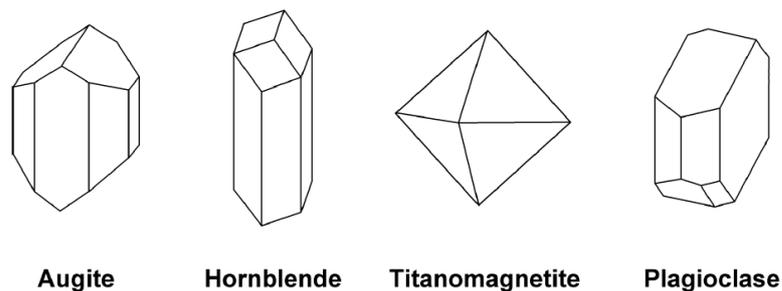


Figure 4.8 Crystal forms of the abundant minerals in the Taranaki black sands.
(Source: Swales et al., 2003).

Petrographic analysis showed the samples were dominated by the heavy mineral titanomagnetite and the opaque minerals augite, hornblende, and plagioclase with minor quantities of calcium carbonate (shell material) (Figure 4.9). Titanomagnetite was the most abundant mineral at the Stony River Mouth and Fitzroy Beach making up 42.5% and 72% of the total sediment, respectively. At Back Beach, there were only small differences in abundance of each mineral, with titanomagnetite and augite at 26.5% and 27.5% respectively. At the Waiwhakaiho River mouth, augite dominated, followed by plagioclase.

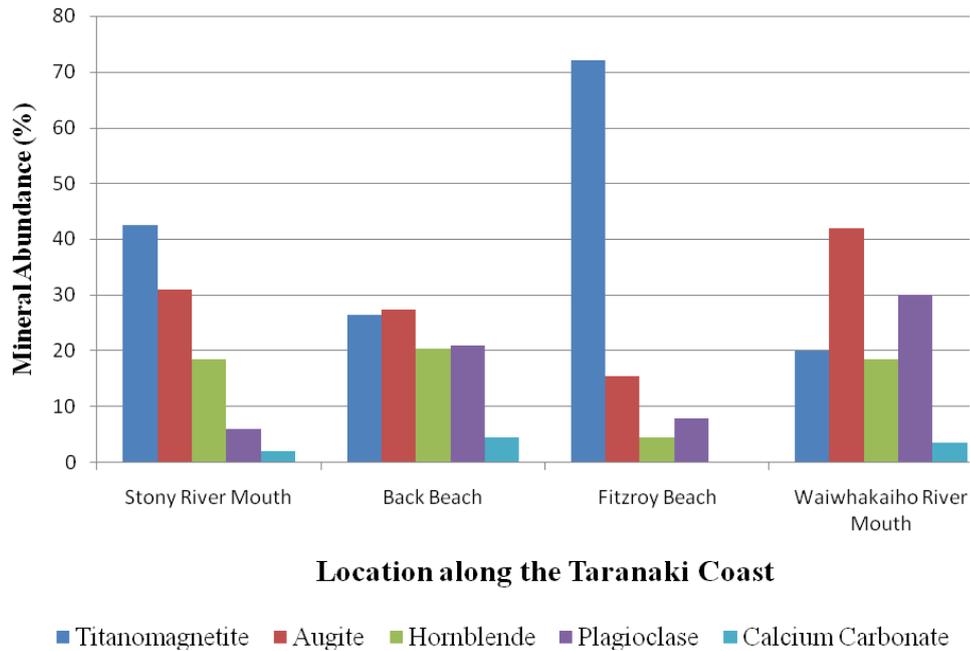


Figure 4.9 Grain mineralogy at four sites along the Taranaki coast from the Stony River mouth just north of Cape Egmont to the Waiwhakaiho River mouth, north of New Plymouth.

4.4 DISCUSSION

4.4.1 Grain Size Analysis

An obvious trend for the mean grain size data was the coarsening of sediment in the seaward direction. Medium sand, dominated the upper beach and this grain size increased in the lower beach, often reaching sizes that were too large to sample. At the low and mid tide medium sand was the dominant size class.

Mean grain size is a reflection of the wave energy. The momentum of the swash decreases as energy is lost to friction and percolation into the beach face. The energy of the swash is derived from arriving waves, while the backwash of the flow is driven by gravitational forces. This backflow reaches its maximum velocity at the base of the slope where it collides with incoming waves. These processes result in the deposition of smaller finer grains at the top of the beach where the water moves slowly. The coarser sediment typically accumulates near the plunging line, the location of the greatest turbulence and energy (Komar, 1998).

Matthews (1977) also identified a coarsening sediment trend in the seaward direction. At Werekino and Harriet, the mid and lower beach sediment is significantly more coarse, likely derived from the sub-tidal boulder platform. At Oakura and Opunake Beaches, the sediments are finer, likely due to their sheltered location. It was found that during the winter of 1976 and 1977 at Oakura and Werekino (Figure 4.10), the mean grain size decreased as a result of swell waves which built up a coarse swash bar that trapped fine sediment as the waves moved landward. After calm conditions, the fine grained sands dominated the beach until a new swash bar formed. Sonu (1972) observed a similar phenomenon in the Outer Banks of North Carolina as well as Inman (1953) in Southern California. Matthews (1977) stated that this fining may have also been due to a concentration of heavy minerals (smaller grain sizes) during storms or a combination of the two processes. This pattern of smaller grain sizes during the winter months is also evident in this particular study of Taranaki where it was found that the average mean grain size for June 2008 across the 12 sites was the finest at mid and high tide locations.

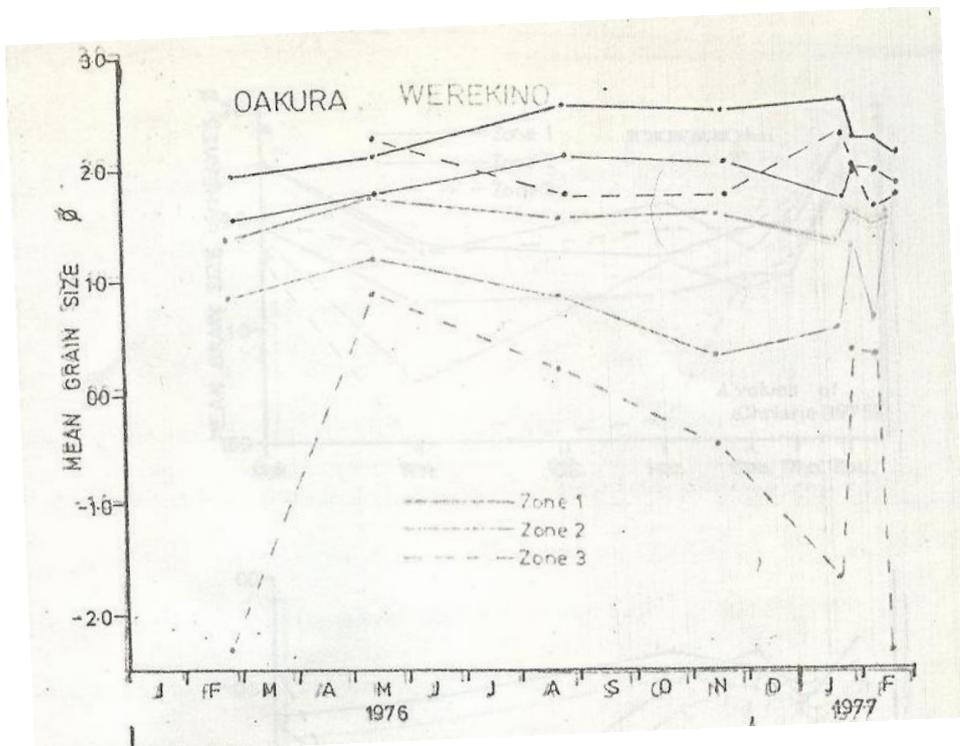


Figure 4.10 Variation in mean grain size during 1976 and 1977 at Oakura and Werekino. (Source: Matthews, 1977).

There was a distinct fining of sediment with the direction of littoral drift as indicated in Section 4.3.1, in agreement with studies by Matthews (1977) and Swales et al. (2003).

Komar (1998) states that variations in grain size in the longshore direction can be produced by:

- variations in the wave energy alongshore; and
- selective transport (i.e. finer less dense grains are easier to transport than coarse dense grains).

Matthews (1977) demonstrated fining in the direction of littoral drift between Opunake and Oakura (Figure 4.11). As explained earlier, Cape Egmont is a division between two directions of littoral drift, one directed north east and the other directed south east (see Chapter Two: Environmental Background).

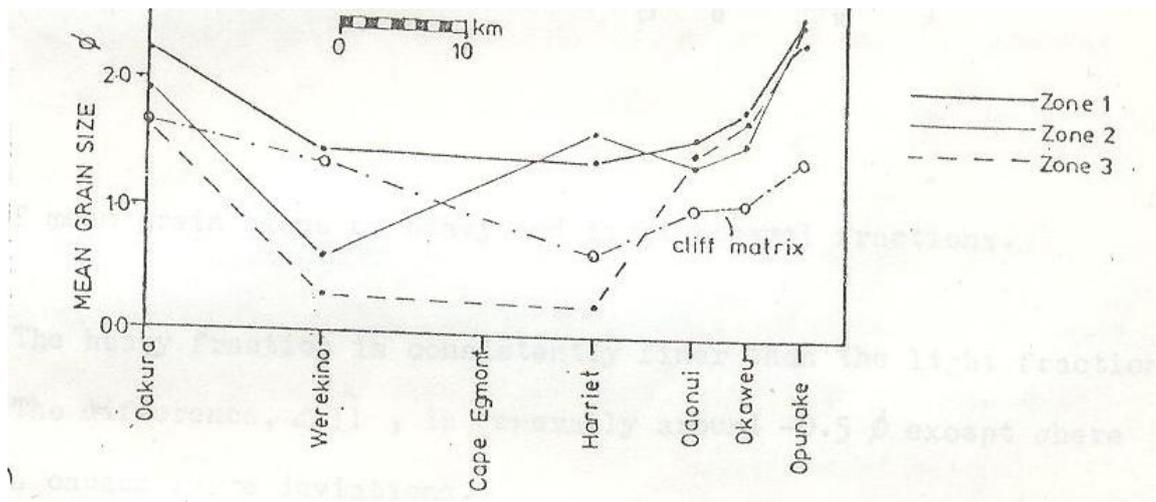


Figure 4.11 Longshore variation in grain size from Oakura to Opunake in 1976. (Source: Matthews, 1977).

Swales et al. (2003) analysed beach sediment changes and mineralogy changes along the North Island's west coast. This study identified a south to north trend of reduced particle size coinciding with the direction of littoral drift (Figure 4.12). Swales et al. (2003) showed that within the first 100 km north of the Stony River mouth, the average particle diameter reduces from 0.45 mm to 0.3 mm. Large increases in particle size occurred at the mouths of the Tongaporutu, Mokau, and Awakino Rivers, north of New Plymouth, which deliver coarse sand sized sediments to the coast.

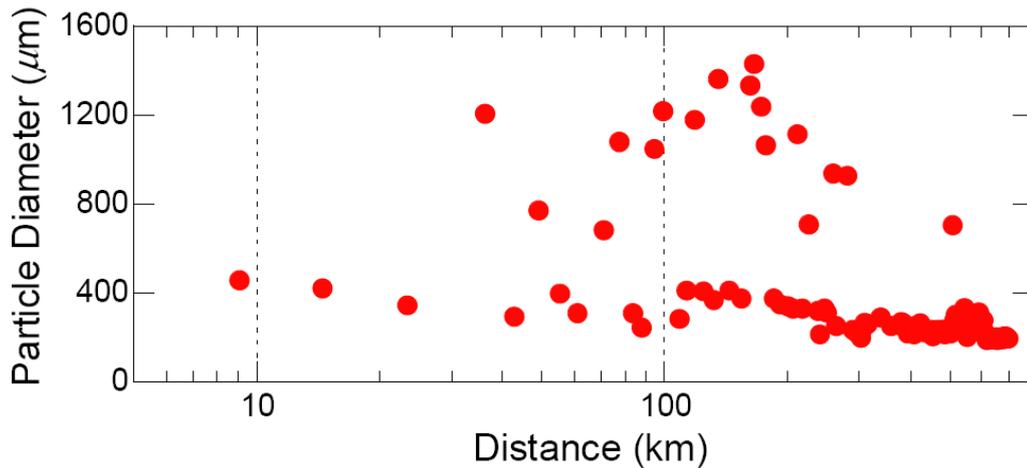


Figure 4.12 Longshore changes in particle diameter of beach sand sized sediment with distance north of the Stony River mouth.
(Source: Swales et al., 2003).

4.4.2 Mineralogy

The mineralogy of samples collected at four locations along the Taranaki coast was dominated by titanomagnetite, but also included smaller quantities of hornblende, plagioclase and augite. Titanomagnetite was the most abundant mineral at the Stony River mouth and Fitzroy Beach, but at Back Beach and the Waiwhakaiho River mouth it was not the dominant mineralogical component.

The shape of particles is dependent on the mineralogy of the sediments which in turn, influences the way that sediments are transported. Transportation results in grain shape change via mechanical abrasion where particles become smaller and more rounded with transport distance. The individual properties of different minerals (i.e. density, hardness, crystal habit, sphericity and magnetism) result in variable abrasion rates. Titanomagnetite, with a Mohs hardness of approximately 5, and its unique cubic shape (Figure 4.8), mean that it will rapidly alter to nearly spherical compared to plagioclase feldspar, which has a hardness value of approximately 6.5 and a more angular shape, taking longer to alter. However, the specific density of titanomagnetite is 5.2 gcm^{-3} , which is double that of feldspar at approximately 2.6 gcm^{-3} (Swales et al., 2003). This means that the longshore transport of titanomagnetite is much slower than that of other minerals, which results in these particles tending to lag behind other minerals and form placer

deposits in the upper beach which can be seen at a number of the field sites monitored along the Taranaki coast.

Swales et al. (2003) analysed the longshore changes in particle size and shape on the black sand beaches of a 750 km stretch of New Zealand's North Island from Cape Egmont to Cape Reinga. This study identified that near the mouth of the Stony River, the beaches were composed of coarse sand and gravel rock fragments. The rock fragments are made up of octahedral shaped titanomagnetite, elongated hornblende and tabular shaped plagioclase as shown in Figure 4.13.

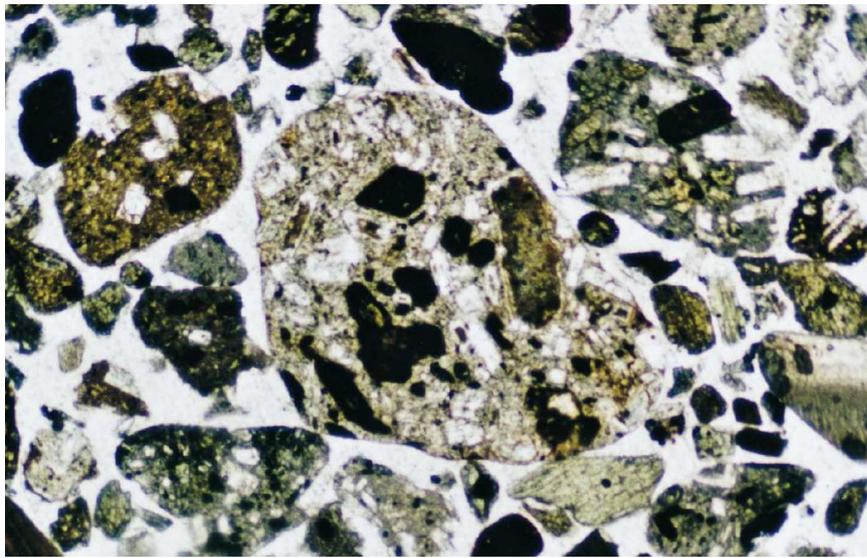


Figure 4.13 Rock fragment (centre of picture) which contains titanomagnetite, plagioclase and hornblende, collected 9 km north of the Stony River mouth. (Source: Swales et al., 2003).

4.5 SUMMARY

Textural and mineralogical characteristics of sediments collected at 12 sites (obtained from the low, mid and high tide water marks) along the coastal sector between Komene Road, just south of the Stony River mouth, and Back Beach in New Plymouth display the following characteristics:

- a decrease in mean grain size with distance north of the Stony River mouth;
- beach sediments are either uni-modal with one size class dominating;

- generally, an increase in sorting with distance north of Site 1: Komene Road. However, the sorting range of all samples is large ranging between poorly sorted to very well sorting; and
- beach sediments are dominated by the heavy mineral titanomagnetite and the opaque minerals of augite, hornblende and plagioclase feldspar. Titanomagnetite dominates at the Stony River Mouth and Fitzroy Beach, at Back Beach all minerals contribute equally to composition, and at the Waiwhakaiho River mouth, augite dominates.

In relation to the slug of sand derived from Little Pyramid, in the headwaters of the Stony River, it can be concluded that this sediment is continually being re-worked as it is transported down the Stony River channel and along the north-east directed littoral system. It is estimated that the sand derived from the 1998 Stony River outbreak has been transported as far north as Ahuahu Beach where there is a sharp change in gradient of the mean grain size of sediment samples analysed over the duration of this study.

These sediments, of predominately one size class, are dominated by the heavy mineral titanomagnetite near the Stony River mouth and as this sediment is transported and dispersed along this coastline, other mineralogy's (augite, hornblende and plagioclase) are contributing greater to the composition of the sediment. This is indicative of the selective sorting of minerals as a result of different mineralogical densities, which in turn indicates an increased distance from the source of this sediment.

The following chapter (Chapter Five: Longshore Sediment Transport) aims to evaluate the potential longshore sediment transport flux, modeled using ten years of wave climate data, and link to the results of the sediment textural and mineralogical findings presented in this chapter.

CHAPTER FIVE: LONGSHORE SEDIMENT TRANSPORT

5.0 INTRODUCTION

The high energy Taranaki coast is exposed to waves predominately arriving from the south-west, dominated by a long period swell (10-14 s). As these waves progress to the shoreline they are exposed to complex bathymetries at depths < 125 m where reef and channel structures are interbedded by lahar deposits and overlain with gravels, boulders and sand (McComb, 2001). This irregular sea bed topography results in waves being refracted and focusing occurring at the shoreline, producing significant variations in wave height (Komar, 1998). The net sediment flux along the coast north of Cape Egmont is towards the north-east (Matthews, 1977).

Previous studies by Matthews (1977), McLennan (1982), McComb et al. (1999b) and McComb (2001) have used a range of methods to estimate the alongshore sediment volumes along the Taranaki headland.

- Matthews (1977) studied beach profile changes of six southern Taranaki beaches and undertook sand budget studies. From his research he deduced that between 75,000 and 180,000 m³yr⁻¹ of sandy sediment moves north-east within a littoral cell between Cape Egmont and New Plymouth.
- McLennan (1982) researched littoral drift processes and longshore drift predictions along the New Plymouth coastline, particularly at Fitzroy Beach. This study incorporated the significant depths of near-shore sediment movement from Hallermeir (1981) and describes the onshore-offshore and longshore drift processes which were determined through annual beach profile changes between 1945 and 1972. McLennan calculated longshore drift rates using the Komar and Inman (1970) and Komar (1977) formulae. However, they proved to over-estimate the annual net sediment movement rate at Fitzroy Beach. A model by Hsu

(1973, 1974) was used to take into account aeolian sand transport, however, this also proved difficult to apply.

- Accretion rates of the tip shoal at Port Taranaki, reported by McComb et al. (1999b) showed that 125,000 m³ per year actively accumulates near the tip of the main breakwater water wall. The mobile nearshore sediments are transported along the wall toward the harbour channel and then advected into the harbour by the refracting waves. Since the breakwater extension in 1967, the harbour dredging records show a consistent ~ 125,000 m³ accreting every year in this outer harbour zone. This value is approximately half the total cross-shore estimates (McComb, 2001). This is broadly consistent with the results of the tracer experiments conducted in 1998 by McComb (2001). Those showed that nearly all material in water depths of less than 10 m are captured by the harbour, and inferring that sediments in greater than 10 m depth can actively bypass the harbour entrance and progress to the north-east.
- McComb (2001) undertook a tracing experiment providing empirical evidence for the path of littoral sediment and used sedimentation and grain size patterns to provide evidence for littoral transport pathways. Suspended sediment concentrations (near the main breakwater in New Plymouth Harbour) were integrated with current velocities to derive a net northeasterly longshore flux of 572 m³ annually, at the 6 m depth contour. Longshore surf-zone sediment transport rates near the main breakwater at New Plymouth were calculated using GENIUS (similar to GENESIS) which estimated that ~ 239,000 m³ of sand is transported along the main breakwater wall annually.

This chapter aims to evaluate Q , the potential longshore sediment transport flux, occurring along the 5 m depth contour between Cape Egmont and Back Beach in New Plymouth in order to evaluate the effect of the Stony River sand slug moving along the coast. Firstly a background on longshore sediment transport is given as well as a description of the wave hindcast model data that was provided by MetOcean Solutions Ltd for use in this study. A description of the well known Coastal Engineering Research Center's (CERC) 1973 sediment transport formula

is then given before discussing the results in firstly the regional scale and then on a smaller local scale.

