HISTORICAL SHORELINE CHANGE AND BEACH MORPHODYNAMICS AT RAPAHOE BAY, WEST COAST, NEW ZEALAND

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Rei Ishikawa

Department of Geography
University of Canterbury
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Abstract

This thesis utilises a range of methodologies to investigate the historical shoreline change and beach morphodynamics at Rapahoe Bay, West Coast, New Zealand. Rapahoe Bay is a small embayment located 15 km north of Greymouth, and contains a complex and dynamic environment under a dominant swell condition. The objectives of this thesis include the investigation the coastline history through aerial photographs and relevant literature, identify and quantify historical shoreline change and the processes that have induced change, examine the short term and seasonal changes in beach profile, identify and quantify wave and transport process and to test the applicability of the zeta shoreline curve on a composite beach. This combined approach investigates the dynamics and process drivers involved in coastline change.

This thesis contributes to the research gap of understanding morphodynamic behaviour and controls of composite beach under a dominant swell. Composite beaches types are a variation from mixed sand and gravel beaches with distinct morphological differences. This thesis provides an insight in to the morphodynamic behaviour of composite beaches. The study area contains a small village based by the shoreline and the potential coastal hazard that threatens people, property and infrastructure. Therefore the results from this thesis have an important management implication towards mitigating coastal hazards.

The historical coastline change was induced through a combination of wave processes and transport, composite beach morphodynamic behaviour, anthropogenic influence and planform shape. Results show that human infrastructure restricted the retreat of a small hapua landward of the gravel barrier. A combination of change in sediment supply, consistent sediment transport and a high wave energy environment resulted in rapid landward retreat through gravel rollover and coastal erosion. The gravel barrier morphodynamics include increase in crest elevation, steeper shore gradients as a response to high swells resulting in erosion or rollover. The wave environment includes a sediment transport hinge point due to a dominant wave refraction and changes in the shoreline orientation, which further induces coastal erosion. The valid applicability of the zeta planform shape concludes that the shoreline may further retreat due to geological controls, potential sediment transport and the transgressive nature of the composite beaches.

The combination of methods and results provide both quantified historical change and also potential future scenarios of coastline reshaping. These methods and results are applicable not only to Rapahoe but along other West Coast composite beaches, and the validity of the combination of methods provides a greater understanding of the behaviour of morphodynamic composite beaches and provides quantified results of historical shoreline change and sediment transport at the field site.

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Chapter One: Introduction

Figure 1.0 Photograph of the Rapahoe Township looking northeast 26/6/07

1.1 Thesis Statement

New Zealand is a country with a long coastline (over 10,000 km of open coast and another 8000 km within inlets), of which 25% is prone to long-term erosion (Gibb, 1978). This situation, combined with more than 70% of the population living in areas near the coast, results in a high national incidence of coastal hazards. One location affected by erosion hazard is Rapahoe Bay on the West Coast of the South Island, where a small settlement has sought protection from on-going coastal erosion hazard over the last 20 years. This thesis investigates the historical coastline change and beach morphodynamics at this composite sand and gravel beach site, using a range of quantitative and qualitative methods to understand the history, dynamics, wave processes and planform shape development of the bay in order to contextualise the erosion processes occurring there and moving toward making recommendations as to possible hazard solutions. Sound geomorphic investigations are regarded as one of the best tools to predict future shoreline change (Cooper and Pikey, 2004) and the methods employed in this thesis include GPS field measurements and observations, GIS analysis of aerial and digital photographs, application of wave refraction and zeta shoreline theory, and evaluation of literature. These methods provide a comprehensive approach towards the further understanding of this embayed composite beach on a swell dominated coastline. The results from this study evaluate the effectiveness of this approach, in terms of future coastal management investigations on composite coastlines.

1.2 Conceptual Context and Framework

Globally rare, composite beaches are commonly categorised alongside mixed sand and gravel beaches and gravel beaches. The existence and distinction of a composite beach in comparison to mixed sand and gravel beaches have only been recently acknowledged by the significant contributions by Jennings and Shulmeister (2002), Mason et al. (1997) and Carter and Orford (1984). The rarity of this beach type and common mis-categorisation of composite beaches with mixed sand and gravel has restricted research development specifically on beach dynamics. The lack of knowledge regarding controls on beach development, morphodynamic behaviour and processes drivers and the importance for coastal management have been identified by Jennings and Shulmeister (2002) and Mason et al. (1997). Therefore, gaps in our understanding of composite beaches form the following research questions:

- What is the morphodynamic behaviour of a composite beach under a high-energy swell condition?
- What are the controls that have induced historical shoreline change on a composite beach?
- How does a composite beach align with the zeta planform shape and how can this be applied towards coastal management?

The West Coast of the South Island of New Zealand is unusual as the majority of the coastline comprises of rocky or composite beaches (Jennings and Shulmeister, 2002) under a dominant high-energy swell condition. Despite the high rates of available sediment supply, the West Coast displays a dynamic scale of fluctuations between erosion and accretion and the coastline south of the Barrytown flats, including Rapahoe, has displayed continuous long term erosion (Benn, 2006). The Rapahoe field site is located in an embayment and contains a complex environment bordered by numerous rocky islets, a prominent headland to the south (Point Elizabeth) and a rocky coastline to the north, resulting in local variations in wave processes and sediment transport from the regional context. This complexity is added to by variations in the geology of the embayment, the presence of the river mouth in the embayment, and increasing anthropogenic influences from coastal protection works.

This thesis proposes to contribute to the existing knowledge of composite beaches by providing an investigation of morphodynamic processes in a complex environment where a range of morphology and processes interact. A broad range of literature has been examined and critiqued in each chapter to identify and explain the site characteristics, the morphological changes, and the use and limitations of research methodologies employed. An advantage of employing a combination of quantitative and qualitative research methods is that it allows for verification and cross checking results regarding the dynamics of individual beach features and processes as well as the impacts of human influences.

This study also has important management implications in a regional context as the majority of the population of the West Coast is located along the eroding composite beach coastlines. Therefore, an improved understanding of the morphodynamics of these beach types will be of use in formulating future management decisions on these beaches as well as other similar shorelines. Due to the on-going hazard issues at Rapahoe Bay, the results from this study are directly applicable to current management decisions within the Bay.

1.3 Aims and Objectives

The aims and objectives of this thesis are as follows:

1. Investigate the coastal environment of the study area and relevant past literature on Rapahoe Bay
2. Identify and quantify the historical coastline change and the responsible processes
3. Examine and map the seasonal and short term changes in the beach profile in particular gravel barrier dynamics
4. Identify and quantify coastal processes operating in Rapahoe Bay and the impacts on beach dynamics.
5. Examine the planform shape of the coastline compared to the zeta model planform literature
6. Summarise the results identifying the interactions and process drivers that have induced the historical coastline change and current beach morphodynamics

1.4 Thesis Structure

The investigation of the historical coastline change and beach morphodynamics at Rapahoe Bay is examined using a variety of coastal characteristics or attributes. The chapters are generally divided up to study individual characteristics or attributes and each chapter includes an individual literature review, method, results and discussion.

Chapter 2 examines the environment in the study area. A literature reviews previous reports, studies and thesis focussed specifically on the study area and geology, sediment and beach, atmospheric and oceanic influences and anthropogenic impacts are examined.

Chapter 3 investigates the historical coastline change through the use of aerial photographs. Literature reviews on gravel barrier movement and hapua are provided alongside the methods, limitations and usage of aerial photographs for coastal research. The movement of the wet/dry line, vegetation line and lagoon change is examined to provide quantitative and qualitative results on shoreline change.

Chapter 4 examines the seasonal and short term beach profile change through the use of digital elevation models (DEMs). This chapter further examines gravel barrier dynamics and reviews composite beach literature. The DEMs provide high resolution results to identify the short term and seasonal changes in the field site and correlates the results with those presented in the literature.

Chapter 5 identifies and quantifies the coastal processes in the study area through the application of wave refraction theory (CERC, 1984). A literature review is provided examining the wave generation model (WAM) and the relevant results, and the application of the wave refraction theory. The outputs provide results to identify wave processes and quantity longshore transport.

Chapter 6 applies the zeta planform theory to Rapahoe Bay. The different aspects of the coastal environment that have been examined in previous chapters are also brought together to evaluate the effectiveness of the research methods and identify the process drivers that have induced historical and current change to the coastline. Chapter 7 includes a summary of the main findings to review the research questions and thesis objective, and provide recommendations for future research.

Chapter Two: Field Site

Figure 2.0 Photograph of the Kaiatan mudstone cliffs located north of the Forbes Property 17/5/07

2.1 Introduction

This chapter reviews relevant information on the field site from the literature, past research, and field observations required to determine the important factors and influences for this study. The review includes information on the geology, anthropogenic history, beach type, atmospheric and oceanic influences, sediment movements and changes in beach position within the study area.