5.1 BACKGROUND

Longshore sediment transport can be measured in a number of ways. Laboratory measurements are thought to underestimate longshore sediment transport due to scale limitations. Experimental measurements can be conducted by surveying impoundments of littoral drift, measuring short term tracer transport rates, and measuring the suspended load transport by pumping or with traps. Sediment transport can be measured qualitatively using indicators which relates to the net transport using evidence such as the blockage by major structures. However, it is important to recognise the effect these structures may have on the local effect of waves and currents. Patterns in sediment grain size, composition and sources can be used as indicators as it is thought that the longshore decrease in sediment size indicates the direction of longshore transport (See Chapter Four: Sediment Characteristics). Longshore sediment transport can be measured using quantitative indicators, however, surveying over time scales greater than a decade is needed for estimates using these methods (U.S. Army Corps of Engineers, 2002).

Storlazzi and Field (2000) investigated the distribution and transport along a rocky, embayed, sediment deficient coast in the Monterey Peninsula and Carmel Bay along the Californian Coast. This coast is characterised by coastal mountains, sea-cliffs and small pocket beaches (typically at river mouths). The headlands extend offshore as bathymetric highs with adjacent bathymetric depressions adjacent to them, interpreted to be paleo-stream channels, which can store substantial volumes of sediment. These headlands steer and focus currents, thus influencing the direction of littoral transport. Their research concluded that the north-west trend of the shoreline and the oceanographic regime greatly influence the distribution of littoral sediment and peaks in wave energy control the timing and magnitude of sediment transport between pocket beaches. The importance of storms for sediment transport along that study area was emphasised, and is likely so for rocky coastlines such as the coast around the

Taranaki Headland. For sediment to be transported and bypass small headlands, high wave orbital velocities are required to mobilise sediment and advect it over bedrock ridges by alongshore flows. Their research concluded that large waves play a very distinct role in longshore sediment transport along rocky, embayed coastlines in comparison with along continuous sandy coastlines. Large waves are often as a result of local storm activity, thus the frequency and intensity of storms significantly affects the timing and magnitude of alongshore sediment transport along rocky coastlines (Storlazzi and Field, 2000).

5.2 QUANTITATIVE LONGSHORE DRIFT PREDICTION

The potential littoral transport is difficult to determine quantitatively (Healy, 1974). The alongshore sediment transport can be estimated using either detailed or bulk sediment transport equations. Detailed equations require computer programs and substantial calibration data. Bulk sediment transport equations and measurements are generally used which calculate the longshore sediment transport rate from measured wave and beach parameters (Kamphuis, 2000). There are a number of empirical formulae which have been developed to determine Q , the potential longshore sediment transport flux. Most of these equations consider the sediment to move in a conveyor belt related to the dominant wave power and direction (Phizacklea, 1993), and include the CERC (1973), Kamphuis (1991), and the Walton and Bruno (1989) equation. The CERC (1973) formula requires the significant wave height (H_s) and the angle of wave incidence at breaking. The Kamphuis (1991) formula additionally takes into account wave period (or wave steepness), beach slope, and grain size (Kamphuis, 1991) while the Walton and Bruno (1989) equation additionally requires the surf zone width and the longshore current velocity (Jaya Kumar et al., 2008). These later formulae have been proven to better estimate a more accurate potential flux (e.g. Kamphuis, 2000, Wang et al., 1998).

Many of these later formulae are deemed inappropriate to use in this study as they introduce too many unknown variables (e.g. beach slope, offshore sediment grain size, average longshore current velocity). However, this study simply investigates Q (the potential longshore transport flux) at 55 points between Rahotu Road and Back Beach. The relative magnitudes of the potential fluxes calculated are based

on the variation of H_s and the angle of incidence at different locations along the coast. It is for this reason that the CERC (1973) was chosen to estimate varying ratios of Q at different locations along this coast.

5.3.1 The CERC (1973) Formula

The Coastal Engineering Research Center's (CERC) 1973 bulk sediment transport rate formula takes into account both the bed-load and suspended sediment load. It is based on data from Watts (1953), Caldwell (1956), Moore & Cole (1960), Komar (1969), and (McLennan, 1982). The basis for this formula is the principal that the volume of sand transported is proportional to the longshore wave power per unit length of the beach (Van Wellen et al., 2000). Williams et al. (2005) found this model to have an accuracy of +/- 30-50 % in ideal conditions.

This CERC formula assumes that:

- the beach is a long and open sandy coast with continuous supply of sand; and
- all the energy is associated with a single peak in the wave spectra.

The CERC formula is:

$$I_s = 0.39P_{asb}$$

Equation 5.1
(Source: Kamphuis, 2000).

where I_s is the underwater weight of the transported sediment and P_{asb} is the alongshore component of wave power in the breaking zone for a significant wave height of irregular waves (CERC, 1984).

By assuming dense sand where $\rho_s=1800 \text{ kg/m}^3$ and a porosity of $n=0.32$, Equation 5.2 can be rearranged into m^3yr^{-1} as:

$$Q = 2.2 \times 10^6 \frac{H_{sb}^{5.2}}{\gamma_{sb}^{1/2}} \sin 2\alpha_b$$

Equation 5.2
(Source: Kamphuis, 2000).

where H_{sb} is the significant breaking wave height, γ_{sb} is the breaker index for a significant wave and α_b is the angle of wave incidence at breaking (Kamphuis, 2000). The incidence angles, for this study, was derived by defining the mean shoreline orientation, at the shoreline immediately adjacent to the offshore point, and calculating how much the wave angle (at each time step) deviates from perpendicular to the shoreline.

On a flat beach where m (beach slope) is close to 0, $\gamma_{sb}=0.56$:

$$Q = 2.9 \times 10^6 H_{sb}^{5/2} \sin 2\alpha_b \text{ (m}^3\text{/yr)}$$

Equation 5.3
(Source: Kamphuis, 2000).

OR

$$Q = 330 H_{sb}^{5/2} \sin 2\alpha_b \text{ (m}^3\text{/hr)}$$

Equation 5.4
(Source: Kamphuis, 2000).

The CERC formula is advantageous as it takes into account the density of the sediment grains, which is a crucial component of this field site differentiating it from other sites around the world. However, it only considers wave-generated currents and disregards wind and tidal currents.

5.3 THE SWAN NUMERICAL MODEL

The Simulating WAVes Nearshore (SWAN) (Booij et al., 1999 and Ris et al., 1999) third generation numerical model is designed for waves propagating over coastal and inland waters and accounts for wave-current interactions. It obtains estimates of wave parameters from given wind, bottom and current conditions (Holthuijsen et al., 1999). Formulated in Cartesian co-ordinates, it describes the evolution of waves over coastal areas with wind input, dissipation, and wave-wave interaction parameters changing due to variable water depths and the affect of currents. This model incorporates bottom and current-induced shoaling and refraction. However, diffraction is only approximately accounted for. The SWAN model is based on the action-balance equation rather than the energy

balance equation because in the presence of currents the action density spectrum is conserved while the energy spectrum is not (Zhang et al., 2003). The basis of the model is:

$$\frac{\partial N}{\partial t} + \frac{\partial(c_x N)}{\partial x} + \frac{\partial(c_y N)}{\partial y} + \frac{\partial(c_\sigma N)}{\partial \sigma} + \frac{\partial(c_\theta N)}{\partial \theta} = \frac{S}{\sigma}$$

Equation 5.5

where N is the action density spectrum and σ and θ are the wave relative frequency and wave direction respectively.

The first term on the left-hand side of the equation represents change in the wave action density spectrum in time. The second and third terms represent the propagation of wave action in space with velocities of c_x and c_y in the x and y directions respectively, accounting for shoaling. The fourth term represents a shifting of the relative frequency due to variations in depth and currents. The fifth term represents refraction (depth induced and current induced). The term on the right hand side of the equation is representative of the source in terms of energy density. It represents the effects of generation, non-linear wave-wave interactions and dissipation.

Wave data were hindcast by MetOcean Solutions Ltd for the period 01-01-1998 to 31-12-2007. The hindcast was at one hour time steps, and wave data were stored every three hours for a nested Taranaki domain. The MSL wave hindcast technique has been validated against numerous locations around New Zealand, including 8 locations within the Taranaki area.

5.4 METHODS

Ten years of wave data (01-01-1998 – 31-12-2007) were extracted along the 5 m depth contour, at 55 locations (Figure 5.1 and Table 5.1) from the wave hindcast netCDF archive. MATLAB code was written to extract this data. The variables extracted were time, site, longitude, latitude, H_s , T_p , $H_{s,swell}$, and wave angle (dpm). Data were available every 3 hours, therefore the assumption was made that the wave condition remains constant over the 3 hour period. The modeling

points are located from just south of Rahoitu Road south of Cape Egmont and the most northern point is located offshore from Back Beach in New Plymouth (Figure 5.1 and Table 5.1). The Sugar Loaf Islands provide a diffusive headland in this area due to the partial sheltering effect on wave energy, and the complexity arising from the adjacent port structures. This means the broad assumptions being made to define the potential Q are not valid for locations to the immediate north of Back Beach.

The angle of incidence was determined by first defining this shoreline orientation relative to north. This was determined by averaging the orientation of the shore adjacent to each of the 55 points along the 5 m depth contour that the hindcast data was derived from. The angle of incidence was then calculated from how much the wave angle at each three-hour time step, within the ten year hind cast, deviates from perpendicular to the shoreline.

Published significant wave heights and incidence angles from Kamphuis (2002) were used to verify the codes written to determine the Q values.

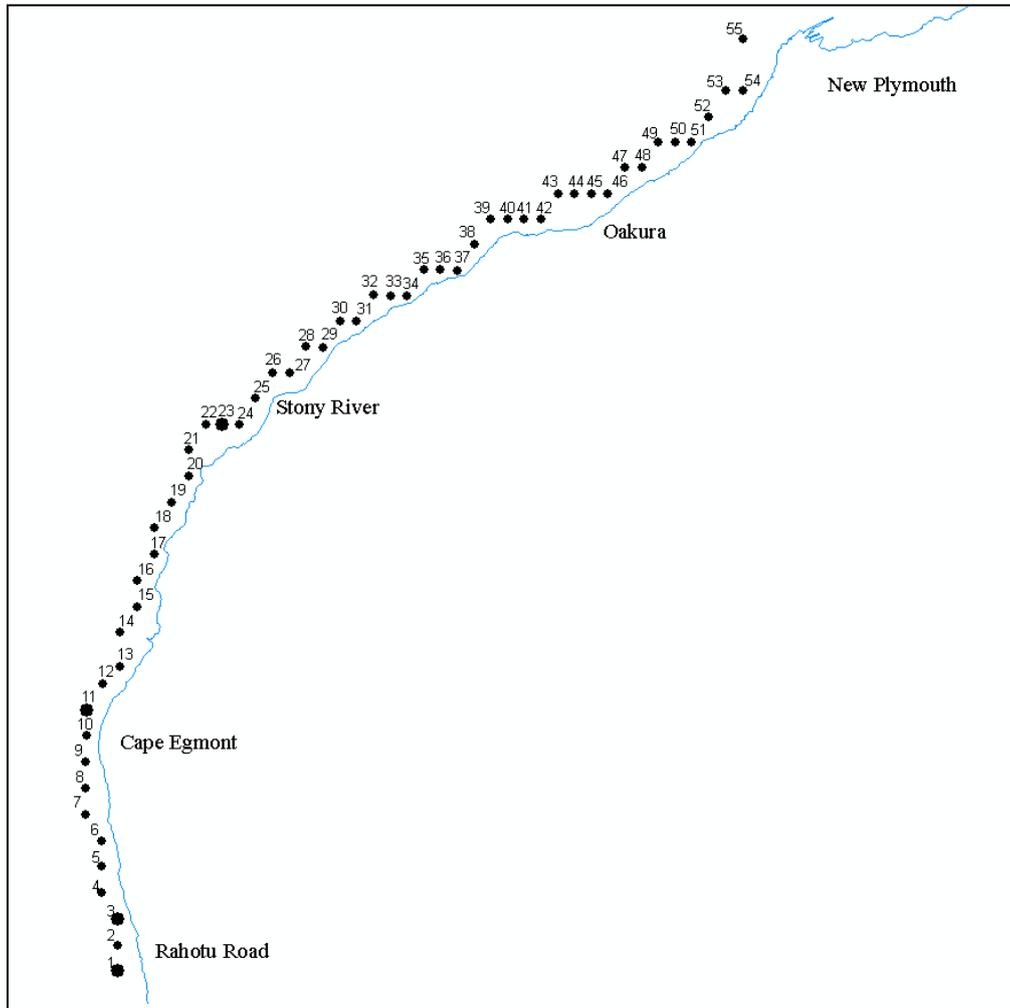


Figure 5.1 Locations of the 55 sites along the 5 m depth contour from where data was extracted between 01-01-98 and 31-12-07 in 3 hour intervals.

Table 5.1 Locations of the 55 points along the 5m depth contour from where data was extracted between 01-01-98 and 31-12-07 in 3 hour intervals.

Point ID	Depth	WGS84		Point ID	Depth	WGS84	
		Latitude	Longitude			Latitude	Longitude
1	3.231	-39.35	173.76	28	8.755	-39.155	173.8333
2	5.426	-39.3419	173.76	29	3.76	-39.155	173.84
3	3.352	-39.3338	173.76	30	8.413	-39.1469	173.8467
4	7.11	-39.3256	173.7533	31	4.934	-39.1469	173.8533
5	6.341	-39.3175	173.7533	32	10.1	-39.1387	173.86
6	5.469	-39.3094	173.7533	33	4.987	-39.1387	173.8667
7	6.519	-39.3013	173.7467	34	2.498	-39.1387	173.8733
8	7.073	-39.2931	173.7467	35	8.171	-39.1306	173.88
9	5.688	-39.285	173.7467	36	4.189	-39.1306	173.8867
10	3.719	-39.2769	173.7467	37	2.958	-39.1306	173.8933
11	5.147	-39.2687	173.7467	38	5.85	-39.1225	173.9
12	5.294	-39.2606	173.7533	39	5.713	-39.1144	173.9067
13	3.431	-39.2525	173.76	40	3.34	-39.1144	173.9133
14	6.942	-39.2444	173.76	41	4.279	-39.1144	173.92
15	6.122	-39.2363	173.7667	42	3.395	-39.1144	173.9267
16	7.346	-39.2281	173.7667	43	7.185	-39.1063	173.9333
17	3.529	-39.22	173.7733	44	10.6	-39.1063	173.94
18	6.677	-39.2119	173.7733	45	7.667	-39.1063	173.9467
19	6.282	-39.2038	173.78	46	2.491	-39.1063	173.9533
20	5.206	-39.1956	173.7867	47	7.721	-39.0981	173.96
21	10.48	-39.1875	173.7867	48	4.031	-39.0981	173.9667
22	15.37	-39.1794	173.7933	49	10.12	-39.09	173.9733
23	10.89	-39.1794	173.8	50	5.509	-39.09	173.98
24	3.902	-39.1794	173.8067	51	2.055	-39.09	173.9867
25	4.251	-39.1712	173.8133	52	4.827	-39.0819	173.9933
26	8.947	-39.1631	173.82	53	8.563	-39.0737	174
27	4.073	-39.1631	173.8267	54	3.184	-39.0737	174.0067
				55	4.942	-39.0575	174.0067

5.5 LITTORAL DRIFT ESTIMATES

5.5.1 Regional Scale Assessment

Depicted in Figure 5.2 are plots of the mean significant wave height (H_s), mean $H_{s_{\text{swell}}}$ and the mean period (T_p), at 55 locations along the 5 m depth contour between Rahotu Road and Back Beach in New Plymouth between 01-01-98 and 31-12-07. The mean H_s and $H_{s_{\text{swell}}}$ is greatest in the south of the study area and

decreases with distance northwards around the Cape Egmont towards New Plymouth. The maximum mean H_s and $H_{s_{swell}}$ is at site 4, near Rahotu, with heights of 2.1 m and 1.8 m respectively. The minimum mean H_s and $H_{s_{swell}}$ is at site 51, immediately south of Back Beach, with wave heights of 0.89 m and 0.74 m respectively. Additionally T_p decreases with distance north around the Taranaki Peninsula. Maximum mean T_p values are greatest at site 3, south of Rahotu, at 12.19 sec, while they are smallest at site 49 with a value of 11.56 sec.

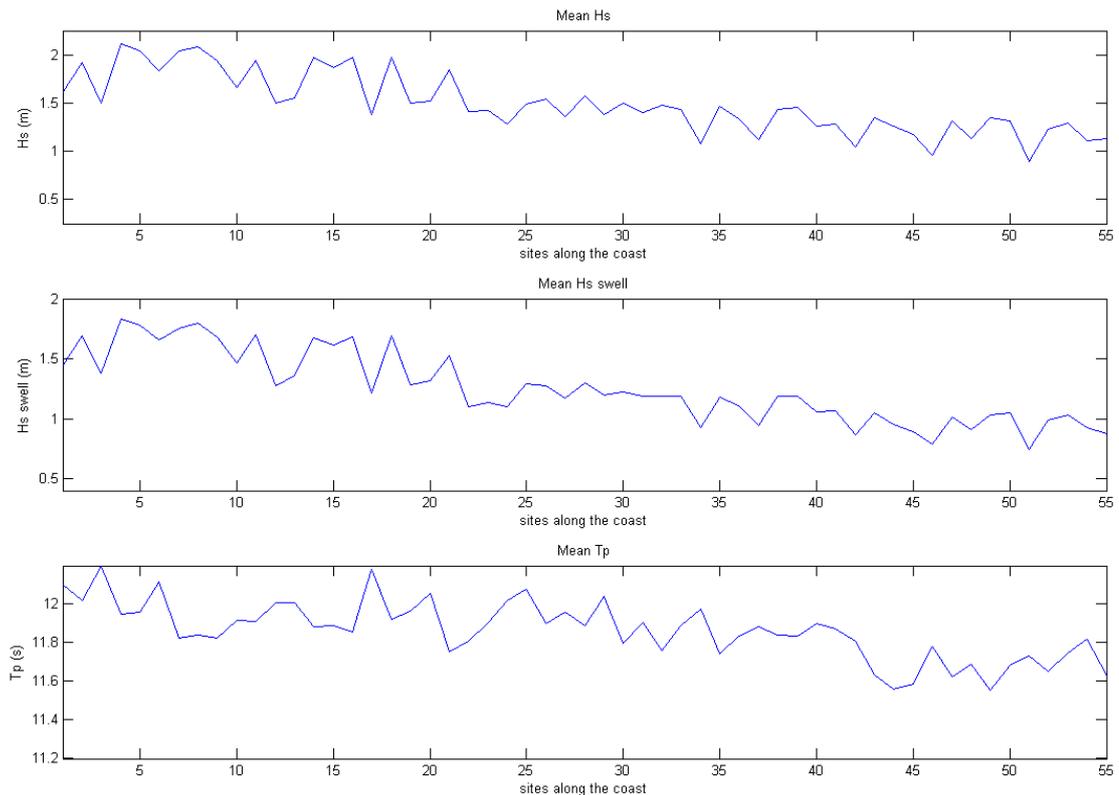


Figure 5.2 Spatial variation in the mean H_s , $H_{s_{swell}}$ and T_p at 55 locations along the 5 m depth contour between Rahotu Road and Back Beach based on hindcast wave data from 01-01-98 to 31-12-07.

This reduction in wave energy with distance northwards around the Taranaki Headland is a result of:

1. The exposed nature of the coast near Cape Egmont to the dominant south-westerly swells.
2. The seabed gradient is much steeper in the vicinity of Cape Egmont, and therefore the frictional attenuation of energy is less. Crofskey (2007) surveyed the depth at a number of stations between Cape Egmont and

Motunui. The mean slope of the seabed was steeper in the south-western region, near Cape Egmont, where a 1 m drop in depth corresponded to an 80 m horizontal distance (Figure 5.3). Near Back Beach, ~ 34 km north of Cape Egmont this slope is decreased where a 1 m drop in depth corresponded to a 95 m horizontal distance (Crofskey, 2007).

3. The orientation of the Taranaki Peninsula and the incidence swells result in a wave refraction shadow zone (Crofskey, 2007).

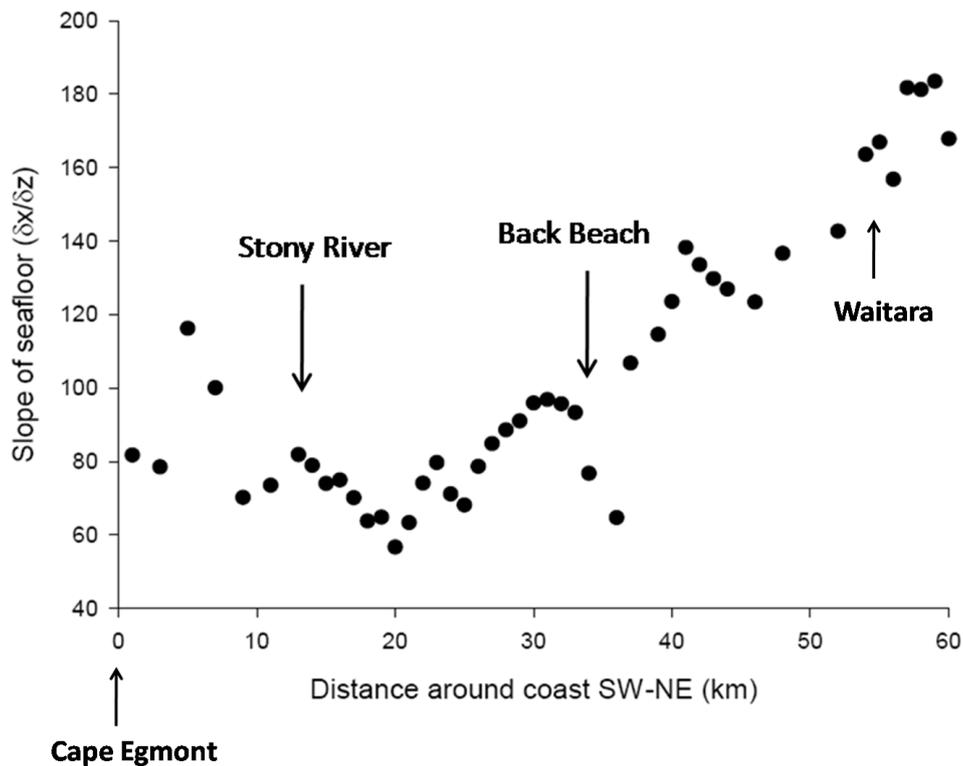


Figure 5.3 The slope of the seafloor (horizontal distance/depth) around the Taranaki Headland (SW-NE/ from Cape Egmont to slightly north of Waitara). The slope index indicates the horizontal distance in metres for a 1 m depth increase.

(Adapted from: Crofskey, 2007)

Illustrated in Figure 5.4 is the mean coastline orientation of each of the 55 sites and the mean incidence angle of the wave field over this 10 year dataset (01-01-98 to 31-12-2007). As the distance between consecutive points varies between 0.5 and 1.5 km the raw coastal orientation data was smoothed using a three point running average. The general trend in this data is that near Cape Egmont the angles of incidence are relatively low. Progressing north around the Taranaki headland the coastal alignment changes to become more NE/SW, and the incidence angle increases, reaching a maximum angle at site 33 where the maximum incidence angle between the approaching waves at 5 m depth and the

shoreline is 58°. This location is some 5.5 km to the north of the Stony River mouth. Further north these angles then reduce further (along with change of coastal orientation) with distance north toward Back Beach. Partly, the effects of wave refraction are acting to re-orientate the incoming waves with the coast and thereby reducing the angle of incidence.

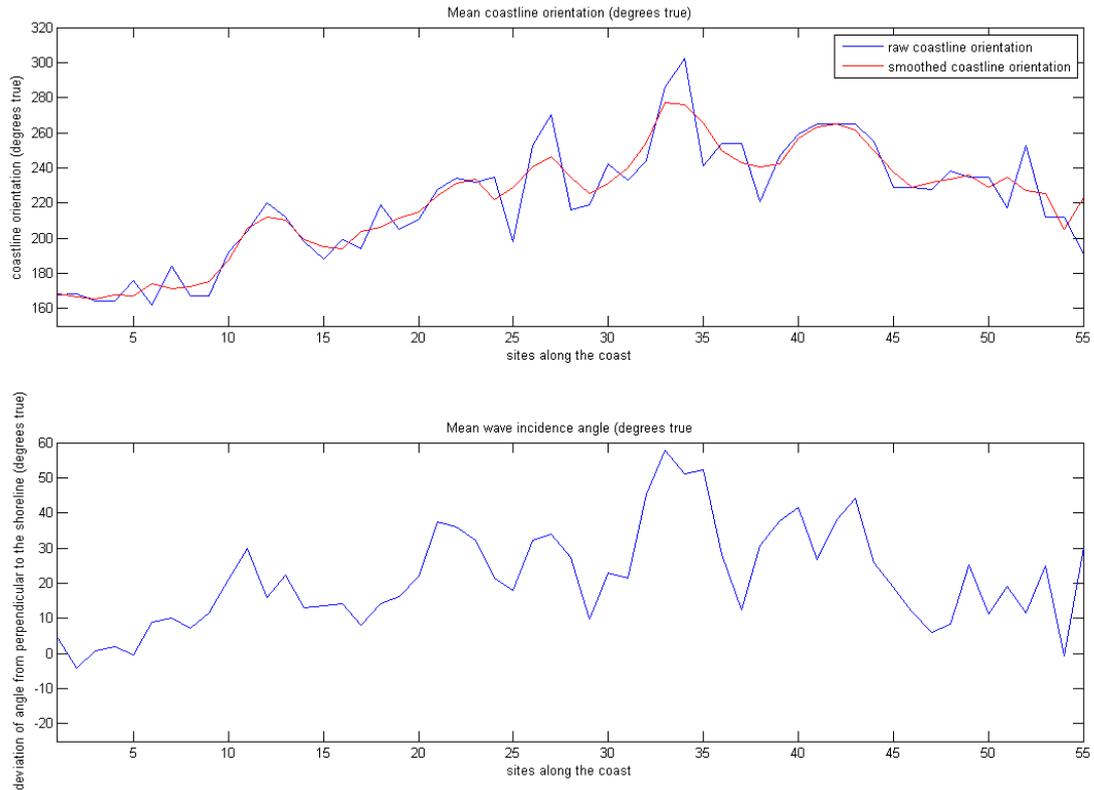


Figure 5.4 Spatial variation in the mean coastline orientation and mean wave incidence angle between 01-01-98 and 31-12-07 at 55 locations along the 5 m depth contour offshore from the Rahoitu Road to Back Beach coastline.

Portrayed in Figure 5.5 are the net potential longshore sediment rates (Q) (black line) and the percentage of the time that Q is directed towards the north-east (bars) for the whole ten years (01-01-98 to 31-12-2007) at the 55 locations along the 5 m depth contour, between Rahoitu Road and Back Beach, which was determined using the CERC (1973) formula. The general trend is that the Q values are relatively low at the southern end of this coastline south of Cape Egmont, slightly north of Rahoitu Road. These Q values have a mean net Q value of $\sim 24.0 \times 10^6 \text{ m}^3$ between sites 1-10 south of Cape Egmont with sites 2 and 3 having a Q value directed towards the south-west, the reverse direction to the net littoral drift. These Q values increase to a maximum net Q value of $\sim 163.0 \times 10^6 \text{ m}^3$ at site 21,

3.2 km south of the Stony River mouth, nearly 7 times greater than the smaller potential flux calculated south of Cape Egmont. Further north these potential Q fluxes decrease to where Back Beach has a mean net Q value $6.2 \times 10^6 \text{ m}^3$ with the Q flux at sites 54 and 55 always being directed towards the south-west. Between sites 4 and 53 the Q flux is nearly all the time directed towards the north-east.

The trend of increasing Q values from site 4 to site 21 before decreasing towards Back Beach in New Plymouth is also evident in Figure 5.6 which illustrates the spatial variation in the mean hourly potential nearshore sediment transport flux estimates (Q), derived using the CERC (1973) formula for wave parameters at the 5 depth contour offshore from Rahotu Road to Back Beach. Slightly south of Cape Egmont, between sites 1 and 10 the mean Q value is $836 \text{ m}^3\text{hr}^{-1}$ directed towards the north-east, increasing to a maximum Q value at site 21 with a flux of $1856 \text{ m}^3\text{hr}^{-1}$, also directed towards the north east, ~ 6 times the magnitude of the flux estimated at site 2 (~ $298 \text{ m}^3\text{hr}^{-1}$ towards the south east). From site 21 towards the north-east, these Q values decrease to Back Beach reaching the smallest flux at site 55, at Back Beach, with a mean value of ~ $20 \text{ m}^3\text{hr}^{-1}$ directed towards the south-west.

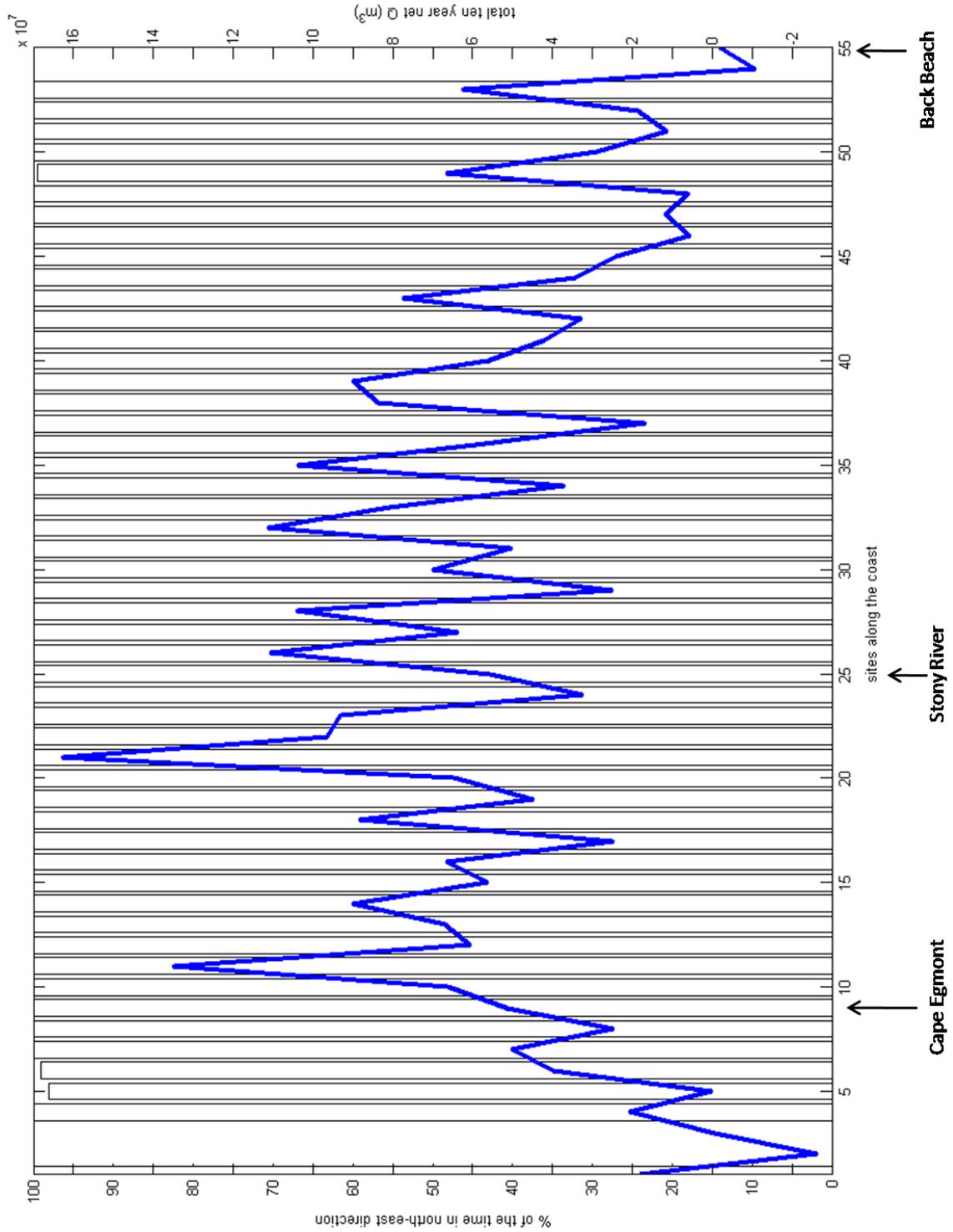


Figure 5.5 Alongshore variation in the total net nearshore sediment transport estimates (Q) (black line) and percentage of time Q is towards the north-east (bars) at each of the 55 locations along the 5m depth contour offshore from the Rahoitu Road to Back Beach coastline between 01-01-98 and 31-12-07.

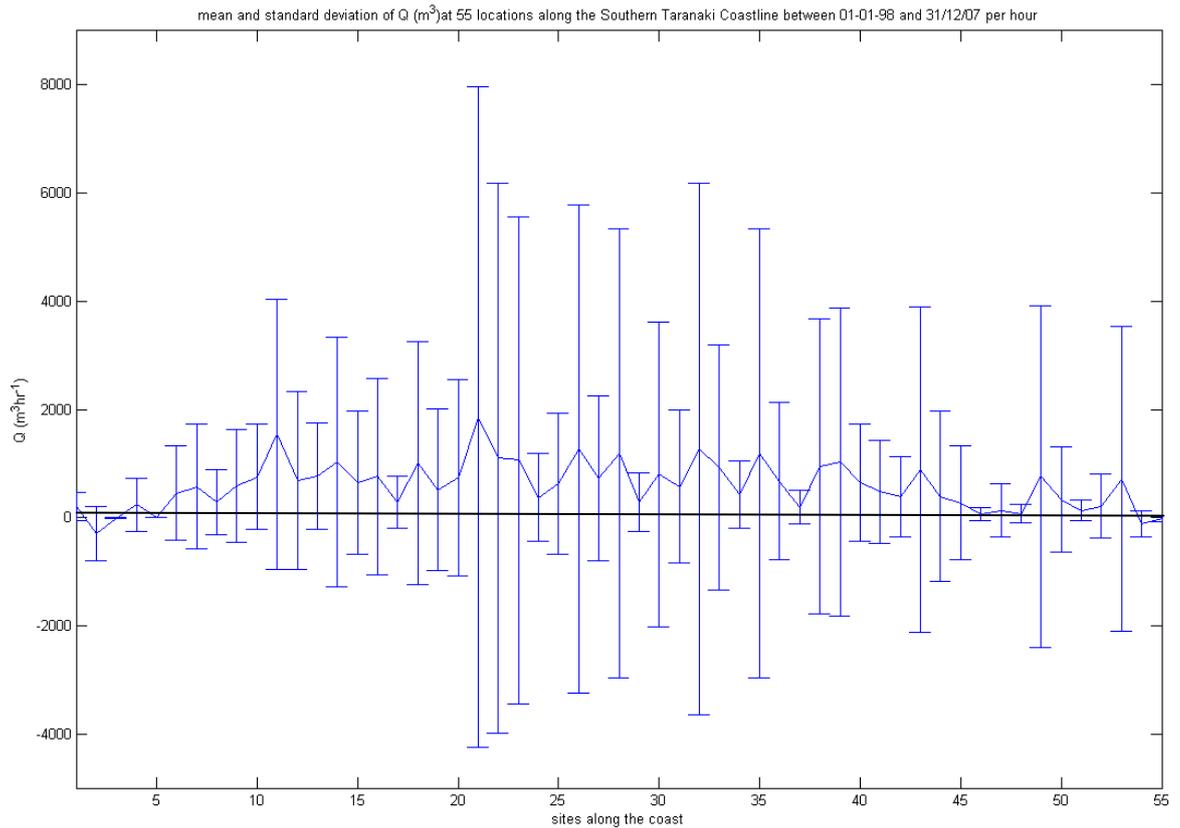


Figure 5.6 Spatial variation in the mean and standard deviation of the potential nearshore sediment transport estimates ($Q(m^3hr^{-1})$) at 55 locations along the 5 m depth contour offshore between Rahotu Road and Back Beach, from where data was extracted between 01-01-98 and 31-12-07.

Summarised in Table 5.2 are the number of storms that occurred over the ten year period between 01-01-98 and 31-12-07. A storm has been defined as when the H_s is greater than the 95th percentile value at over half of the 55 points, between Rahotu Road and Back Beach, which were maintained for greater than 24 hours. Over this ten year period, the greatest number of storms (12) occurred in the months of June followed by October, having 10 storms. In the summer months (December, January, and February) there were only 2 storms, significantly less than the 25 storms that occurred over the winter months (June, July, and August). The mean number of storms to occur annually is 5.6 with a greater number of storms occurring in 1998 followed by 2002, 2006 and 2007 while the fewest storms (3) occurred in 2005. This greater number of storms in 1998 may be a result of the El Niño phase which brings strong south-westerly winds in the spring and summer months (NIWA, 2008).

Table 5.2 Number of storms that occurred between 01-01-98 and 31-12-07 between Rahoitu Road and Back Beach. A storm is defined as when H_s at the 5 m depth contour is greater than the 95th percentile at over half of the 55 sites and is maintained for at least 24 hours.

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	TOTAL
Jan											0
Feb							1				1
Mar	1									1	2
Apr	1	1							1	1	4
May	1			1	2		1	1			6
Jun	1	1	1	1	1	1	2	1	2	1	12
Jul	1				1		1		1		4
Aug		1	1	2	2		1		1	1	9
Sep			1		1	3				1	6
Oct	3		2					1	2	2	10
Nov						1					1
Dec		1									1
TOTAL	8	4	5	4	7	5	6	3	7	7	56

Represented in Figure 5.7 is the variation in the mean net monthly Q over the ten years of data (01-01-98 to 31-12-07) which was calculated along the 5 m depth contour between Rahoitu Road and Back Beach. There is a strong correlation between the number of storms, presented in Table 5.2, and the mean monthly potential Q flux, estimated from the CERC (1973) formula. The greatest potential Q flux was estimated to have occurred in the months of June and October, the months that had the most storms over this ten year dataset (Table 5.2) while the months which had the fewest storms over then ten years (January, February, March, November, and December) had the smallest potential flux Q values.

This correlation between the Q values and the number of storms can be seen when the variation in the annual mean net Q over then ten years of data plotted as is in Figure 5.8. The year with the greatest number of storms over this ten year data set, 1998, has large Q values in comparison with other Q values estimated, while in 2005, the year with the fewest storms, the Q values estimated were relatively small.

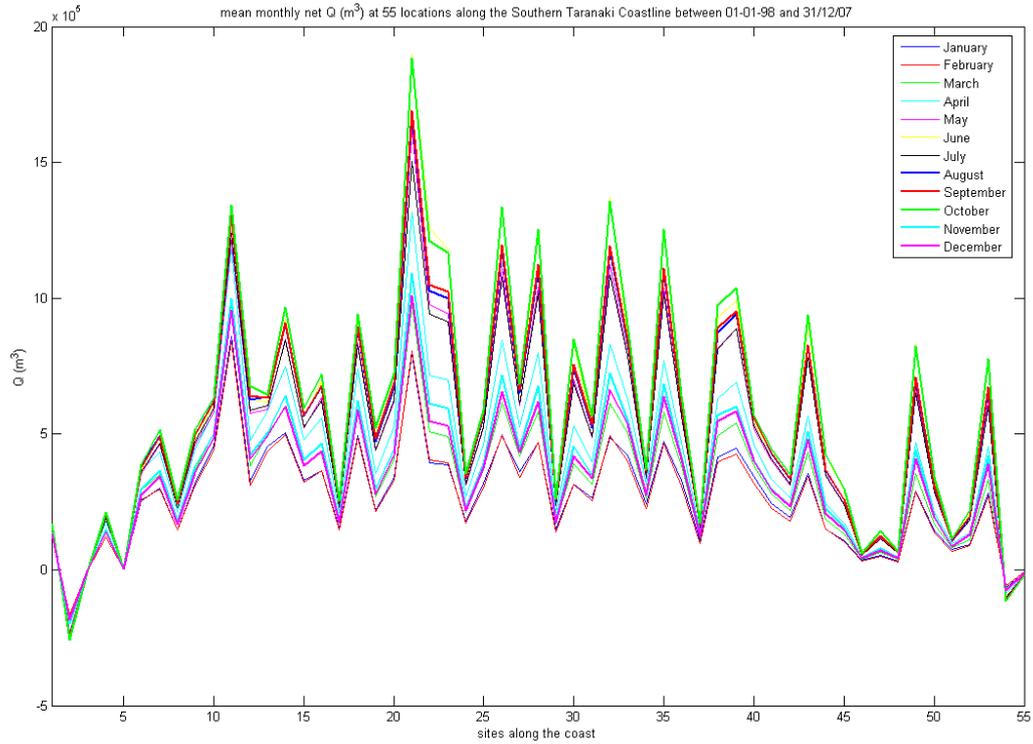


Figure 5.7 Spatial variation in the mean net monthly nearshore sediment transport estimates (Q) at 55 locations along the 5m depth contour offshore from the Rahotu Road to Back Beach coastline between 01-01-98 and 31-12-07.

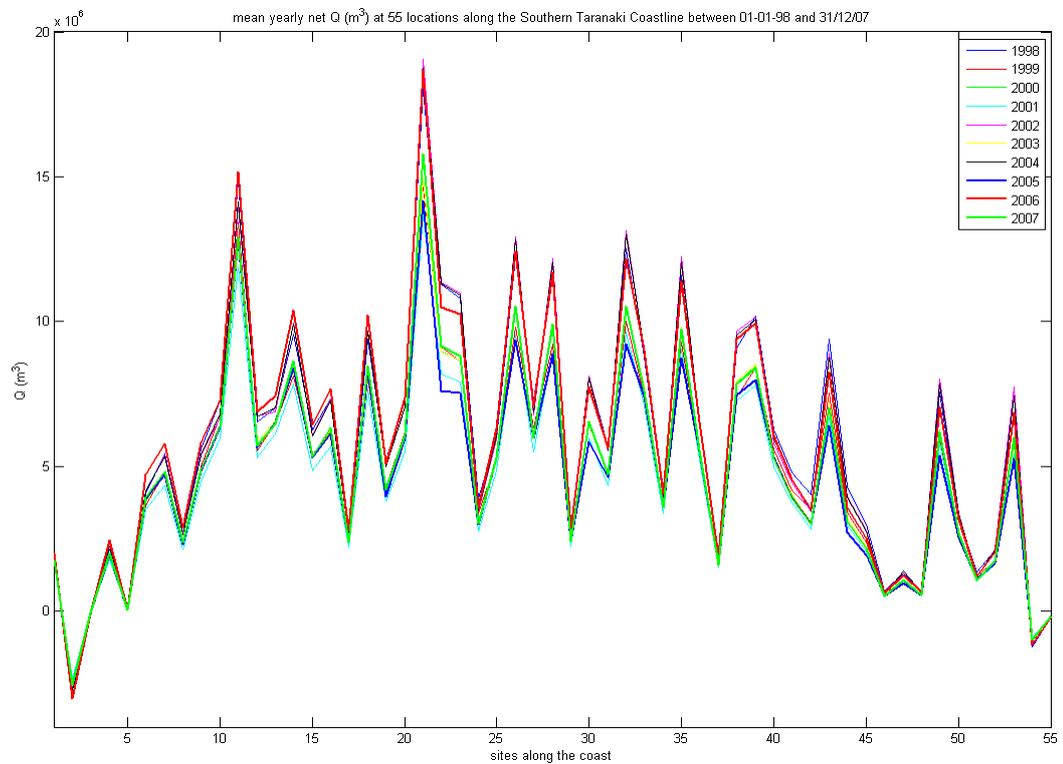


Figure 5.8 Spatial variation in the mean annual net Q nearshore sediment transport estimates (Q) at 55 locations along the 5m depth contour offshore from the Rahotu Road to Back Beach coastline between 01-01-98 and 31-12-07.