2.2 Study Area Location and Description

Rapahoe Bay is located on the West Coast of the South Island, approximately 15 km north of Greymouth. Figure 2.1 shows the location of the study area. The study area comprises of a 3.7 km stretch of coastline from Point Elizabeth, a prominent limestone headland, north to Coin Creek. Notable features in the area include the headland (Point Elizabeth), the numerous rocky islets north of Point Elizabeth, the mouth environment of Seven Mile Creek/Waimatuku, the settlement of Rapahoe, and State Highway 6 which runs through Rapahoe and then north along the coastline.

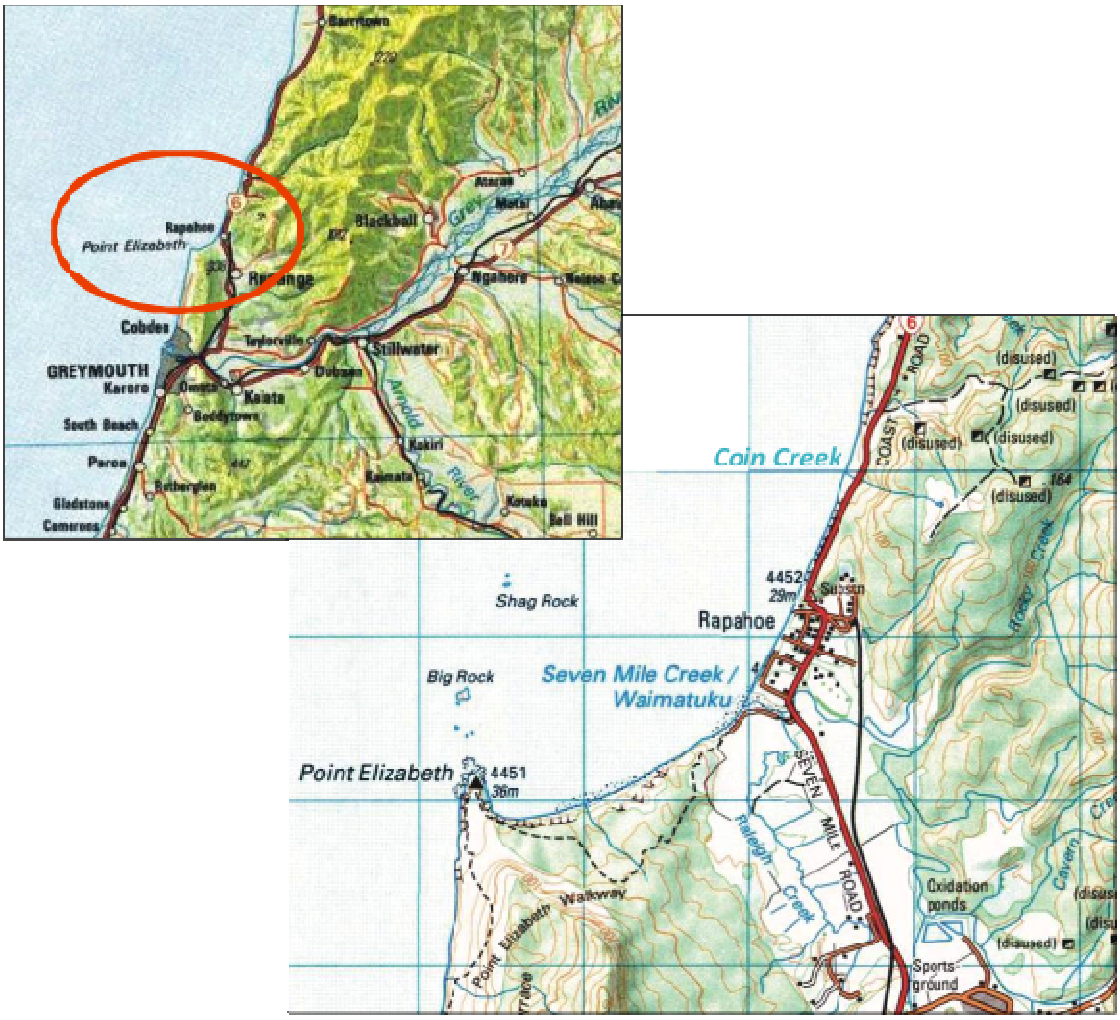


Figure 2.1 Location Map of Rapahoe Bay (MapToaster Topo, 2007)

2.3 Previous Research

Pfahlert's (1984) thesis on the coastal dynamics and sedimentation at Point Elizabeth is the most comprehensive research on the coastal processes of the study area. Pfahlert's results are used in numerous consultancy and government department reports including DTec (2007), Neale (2000), Westlake (2000) and Ramsay (2006). These reports focus on current coastline conditions and discuss a variety of coastal hazard management options. Prior to these reports, Pfahlert considers the works of Furkert (1947), Mangin (1973) and Gibb (1978) to be an exception to the relative lack of research on the West Coast beaches (Pfalhert, 1984). Jennings and Shulmeister's (2000) beach classification provide a conceptual model for composite beaches and a field based classification of the South Island including the West Coast. The importance of this beach classification is discussed in the section 2.5.

On the contrary, the geology of the West Coast has been extensively researched by institutions and societies such as the Geological Society of New Zealand (Hayward and Kenny, 1999), Institute of Geological and Nuclear Sciences (Nathan et al. 2002), Department of Lands and Survey (1983), University of Canterbury Geology Department (Nunweek, 2001; Lever, 1999; Moore, N.A. 1996; McNee, 1997) and other private consultancy companies. The potential for natural resource mining such as coal has been the main incentive for the abundant geological research.

2.4 Geology

Thornton (2000) describes the area near and around Greymouth as displaying excellent geological features from the Arnold Series, in the late Eocene stages. Figure 2.2 displays the geological variety that can be found with in the study area vicinity. The underlying base is Devonian greywacke (Paleozoic), identifiable by the greenish-grey to dark grey sandstones and argillites that are evident further north towards Thirteen Mile Bluff. Layering these higher plateaus are the Cretaceous-Eocene coal measures, further layered by Eocene sandstones and Eocene mudstones (Nathan et al. 2002). Large coal seams are apparent and accessible through thinner and eroded layers of sand and mudstones with numerous mine sites such as Strongman Mine, Mt. Davy and a large numbers of abandoned mines in the region. The Eocene sandstones were formed in the Bortonian (Early Arnold) stage, where the seas moved in to form a hard and thick layer of marine sandstones. As the seas deepened, the brown, carbonaceous conglomerate-mixed Kaiata Mudstones (Eocene mudstone) built up and the Kaiatan and Runangan Stages are apparent on the Northern extents of Rapahoe Bay (Nathan et al. 2002).

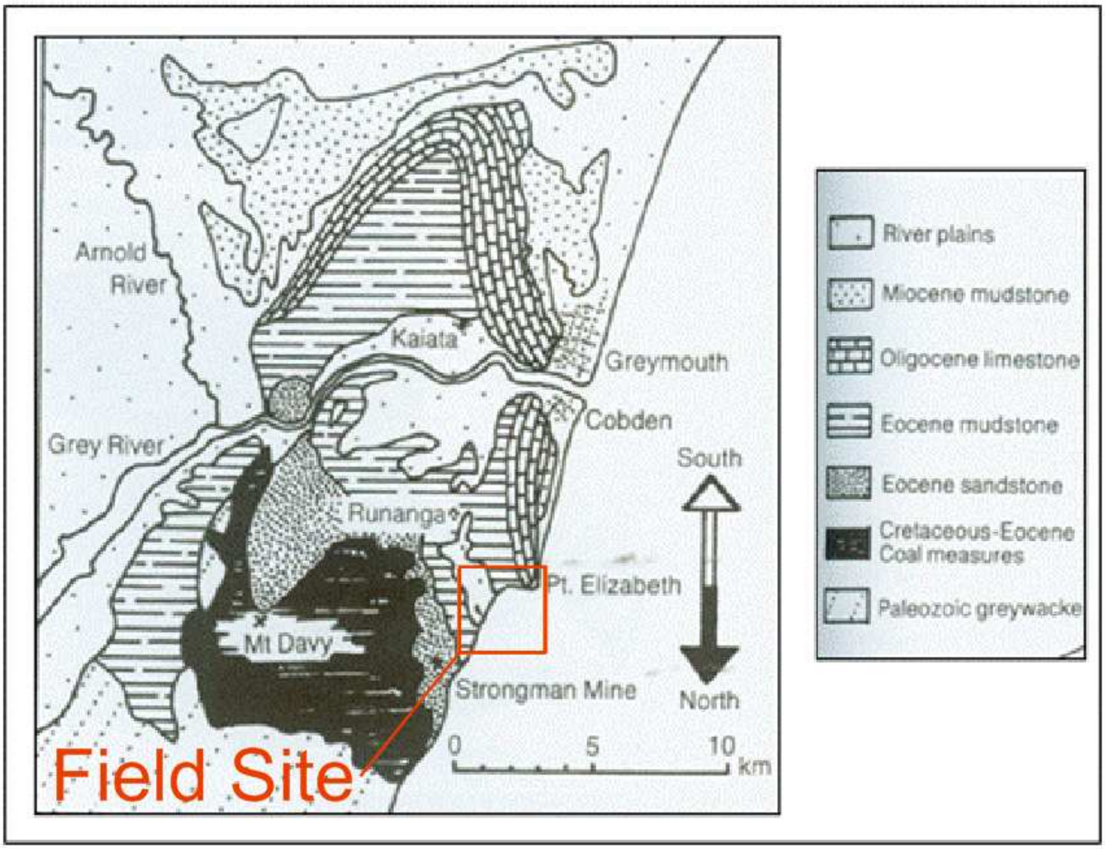


Figure 2.2 Geological Map from Greymouth to Strongman Mine (Thornton, 2000)