Analysis of the forcing factors of the CERC (1973 formula) (H_s and the incidence angle) and Q data indicate that there are 4 distinct sectors along this coastline from Rahotu Road, south of Cape Egmont, to Back Beach in New Plymouth, identified as Segment A, Segment B, Segment C, and Segment D (Table 5.3)

Table 5.3 Statistics for the segments A, B, C, and D, between Rahotu Road and New Plymouth.

	Segment A (Sites 1-10)	Segment B (Sites 11-20)	Segment C (Sites 21-42)	Segment D (Sites 43-55)
Mean coastal orientation (true degrees)	10	37	68	51
Mean wave incidence angle (true degrees ^o)	6.1	16.9	32.5	18.2
Mean H_s (m)	1.88	1.72	1.39	1.19
Mean Q (m ³ yr ⁻¹)	835.6	2389.6	2454.6	881.9
Mean ten year cumulative Q (m ³ towards NE)	24.4 x 10 ⁶	69.8 x 10 ⁶	71.7 x 10 ⁶	25.8 x 10 ⁶

5.5.1.1 Segment A (Sites 1-10)

From Rahotu Road to Cape Egmont, the southern segment, (sites 1-10) the incidence angle is small, however, the waves are large and the Q values are intermediate in comparison with the central and northern segments estimated along this coastal sector (Table 5.3).

5.5.1.2 Segment B (Sites 11-20)

Immediately north of Cape Egmont, Segment B (sites 11 to 20) the mean incidence angle of the waves are slightly smaller than those of the northern segment (Table 5.3). However, the waves are significantly larger than the northern segment (Segment D). This combination of relatively moderate incidence angles and large waves has resulted in a mean Q flux, nearly 3 times the flux found in Segment A and D and slightly lower than the mean Q flux in Segment B.

5.5.1.3 Segment C (Sites 21-42)

Within the central segment of this coastline, the waves are relatively large and the incidence angle increases significantly, being over 5 times the magnitude of the average incidence angle in the southern segment of this coast (Table 5.3). This results in a significantly increased Q value, slightly larger than the average Q flux for Segment B and ~ 3 times the magnitude of the mean Q flux in Segments A and D.

5.5.1.4 Segment D (Sites 43-55)

From Oakura to Back Beach (sites 42-55) in the northern segment of the coastline between Rahotu Road and Back Beach, the incidence angle is of a similar magnitude to that of segment B. However, the wave energy decreases leading to a decrease in the mean Q flux ~ 2.7 times smaller than the Q flux in Segment B.

The small Q values estimated at Back Beach, and the natural basin of sediment that has been deposited, suggest this beach is approximately in dynamic equilibrium. The pinnacles, sea stacks and islands decrease energy of the nearshore wave climate, which in turn has led to the deposition of significant mobile sediments in this region. This natural reservoir of sand may have formed as a result of the coastal orientation changing around the Paritutu headland (McComb, 2001). Quantities of sand in the Back Beach area were identified in the research of Crofskey (2007) who undertook Drop Video (DV) surveys to identify the substrate along a 60 locations around the northern Taranaki headland from Cape Egmont to Motunui during 2005 and 2006 (Figure 5.9). Those survey data clearly showed that the seabed area from Back Beach and Marine Reserve areas had anomalously high coverage of sand, compared with locations to the south.

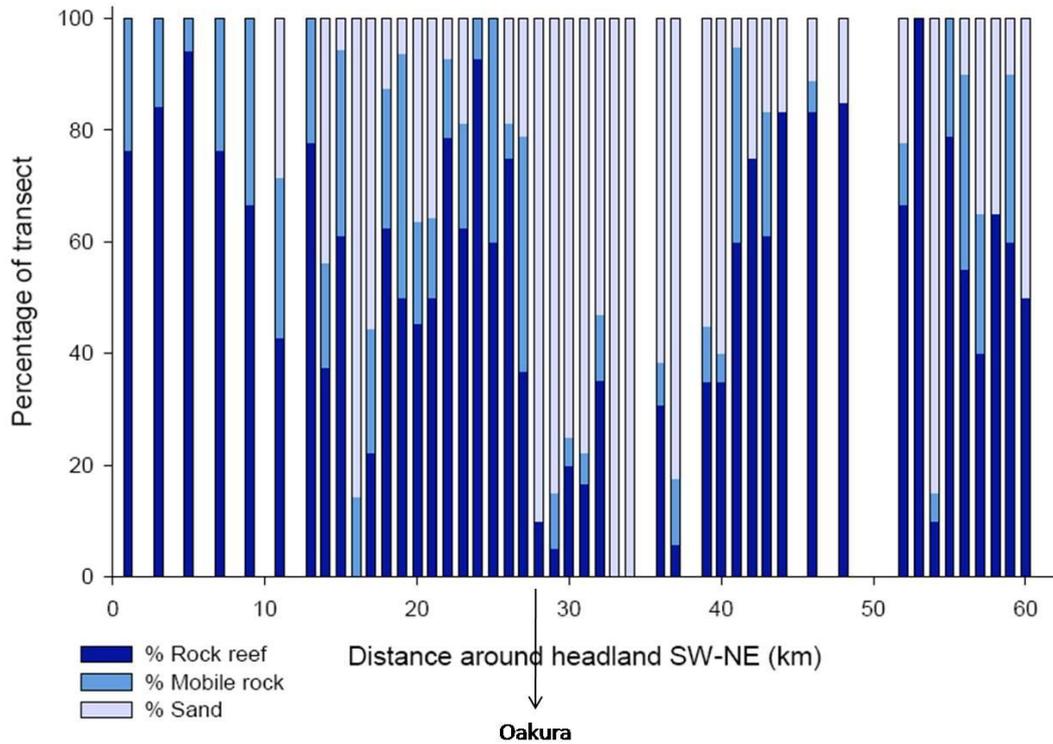


Figure 5.9 The percentages of rock reef, mobile rock and sandy within each transect around the Taranaki Headland. Transect 1 is Cape Egmont, Transect 15 is the Stony River Mouth and transect 36 is Back Beach at New Plymouth.

(Source: Crofskey, 2007).

5.5.2 Local Scale Assessment

Illustrated in Table 5.4 is the median, mean, net Q and the net Q flux per year at 5 key locations between Rahotu Road and New Plymouth.

5.5.2.1 Cape Egmont (Site 10)

At Cape Egmont the coastline is orientated $\sim 7^\circ/187^\circ$ and the mean incidence angle is 21° with a standard deviation of 10.2° . Over the 10 years of model run the sediment transport was always in the positive direction towards the north with a mean potential Q flux value of $2268 \text{ m}^3\text{yr}^{-1}$ at the 5 m depth contour (estimated from the CERC (1973) formula), the largest potential flux, twice than of the flux estimated at Komene Beach and further north at Oakura Beach. The beaches in the vicinity of Cape Egmont expose the wave-cut shore platform (Figure 5.10), which is predominately rocky. A periodic southward directed littoral transport south of Cape Egmont occurs where the average coastal orientation for these

beaches (sites 1-7) is $168^{\circ}/348^{\circ}$. The 10 year SWAN wave data and the CERC 1973 formula gives a mean Q flux of $\sim 500 \text{ m}^3\text{yr}^{-1}$ for these beaches south of the Cape, a significantly smaller potential flux than is estimated north of Cape Egmont.

Table 5.4 Statistics for 5 key locations between Raho Road and New Plymouth.

		Cape Egmont (Site 10)	Komene Beach (Site 24)	Kaihihi Beach (Site 27)	Oakura Beach (Site 44)	Back Beach (Site 55)
Mean (m^3yr^{-1})		2268	1115	2188	1178	-60
Median (m^3yr^{-1})		2251	999	1985	605	-48
Net Cumulative ten year Q (m^3)		66×10^6	32.6×10^6	63.9×10^6	34.4×10^6	-1.76×10^6
Net Q (m^3)	1998	7.3×10^6	39.0×10^6	7.31×10^6	4.32×10^6	-2.06×10^5
	1999	6.7×10^6	3.38×10^6	6.34×10^6	3.42×10^6	-1.74×10^5
	2000	6.3×10^6	3.00×10^6	5.98×10^6	3.21×10^6	-1.6×10^5
	2001	6.0×10^6	2.76×10^6	5.52×10^6	2.97×10^6	-1.55×10^5
	2002	6.7×10^6	3.43×10^6	6.78×10^6	3.97×10^6	-1.95×10^5
	2003	6.4×10^6	3.04×10^6	6.05×10^6	3.22×10^6	-1.65×10^5
	2004	6.8×10^6	3.48×10^6	6.88×10^6	3.93×10^6	-1.94×10^5
	2005	6.4×10^6	3.01×10^6	5.98×10^6	2.72×10^6	-1.57×10^5
	2006	7.3×10^6	3.59×10^6	7.10×10^6	3.58×10^6	-1.87×10^5
	2007	6.4×10^6	3.02×10^6	5.98×10^6	3.09×10^6	-1.61×10^5

Other potential sources of sediment at Cape Egmont are the Oaonui, Okahu and Kapoia Streams which discharge nearby. The median flows of these streams are 430 ls^{-1} , 1045 ls^{-1} and 690 ls^{-1} significantly less than the 3860 ls^{-1} discharge of the Stony River (Taranaki Regional Council, 2005). This reduction in sediment supply and the dominant net northwards directed littoral drift is the reason for the sand-starved nature of beaches in the vicinity of Cape Egmont despite the massive sand injection from the Stony River in 1998.



Figure 5.10 Shore cut platform at Stent Road, Cape Egmont (November 2008).

5.5.2.2 Komene Beach (Site 24)

Approximately 12 km north of Cape Egmont between the Werekino Stream mouth and the Stony River mouth is Komene Beach (Figure 5.11).



Figure 5.11 Komene Beach (South of the Stony Rive) looking south (June 2008).

Komene Beach is a small pocket beach orientated $48^{\circ}/228^{\circ}$. The mean potential Q flux is $1115 \text{ m}^3\text{yr}^{-1}$, similar to Oakura Beach's estimated Q value, and half the Q value magnitude of Cape Egmont and Kaihihi beach. The net potential Q value at Komene Beach (site 24) is $33 \times 10^6 \text{ m}^3$. This reduction in potential Q flux values, and increasing sediment supply from the Stony River, is likely the reason for the accumulation of sediment at Komene Beach. The small headland at the southern end of Komene Beach is responsible for reducing the exposure of this beach to the westerly wave climate (resulting in a low Hs value (1.28 m)) thus reducing the potential Q flux.

5.5.2.3 Kaihihi Beach (Site 27)

On the northern side of the Stony River is Kaihihi Beach, a stretch of coast that has been affected significantly from the influx of sediment from the Stony River (see Chapter Three: Coastline Changes). Kaihihi Beach has an orientation of $67^{\circ}/247^{\circ}$ with an average incidence angle of 34° . The average Hs at the 5 m contour parallel to this beach is 1.35 m. This produces a mean Q potential flux of $2188 \text{ m}^3\text{yr}^{-1}$ with a net potential flux Q value of $6.3 \times 10^7 \text{ m}^3$, slightly less than potential fluxes estimated at Cape Egmont, however twice the magnitude of the flux estimated at Oakura Beach and Komene Road. This indicates that the Kaihihi coast is less conducive to the establishment of the long term sandy beach, and the sediments that are currently observed here are in active transport. Prior to the sandy inundation of 1998 this beach was mostly rocky and devoid of intertidal sand.

5.5.2.4 Oakura Beach (Site 44)

Approximately 13 km north of the Stony River mouth is Oakura Beach, a small pocket beach which has been suffering net erosion since monitoring commenced in the 1970s. Oakura Beach has an average coastal orientation of $70^{\circ}/250^{\circ}$ with an average incidence angle over then ten years of data of 26° and Hs of 1.3 m at the 5 m offshore depth. These variables and the resulting potential net Q flux mean of $3.4 \times 10^7 \text{ m}^3$ is comparable with Q estimated offshore from Komene Beach, ~ 14 km south of Oakura, south of the Stony River mouth. The coastal morphology and volume of sand deposited on Oakura and Komene Beaches are significantly different. It is likely that the vast differences in morphology between

these beaches despite the similar potential Q fluxes estimated is due to the sediment derived from the 1998 Stony River outbreak having not been transported in the north-east directed littoral drift as far as Oakura Beach. Oakura beach is controlled by the headland/reef immediately to its south which injects sediment pulses periodically onto the beach (McComb et al., 2005). This headland is substantially larger than the smaller headland to the south of Komene Beach and from monitoring of coastline changes and sediments (see Chapters Three: Coastline Changes and Four: Sediment Characteristics) it is thought that the sediment derived from the Stony River is accumulating on the southern side of this headland.

5.5.2.5 Back Beach (Site 55)

The most northern point modeled, Back Beach, in New Plymouth is orientated at $43^{\circ}/223^{\circ}$ in the lee of the Sugar Loaf Islands with a relatively large mean incidence angle of 30° and a small H_s of 1.1 m at the offshore depth of 5 m. Over this ten year data set this incidence angle frequently changes between a potential flux towards the positive (north-east) and negative (south-west) direction. Back Beach has a mean potential Q flux value of $60 \text{ m}^3 \text{ yr}^{-1}$ towards the south-west, and a net potential Q flux value of $1.8 \times 10^6 \text{ m}^3$ also towards the south-west. Essentially this suggests that Back Beach is in a dynamic equilibrium with respect to the wave-driven sediment transport potentials. The surveys and observations to date indicate that Back Beach has not been significantly influenced by the sediment outburst from the Stony River in 1998. However, there may be other dynamical processes occurring at Back Beach, as a result of the Sugar Loaf Islands and active sediment bypassing of the headland due to current patterns that are not considered with the CERC potential Q estimates.

At Back Beach the governing factor for sediment to diffuse around the headland is the wave energy and sediment supply. Only would a very large increase in sediment elevation at depths $< 10 \text{ m}$ result in the sediment transport fluxes increasing around the Paritutu headland and sediment diffusing into Port Taranaki. With the diminishing size of the 'pulse' of sediment, derived from the Stony River, it is not likely to result in an increase in sediment transport around

the headland, thus there will not be a need for more frequent dredging within Port Taranaki.

5.6 SUMMARY

Longshore sediment transport fluxes offshore along the 5 m contour between Rahotu Road and Back Beach in New Plymouth has been examined, based on a 10-year wave hindcast. The nearshore wave height and wave direction were used to estimate a flux potential at 55 discrete locations with the CERC (1973) formula.

Significant wave heights decreased with distance north of Rahotu Road around the Northern Taranaki headland due to:

- the exposed nature of the coast near Cape Egmont to the dominant south-westerly swells;
- the greater seabed gradient near Cape Egmont; and
- the orientation of the Taranaki Peninsula and the incidence swells resulted in a wave refraction shadowing pattern occurring.

The number of storm events and the mean monthly and annual net Q value is highly correlated, as expected. The greatest Q fluxes were estimated to have occurred in June and October, the months that had the most storms over the ten year data sets and those months with the fewest storms had the smallest Q values. Annually, the greatest number of storms occurred in 1998, a year with relatively large Q values, while in 2005 there were few storms with small Q flux values estimated.

There are four distinct regions along this coastal sector:

- *Segment A (from sites 1 – 10)* – low incidence angles, large waves, and intermediate potential Q flux values. At Cape Egmont, the northern point within this segment, the coastline is relatively north-south orientated. Typically the potential Q flux is low at the southern end of this segment, near Rahotu Road, and increases with distance north to Cape Egmont.

- *Segment B (from sites 11-20)* – moderately sized incidence angles with large waves leading to a large potential Q flux. Like Segment A, this coastal segment is devoid of sediment deposits. Along this segment the potential Q flux values decrease until site 17, indicative of deposition occurring, before increasing to a maximum potential Q flux at site 21, slightly south of the Stony River mouth.
- *Segment C (from sites 21-42)* – large waves and large incidence angles result in the potential Q flux estimated slightly larger than the average potential Q flux estimated in segment B and ~ 3 times the magnitude of the Q flux estimated in segments A and D. Within this central segment is Komene Beach, immediately to the south of the Stony River mouth and Kaihihi Beach to the north of the river mouth. Komene Beach is a small pocket beach bounded to the left by a small headland. This headland shelters this beach from the dominant south-westerly swells, reducing the Q values estimated and can potentially be attributed to the repository of sediment that has accumulated here. On the northern side of the Stony River mouth, the once sediment starved beach, Kaihihi Beach, is a large repository of sandy sediment derived from the Stony River mouth. The potential longshore sediment flux estimated along this beach is nearly twice that of the flux estimated along Komene Beach however the quantity of sediment deposited here is much greater due to the dominant north-east directed littoral transport depositing material derived from the Stony River. Alongshore variations in the potential Q flux values shown that from Kaihihi Surf Beach to Back Beach the general trend is decreasing potential Q flux values.
- *Segment D (from sites 42-55)* – large incidence angles and decreased wave energies result in a decreased Q value. The sediment derived from the Stony River has not yet been transported into this northern segment. Decreasing potential Q flux values from site 21 to Back Beach in this segment has resulted in significant volumes of sediment being deposited on the sub-aerial beach and offshore. A diffusive headland has formed as a result of the Sugar Loaf Islands which significantly reduce the nearshore wave energy.

The findings of this chapter in relation to the slug of sand that was eroded in Little Pyramid and transported down the Stony River indicate that the majority of the sediment that reaches the littoral system has the potential to be transported at great rates south of Oakura Beach before these potential rates decrease, indicative of the natural basin of sediment that is present between Oakura and Back Beach. This decrease in the potential sediment transport flux is indicative of the high residence time of individual sediment grains within these equilibrium beaches. This sand slug is likely to have diminished in size substantially when it reaches the diffusive Paritutu headland, where there will be insufficient sediment supply and energy for any substantial volumes of sediment to be transported into Port Taranaki.

An increase in sediment within the Port of Taranaki, and the need for more frequent dredging will be preceded by a substantial increase of volume in depths < 10 m along Back Beach. It is therefore recommended that Back Beach be regularly monitored through regular beach profiling which would indicate a substantial increase in beach sediment offshore.

The following chapter aims to quantify the volume of material that has been eroded from the headwaters of the Stony River and the present volume of sediment that can currently be identified.

CHAPTER SIX: SEDIMENT BUDGET FOR A SEGMENT OF THE TARANAKI PENINSULA

6.0 INTRODUCTION

The Shore Protection Manual (U.S. Army Corps of Engineers, 1984) defines a sediment budget as ‘a sediment transport volume balance for a selected segment of the coast....based on the quantification of sediment transportation, erosion, and deposition’. A sediment budget is an accumulation of all sediment inputs, transport pathways, and sinks. The difficulty in undertaking sediment budgets is to accurately quantify all the sources and sinks across a coastal sector. Sources of sediment (inputs) to the littoral system include erosion from the beach and cliffs, fluvial inputs, supply from dunes and from the offshore beach while sediment sinks (outputs) include losses from the system via dredging, the mining of sediment in the beach and nearshore, losses to submarine canyons, sediment storage in the backshore and dunes, and losses to inlets and lagoons. Sediment transport pathways within a beach system include parabathic (longshore) sediment transport, diabathic (cross-shore) sediment transport, aeolian transport, and bypassing of tidal inlets.

A paper incorporating data from this chapter was presented at the Coasts and Ports Conference and Wellington, New Zealand in September 2009 and a proceedings paper (Appendix A) was published as:

Cowie, N.A., Healy, T. R., and McComb, P. J., 2009. Sediment Budget for an Episodic Injection on a High Energy Coast, Paper 17.

This chapter attempts to quantify the volume of material that has been eroded from the gully in the upper catchment, near the headwaters of the Stony River, and the present-day volume of sediment deposited on the sub-aerial coast between Komene Road and Ahuahua Beach and in the Stony River channel, as aggradation deposits. This forms the basis of sediment budget estimates. Additional estimates of sediment derived from streams, cliff erosion, and pebble abrasion, from Matthews (1977) has been incorporated into this budget as well as potential

longshore sediment transport flux rates (see Chapter Five: Longshore Sediment Transport). The exchange of sediment in the cross-shore direction (diabathic sediment transport) has been ignored, but it is important to note that the cross-shore sediment transport processes do occur along this coastal sector, as it is necessary to transport sediment outside the surf zone and bypass intervening headlands along this rocky coastline.

6.0.1 Previous Applications of Sediment Budgets along the Taranaki Coast

- Matthews (1977) estimated sand budgets for two littoral cells, Cape Egmont to Opunake and Cape Egmont to New Plymouth. His research determined the longshore transport rate by incorporating dredging records, rates estimated by Holmes (1976), and drift rates estimated by the Hydraulics Research Station (1963) in Wallingford. To determine the stream supply he used the Langbein and Schumm (1958) relationship (later modified by Komar (1976)) between runoff, catchment area and sediment discharge and estimated that between 36,000 m³ and 55,000 m³ of sand is annually supplied to this coastline, between Cape Egmont and New Plymouth. This input of sediment was considered the greatest supply of sediment to the coast. Sediment inputs via cliff erosion were estimated by evaluating erosion rates, which were calculated using cliff heights and lengths, aerial photographs, and surveying erosion with marker pegs. It was estimated that the rate of erosion from cliffs is 0.38 m annually, and the volume of active cliff face between Cape Egmont and New Plymouth was ~ 600,00 m². Assuming that the cliffs are composed of 30% sand it was estimated that between 35,000 m³ and 45,000 m³ is delivered to the littoral system annually. Grain analysis estimated that 5-10 % of the sediment that is in littoral transport is skeletal calcium carbonate, resulting in the total volume estimate from biogenic inputs for the littoral cell between Cape Egmont and New Plymouth, estimated to be between 4,000 m³yr⁻¹ and 18,000 m³yr⁻¹. The volume of sediment derived from pebble abrasion, between Cape Egmont and New Plymouth, was crudely estimated to be < 10,000 m³yr⁻¹ from the analysis of pebble abrading

processes. Side-scan sonar indicated that there were no large reservoirs of sand that could provide sediment to the littoral system and data from Holmes (1976) proved that there was little movement of dredge spoil from Port Taranaki. It was thus concluded that the supply of sediment from the continental shelf was negligible. The contribution of sediment to the shore via aeolian processes was also considered negligible as the dunes are semi-fixed and vegetated with marram grass, lupin and box thorn and reference pegs showed no notable movement in the dunes. The estimated sediment inputs determined from his research indicates that the littoral cell between Cape Egmont and New Plymouth is in a deficit where more sand is moving out of the cell than into it.

6.1 METHODS

6.1.1 The Scarp in the Headwaters of the Stony River

To determine the volume of sediment derived from the gullied upper Stony River, the actively eroding part of the gully was divided into sections with approximately the same valley width and depth. This was completed with the aid of stereoscope images taken in 2007. The scarp evident on these images was then projected onto a 1:50,000 topographical chart. This enabled cross-sections of each sector to be undertaken. The length of each sector was measured enabling the volume of each sector that has been eroded away to be estimated. Lastly each of the segment volumes were summed together to give an estimate of the volume of sediment that has been eroded from the gully.

6.1.2 Sand deposited along the Stony River Channel

The rate at which sediment, derived from the scarp at Little Pyramid in the headwaters of the Stony River, is transported down the river affects the building and modification of alluvial landforms. The construction of bars, floodplains, and deltas is dependent on sediment supply where a large increase in sediment supply in a channel results in floodplain aggradation and the construction of terraces (Hoffman and Gabet, 2007).

To determine the sediment deposits along the Stony River channel firstly the aggradational areas of the Stony River were identified using stereoscope images. From the analysis of stereoscope images, it was assumed that the average thickness of these deposits is 1 m and this enabled an estimate of the volume of sediment deposited along the Stony River channel to be calculated.

6.1.3 Sand in the sub-aerial beach system

Previous photographic, visual (see Chapter Three: Coastline Changes) and grain size (see Chapter Four: Sediment Characteristics) data has indicated that the sediment derived from the Stony River has been transported in the north-east directed littoral transport, and has reached as far north as Ahuahu Beach. This sediment sits on the upper beach and is only eroded away during high tide storm events where there is sufficient energy to mobilise this sediment. The volume of sand in the sub-aerial beach system was determined in Chapter Three: Coastline Changes, and these results are incorporated into this sediment budget.

6.1.4 Offshore Sediment

Offshore from profiles 1-6 (see Chapter Three: Coastline Changes) the substrate was determined as being either boulders or sand. Using the Department of Conservation's Orca boat drop video (DV) images were taken along transects every 50 m from ~ 22 m to ~ 6 m depth. This method proved successful with the substrate being clearly identifiable with a visibility of ~ 6-7 m.

Transects offshore from sub-aerial beach profiles 1, 2, 3 and 5 were undertaken on Tuesday 4th February 2009 at 0906 hrs, 0830 hrs, 1010 hrs and 1045 hrs respectively, while the transects offshore from profile 4 was undertaken on Monday 2nd February at 1330 hrs (See Figure 3.2 in Chapter Three: Coastline Changes). Four different substrates were identified along this coastline shown as illustrated in Figure 6.1.

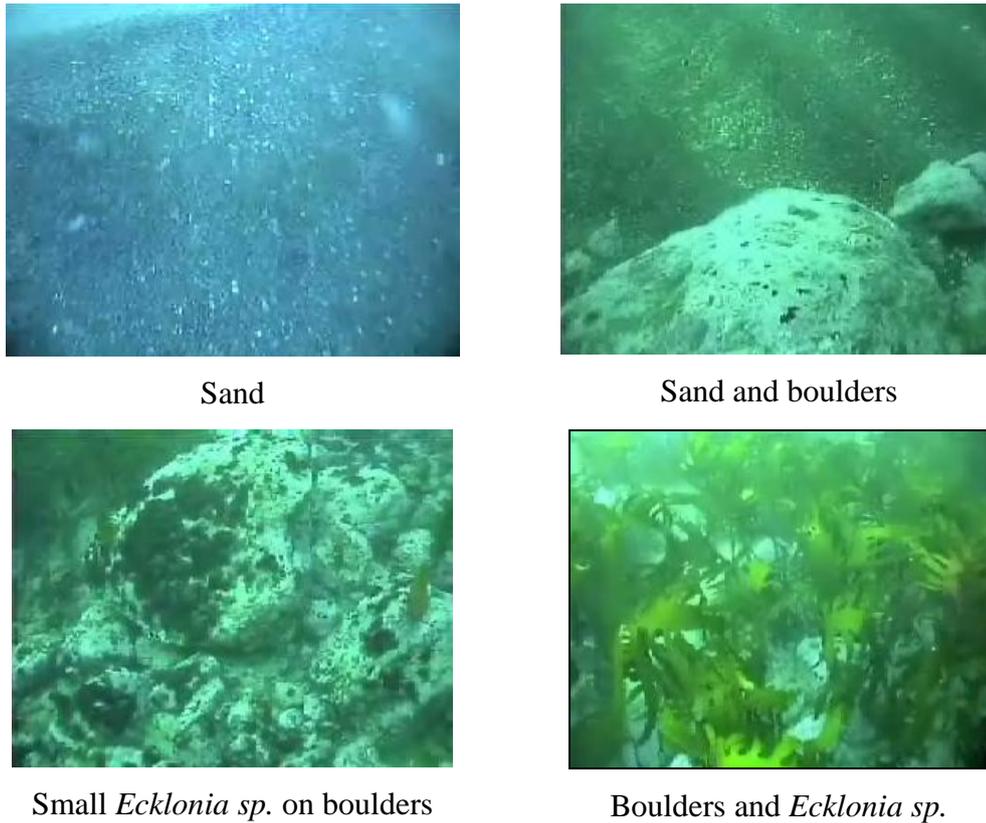


Figure 6.1 Different substrates encountered offshore from the Taranaki Headland

6.2 SEDIMENT BUDGET

6.2.1 The Scarp in the Headwaters of the Stony River

Illustrated in Figure 6.2 is the eroded part of the gully divided into sections with approximately the same valley width and depth. This gully is composed of three small tributaries which have formed before joining the large channel gully. The cross sections of each of these sections are illustrated in Figure 6.3 and the length, cross-section area and volume of each sector is listed in Table 6.1. The gully system was estimated to have had $\sim 14,400,000 \text{ m}^3$ of sediment eroded away. Not all of this sediment can be attributed to the 1998 breakout. This is evident in Figure 6.3 (particularly the sectors 1B, 1C, 3A, and 3H) where the cross-sections indicate that there have been at least two main erosive events.



Figure 6.2 The eroded gully in the headwaters of the Stony River (Little Pyramid), divided into segments to determine the cross-sectional area and volume of the material that has been eroded from this scarp.

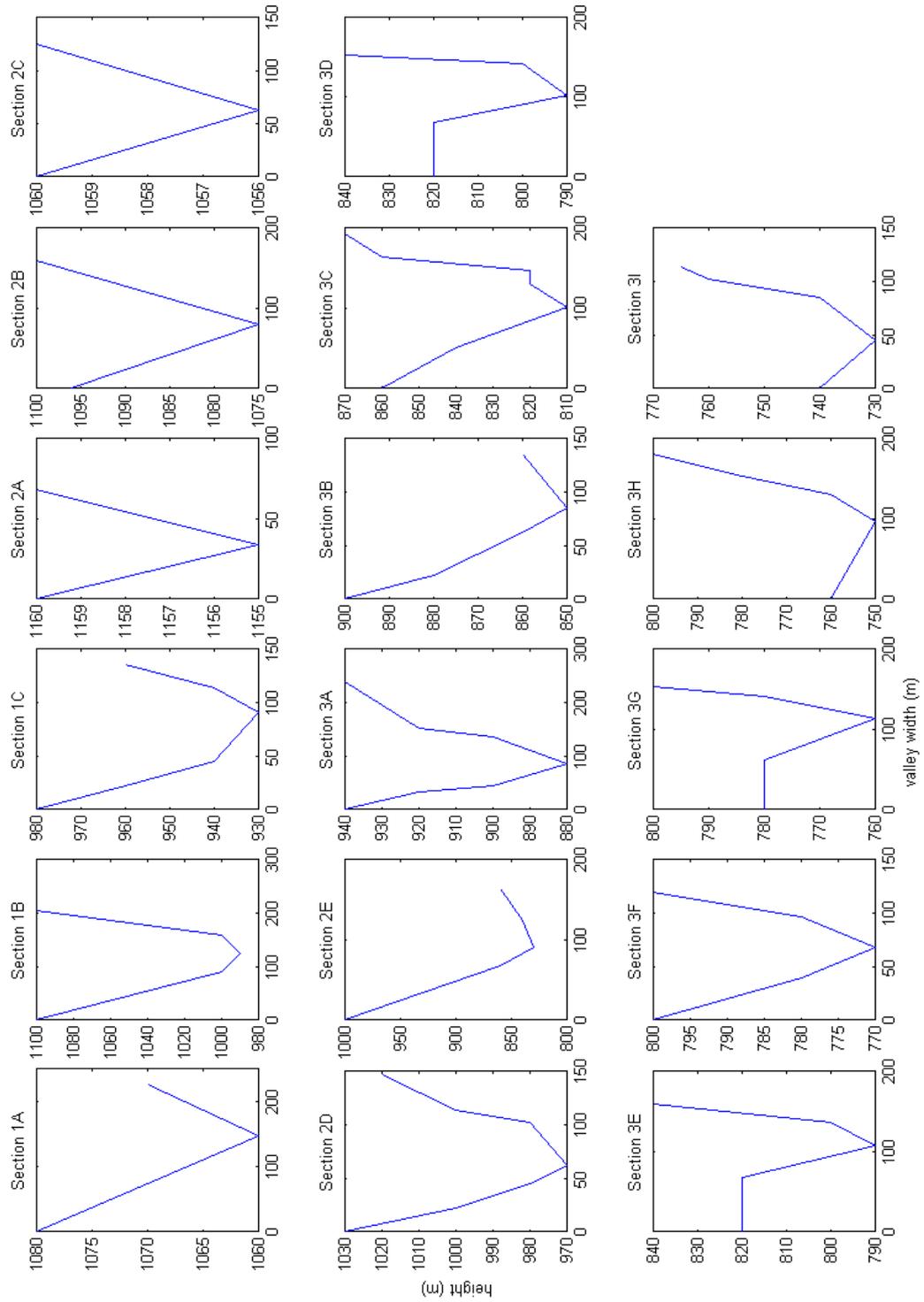


Figure 6.3 Cross-sections of the gully illustrated in Figure 6.2

Table 6.1 Length, cross-section area, and the volume of each sector (as illustrated in Figure 6.2 and Figure 6.3).

Section	Length (m)	Cross-Section Area (m ²)	Section Volume (m ³)
1A	476.7	1440	686,448
1B	227	13840	3,141,680
1C	261.05	3243	846,585
2A	368.875	170.25	62,801
2B	197.5	124.85	24,658
2C	249.7	238.35	59,516
2D	4854.75	221.325	1,074,478
2E	8321.5	351.85	2,927,920
3A	351.85	6494.5	2,285,090
3B	158.9	2007	318,912
3C	124.85	5147.5	642,665
3D	175.925	2612	459,516
3E	175.925	216.5	38,088
3F	124.85	2018.75	252,041
3G	136.2	1589.1	216,435
3H	244	3558	868,152
3I	317.8	1468.875	466,809
4A	387.5	140.74	54,537
TOTAL VOLUME ERODED FROM SCARP (m³)			14,426,330

6.2.2 Sand Deposited Along the Stony River Channel

From the base of the scarp (see sector 3I in Figure 6.2) the Stony River channel has sediment deposited for 10.3 km. From the use of stereoscope images it was estimated that over this 10.3 km length the approximate volume of sediment is 3,289,000 m³.

6.2.3 Sand in the sub-aerial beach system

Illustrated in Table 6.2 is a summary of the sediment that can be identified in the sub-aerial beach between Komene Beach and Ahuahu Beach. This data was estimated from averaging the volume of sediment per metre, (from beach profiles undertaken in 2008/2009) and using aerial photos, dated 2007, to determine the sand coverage at each area (see Table 3.5 in Chapter Three: Coastline Changes).

Table 6.2 Sediment that can be identified in the sub-aerial beach between Komene Beach and Ahuahu Beach

Location	Sub-Aerial beach (m ³)
Komene Beach	535,000
Kaihihi Surf Beach	1,468,000
North of Kaihihi River	817,000
Fort St. George	455,000
Ahuahu Beach	274,000
TOTAL	3,549,000

6.2.4 Offshore Sediment

From offshore images undertaken in the vicinity of the Stony River mouth, it is estimated that sand is deposited between 6 and 19.5 m depth offshore between Komene Road and Ahuahu Beach with an area of ~122,000 m². However, the depth of this sand coverage is unknown as it occupies the crannies and interstitial spaces between larger sediments. Crofskey (2007) undertook a much more comprehensive study also using the drop video technique to map the area and identify prevalent characteristics of the sub-tidal bottom topography (rocky reef and surficial sediments), between Cape Egmont and Motunui (see Chapter Five: Longshore Sediment Transport for methodology). Her research found areas of boulder rocks and mobile reefs dominate between 800 m and beyond 4 km offshore near Cape Egmont. Approximately 15 km north of Cape Egmont where the Stony River discharges into the Tasman Sea her survey identified a rapid change in substrate where the whole rocky reef is predominately (83 %) covered by sand. With distance north from the Stony River mouth the percentage of rock reef increases to a maximum 24 km north of Cape Egmont slightly south of Oakura (Figure 5.9).

6.2.5 Longshore Sediment Transport

Using quantitative longshore drift prediction from Chapter Five: Longshore Sediment Transport, longshore sediment rate flux values annually over 10 years (01-01-98 to 31-12-07), were estimated. The mean potential sediment transport flux rates (Table 5.3) were incorporated into this sediment budget illustrated in

Figure 6.4. Sedimentation rates within Port Taranaki are $174,000 \text{ m}^3\text{yr}^{-1}$ (McComb and Black, 2000), thus it can be concluded that significant volumes of sediment are deposited in the vicinity of Back Beach. At Back Beach, a natural basin of sediment has been deposited as a result of pinnacles, sea stacks and islands (The Sugar Loaf Islands) causing wave refraction, thus the deposition of sediment.

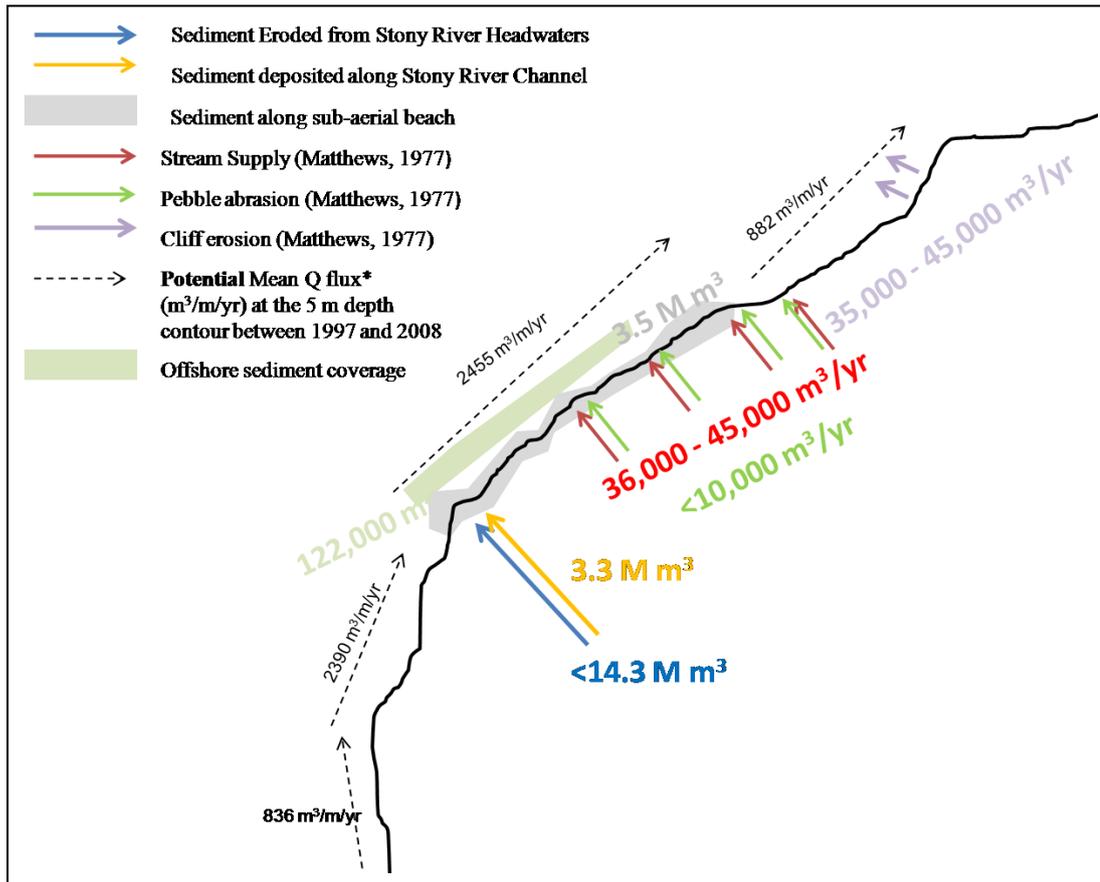


Figure 6.4 Schematic illustrating the estimates of annual inputs, outputs and throughputs to the coastal sector between Cape Egmont and New Plymouth. *The potential longshore sediment transport flux was calculated using the CERC (1973) formula. This formula assumes that the beach is a long and sandy open coast with a continuous supply of sand that that all the energy is associated with a single peak in the wave spectra (see Chapter Five: Longshore Sediment Transport).

6.3 DISCUSSION

Of the 14.4 M m^3 of sediment estimated to have been eroded from the gully system located at the headwaters of the Stony River, only 6.8 M m^3 of sediment can be accounted for in the current sub-aerial beach between Komene Road and Ahuahu Beach (Table 6.2) and deposited along the Stony River channel.

As illustrated in Figure 6.5 substantial volumes of sediment are retained, along the Stony River channel, as boulders. Visually, this is likely to account for ~ 20% of the sediment that was estimated to have been eroded from the scarp in the headwaters of the Stony River.



Figure 6.5 Aerial view of a segment of a Stony River channel illustrating significant volume of sediment retained in boulder clasts.

The remaining 7.6 M m^3 of sediment that has been eroded from the gully system may have been deposited offshore. If all this sand was deposited offshore (500 m from the shoreline up to Ahuahu Beach, 14 km from Komene Road) a 2 m thick layer of sediment would be deposited. The interstitial spaces within the rocky cobble and boulder reefs provide significant sandy sediment storage are not accounted for from undertaking DV images. McComb (2001) undertook side-scan surveys and found that regions of significant offshore sediments coincide with seabed depressions and on the western flanks of raised bathymetric features. His study found that while the seabed topography influences the sediment transport, rocky regions do not bring about the long term settlement of littoral sediments.

Significant quantities of sediment derived from the scarp in the headwaters of the Stony River have been transported further north along the Taranaki headland, and to date have reached as far north as Ahuahu Beach. It was estimated that the mean potential longshore sediment flux along this coast at the 5 m contour between 01-01-98 and 31-12-07 ranged between 836 m³/m/yr and 2455 m³/m/yr with the greatest potential transport occurring in the vicinity of the Stony River mouth. Sediment is therefore rapidly transported as it is ejected from the Stony River mouth. As this sediment is transported north-east around the Taranaki headland the potential sediment transport flux decreases, aiding in the deposition of sediment derived from the Stony River. As discussed in the previous chapter this potential flux was calculated under the assumptions that the beach is a long and open sandy coast with a continuous supply of sand, and all the energy is associated with a single peak in the wave spectra.

6.5 SUMMARY

Of the 14.4 M m³ of sediment identified as having been eroded from the gully system in the headwaters of the Stony River, approximately 3.5 M m³ of sediment has been accounted for on the sub-aerial beach between Komene Road and Ahuahu Beach. Approximately 3.3 M m³ has been identified as being deposited along the Stony River channel. The remaining 7.6 M m³ of sediment is likely to be deposited in the nearshore, overlying the wave swept boulder platform and in the interstitial space of the sediments that form these shore platforms. A significant volume of this sediment is also likely to have been transported in the north-east directed littoral transport as far north as Ahuahu Beach. Additional minor inputs include stream supply, pebble abrasion, cliff erosion which has been estimated by Matthews (1977) and are incorporated into this sediment budget.