Further south, Point Elizabeth is geologically considered to be an area of scientific, educational and aesthetic importance in a national scale due to the sections of exposure portraying late Eocene and Oligocene sequences of strata which have been selected as the type reference section for this period time in New Zealand (Hayward and Kenny, 1999). The point displays a layer of Cobden limestone (Oligocene) developed after the Kaiatan Stage. The limestone is a micritic, fine-grained, creamy-white to light brown, muddy limestone and can be traced from Point Elizabeth, to further south toward Cobden. In between the Kaiatan mudstone banks on the Northern extents of Rapahoe Bay and the limestone covered Point Elizabeth lies the township of Rapahoe, based predominantly on marine gravels backed by a mixture of alluvial deposits, mainly postglacial deposits which include river gravel and sand deposits (Thornton, 2000). A most detailed geological map of the area is provided by the Department of Scientific and Industrial Research (1978), Sheet S44, which is reproduced in Appendix 2.1. The controls and influences that the geology has on the beach will be discussed in further detail in Chapter 6.

2.5 Rapahoe Beach

Rapahoe beach is described as a swash-aligned beach featuring a gravel beach barrier, backed by land that is lower in elevation than the height of the gravel barrier. The ‘typical’ West Coast gravel barrier system is described to be in a state of long-term sediment starvation due to insufficient fresh gravels entering the beach system combined with the relatively stable sea levels over the last 6,000 years (Ramsay, 2006). Therefore the natural beach response is for the beach to migrate landward (Shulmeister and Rouse, 2003).

The beach in front of Rapahoe township has been described by Pfahlert (1984) as being mainly mixed sand and gravel (MSG) with exception to the southern section of the beach (towards Point Elizabeth) which is described as a pure sand beach. Pfahlert’s (1984) description of the MSG beach was that the beach was predominantly in a state of two separate morphological units. The lower foreshore was characterised by low gradient sandy sediment with patches of small pebbles while the upper foreshore layered above the sand with larger gravels and pebbles and had a much steeper gradient. Recent literature by Jennings and Shulmeister (2002) classified the West Coast of the South Island as having predominantly meso-tidal composite beaches. The characteristics of composite beaches given by Jennings and Shulmeister (2002) closely fit in with Pfahlert’s descriptions and field observations of Rapahoe Beach. The beach observations during this study are presented in Figure 2.3 (A&B) also align with Pfahlert’s descriptions. It is therefore considered that Pfahlert’s previous classification of the Rapahoe beach as MSG is inaccurate, and its more correct classification is as a composite beach. Further details on composite beach characteristics and dynamics have been discussed in the chapter 4.

Figure 2.3 (A): Rapahoe Beach at High Tide 19/5/2007
(B): Rapahoe Beach at Low Tide 17/5/2007

2.6 Sediment and Beach Movement

It is widely accepted that Rapahoe Beach has been extensively eroding since the 19^{th} century and this is consistent with many West Coast beaches nearby (Neale, 2000; Ramsay, 2006; Westlake, 2000). Pfahlert's (1984) report provided some quantitative figures and the majority of reports refer back to these rates. During 1882-1984, the southern end of the beach indicates an erosion rate of 0.4m/yr and the northern end eroded at a rate of 0.8m/yr (Pfalhert, 1984). Pfalhert estimated an annual erosion rate of 3,500 cubic metres per year along the beach, although there is no description to what extent of the beach experiences this annual loss. The accuracy of these erosion rates has been questioned in recent literature (Neale, 2000 and Westlake, 2000).

There are a variety of conclusions behind erosion and sediment movement on Rapahoe Beach. Pfahlert (1984) and Neale (2000) explains that the erosion is caused by or related to sediment trapping at the Blaketown groyne and the commercial gravel extractions on the Blaketown beaches and the Grey River. The trapping and extraction of gravels acts to 'starve' the beaches north of Greymouth, leading to the erosion on Rapahoe Beach. Ramsay (2006) and Westlake (2000) disagree with the above, noting that the beaches directly north of Greymouth (Cobden) are mainly comprised of sand, and therefore the gravels found in Rapahoe Bay are mainly sourced locally or a previous relict deposit. The loss of gravel is explained as a direct result from abrasion and the northward sediment transport. Upon investigation during a field visit for this study (08/08/07), Cobden beach appears to be a mainly sandy beach, but a distinct gravel barrier is present. This implies that longshore movement of gravel is a possibility, but whether the gravel movement extends around Point Elizabeth or bypasses Rapahoe Bay further north is still uncertain.

Seven Mile Creek is a tributary that is not regarded as having a significant impact to the sediment supply of the study area. Ramsay (2006) concludes that low volumes of sand and gravel wash down through Seven Mile Creek during flood event but it is unlikely to be the main source of gravel to Rapahoe Beach.

Despite the debate in reasons for coastal erosion, the idea of the existence of a wave hinge point resulting in a change in sediment transport direction is commonly agreed on (Neale, 2000; Westlake, 2000; Ramsay, 2006). This hinge point would be an area suffering from erosion, where sediment will drift in either longshore direction. The hinge point has been stated by the previous reports due to the relative importance towards coastal management, with the possibility of introducing a coastal groyne north of this point to act as a sediment trap. The existence and location of the hinge point will be examined in chapter 5 through the wave refraction modelling. The above three reports also mention planform shape and the reaching of a 'dynamic' or static equilibrium position, which is a relatively stable position around which the beach fluctuates in response to short term changes in wave approach angle. Equilibrium beach plan shapes will be examined further in chapter 6.

2.7 Atmospheric and Oceanic Influence

2.7.1 Rainfall

The West Coast of the South Island is an area of high rainfall. The prevailing westerlies are forced upward upon the Southern Alps leading to an orographic effect leading to intense amounts of precipitation along the entire West Coast (Sturman 2001). The closest climate station to the study area is located at Hokitika, and has recorded an annual average rainfall 2875 mm per annum with up to 171 'wet' days per year (NIWA, 2007). This high level of rainfall influences fluvial processes and its parameters, and other related processes such as weathering, fluvial erosion, flow rate and sediment discharge determines the amount of sediments introduced into the rivers (McConchie, 2001).

2.7.2 Wind and Wave Processes

The study area is exposed to a dominant prevailing westerly winds which produces predominantly south westerly to westerly ocean swell conditions. Figure 2.4

illustrates a wave rose of the range of hindcast wave conditions over a 20 year period for a site immediately to the south of Point Elizabeth (Lat -42.4, Long 171.18). This data was obtained from WAM (Wave Analysis Model) hindcast provided by NIWA. The combination of high wind speeds and extensive fetch length across the Tasman Sea can produce large wave heights as shown in the wave rose. The predominance of south-westerly swell conditions results in a net longshore drift direction towards the North along the West Coast (Pfalhert, 1984; Neale, 2000; Westlake, 2000; Ramsay, 2006).

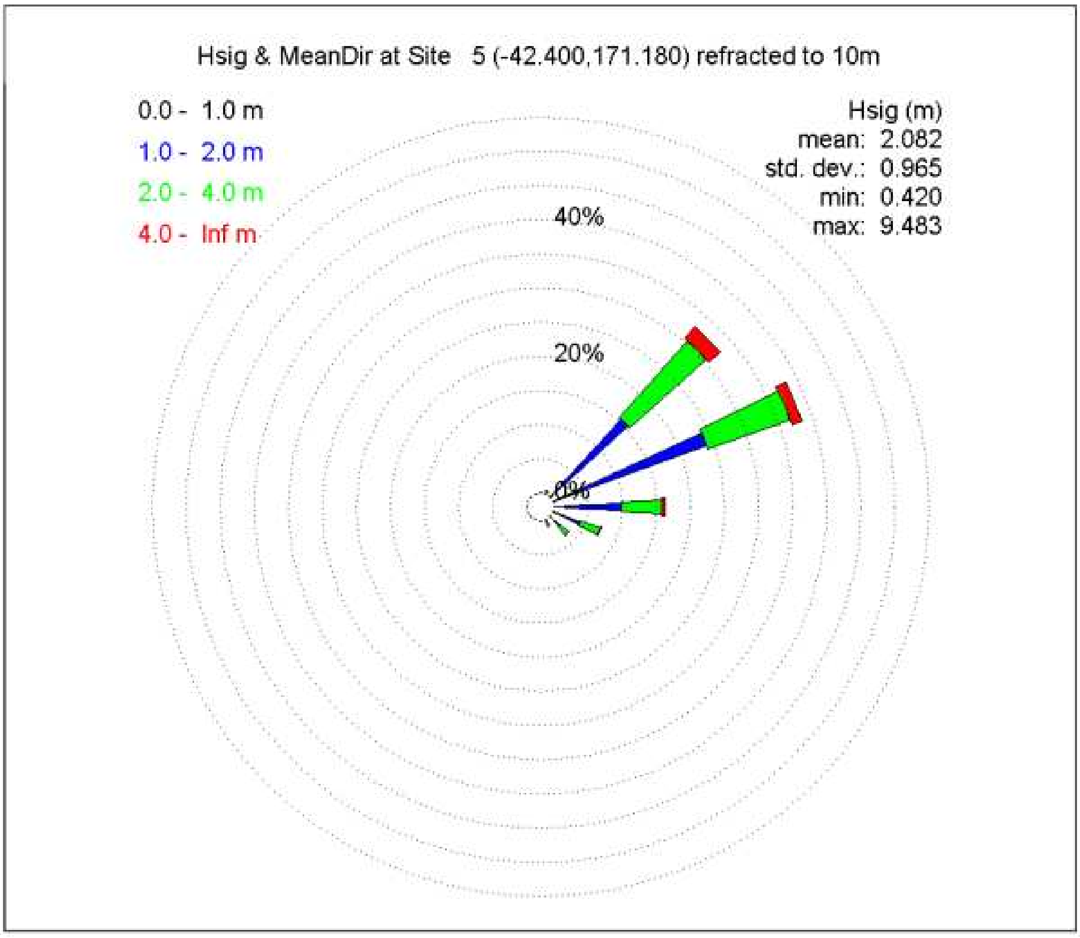


Figure 2.4 Wave rose displaying the wave directions and height at a WAM site South of Point Elizabeth (Lat -42.4, Long 171.18). Note directions are given as "directions to" rather than the more common" approach directions from".

The dominant wave approach will influence nearshore coastal processes and parameters as it approaches the coastline. The nearshore bathymetry interacts with the incoming waves and results in wave processes such as wave refraction, longshore drift, and sediment transport. Wave refraction is the process of waves 'bending' towards the coastline due to the bathymetry becoming shallower towards the headland. The waves approaching Point Elizabeth undergo refraction due to the difference in orientation of wave approach and the shallow water bathymetry which mirrors the planform shape of the coastline. Wave refraction is clearly visible in Figure 2.5. The refracted waves cause a localised eddy effect behind the headland in Rapahoe Bay, resulting in a southerly longshore drift direction within Rapahoe Bay as noted by Neale (2000), Westlake (2000), Ramsay (2006) and Pfalhert (1984). These local wave processes will be discussed in further detail in chapter 5 as the wave refraction theory is applied.

Figure 2.5 Aerial Photograph of the Rapahoe Bay Area (LINZ, 2007). The area in the red box displays the wave refraction in the lee of Point Elizabeth.

2.7.3 Tides

Rapahoe Bay is located very close to Greymouth and the tides experienced are assumed to be very similar. The New Zealand Nautical Almanac (HydroLINZ, 2007) provides the following tide figures for Greymouth relative to the Lowest Astronomical Tide (LAT):

Mean High Water Spring (MHWS): 3.4 m
Mean High Water Neap (MHWN): 2.7 m
Mean Sea Level (MSL): 2.0 m
Mean Low Water Spring (MLWS): 0.7m
Mean Low Water Neap: 1.5 m

Tidal range is relevant when calculating maximum storm runup and assessing beach rollover processes and inundation risks. Another important feature is that the large tidal range (2.7 m at spring) results in considerable changes the appearance of the beach at different tides. Numerous beach misclassifications, especially of composite beaches have occurred due to observations during high tide. Figure 2.3 (b) displays Rapahoe Beach at high tide, and the low gradient beach face is not clearly visible. This beach could be confused as a MSG beach, which comprises different characteristics to a composite beach. This form of misclassification is partly due to observation time and the relatively new introduction of the composite beach classification.

2.8 Anthropogenic History and Potential Impacts

The area of Rapahoe-Runanga has a population of 1305 people, including 351 families (Statistics NZ, 2006). Rapahoe settlement has a colourful history, mainly known as an area of residence for miners and loggers. During 1882, the town was first established (Ewen, 2003) as a base near the numerous coal mines. In 1889, Rapahoe Bay was investigated for the possibility of the development of a harbour (Balfour, 1889). Establishment of the James Mine in 1918 led to developments of the branch railway line to Runanga and Rapahoe in 1923. The railway line is still a distinct piece of infrastructure in the area. Following the James Mine was the Strongman Mine, established in 1939. Known for producing a higher quality coal than from the James Mine, the area quickly benefited leading to further purchase and development of real estate in the Rapahoe, Runanga and Reefton regions. Aerial photographs show slow development of buildings and houses in the settlement and by 1959, State Highway 6 was introduced through Rapahoe headed north towards Westport. Point Elizabeth is considered to be an area with significant aesthetic and scientific value and the Rapahoe Range Scenic Reserve Management Plan was developed and approved in 1983 (Department of Lands and Survey, 1983).


Figure 2.6 Photograph looking north displaying the riprap revetment protections along Rapahoe Beach (25/7/07)

The Rapahoe Beach has an interesting background, which includes war time submarine sightings, the establishment and disbandment of the Kotuku Surf Life Saving Club and numerous whale strandings (Ewen, 2003). The beach has always been a popular destination for swimming and sunbathing. Seven Mile Creek has also been known as a popular spot for local white baiting in the past and some local gold panning is present to this day. The most significant anthropogenic impact regarding the beach is the introduction of rock revetments, in the form of riprap placements on the beach. These revetments were introduced during 1996 by the Grey District Council, over a 200 metre length on the beach frontage. Further revetments were added over a 320 metre length by the leaseholder of the local campground, extending south from the mudstone outcrop on the northern boundary (Ramsay, 2006). This revetment is shown in Figure 2.6.

Figure 2.7 Photograph facing north displaying riprap revetments by the mudstone cliffs introduced by Transit (24/7/07)

Transit New Zealand, who is responsible for the safety and maintenance of the roads also commissioned the placement of riprap protection along the seaward edge of State Highway 6 along the mudstone cliff to the north of the township. Reports of the cliffs being undercut by wave processes date back to 1978 (Gibb, 1978) and the riprap dumping commenced shortly after. Riprap dumping still occurs frequently and a ‘top up’ is regularly witnessed post storm events (Fletcher, 2007. pers. Comm. 25th June). Figure 2.7 displays a recently ‘topped up’ riprap protection for the state highway.

Chapter Three: Historical Shoreline Change

Figure 3.0 Aerial Photograph of Rapahoe Township 1939

3.1 Introduction

Identifying shoreline variability and shoreline erosion/accretion trends are fundamental investigations towards understanding the coastal history of an area. This section seeks to explore the historical coastline change in front of Rapahoe Village with the use of aerial photographs. The main purpose of this chapter is to:

- Provide comparisons of each aerial photograph to identify change in the Rapahoe village area
- Analyse the coastline history and identify trends
- Provide quantitative rates and figures of historical changes that have occurred

3.2 Gravel Barrier and Hapua

The gravel barrier and the former hapua feature are two significant coastal morphology features in Rapahoe Bay. The dynamics and nature of these morphologies are an important part to understanding the coastline history and change in the study area, therefore some past research on the two features will be discussed below.

The gravel barrier is a prominent morphology feature at Rapahoe Bay, located on the seaward side of Beach Road. The barrier is the only line of defence for Rapahoe village against the dominant SW swell of the West Coast. Gravel barriers are a common feature on paraglacial coastlines such as New England, New Zealand and Nova Scotia (Forbes and Syvtiski, 1994). Masselink and Hughes (2003) note that the three main responses that a barrier may undergo include barrier erosion, translation and overstepping barrier processes are evident in Nova Scotia, where a swash aligned, transgressive barrier has migrated onshore over time through the roll over process during storm events (Buscombe and Masselink, 2006). Therefore, the materials that have been rolled over are temporarily lost from the beach system, and the continuous process results in the transgressive movement. Orford et al. (2002) argues that sediment supply and the terrestrial basement are the main controls on a gravel barrier, and barrier alignment is achieved by means of wave processes and longshore transport. A decrease in sediment supply would be liable for erosive action on the beach, combined with storm events leading to loss of beach width as well as landward retreat of the barrier. The movement of this barrier provides clues to past coastline change as the barrier is susceptible to variations in both sea conditions and sediment supply. However, difficulty in identifying the position of the barrier ridges in aerial photographs makes it difficult to use this feature for accurately mapping change. The alternative utilized in this chapter is the identification and measurement of the wet/dry line and vegetation line on the beach to identify the movement, as the two parameters shift in accordance to the barrier. On a composite beach, the reflective face of the barrier is characterized by a steep beach face composed of gravels and other clastic sediments. The thin stratigraphy of the gravel barrier is prone to dynamic movement influenced by the exposure to wave energy during ambient or storm conditions (Kirk, 1980) and changes in sediment supply. More details on the short term barrier dynamics are described in section 4.2.