In order for a fully quantifiable sediment budget to be completed between the Stony river mouth and Back Beach, it is recommended that future research entails:

- a quantification of the cross and longshore sediment transport rates;
- an estimation of the sediment load currently being discharged from the Stony river channel; and

- an accurate survey to determine the extent and thickness of the offshore sand coverage.

CHAPTER SEVEN: CONCLUSIONS

7.0 INTRODUCTION

In 1998, persistent heavy rainfall resulted in the collapse of scoriaceous sand and gravel on the side of Mount Taranaki, leading to a massive injection of sediment directly into the Stony River and into the rugged Taranaki coastline. This shoreline was typically comprised of narrow cobble to boulder foreshore above a rugged wave-cut shore platform, carved into lahar deposits from the nearby andesitic cone of Mount Taranaki.

Since the initial collapse in 1998, the adjacent shoreline has experienced considerable influx of dense 'black' titanomagnetite rich volcanic sands from the Stony River. These sediments are being rapidly transported to the north-east by the energetic wave climate, creating upper-shore sandy beaches on what is normally a rocky boulder coast devoid of sand.

This study aimed to investigate the extent of the sand injected into the littoral zone of the Taranaki high energy coast, and the impacts this sediment has had on this coastline to date. The key findings of this study follow.

7.1 SUMMARY OF KEY FINDINGS

7.1.1 Coastline Changes

The analysis of aerial photos dated 1995 (prior to the Stony River outbreak), 2001, and 2007 illustrate a rapid increase of aerial sand coverage since the injection of sediment into this littoral system as a result of the Stony River outbreak in 1998. Beach profiles, on the sub-aerial beach, conducted during the course of the study illustrate that beaches to the south, and including Ahuahu Beach characteristically have greater elevated dunes than those further north towards Back Beach in New Plymouth. By combining this beach profile data with the historical aerial photographs, volumes were estimated. It was estimated that between Komene Road and Ahuahu Beach there is nearly 3.5 M m³ of sediment deposited along the sub-aerial beach. The findings illustrate that the sand derived

from the Stony River sits on the upper portion of the sub-aerial beach above the high tide mark. This sediment is only transported on the high/spring tide storm events where there is sufficient energy for this dense iron-sand to be mobilised. To date, the sediment derived from the Stony River has only been transport as far north as Ahuahu Beach.

7.1.2 Sediment Characteristics

Analysis of sub-aerial beach samples collected during the course of this study, were analysed using the Rapid Sediment Analyser at the University of Waikato. These analysis results indicated that (1) with distance north of Komene Road, just south of the Stony River mouth, there is an decrease in the sediment's mean grain size from an average size of 0.41 mm at Komene Road to an average sediment size of 0.29 mm at Back Beach; and (2) there is a slight increase of sorting with distance north-east of the Stony River mouth from an average sorting value of 0.69 mm at Komene Road to an average sorting value of 0.72 mm at Back Beach. This decrease in mean grain size and increase in sorting is indicative that sediment is continually being reworked as it is transported in the north-east directed littoral system.

Mineralogical analysis was conducted on samples collected in February 2009 at four locations along the Taranaki coast, namely, the Stony River mouth, Back Beach, Fitzroy Beach and the Waiwhakaiho River mouth. Using an Olympus Petrographic Microscope and a swift point counter the proportion of the dominant minerals at each site was determined on the first 200 grains encountered in each sample. It was found that at the Stony River mouth and Fitzroy Beach, all the sediments were dominated by the heavy mineral titanomagnetite, and contained smaller proportions of the opaque minerals, augite, hornblende, and plagioclase feldspar.

7.1.3 Longshore Sediment Transport

Using the SWAN numerical model, wave climate parameters were determined at the 5 m depth contour, approximately every 200 m between Rahoitu Road (south of Cape Egmont) and Back Beach, immediately south of Pork Taranaki in New Plymouth. Data was stored every three hours between for ten years, between 01-

01-98 and 31-12-07. H_s decreased with distance around the headland, north of Rahotu Road towards Back Beach due to:

- the exposed nature of the coast, near Cape Egmont, to the north-westerly swells;
- the increased gradient of the coast near Cape Egmont (1:80) in comparison to the more subtle gradient at Back Beach (1:95); and
- the orientation of the Taranaki peninsula and incidence swells result in a wave refraction shadow pattern.

The H_s and α_b were input parameters into the CERC (1973) longshore sediment transport equation, which was used to determine the potential longshore sediment transport (Q) flux at each of the 55 locations. The potential Q flux was divided into four main segments from Rahotu Road to Back Beach, namely A, B, C, and D.

Segment A – The southern segment, between Rahotu Road and Cape Egmont has moderate potential Q flux values as a result of relatively low incidence angles and moderate wave energies. Typically this segment's shoreline is devoid of sediment.

Segment B – Between Cape Egmont and the headland to the south of the Stony River, large potential Q flux values were estimated as a result of moderate sized incidence angles and high wave energies. Like segment A, this segment's shoreline is also devoid of sediment.

Segment C – Between the headland of the Stony River and slightly south of Oakura, is where there have been large alterations to the sub-aerial beach as a result of the 1998 influx of sediment from the Stony River. The large waves and high incidence wave angles along this coastal sector result in a Q value substantially greater than other sectors along this coast.

Segment D –The beaches in the northern segment, between Oakura and Back Beach have lower potential sediment transport rates than Section C. At Back Beach, the Q values suggest the coastal alignment is in approximate equilibrium with the wave climate. The survey results to date suggest the sediment slug will

have only minimal effects on Back Beach, as the sub-aerial sediment volumes are observed to diminish rapidly with distance north of the Stony River mouth. Similarly, it is possible that the sediment injection will not substantially increase the annual volumes of sediment entering Port Taranaki. A significant change to the nearshore sediment volumes at the eastern end of Back Beach would precede any changes to the flux past the Paritutu Headland.

7.1.4 Sediment Budget for a Sediment Starved Coast

It was estimated that $\sim 14.4 \text{ M m}^3$ of sediment has eroded from the gully system at Little Pyramid in the headwaters of the Stony River. Beach profile and aerial photo analysis have estimated that $\sim 3.5 \text{ M m}^3$ of sediment is currently situated on the sub-aerial shore between Komene Road and Ahuahu Beach, and stereoscope images were used to estimate that $\sim 3.3 \text{ M m}^3$ of sediment is deposited along the Stony River channel as aggradation deposits. The remaining 7.6 M m^3 of sediment is likely to have been transported to the sub-tidal zone, overlying the wave-swept boulder platforms and within the interstitial space of the boulders that overly this platform. Significant volumes of sediment have been transported to the north-east in the littoral drift system, with a large potential sediment transport rate between Komene Road and Oakura Beach. Including and north of Oakura, theoretically, the transport will reduce significantly as a result of decreasing wave energy and accordingly the modeled potential sediment transport rates will result in sediment being deposited.

7.2 IMPLICATIONS FOR SPONSORS

The Taranaki Regional Council aims to manage the use, development and protection of our natural and physical resources for present and future generations while the New Plymouth District Council is responsible for the management of the environmental, social, economic, and cultural well-being of the New Plymouth District. Within the New Plymouth District Council the Coast Care Programme aims to protect and sustain the natural and manmade coastal area through the monitoring of erosion and seasonal tidal events (NPDC, 2009). The issues of concern to both the Taranaki Regional Council, and the New Plymouth

District Council, arising from this study, relate to the impact on the sand 'slug' has on the nearby coastline. The sediment derived from the scarp in the headwaters of the Stony River, is either deposited along the Stony River channel, deposited on the sub-aerial beach, or deposited in the interstitial spaces between boulders and cobbles on the wave-cut offshore platforms of lahar deposits. This research has illustrated the slow moving nature of the sand 'slug' derived from the Stony River, and the large impact this sand has had on beaches adjacent to the Stony River mouth. It is suggested that the district and regional councils would find it beneficial monitoring the sediment discharge from the Stony River, to predict when there is likely to be the addition of sediment to nearby beaches and adjust their regulatory regimes to adapt to these changes.

Port Taranaki is the only deep water seaport on New Zealand's west coast which is capable of handling a wide variety of cargoes. Around the Paritutu Headland, this diffusive zone, is a large natural basin for sediment storage. Sediments 'leak' around Paritutu headland, both nearshore and offshore, a process that is driven by the incidence energy, not necessary the supply of sediment (McComb, 2001). It is likely that any changes to the volume of sediment within the port, would be preceded by a significant change of sediment volume and bathymetry at Back Beach and/or within the Sugar Loaf Islands. It is therefore recommended that monitoring Back Beach, through beach profiling, and hydrographic surveying is undertaken regularly to detect changes in bathymetry and sediment volume.

The Department of Conservation is responsible for the Nga Motu/Sugar Loaf Islands Marine Protected Area (SLIMPA) and the Tapuae Marine Reserve. The sub-tidal marine habitats include canyons, caves, rock faces with crevices and overhangs, large pinnacles, boulder fields and extensive sand flats. These marine reserves offer a range of habitats for sponges, sea squirts and encrusting coralline algae. Approximately 1/3 of the Tapuae Marine Reserve is rocky reef which is covered in macroalgae, bryozoans, kina, sea cucumbers, mollusks and starfish. These protected areas and this nearby coastline are also important breeding and haul-out sites for New Zealand fur seals (*Arctocephalus forsteri*) and marine mammals such as dolphins, pilot whales, orca, humpback whales and southern right whales are commonly observed. Additionally, these areas are popular for the recreation activities of diving, snorkeling, boating, sea kayaking, fishing, seal

watching, walking, and surfing (DoC, 2009). As this sediment moves north-east along the Taranaki coast, localised effects are possible as previously rocky habitats become inundated with sand.

7.3 FUTURE RESEARCH OPPORTUNITIES ALONG THE SOUTHERN TARANAKI COAST

This research focused on identifying a sand ‘slug’, derived from the headwaters of the Stony River, which is currently becoming dispersed along a high energy, previously sand starved coast. Investigation of beach changes, sediment characteristics, a sediment transport flux study, and an episodic sediment budget was carried out. More detailed analysis of processes is required to improve the understanding of the effect the 1998 sediment injection from the Stony River. This might include:

- continuation of long-term beach monitoring, especially on Back Beach and around the Sugar Loaf Islands as this is the primary controller of the sediment that seeps around the Paritutu headland;
- evaluation of the volume of sediment situated offshore between Cape Egmont and New Plymouth;
- determination of the rate at which sediment is currently being delivered to the coast via from the Stony River; and
- greater refinement of the longshore sediment transport flux rates, especially as substantial volumes of sediment are transported in the longshore in depths shallower than 5 m.

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APPENDIX A

Sediment Flux on the High Energy Taranaki Coast, New Zealand

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ABSTRACT

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The Taranaki headland in New Zealand protrudes into a high energy wave climate system with a potential for strong littoral transport. The shoreline is typically comprised of a narrow cobble to boulder reflective beach, surmounting a rugged wave-cut shore platform which is carved into lahar deposits from the nearby andesitic composite cone of Mount Taranaki. Historically along this coast, pocket sandy beaches have endured within embayments and adjacent to headland features. The Taranaki littoral system has been described as sand-starved. However, in 1998 persistent heavy rainfall resulted in the collapse of scoriaceous sand and gravel on the side of Mount Taranaki, leading to massive injection of sand and gravel directly into the Hangatahau (Stony) River catchment. Since the initial collapse in 1998, the adjacent coastal shoreline has experienced a continuous influx of dense 'black' titanomagnetite-rich volcanic sands from the Stony River. These sediments are being rapidly transported to the north-east by the energetic wave climate, creating upper-shore sandy beaches on what is normally a rocky boulder coast devoid of sand. This study focuses on onshore geomorphology and sediment characteristics of this coast in June, September and November 2008. Between June and September 2008, results indicate that there has been a decrease in the beach sediment volume and mean grain size with distance north-east of the Stony River. This "sand lens" ejected from the Stony River mouth in 1998 sits on the upper shore, being transported only when high tides coincide with energetic wave conditions.

ADDITIONAL INDEX WORDS: *black sand, sediment transport, rocky coast*

INTRODUCTION

The Taranaki headland on the North Island of New Zealand (Figure 1) is a ring plain of a lahar deposit originating from the andesitic shield volcano, Mt Taranaki. Like much of the West Coast of New Zealand, this region is exposed to swells that are generated in the Tasman Sea and the Southern Ocean (Pickrill et al., 1979). Prior to 1998 this high wave energy coastline comprised narrow cobble and boulder beaches surmounting a rugged wave-cut shore platform carved from lahar deposits.

From 1998, this sand-starved system has undergone dramatic changes due to a massive injection of sand and gravels from a local river that is sourced on Mount Taranaki. Collapse of several scarps and volcanic detritus in the headwaters of the river on the mountain have led to a dramatic increase in the sediment supply and bedload in the Hangatahau (Stony) River. The resultant influx of black sand and scoriaceous gravel into the coastal littoral system, and subsequent transport along the coast to the northeast, has caused fundamental changes to the sedimentary character of a 22 km section of the coast. Wide sandy beaches now exist along a shore that previously only featured boulders and cobbles.

The influx of sandy sediment into the coastal littoral system has many potential implications for downdrift shoreline. For example as this "lens" of sand seeps past the rocky headland at New Plymouth, issues may arise for the maintenance of the shipping channel to Port Taranaki, and higher infilling rates may require

more frequent dredging. Positive outcomes may be that the New Plymouth beaches become more robust and that long-term erosion trends are temporarily reversed.

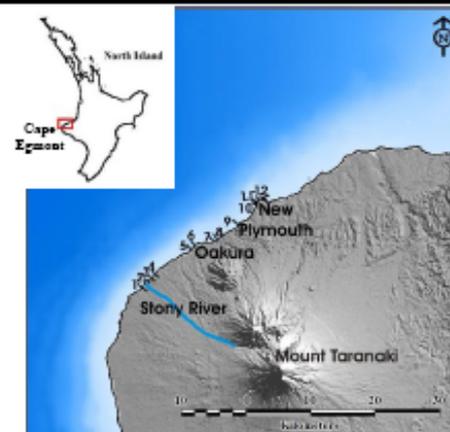


Figure 1. The Taranaki coast, showing the location of the Stony River and the 12 monitoring sites.

This paper presents initial results from a program of field measurements that examine the characteristics of the sediment injected into the littoral system, including beach profiles, volume estimates of sandy sediments and spatial gradients in sediment texture.

FIELD SITE

The Taranaki headland formed from the ring plain of a lahar deposit originating from the andesitic shield volcano, Mount Taranaki (also known as Mount Egmont), as well as subsequent lava flows that have been built since the early Pleistocene from the Puakai and Kaitake Ranges (NEALL, 1974). This ring plain is composed predominately of laharic breccia flows, tephra deposits, alluvium and dune sand ranging from 2-3 m thick (KIBBLEWHITE et al., 1982). This ring plain terminates at the coast where sea cliffs have formed exposing lahar deposits composed of graded andesitic rock fragments, ancient dune sands, tephra and occasionally peat. The ~3.5 m tidal range means the intertidal platforms are typically 100-300 m wide. This Egmont andesite, a light or dark grey rock, contains a number of white specks representing feldspar as well as patches of dark green augite and black hornblende, the dominant mineral being titanomagnetite (NEALL, 2003).

The Taranaki coast is irregular and rocky with variable offshore topography composed of sandy flats and rocky reefs (McCOMB, 2001). Historically the coastline is depleted in sediment, and eroding at a rate between 0.05 m and 1.89 m annually; cutting into lahar deposits exposing remnant boulders up to 5-10 km offshore (McCOMB, 1999). This coastal sector is dominated by long period swell waves 1-6 m in height and the net direction of littoral sediment flux is to the northeast. McCOMB et al., (1999) estimated a net littoral transport near New Plymouth to be greater than 220,000 m³yr⁻¹ while MATTHEWS (1977) estimated that three times as much sand moves to the north as does to the south. Diabathic sediment transport has not been quantified, but offshore surveys (e.g. McCOMB et al, 2003) suggest the nearshore regions along the Taranaki coast (i.e. to 20-30 m depth) are predominantly rocky, with sandy sediments persisting only within the bathymetric depressions.

Studies by KIBBLEWHITE et al., (1982) have indicated that while tides and waves are responsible for sediment transport on the inner and middle shelf most of the sediment transport occurs during storm periods where wave suspended sediment is transported by tidal and wind-driven circulation.

The incident wave climate is dominated by long period (12-14 s) swell from the SW-W sector, plus local seas that rise from the SW-N sectors. The swells approach the northern Taranaki headland oblique to the coastal orientation, driving the net northeast sediment flux and resulting a refraction shadowing that leads to a gradient in wave energy from Cape Egmont to New Plymouth (CROSSKEY, 2007).

METHODS

Beach Profiles

Beach profiles at 12 sites (Figure 1) were obtained using the Emery method. Profiles were surveyed as close to low tide as possible to maximise sub-aerial beach representation. Adjustments were made to plot profiles to a common datum (MLWS) using the following formulae:

$$h = h_1 + \left(h_2 - h_1 \frac{\cos A + 1}{2} \right) (1) \quad A = \pi \frac{(t - t_1)}{(t_2 - t_1)} \rightarrow \text{radians} (2)$$

where t_1 and h_1 is the time and height of the tide immediately preceding time t (when the profile was undertaken), and t_2 and h_2 are the time and height of the tide immediately following time t .

MATTHEWS (1977) also undertook beach profiles at Oakura Beach in 1976 and 1977 (sites 7 & 8) and these data have been used for comparison with this study.

Beach Volume Estimates

Aerial photographs were available from 1997 and 2007. Standard GIS techniques were used to rectify the images. The aerial photographs and anecdotal observations enabled comparisons of the coast to be made, both prior and after the Stony River outbreak. An initial estimate of the progress of this "sand lens" as it slowly moves up the coast was calculated using preliminary estimates of the volumetric changes from beach profiles obtained during 2008.

Sediment Grain Analysis

The longshore trends in grain size were examined by sampling and analysis of the beach sediments at 3 month intervals (June, September and November 2008) at 12 sites (Figure 1).

Surficial sediment samples were collected in the top 15 cm of sand at the low, mid and high tide levels at each of the 12 sites. The samples were wet sieved in a laboratory, firstly in a -2.00 phi (4 mm) sieve removing the coarse fraction. The samples were then sieved through a 4.00 phi (0.063 mm) sieve removing any silts, clays or precipitated salts (DELANGE et al., 1997) resulting in the medium fraction (sand) remaining. Of all the samples collected no sediment was finer than 4.00 phi (0.063 mm). Samples were dried for 48 hours and analysed using the Rapid Sediment Analyser (RSA) at the University of Waikato (DELANGE et al., 1997).

An advantage using the RSA rather than other standard mechanical sieve techniques is that the data is based on the hydraulic equivalent behaviour of sediments which is useful in calculations of littoral drift. Output results from the RSA are normal and frequency curves with particles size results given for graphical and moment method parameters. In this study, moment method parameters are used as they are more sensitive to environmental processes compared with graphical methods (FRIEDMAN and SANDERS, 1978).

RESULTS AND DISCUSSION

Beach Profiles

South of the Stony River (site 1), a 1.2 km beach exists approximately 80 m wide (Figure 2). Prior to the Stony River input of sediment, this beach was predominantly rocky. While there was little change in beach morphology between September and November 2008, in June the upper beach had an extra 180 m³/m of sediment and two berms.

Immediately north of the Stony River (site 2) the beach profiles exhibit large fluctuations in morphology (Figure 2). The profile of June 2008 has a much steeper dune while September and November profiles exhibited two berms.

Approximately 3 km northeast of the Stony River (site 3), the widest sandy beach along this stretch of coast, exists with an average width of 150 m. This beach has two berms with a steep beach face. The morphology has remained relatively regular over the three profile measurements (Figure 2).

At site 5 (Ahu Ahu) some 11 km from the Stony River, sandy sediments lie over a gravel and pebble layer shore platform. In comparison with other sites there have been small changes in morphology during the course of this study (Figure 2).