The coastal lagoon that is identified in the early aerial photographs is comparable to the coastal morphology classified as a ‘hapua’, as described by Kirk and Lauder (2000). A river mouth lagoon frequently forms parallel to mixed sand and gravel beaches on a high energy, erosive coastline with predominantly fresh water impounded by a narrow spit. The magnitude of river mouth offset can vary due to the river flow conditions and the river mouth has effectively no tidal prism. Hart (1999) has identified the dynamic nature of the hapua and cycles of change it can experience in a mixed time frame. Although Seven Mile Creek can not be classified as a moderately steep, braided channel river and the study area is a meso-tidal composite beach as opposed to the required micro-tidal, mixed sand and gravel beach, the remainder of the characteristics aligns with the characteristics by Kirk and Lauder (2000). They also note that despite the long term chronic erosion on the coastline, hapua progressively retreat landward and maintain their morphology. The results of the aerial photograph analysis identify that this is not the case for Seven Mile Creek, with the loss of the hapua occurring over time. The discussion in this chapter examines the interactions between the barrier and hapua, and the potential anthropogenic impacts that lead to the loss of the hapua.

3.3 Method

This part of the study utilized eight digitised aerial photographs from New Zealand Aerial Mapping (NZAM). The aerial photographs were taken in the following years; 1939, 1948, 1959, 1970, 1980, 1988, 1997 and 2005. These photographs are roughly at ten year intervals and were utilized to allow for decadal changes to be identified and quantified. Further details on each photograph can be found in appendix 3.1. The use of aerial photography by coastal scientists, engineers, consultants and coastal managers is a common method of assessing historical change in coastal areas (Boak and Turner, 2005; Dahdouh-Guebas et al., 2006; Romagnoli et al., 2006; Vinther, 2006; Al-Tahir and Ali, 2004; Solomon, 2005; Kirk, 1975). Although more recent methods involve the use of satellite images (Sulong et al., 2002; Al-Tahir and Ali, 2004), aerial photographs are seen as a cheap, effective and simple-to-use method which still provides a quality results for identifying coastline change. Also importantly aerial photographs are available for larger areas and over longer time spans than satellite images (Dahdouh-Guebas et al., 2006). The decadal time frame of photographs used in this study provides a valuable insight between the “long term” (time span of hundreds to thousands of years) and “short term” (seasonal and tidal time frame) as identified by Kirk (1975).

Al-Tahir and Ali (2004) demonstrate that aerial photographs can be examined in a qualitative and quantitative method allowing for human interpretation of change as well as statistical outputs. The combination of the methods allow for identification of spatio-temporal change to the greatest detail. The aerial photographs were initially examined in a qualitative method, by human interpretation of visible changes throughout the eight photographs. The purpose of this method is to provide some visual descriptions of obvious changes and trends that were identified on the photographs. The changes were identified in seven different categories as follows; river mouth position and condition, lagoon size and location, beach conditions and width, vegetation position, nearshore conditions, anthropogenic change, and rock revetments. The results are discussed in section 3.5.

The quantitative methods involve the use of ArcGIS. The digitized photos provided by NZAM were not orthorectified, and potential errors from this will be discussed later in this chapter. The initial step was to reference all the aerial photographs together, and this was achieved by setting common ground control points (GCP) with in each photograph. Ground control points are usually utilized alongside GPS points (Al-Tahir and Ali, 2004), but this was not available for this research. Due to the lack of prominent and stable natural features and the lack of visible benchmarks, buildings such as the Rapahoe Hotel, the railway stations, and certain households that have not changed or moved throughout the photographs were used as GCPs. Three to four GCPs were used on each photograph to provide the best aerial triangulation and all the photographs were referenced back to the 1959 aerial photograph. This photograph was used because the physical photograph was available and the area of interest was in the centre of the photograph, reducing photographic distortions. A copy of this photograph is presented in appendix 3.2. The aerial photographs were not spatially referenced to the New Zealand Map Grid. Therefore, the output distances from ArcGIS had to be converted to metres as a separate process.

Once the aerial photographs were referenced with the GCPs, a baseline placed parallel to the coastline was made in GIS using a polyline file, which became the baseline for 21 perpendicular determination lines orientated seaward at 40 m intervals as displayed in Figure 3.1. The determination lines were divided in to 4 different longshore sections, A to D based on the variety of geology and coastal setting. The division of the study area is displayed in Figure 3.1. Section A includes lines 1 to 4 and covers the northern edge of Rapahoe Village. This section's geology differs from the other sections, being the area of Kaiatan Mudstone base, and topographically is mainly a steep cliff face. The state highway runs along the top of the cliff and is has continuous riprap protection work by Transit New Zealand. Section B and C covers the sea frontage of Rapahoe Village. It is apparent when viewing the aerial photographs that the beach is eroding at different rates spatially, so the village frontage was split to two sections to identify the variety of erosion rates along this shoreline. Section B is covered by lines 5 to 11 and section C by lines 12 to 19. Section B runs from the Forbes Property in the north (Line 5) to roughly half way in between Morpeth Street and Stathan Street (Line 11) in the south. Section C runs from the southern end of section C (Line 12) to south of the northern bank of Seven Mile Creek (Line 19). Although line 19 is included in this section, due to dynamic vegetation line change as a result to fluvial influences, the figures from line 19 are not included in the overall averages. Section D, is covered by Line 20 and 21, which are located south of the mouth of Seven Mile Creek. The determination lines are used to measure distance change between each photograph for the seaward boundary of the following features; the wet/dry line, lagoon boundary and vegetation line. The seaward boundary lines were mapped out using individual polylines for each year. Appendix 3.3 displays a screen shot of the process using the 2005 vegetation line. The lagoon area was also mapped out, to identify the change in surface area using individual polygon shape files for each year. Previous studies calculating quantitative change of coastlines and coastal features using similar methods include Solomon (2005), Boak and Turner (2005), and Romagnoli et al. (2006). A spreadsheet was used to compile the results of the analysis for the individual determination lines and average changes within each of the 4 larger alongshore sections. The results from the quantitative method are presented in section 3.6.

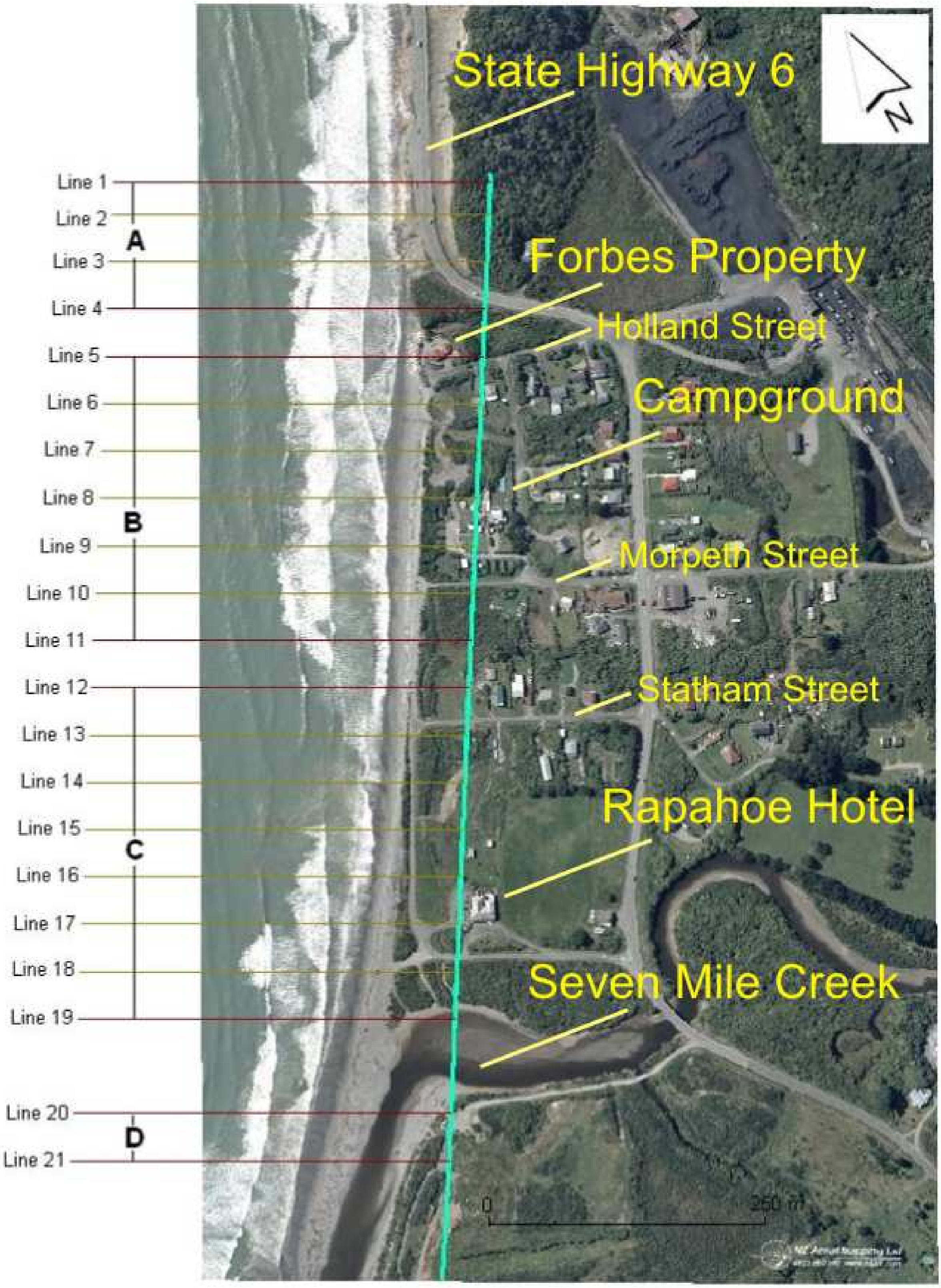


Figure 3.1 Map displaying the 21 determination lines and the 4 main sections

3.4 Limitations and Errors

Although aerial photography is a practiced method for historical coastline change and monitoring study, there are many limitations and potential errors. Firstly, this method is restricted to photographic availability, area of coverage, costs and equipment. Initially, the aerial photographs were going to be referenced to the New Zealand Map Grid by the use of an orthorectified, geo-referenced photo from 1997. This process was not followed because the resolution of the aerial photograph was of such poor quality that distinct features could not be identified, leading to vast inaccuracies in coastline mapping. Therefore, all of the photographs were referenced to the 1959 photo as described in section 3.3. Due to the lack of spatial referencing, a non-standard unit of measurement was formed by ArcGIS, which had then to be converted to metres for the output of quantitative results. This issue became an inconvenience throughout the analysis with conversions required for all measured distances.

The human interpretation and accuracy plays a large part of potential error, and consideration of photographic parameters as described by Dahdouh-Guebas et al., (2006) contributes towards feature identification. These parameters are directly affected by the resolution of the digitized photos. The resolution of the aerial photographs were generally of good quality and several were available in colour, allowing for easy digitising of the beach features used. However, the older photographs' (1939 and 1948) resolution were not of the greatest quality and may have affected the accuracy of the excursion distances of each feature. The majority of the features were of low elevation, negating errors of vertical displacement. Feature identification is dependent on the researcher's perspective on what he/she identifies as the boundary. The wet/dry line, vegetation line and lagoon line and surface area was chosen due to its ease of identity, relevance, importance and relationship and impacts towards shoreline change. Dahdouh-Guebas et al., (2006) and Boak and Turner (2005) notes that photographic parameters such as tonality, texture, structure, size, shape, shade and position are some of the many parameters as well as common sense and the researcher's visual interpretation must be considered when identifying and mapping out independent features. Features such as the vegetation boundary and lagoon areas are easier to identify due to the distinct changes in the mentioned parameters. The most difficult feature is the wet/dry line, defined by Boak and Turner

(2005) as the "distinct edge in image based on tonal differences (brightness) between the dry and wet beach areas. It is clearly visible on all photos, a stable marker on the shore and the there is little impact by sand drying and wind." The wet/dry line is effectively the high tide line and is a consistent marker for beach extent. During this research, the coastal features were mapped as accurately and consistently as possible but low resolution photographs made the task difficult at times.

3.5 Qualitative Approach: Descriptions of visible change

All seven categories were examined over the eight photographs from 1938 to 2005 with the photographs presented in appendix 3.4. Below is a summary of the main results:

3.5.1 Seven Mile Creek

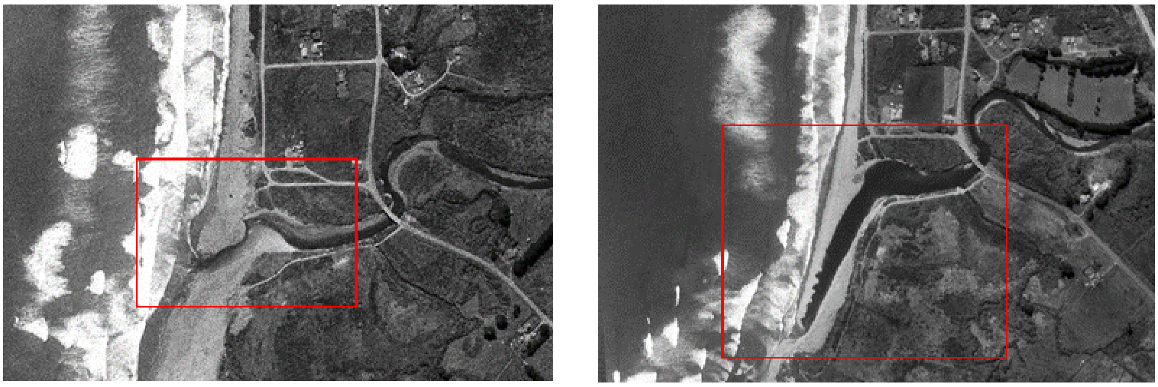


Figure 3.2 Diagram displaying the dynamic characteristics of the Seven Mile Creek (Left-1959, Right 1997)

Seven Mile Creek is the only outlet in the study area and the dynamic state of the river and river mouth impacts on the coastline in the immediate area. The West Coast is an area that receives a high magnitude of rainfall, and this has a clear impact on the river flow and vegetation. The lower reaches and mouth of Seven Mile Creek appears in all the photographs, with large changes in flow, channel position and shape being evident. High flows are assumed in the photographs from 1939, 1948 and 1997 due to the lack of visible river banks and the water levels reaching the vegetation on the sides of the river.

At the river mouth, all of the photographs display the river deflecting south before meeting the ocean (refer to Figure 3.2.), suggesting that the dominant longshore drift direction at this location is to the south. The 1939 photo is a slight exception, with the main river mouth channel flowing south, but a large lagoon formation being present in front of the main village area to the north, reaching as far north as the Forbes residence. This has important implications for erosion processes and trends and will be discussed in more detail in the next section. The change in river flow impacts the movement of sediment from the river and this in turn has effect on the morphology of the river outlet. The aerial photographs that show the river mouth (1959, 1970, 1980, 1988 and 1997) display evidence of a small delta formation, leading to a shallow zone directly seaward of the river mouth. This is identified by the waves breaking earlier compared to rest of the shoreline, and results in less wave energy reaching the beach face. It is not known if the delta has always been present by the river mouth. . The implications of this early wave break indicate that the southern end of the village would have less erosion due to the reduced wave energy reaching the shore.

3.5.2 Lagoon

Figure 3.3 Diagram displaying the dynamic characteristics of the lagoon (Left-1939, Right-1948)

The 'hapua' commonly known as a river mouth lagoon, as described in section 3.2 is a deflected section of a river channel which runs parallel to the coastline (Kirk, 2001). This section refers to the hapua feature as the bodies of water located north of the main river channel, the opposite direction to the general flow, whether it is separate or attached to the river itself.

The lagoon is found on the seaward side of Beach Road and the vegetation line. A lagoon is present in all five photos from 1939 to 1988, with the lagoon size progressively decreasing in surface area in each photograph. The 1939 photograph in Figure 3.3 displays the lagoon when the surface area is at its largest (as mentioned in the river section), reaching as far north as the Forbes residence. The river appears to be at abnormally high levels at this time resulting in increased water levels in the lagoon, which may indicate the maximum area of extent. There is also the presence of a depositional ‘tongue’ landform, surrounded by high river discharge heading north indicating the direction of river flow and movement of sediments. The lagoon size appears to decrease largely from being separated from the river, as shown in the 1948 and 1959 photographs, so that from 1970 there is little evidence of the lagoon morphology. In the photographs from 1970 to 1988 the former lagoon appears as a depression in the beach, which is periodically filled with rainfall. The red box in the 1948 image (figure 3.3) displays evidence of washover lobes in the southern section of the remaining lagoon, suggesting the lagoon was cut off from the Seven Mile Creek, through gravel roll over on the southern end of Rapahoe village.