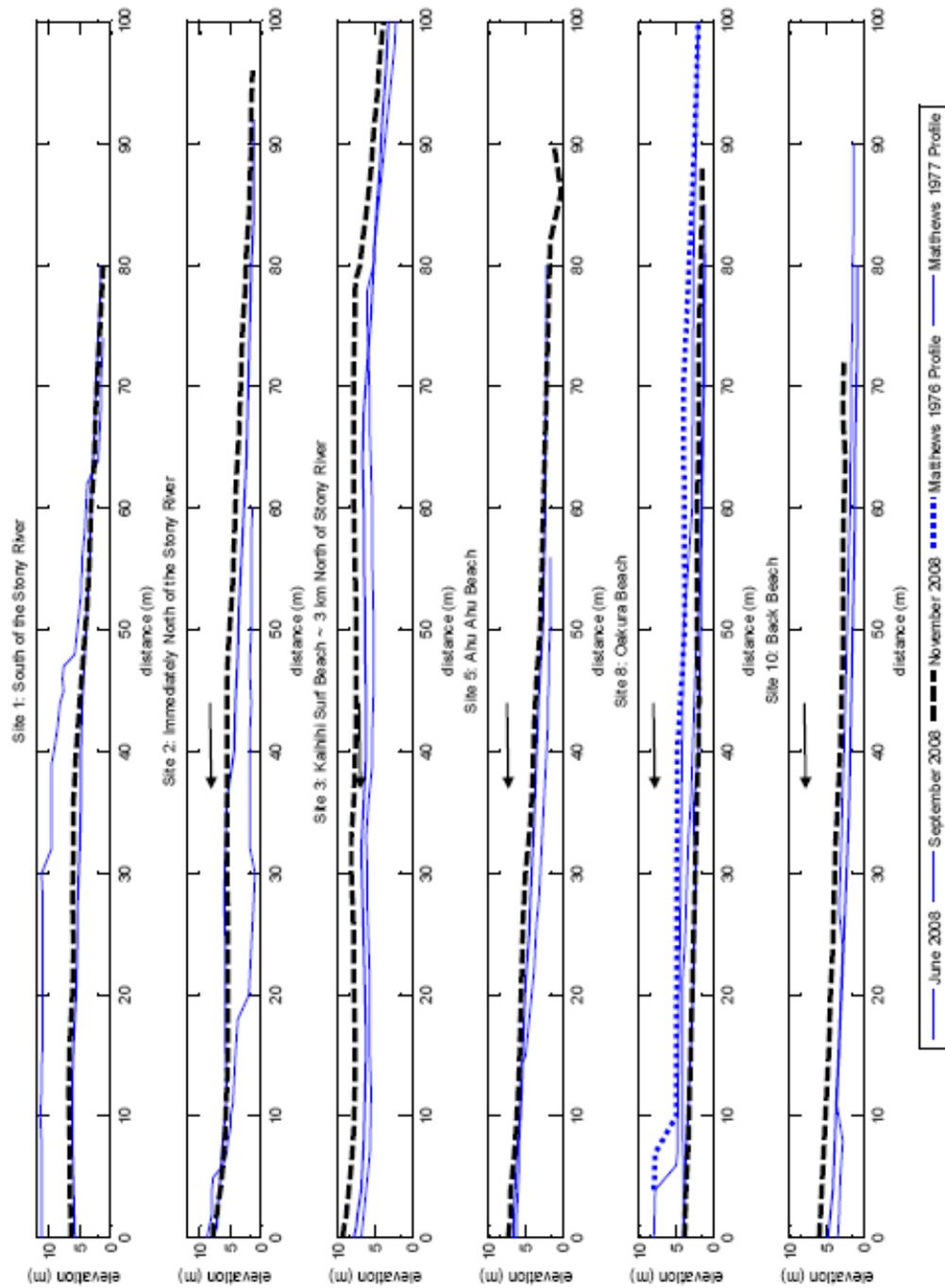


Figure 2. Onshore beach profiles of six sites from just south of the Stouy River to Back Beach New Plymouth for June, September and November 2008 and profiles undertaken by Matthews (1977) at Oakura Beach and adjusted to MLWS datum.

Oakura Beach (sites 7 & 8) is located in the lee of an offshore reef which alters the local wave patterns and provides a degree of wave sheltering conducive to a persistent sandy beach within this sediment-starved environment. Profiles from 1997 and 2008 show the beach shape is very similar, including berms (Figure 2), although the dunes show considerable variability. McCOMBS *et al.*, (2005) reported that this section of Oakura Beach retreated between 1970 and 1981, accreted between 1981 and 1986, and the shoreline has been eroding at a mean rate of 0.4 m/yr since 1970.

The geomorphology at Back Beach, New Plymouth, is influenced by adjacent cliffs which expose lahar deposits, tephra and dune paleosols. During the winter months substantial erosion occurred from these cliffs resulting in the beach volume increasing substantially.

Beach Volumes

The survey data have clearly identified sub-aerial sandy deposits sourced from the Stony River. These show a diminishing volumetric trend from the source upper shore locations near New Plymouth, some 22 km away. The deposits are a thinning wedge of sand, stored along the upper beach, and likely only being actively transported on the high tide during large storm events. Below these deposits, the lower shore typically remains a wave-swept boulder platform, devoid of significant sandy areas (e.g. Figure 3).

For example, along the first 3 km of coast north of the Stony River, there is approximately 5 m of mobile sediment deposited on the upper shore, and at least 750 m³ of sediment per metre of beach. Accordingly, this section of coast has probably retained 2-3 million cubic metres of fluvial sands, and the anecdotal evidence is that this volume had accumulated by 2001.

Site 5 (Ahu Ahu) is ~11 km from the source, and features localised accretion within the embayment, and considerably less accretion of sand on the upper shore. This beach is bounded by a rocky reef which no doubt increase the cross-shore diffusion of the littoral sediments. McCOMBS *et al.*, (2005) reported that in the 1930's Ahu Ahu beach was a rocky embayment with very little sand.

Like Ahu Ahu Beach, Oakura Beach is influenced by the headland/reef at the southern end of the beach which affects the local wave climate. This beach is dynamic responding to a fluctuating sediment supply; complex nearshore reefs; human intervention; beach orientation (with respect to prevailing winds) and coastal vegetation. However, the survey and photographic data do not indicate morphology changes in this beach that can be directly attributed to the 1998 outbreak.

Further north (site 9) at the Tapuae Stream, the shoreline is more wave-exposed than Oakura, and has sandy deposits along the upper shore and a rocky platform on the lower beach. This region has approximately 120 m³ of sandy sediment per metre of beach, and the anecdotal evidence suggests that this volume will be due to the increased fluvial sediments since 1998.

At Back Beach, approximately 22 km north of the Stony River a long sandy beach has formed in the lee of the Sugar Loaf Islands. This beach sits beneath an eroding cliff which frequently alters its sediment characteristics. This sediment derived from the Stony River has not travelled as far north as Back Beach and therefore no changes can be seen on this beach as a result of the Stony River outbreak.

Sediment Analysis

Mean grain size and sorting textural parameters were obtained undertaking RSA on the sediment samples collected at low, mid,



Figure 3. Wave-cut shore platform of cobbles and boulders

and high-tide mark. This paper presents the results of the samples collected at mid tide (Figure 4).

Normally it is assumed that sediments become finer in the direction of transport as a result of selective sorting with smaller particles winnowing out from the larger particles in the down current direction (FOLK, 1968). The sediment samples collected in June and November 2008 both demonstrated the decreasing size of sediments (Figure 4). The sediment collected in June, September and November 2008 decreased in size with gradients of -0.187, -0.021, and -0.0276 mm respectively, along this entire coastline, consistent with the assumption that sediments become finer with the direction of littoral transport.

Sorting is an important parameter in studying sediment transport as sediment is transported from the coast (the sorting generally improves (i.e. the sorting value decreases)) (FOLK, 1968). The sediments collected in June, September, and November 2008 possessed sediment sorting that decreased slightly (i.e. the sorting values increased) (Figure 4). The mean sediment size for each site ranges from approximately 2.00 phi to 1.25 phi, a possible explanation for the poor sorting along with sediment derived from cliffs (sites 10, 11 and 12) which possess poor sorting values.

CONCLUSION

This paper presents field measurements of beach profiles, beach volume estimates and sediment grain analysis at 12 sites along a 22 km stretch of the Taranaki coast. Typically this coast is depleted in sand-sized sediment, however in 1998 a collapse in the headwaters of the Stony River on Mount Taranaki resulted in the injection of andesitic sediment into the coastal littoral system. A decade later this sediment has been nourishing beaches as it is transported in the north-east directed littoral transport.

Beach monitoring has been undertaken in June, September, and November 2008. The results show a notable decrease in sub-aerial beach sediment volume and a decrease in mean grain size with distance north-east from the Stony River mouth confirming the littoral transport direction. This "sand lens", which continues to be discharged onto the coast, is slowly moving its way up the coast as a thinning wedge of sediments, extending as far 16 km north from the Stony River source. Presently, the sediments provide a significant store of material on the upper shore, transported only over the high tides with energetic waves. The ongoing survey provides a unique opportunity to observe a new dynamic equilibrium establishing in this energetic environment.

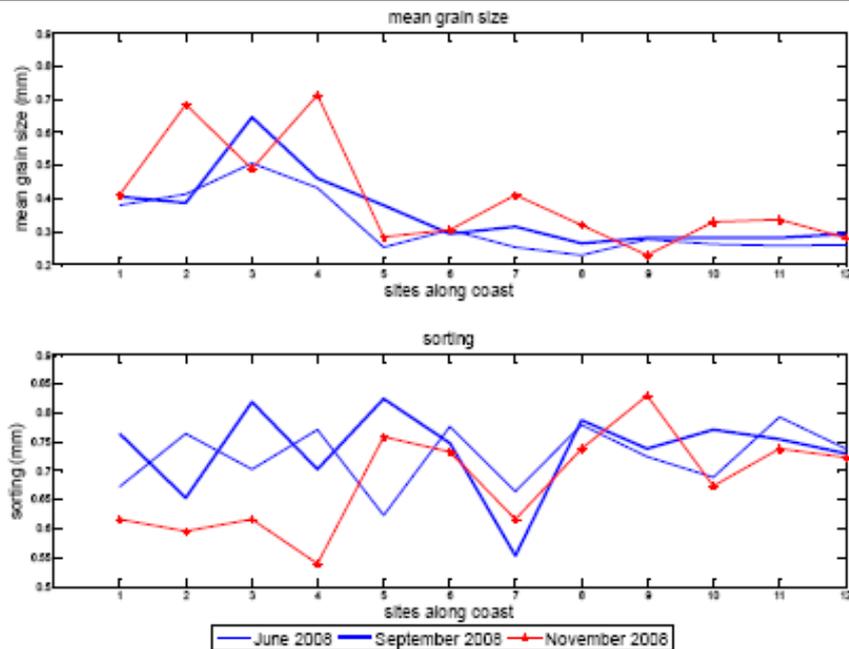


Figure 4. Sediment grain size and sorting textural parameters at 12 sites from just north of the Stony River (1) in the south to Back Beach (12) at New Plymouth.

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Sediment Budget for an Episodic Injection on a High Energy Coast

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Abstract

The Taranaki volcanic headland protrudes into a high energy wave climate and an active littoral transport system. The shoreline typically features a narrow cobble / boulder shore, surmounting wave-cut platforms of boulders and relict lahar deposits from the nearby andesitic composite cone of Mt Taranaki. Sandy pocket beaches have endured within isolated embayments and adjacent to headland features, but otherwise the coastline has little sand deposits. In 1998, persistent heavy rainfall on Mt Taranaki lead to a massive injection of sand and gravel directly into the Stony River via an erosion scarp on the mountain. Since 1998, the adjacent shoreline has experienced a continuous influx of dense, "black" titanomagnetite rich volcanic sands from the Stony River. These sediments are being actively transported alongshore to the north-east, creating upper-shore sandy beaches on what is normally a rocky boulder shoreline devoid of sand. This paper focuses on estimating the volume of sand that has recently been eroded from the scarp on the mountain, and the volume of sediment that can be accounted for today on the beaches, and in the Stony River channel, as aggradation deposits. Volumes were estimated by using stereoscope images and beach profile surveys. Up to 14.4M m³ of sediment was estimated to have been deposited in the Stony River system directly from the scarp. The recent volumetric changes to the downstream river system and coastal environment amount to a total of 8.8M m³. Of this, approximately 3.5M m³ has accumulated on the sub-aerial beach over a distance of 14 km to the east from just south rivermouth, and 3.3M m³ has been deposited along the Stony River channel. Thus, approximately 47 % of the recently eroded volume is currently evident in the adjacent fluvial and coastal sub-aerial system.

1.0 Introduction

The Taranaki headland on the west coast of the North Island of New Zealand (Fig. 1) comprises a ring plain of a lahar deposit originating from the andesitic shield volcano, Mt Taranaki (also known as Mt Egmont). Like much of the West Coast of New Zealand, this region is exposed to swells that are generated in the Tasman Sea and the Southern Ocean (Pickrill and Mitchell 1979). Prior to 1998 this high wave energy shoreline comprised narrow cobble and boulder beaches surmounting a rugged wave-cut shore platform carved from lahar deposits.

now exist along a shore that previously featured only boulders and cobbles.

The influx of sandy sediment into the coastal littoral system has many potential implications for the down-drift shoreline. For example, as this "lens" of sand seeps past the rocky headland at New Plymouth, issues may arise for the maintenance of the shipping channel at Port Taranaki, and higher infilling rates may require more frequent dredging. Positive outcomes may be that the New Plymouth beaches become more

From 1998, this sand-starved system has undergone dramatic changes due to a massive injection of sand and gravels from a local river that is sourced on Mount Taranaki. Collapse of several gully scarps and volcanic detritus in the headwaters of the river on the mountain have led to a dramatic increase in the sediment supply and bedload in the Hangatahua (Stony) River. The resultant influx of black sand and scoriaceous gravel into the coastal littoral system, and subsequent transport along the coast to the north-east, has caused fundamental changes to the sedimentary character of this coast. Wide sandy beaches

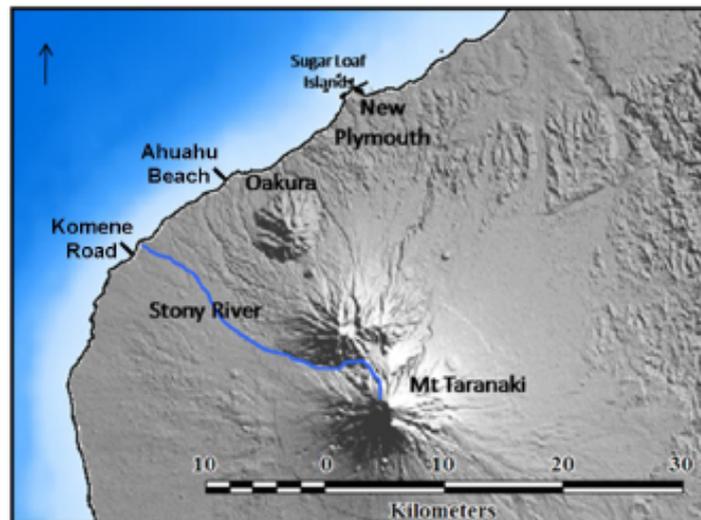


Figure 1. The Taranaki coast showing the location of the Stony River.

sandy and that long-term erosion trends are temporarily reversed.

This paper attempts to quantify the volume of material that has been eroded from the gully in the upper catchment and the present volume of sediment deposited on the sub-aerial coast between Komene Road and Ahuahu Beach (Fig. 1), along with the sediment deposits along the Stony River channel.

2.0 The Southern Taranaki Coast

Mount Taranaki volcanic cone and subsequent lava flows have been built since the early Pleistocene from the Puakai and Kaitake Ranges (Neall 1974). The Taranaki ring plain is composed predominately of laharic breccia flows, tephra deposits, alluvium and dune sand ranging from 2-3 m thick (Kibblewhite et al., 1982). This ring plain terminates at the coast where sea cliffs have formed exposing lahar deposits composed of graded andesitic rock fragments, ancient dune sands, tephra and occasionally peat. This Egmont andesite, a light or dark grey rock, contains a number of white specks representing feldspar as well as patches of dark green augite and black hornblende, the dominant mineral being titanomagnetite (Neall 2003).

The ~3.5 m tidal range means the intertidal platforms are typically 100-300 m wide. Offshore surveys (e.g. McComb et al., 2003) suggest that near-shore regions of the Taranaki Coast (i.e. 20-30 m depth) are predominately rocky, with sandy sediment persisting only within the bathymetric depressions.

Mount Taranaki has suffered severe erosion, due to episodic heavy rainstorms. Over the past 400 years, unstable jointed lava flows and debris flows have collapsed, a large proportion originating from the rim of the western crater (Neall, 1974). As a result sand and gravel has discharged into the littoral system via a series of rivers, the dominant ones being the Waitara, Waiwhakaiho and the Stony River (Bruce Wallace & Partners, 1981).

Typically, the Taranaki coast is irregular and rocky with variable offshore topography composed of sandy flats and rocky reefs (McComb 2001). Historically the coastline is depleted in sediments, and eroding at a rate between 0.05 m and 1.89 m annually; cutting into lahar deposits exposing remnant boulders up to 5-10 km offshore (McComb et al., 1999).

The incident wave climate is dominated by long period (12-14 s) swell from the SW-W sector of 1-6 m in height, plus local seas that rise from the SW-N sectors. The swells approach the northern Taranaki headland oblique to the coastal orientation, driving a net north-east sediment flux

and resulting in a refraction shadowing that leads to a gradient in wave energy from Cape Egmont to New Plymouth (Crofskey, 2007). McComb et al., (1999) estimated a net littoral transport near New Plymouth to be greater than 220,000 m³yr⁻¹. Matthews (1977) estimated that three times as much sand moves to the north as does to the south.

Studies by Kibblewhite et al., (1982) have indicated that while tides and waves are responsible for sediment transport on the inner and middle shelf most of the sediment transport occurs during storm periods where wave suspended sediment is transported by tidal and wind-driven circulation.

3.0 Methods

3.1 Sediment derived from the scarp

To determine the volume of sediment derived from the gullied upper Stony River, the actively eroding part of the gully was divided into sections with approximately the same valley width and depth (Fig. 2). This was completed with the aid of stereoscope images taken in 2007. The scarp evident on these images was projected onto a 1:50,000 topographical chart. This enabled cross-sections of each sector to be undertaken (i.e. cross section shown in Fig. 2). The length of each sector was measured enabling the volume of each sector that has been eroded away to be determined. Lastly each of the segment volumes were summed together to give an accurate estimate of the volume of sediment that has been eroded from this region.

3.2 Sand deposited along the Stony River channel

Using stereoscope photographs dated 2007, segments of the Stony River were identified as being aggradational. By assuming the thickness of these deposits is 1 m, an estimate of the volume of sediment deposited along the river channel was able to be calculated.

3.3 Sand in the sub-aerial beach system

Previous photographic, visual and grain size evidence has indicated that the sediment derived from the Stony River has reached as far north as Ahuahu Beach. This sediment sits on the upper beach and is only eroded and transported during high tide when there is sufficient energy to mobilise this sediment. To determine the volume of sediment in the sub-aerial beach this section of coast (between Komene Road) and Ahuahu Beach) was divided into sectors.

Beach profiling (using the Emery, 1961 method) at these sectors was undertaken in June 2008, September 2008, November 2008, February 2009 and May 2009 (Fig. 3). These profiles were averaged to give an average volume of sediment

per m^2 and an average gradient which enabled the volume of sand along each stretch of beach (between Komene Road and Ahuahu Road) to be calculated. When determining sediment volumes it is assumed that the wave-cut shore platform has a slope of 1:100.

Combining this profile data with aerial photograph data, from 2007, enabled the volume of sediment along the beach to be identified. Firstly the aerial photographs were rectified using standard GIS techniques. The width of the coast at different locations was determined and the beach profile data was altered to compensate for this.

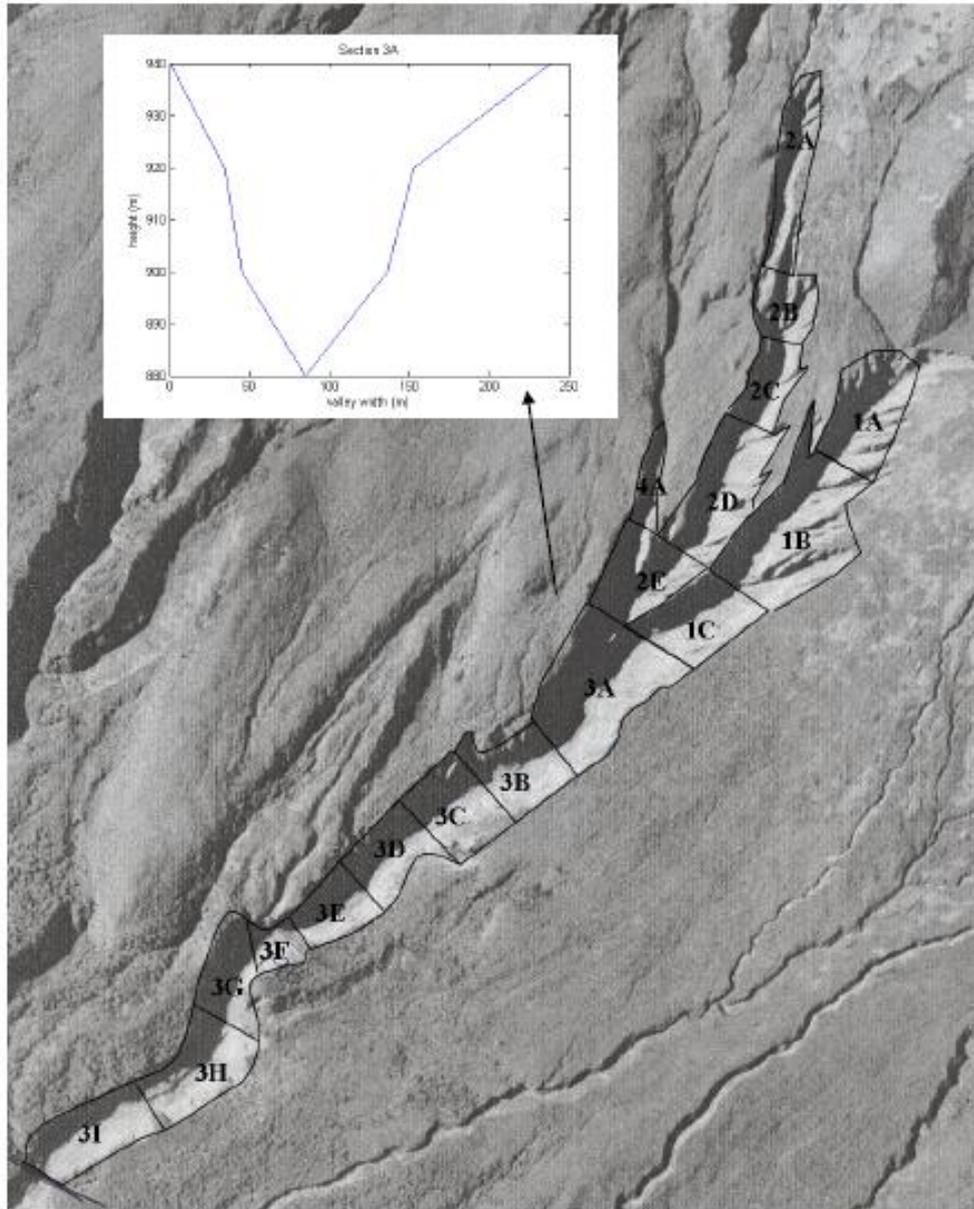


Figure 2. The scarp in the headwaters of the Stony River (Little Pyramid), divided into segments to determine the cross-sectional area and volume of the material that has been eroded from this scarp. An example of a cross-section of this scarp (from segment 3A) has been superimposed on this image.