3.5.3 Beach Conditions and Width

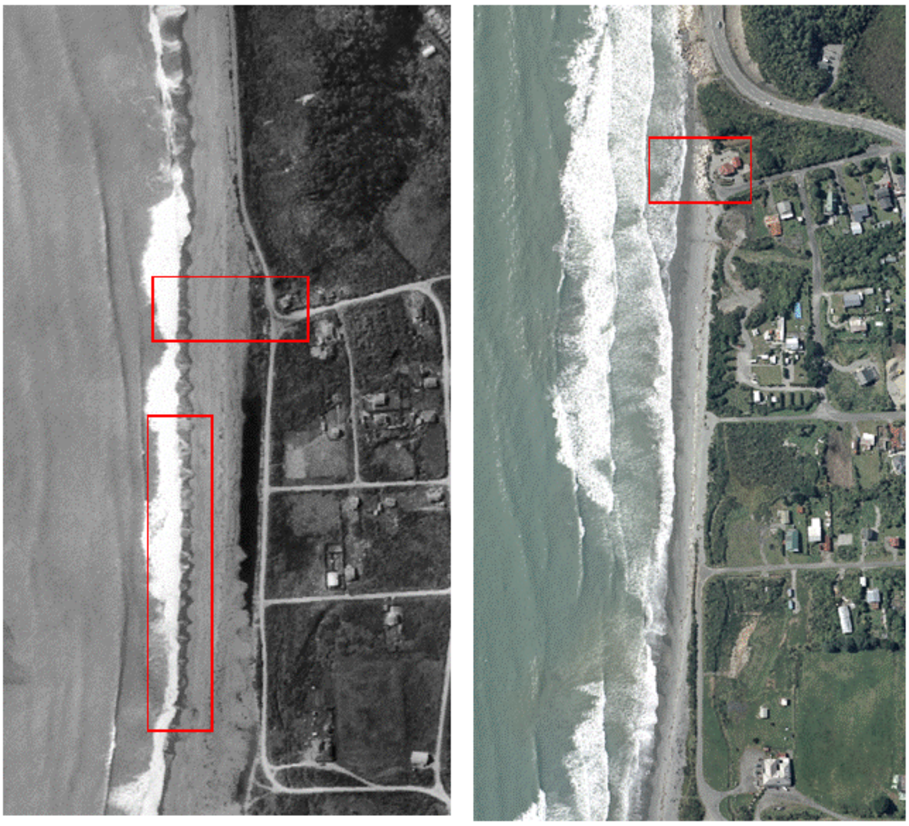


Figure 3.4 Diagram displaying beach width change and beach characteristics (Left-1948, Right-2005)

Beach sediments can describe the characteristics of the beach, and the change in beach width can provide clues to the cross shore movement of the beach. The resolution of the aerial photographs is not always clear to identify sediment changes and characteristics, but the aerial photographs display several features such as the change in sediment type (composite layering) and a storm berm. Layering is a distinct characteristic of composite beaches, and the line between sand and gravel or the composite line can be seen in the majority of the photos. The storm berm is not always clear in the photos, but driftwood can be used as an indication of the wave extent of the storm high tide and drift wood tends to be located on or near the storm berm (Boak and Turner, 2005). The sediment also indicates some rhythmic topography, and cuspate features are present in 1948 and 1980, mainly on the northern half of the beach as seen on figure 3.4.

The beach width appears to decrease overall in the photographs. Figure 3.4 displays the reduction of beach width of northern extents past the Forbes Property, which appears to have been eroded, as Beach Road is seen to run north seaward of the Kaiatan Mudstone cliffs. This road is then eroded away, and the State Highway has been excavated out of the cliffs. The introduction of the rock revetments by Transit indicates that the cliffs are eroding and the highway is at risk. The beach width in front of the village decreases drastically after the lagoon is no longer present and this in turn leads to the movement of the vegetation line.

3.5.4 Seaward Vegetation Position

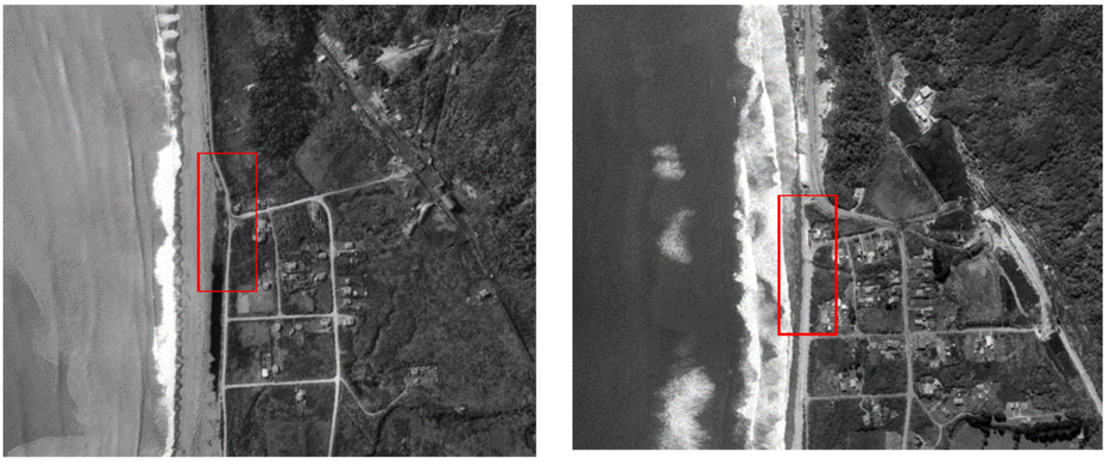


Figure 3.5 Diagram displaying the movement of the seaward vegetation position (Left-1948, Right-1997)

Figure 3.5 shows the vegetation position is retreating landward, initially being seaward of Beach Road, and now being landward of the road. At the southern end of the village, the vegetation was initially kept landward by the presence of the river mouth lagoon, and is restricted to a narrow area between beach road and the lagoon (visible in 1939 to 1970). The loss of the lagoon by allowed for the vegetation to advance seaward. By 1988, the wet/dry line advance landward, forcing the vegetation line to retreat and the vegetation line was no longer present on the north-seaward side of Beach Road. The southern end of Beach Road’s vegetation position experiences a prolonged seaward advance after the lagoon is no longer present, but appears to retreat landward later in the photographs (1970-2005). South of Seven Mile Creek shows a consistent landward retreat of the vegetation position. The vegetation has been mapped in a quantitative method later in this section.

3.5.5 Nearshore Conditions

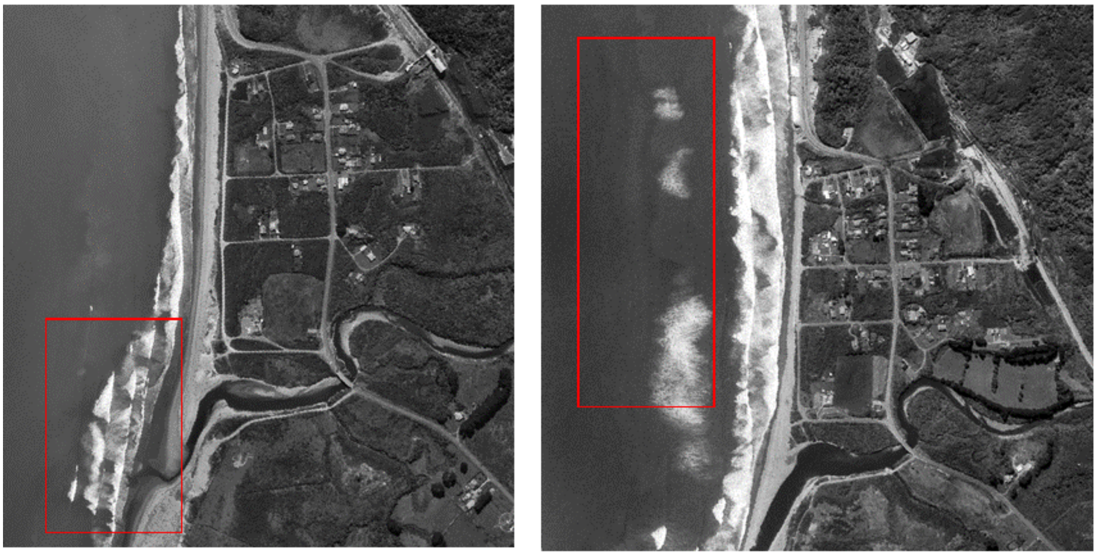


Figure 3.6 Diagram displaying a variety of coastal nearshore processes (Left-1970, Right-1997)

Figure 3.6 displays the visible nearshore features which illustrate the bathymetry of the immediate coastline. In most photographs (e.g. 1948, 1970, 1988 and 2005), many lines of breakers can be seen which is evidence of the consistent high swell that this region is exposed to, breaking on a flat nearshore seabed. The 'bending' of waves indicates wave refraction, resulting in the focus of wave energy to specific areas of the coastline. The breaking of waves offshore seen in Figure 3.6 (1970) suggests the presence of an offshore bar. Water discolouration is clearly present in 1948, 1970 and 1988 suggesting the longshore and cross shore movement of sediments. Another area of interest is by the river mouth, where a small delta or nearshore bar is present. The existence of the morphology is assumed due to the visible earlier wave break and was possibly formed by the effects of river discharge and a dominant longshore sediment movement.