4.0 Results

4.1 Sediment derived from the gully system

The gully system illustrated in Fig. 2 has had 14,400,000 m³ of sediment eroded away (Table 1). Three small tributaries have formed before joining forming the large channel gully. Not all this sediment can be attributed to the breakout in 1998. A number of the cross sections indicate that there have been two main erosive events. (e.g. the cross-section shown in Fig. 2).

4.2 Sand deposited along Stony River Channel

From the base of the scarp (see sector 3I in Fig. 2) the Stony River channel has sediment deposited for 10.3 km. From the use of stereoscope images it was estimated that over this 10.3 km length the approximate volume of sediment is 3,289,000 m³.

Table 1 Length, cross-section area, and the volume of each sector (as illustrated in Figure 2)

Section	Length (m)	Cross-Section Area (m ²)	Section Volume (m ³)
1A	478.7	1440	688448
1B	227	13840	3141680
1C	281.05	3243	848585
2A	368.875	170.25	62801
2B	197.5	124.85	24658
2C	249.7	238.35	59516
2D	4854.75	221.325	1074478
2E	8321.5	351.85	2927920
3A	351.85	8494.5	2285090
3B	158.9	2007	318812
3C	124.85	5147.5	842865
3D	175.925	2812	458516
3E	175.925	218.5	38088
3F	124.85	2018.75	252041
3G	136.2	1589.1	216435
3H	244	3558	868152
3I	317.8	1468.875	466809
4A	387.5	140.74	54537
			14,426,330

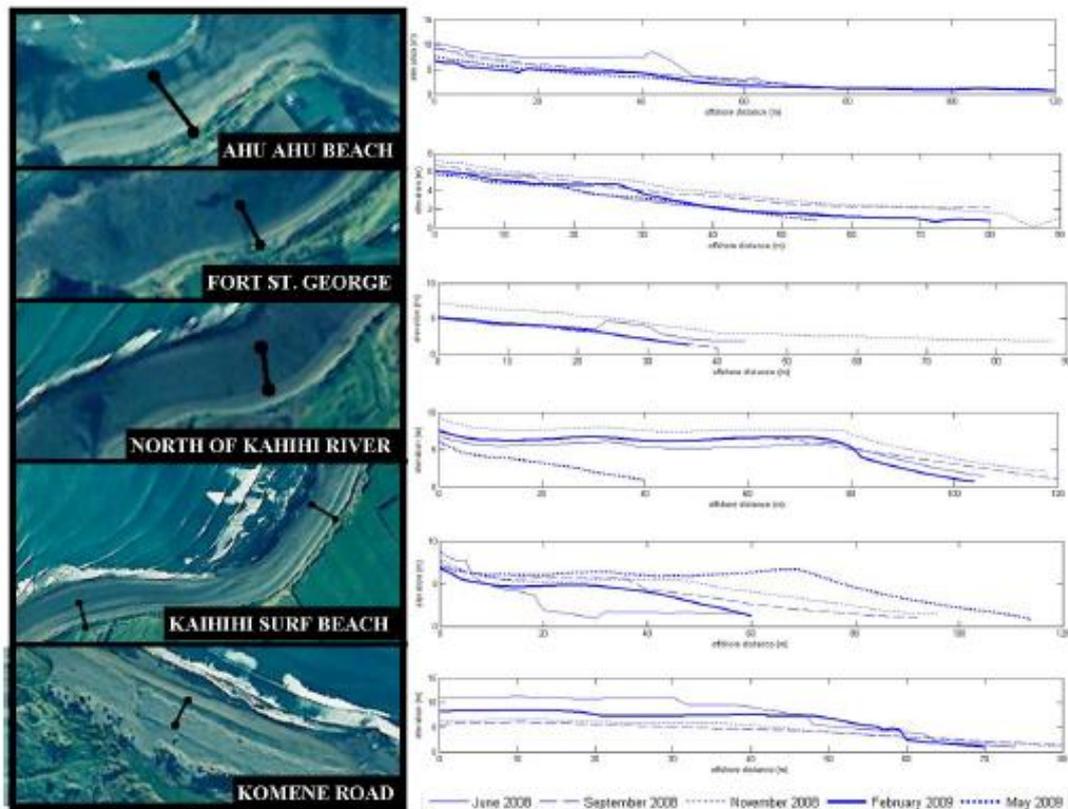


Figure 3. Sub-aerial beach profiles at 6 locations along the Southern Taranaki Coast which have been inundated with sediment as a result of the Stony River outbreak in 1998. Profiles were undertaken in June 2008, September 2008, November 2008, February 2009 and May 2009. Black lines indicate where the profiles were taken.

Table 2. Volume of sediment in the sub-aerial beach profiles taken during 2008 and 2009 along the Southern Taranaki Coast

Location	Volume of sediment in sub-aerial beach profile (m^3m^{-1})					Average
	June 2008	September 2008	November 2008	February 2009	May 2009	
Ahu Ahu Beach	360	246	292	227	174	259.8
Fort St. George	96	194	232	128	82	146.4
North of Kaihihi River	110	75	276	64	-	131
Kaihihi Surf Beach (Northern Profile)	429	627	674	469	24	444.6
Kaihihi Surf Beach (Southern Profile)	68	258	319	149	447	254.2
Komene Road	496	163	291	380	-	332.5

4.3 Sand in the sub-aerial beach system

The beach sediment deposits originating from the headwaters of the Stony River, present along the stretch of coast between Komene Road and Ahuahu Beach are a thinning wedge of sand that is stored primarily in the upper beach, and are only transported on the high tide during stormy events. These deposits sit on a wave-scoured boulder platform.

The northern most site where the sand derived from the Stony River outbreak is thought to have reached is Ahuahu Beach (Fig. 4). Ahuahu Beach suffers from the down-coast affects of sediment pulses, resulting in large variations in sand volume at the intertidal and sub-tidal areas (McComb et al., 2005). This variation is evident in historical photographs, where in the 1930s Ahuahu Beach was a rocky embayment, with a steep coarse grained beach face. Ahuahu Beach has a relatively large volume of sediment compared to the nearby beaches at Fort St George, the beach north of the Kaihihi River and Oakura Beach. The beach profiles surveyed over 2008/2009 show Ahuahu Beach to have an average volume of $\sim 260 m^3s^{-1}$ (Table 2). This greater sediment volume at Ahuahu Beach may be attributed to the small headland as shown in Fig. 4. resulting in the groin affect.



Figure 4. Sediment Coverage at Ahuahu Beach

In comparison with other beach profiles, there have been small changes in morphology during the course of this study at Fort St. George, just north of the Timaru Stream mouth (Fig. 5). As is the case with the remainder of the profiles surveyed along this coast, in November 2008 there are greater volumes of sediment present (Table 2) with the profile taken at Ahuahu Beach having an extra $\sim 1 m$ elevation. At each surveying time, a berm was present – evidence this beach is in an accretionary phase (Fig. 3).



Figure 5. Sediment Coverage at Fort St. George

To the north of the Kaihihi River, the wave-cut shore platform is exposed from approximately mid-tide level (Fig. 6). The profiles undertaken at this location have been used to estimate \sim

785,000 m³ of sediment is situated on the sub-aerial beach along this 4.78 km stretch of coast. The profiles surveyed from this narrow stretch of coast contain the smallest volume of sediment in comparison with the other sections of this coast (Table 2).



Figure 6. Sediment Coverage north of Kaihihi River

Immediately to the north of the Stony River is Kaihihi Surf Beach (Fig. 7). Located adjacent to the Stony River mouth, it experiences large sediment quantity fluctuations. After the 1998 collapse, this site was inundated with coarse sand resulting in a berm 5 m high and 22 m wide. The profiles taken during the course of this study contain substantially greater amounts of sediment in comparison with other beaches along this stretch of coast with often two significant berms (Fig. 3) Between the Stony River mouth and the Kaihihi River mouth it is estimated that presently ~1,450,000 m³ of sediment is deposited along Kaihihi Surf Beach, the greatest depository of sediment along the southern Taranaki Coast.



Figure 7. Sediment Coverage along Kaihihi Surf Beach

Immediately south of the Stony River, at the end of Komene Road is a beach approximately 1.25 km in length (Fig. 8). Surveyed sub-aerial beach profiles indicate that at least 403,000 m³ of sediment is deposited along this beach. These profiles have been extrapolated in the lower and upper shore (left and right polygons on Fig. 8) to determine the total sediment along this sector (535,000 m³). Despite being to the south of the

Stony River mouth, this sediment is diffusing from the river mouth.



Figure 8. Sediment Coverage at beach at the end of Komene Road

4.5 Discussion

Of the 14.4M m³ of sediment calculated to have been eroded from the gully system, located at the headwaters of the Stony River, only 6.8M m³ of sediment can be accounted for sitting on and offshore (between Komene Road and Kaihihi Surf Beach), or having been deposited along the channel of the Stony River (Table 4).

Table 4. Summary of sediment that can be identified in the sub-aerial beach between Komene Road and Ahuahu Beach.

Location	Sub-Aerial Beach (m ³)
Komene Road	535,000
Kaihihi Surf Beach	1,468,000
North of Kaihihi River	817,000
Fort St. George	455,000
Ahuahu Beach	274,000
Deposition along Stony River Channel	3,289,000
TOTAL	6,838,000

The remaining 7.6M m³ of sediment that has been eroded from the gully system in the headwaters of the Stony River may have been deposited offshore. If all this sand was deposited offshore (500 m from the shoreline up to Ahuahu Beach, 14 km from Komene Road) a 2m thick layer of sediment would be deposited.

It is likely that not all of this 14.4 M m³ sediment derived from the gully was transported down the Stony River due to the 1998 collapse. Cross-sections of the scarp indicate that there was likely to be other events of significant erosion prior to 1998 which could account for large volumes of sediment being transported to the coast.

Drop camera images have been undertaken offshore in the immediate vicinity of the Stony River mouth. From these images it is estimated that sand is deposited between 6 and 19.5 m depth between Komene Road and Ahuahu Beach. This offshore sediment is likely to be a significant source of sediment derived from the gully system in the headwaters of the Stony River.

Crofskey (2007) identified different benthic substrates around the Taranaki headland. This study found that areas of boulder rocks and mobile reefs dominated between 800 m and beyond 4 km offshore near Cape Egmont. The interstitial space between the cobbles and boulder that make up these reefs can provide significant space for sediment to accumulate and may present a major store of sediment that has been derived from the gully system at the headwaters of the Stony River. Crofskey (2007) also identified a large area of sand between Oakura and the Sugar Loaf Islands. This sand may have been deposited due to offshore islands decreasing current velocities and resulting in the deposition of sediment. Likewise this may be a major store of sediment derived from the gully system in the headwaters of the Stony River.

Significant quantities of sediment derived from Mt Taranaki may have been transported further north of Ahuahu Beach in the north-east directed littoral transport. Ironsand derived from Mt Taranaki has been found to cover a 300 mile distribution from the Kapiti Coast in the south of Pandora's Bank in the north (Kear, 1979). It may be likely that the sediment derived from the Stony River gully scarp system is being transported around Port Taranaki in New Plymouth.

4.6 Conclusions

Of the 14.4M m³ of sediment that has been eroded from the gully system in the headwaters of the Stony River approximately 3.5M m³ has been identified on the sub-aerial beach between Komene Road and Ahuahu Beach and 3.3 Mm³ has been deposited along the Stony River channel. The remaining 7.6M m³ of sediment is likely to be deposited offshore, overlying the wave-swept boulder platform and in the interstitial space of the sediments that form these shore platforms. Significant quantities of this sediment are also likely to have been transported in the north-east directed littoral transport.

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APPENDIX B: MOMENT MEASURES

The first moment (**mean**) is calculated by:

$$m_1 = \frac{\sum fx}{n}$$

where: x=grain size class midpoint

f=class frequency

$n = \sum f$

the higher order moments are calculated by:

$$m_p = \frac{\sum f(x - m_1)^p}{n - 1}$$

Where: p is an integer

m_p is the p^{th} moment about the mean

The first four moments are used to calculate the sorting, skewness and kurtosis.

Sorting

$$\sigma_\phi = \sqrt{m_2}$$

Skewness

$$Sk_\phi = \frac{m_3}{m_2^{1.5}}$$

APPENDIX C: SEDIMENT TEXTURAL RESULTS

LOW TIDE

Site	Mean Grain Size (mm)					Sorting					Skewness				
	June 08	Sept 08	Nov 08	Feb 09	May 09	June 08	Sept 08	Nov 08	Feb 09	May 09	June 08	Sept 08	Nov 08	Feb 09	May 09
1	0.29	0.45	0.47	0.37	-	0.66	0.77	0.69	0.63	-	1.56	0.95	0.59	4.0	-
2	-	0.56	-	-	0.46	-	0.63	-	-	0.56	-	0.45	-	-	4.0
3	0.58	0.62	-	0.6	-	0.58	0.76	-	0.60	-	0.19	0.42	-	0.29	-
4	0.42	0.61	-	-	-	0.74	0.75	-	-	-	1.2	1.5	-	-	-
5	-	0.37	0.38	0.39	-	-	0.78	0.78	0.65	-	-	1.3	0.28	65.5	-
6	0.31	0.29	0.27	0.3	0.29	0.79	0.77	0.74	0.69	0.67	1.05	2.99	0.50	2.4	0.48
7	0.30	0.30	0.30	0.31	0.23	0.74	0.69	0.6	0.65	0.61	0.82	0.41	3.36	4.9	3.24
8	0.24	0.28	0.28	0.31	0.23	0.70	0.68	0.76	0.69	0.54	0.93	0.93	2.51	3.0	1.06
9	0.29	0.27	0.38	0.17	0.26	0.66	0.71	0.72	0.58	0.54	4.59	0.52	2.36	1.5	4.24
10	0.30	0.31	0.34	0.27	0.28	0.72	0.76	0.73	0.76	0.50	0.39	0.54	2.25	0.95	3.15
11	0.30	0.28	0.30	0.32	0.27	0.78	0.81	0.77	0.72	0.53	1.51	0.40	1.14	45.4	1.92
12	0.30	0.28	0.33	0.28	0.26	0.66	0.73	0.78	0.71	0.62	3.67	1.16	0.57	11.9	2.95

MID TIDE

Site	Mean Grain Size					Sorting					Skewness				
	June 08	Sept 08	Nov 08	Feb 09	May 09	June 08	Sept 08	Nov 08	Feb 09	May 09	June 08	Sept 08	Nov 08	Feb 09	May 09
1	0.38	0.41	0.42	0.47	-	0.67	0.76	0.62	0.64	-	1.78	0.83	0.3	10.41	-
2	0.41	0.39	0.72	0.62	0.44	0.76	0.65	0.70	0.67	0.53	0.74	0.96	0.61	0.49	1.78
3	0.51	0.64	0.49	0.67	-	0.7	0.82	0.62	0.69	-	1.46	1.42	0.27	0.47	-
4	0.43	0.46	0.68	-	-	0.77	0.7	0.67	-	-	0.54	0.78	0.19	-	-
5	0.25	0.38	0.31	0.44	0.16	0.62	0.82	0.77	0.61	0.41	0.99	0.60	1.51	50.05	1.62
6	0.30	0.29	0.32	0.3	0.22	0.78	0.75	0.74	0.77	0.70	1.06	0.47	0.74	1.35	0.46
7	0.25	0.31	0.37	0.29	0.19	0.66	0.55	0.68	0.75	0.57	3.64	1.17	0.69	0.89	9.82
8	0.23	0.26	0.34	0.33	0.17	0.78	0.79	0.76	0.54	0.48	0.67	0.82	1.46	6.05	2.41
9	0.28	0.28	0.26	0.31	0.22	0.72	0.74	0.77	0.71	0.49	2.29	0.70	1.97	2.19	1.38
10	0.26	0.28	0.32	0.38	0.27	0.69	0.77	0.7	0.63	0.46	1.08	0.66	0.83	17.59	4.98
11	0.26	0.28	0.32	0.32	0.30	0.79	0.75	0.77	0.67	0.56	0.67	0.68	0.74	6.32	2.12
12	0.26	0.29	0.29	0.27	0.27	0.74	0.73	0.77	0.61	0.66	1.17	1.54	0.66	0.78	3.22

HIGH TIDE

Site	Mean Grain Size					Sorting					Skewness				
	June 08	Sept 08	Nov 08	Feb 09	May 09	June 08	Sept 08	Nov 08	Feb 09	May 09	June 08	Sept 08	Nov 08	Feb 09	May 09
1	0.39	0.44	0.43	0.47	-	0.74	0.73	0.65	0.77	-	4.14	1.03	0.44	0.65	-
2	0.40	0.44	0.40	0.48	0.33	0.76	0.78	0.61	0.67	0.57	0.61	1.48	0.41	4.72	1.04
3	0.43	0.51	0.51	0.46	0.35	0.70	0.75	0.73	0.60	0.57	0.59	1.85	0.57	0.46	3.18
4	0.37	0.58	0.61	0.65	-	0.66	0.70	0.78	0.71	-	0.80	0.53	0.33	0.29	-
5	0.34	0.33	0.34	0.38	0.24	0.68	0.79	0.71	0.72	0.54	0.39	1.92	0.26	4.14	0.48
6	0.36	0.30	0.34	0.33	0.27	0.76	0.72	0.77	0.77	0.75	1.19	0.66	0.77	0.85	0.87
7	0.27	0.25	0.29	0.36	0.21	0.77	0.70	0.76	0.73	0.50	1.21	2.21	1.74	0.88	5.29
8	0.27	0.23	0.24	0.31	0.22	0.78	0.75	0.75	0.72	0.76	0.59	1.87	0.57	3.67	3.13
9	0.28	0.30	-	0.27	0.26	0.78	0.74	-	0.55	0.67	0.76	0.66	-	12.0	3.71
10	0.23	0.28	0.31	0.33	0.29	0.71	0.78	0.78	0.72	0.67	1.97	2.44	2.75	3.66	2.74
11	0.22	0.27	0.28	0.32	0.26	0.74	0.75	0.75	0.69	0.66	2.92	8.69	2.82	0.86	0.87
12	0.29	0.30	0.27	0.32	-	0.76	0.73	0.73	0.66	-	1.24	2.31	0.39	27.0	-

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	Site 1			Site 2		Site 3		Site 4		Site 5			Site 6			Site 7			Site 8			Site 9		Site 10			Site 11			Site 12								
	L	M	H	M	H	M	H	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	L	M	H	L	M	H	L	M	H						
-1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	2	0	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0				
-0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
-0.5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
-0.25	1	0	0	2	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0	3	1	0	1	0	1	1	4	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.25	5	2	2	10	0	2	3	36	3	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	10	4	6	60	-1	7	8	40	1	0	0	0	0	0	0	13	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.75	14	9	13	19	6	20	17	11	38	1	0	0	0	0	0	1	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	19	16	19	4	20	28	25	3	35	8	1	4	0	1	2	2	3	0	0	5	0	17	0	1	2	1	0	2	0	0	0	0	0	0	0	0	0	
1.25	17	36	21	2	29	22	22	1	4	34	9	18	1	4	15	5	20	2	0	22	0	24	0	9	15	3	3	12	0	6	0	0	0	0	0	0	0	
1.5	15	18	18	0	22	9	13	0	0	33	35	31	14	25	30	17	31	11	6	30	2	22	0	35	30	21	25	30	4	30	13	15						
1.75	8	9	10	0	8	3	6	0	0	15	31	28	35	30	26	30	22	28	25	20	20	13	5	27	27	37	38	30	39	35	37	33						
2	3	3	5	0	3	1	2	0	0	5	17	10	20	21	16	22	14	31	36	13	31	7	33	13	12	23	22	15	32	17	27	28						
2.25	1	1	0	0	1	1	1	2	0	2	5	4	13	10	7	7	8	15	18	7	19	0	32	6	4	10	7	6	14	6	10	13						
2.5	0	0	0	0	0	1	1	0	0	0	2	1	9	6	2	3	4	6	10	2	9	0	22	3	2	3	2	2	7	8	4	7						
2.75	0	0	2	0	0	0	0	0	0	0	1	2	4	1	0	2	0	3	3	0	5	0	7	3	1	2	1	1	2	0	0	2						
3	0	0	5	0	0	0	0	1	0	1	0	0	2	1	0	1	0	0	2	0	3	0	2	0	1	0	1	0	1	0	1	0	0	0	0	0		
3.25	0	0	0	0	0	1	1	0	0	1	0	0	0	2	1	0	0	0	0	0	7	0	0	0	1	0	0	0	0	0	5	0						
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	
3.75	0	0	0	0	0	3	1	0	0	1	0	3	1	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	
4	0	4	0	0	9	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	2	0	0	0	1	0	0	1	0	0	0	0	0	