3.5.6 Anthropogenic Impacts

Figure 3.7 Diagram displaying anthropogenic impacts in the study area (Left-1948, Right-2005)

Anthropogenic changes over the 65 years covered by the photos include increase in buildings and additional infrastructure. Building increase and the development of the railway station suggest a rise in population and work opportunities, which is assumed to be mainly through coal mining. The main point of interest is the change of Beach road and the introduction of the State Highway. Figure 3.7 shows that Beach Road is initially protected from the sea by lagoon and vegetation as seen in figure 3.7 (1948), but the disappearance of the lagoon and landward retreat of the vegetation leads to the erosion of the majority of Beach Road. In section A, Beach road is no longer present by 1959 and in section B, the vegetation line moves landward of the road, and the road is clearly eroded north of Stathan Road by 1997. This in turn leads to the introduction of coastal revetments, which will explored in the following section.

3.5.7 Revetments

Figure 3.8 Diagram displaying the location of coastal protection (Riprap revetments) in the study area (2005)

Rip rap revetments are a form of coastal protection where large rocks are placed on an eroding shoreline to reduce or stop the erosion. Photos from 1980 show ripraps placed by Transit to protect the highway in Section A. The increase in riprap along this section is clearly seen from the period of 1980 onwards to 2005 (figure 3.8). Ripraps were also introduced on village beach front by 1997, through out section B from the Forbes property, and as far south as Stathan Road. These ripraps are still visible in 2005 and more ripraps have been placed after 1997 by local residents to attempt to decrease the rate of erosion.

3.6 Quantitative Approach – Mapping and measuring change in position of shoreline features

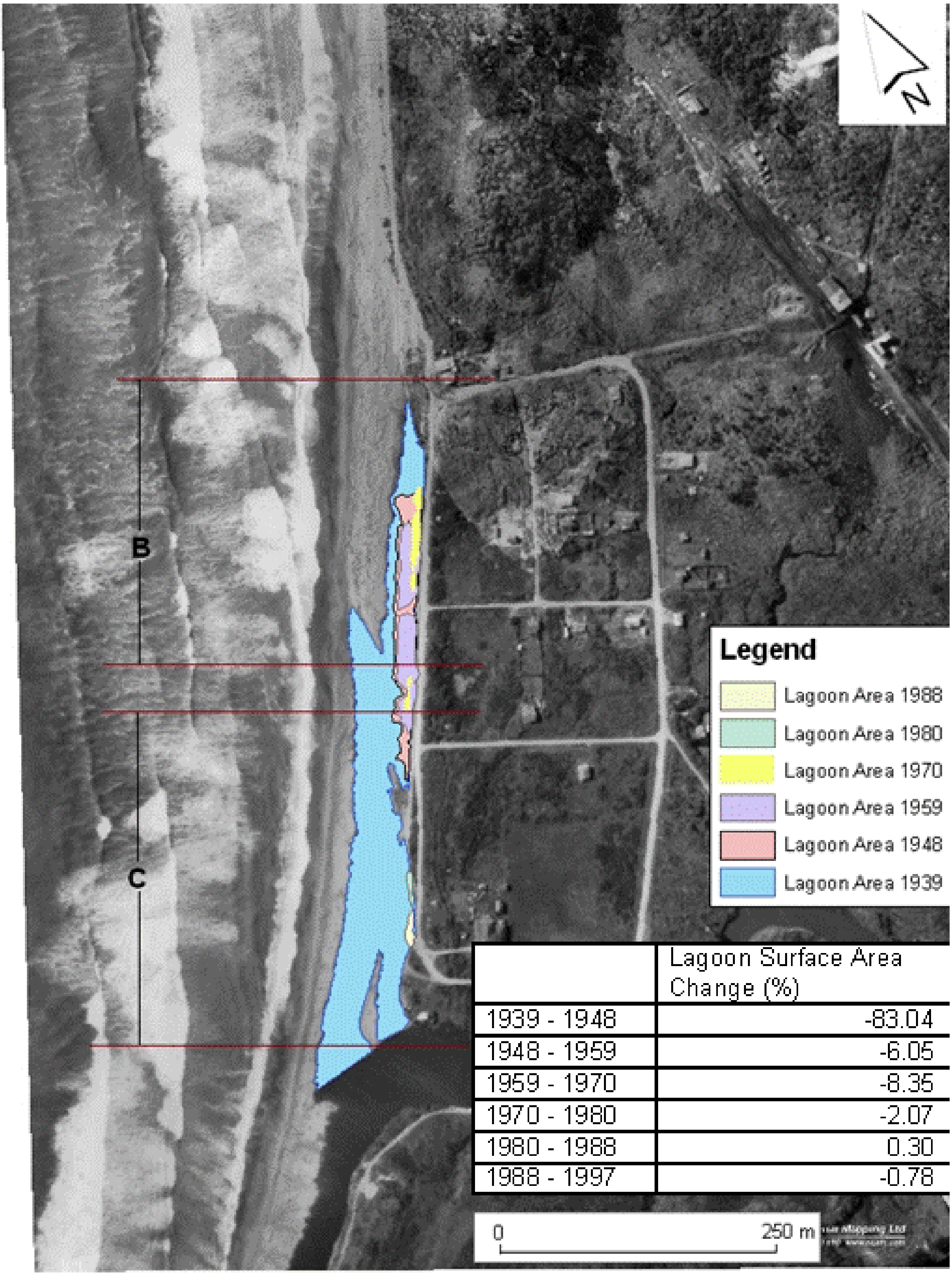
The qualitative approach of studying the aerial photographs concluded that the coastline in front of the Rapahoe Village has been through drastic changes through fluvial processes, coastal processes and anthropogenic impacts. To quantify the changes to the coastline, this section has implemented a quantitative approach as described in Section 3.3 measuring the change in the lagoon area and the movement of the vegetation and beach extent line.

3.6.1 Lagoon Area Change

The lagoon in front of Rapahoe village was a prominent feature in the 1939 photo and has had a large impact towards shaping the coastline to its current state. The existence of the lagoon has not been mentioned in any previous research and literature, and the importance of this finding will be examined further in section 3.6. Appendix 3.5 displays the distances measured for the most seaward extent of the lagoon from the baseline and appendix 3.6 displays the difference within transects between the aerial photographs. The results in appendix 3.5 and 3.6 conclude that the general trend of the lagoon is a continuous decrease of the northward and seaward position of the lagoon since 1939, when the lagoon size was at its maximum. The 1939 lagoon extended 560 m longshore (across 14 determination lines) and a seaward extent from the baseline of up to 129.2 m. The lagoon appears to be at the smallest state by 1970, only extending over 2 perpendicular lines and the seaward boundary only 65.5 m from the baseline. There is an anomaly in the data seen in line 16 of appendix 3.5, where a smaller depression feature has been filled with either rain water or sea water and appears to be a lagoon feature. This feature is no longer identifiable in later photographs.

The surface area of the lagoon was another parameter that was examined and the results are displayed in appendix 3.7. The surface area directly relates to the longshore and cross shore extent of the lagoon, and changes in surface area over the years closely links to the results from appendix 3.5 and 3.6. Figure 3.9 exhibits the location and extent of the former lagoons and the rate of change between every photograph.

The lagoon was generally located in Section B and the northern extents of section C for the majority of the years. The largest rate of change is between 1939 and 1948, where the lagoon size decreases by 83%. The 1939 lagoon covers the majority of the beachfront and all future lagoons are located within the boundaries of the initial lagoon. The lagoon surface area then decreases gradually, and 1970 is regarded as the last year to have the lagoon present in front of the village. 1980 and 1988 show 2 different lagoon-like features in the southern half of Section C. This is believed to be not a lagoon feature but past lagoon depressions that have been filled by either rainfall or breaching of waves over the barrier. This also explains the anomaly found on line 16 and in appendix 3.6 and 3.7 in the previous paragraph. Therefore, the minor increase of 0.3% from 1980 to 1988 (as shown in Figure 3.9) is also considered to be an anomaly and is not a reflection of the general lagoon trend. These results have indicated that at 1939, the lagoon was at the maximum size that is recorded, and the rapid decrease in surface area is due to the water and sediment cut off from Seven Mile Creek.



	Lagoon Surface Area Change (%)
1939 - 1948	-83.04
1948 - 1959	-6.05
1959 - 1970	-8.35
1970 - 1980	-2.07
1980 - 1988	0.30
1988 - 1997	-0.78

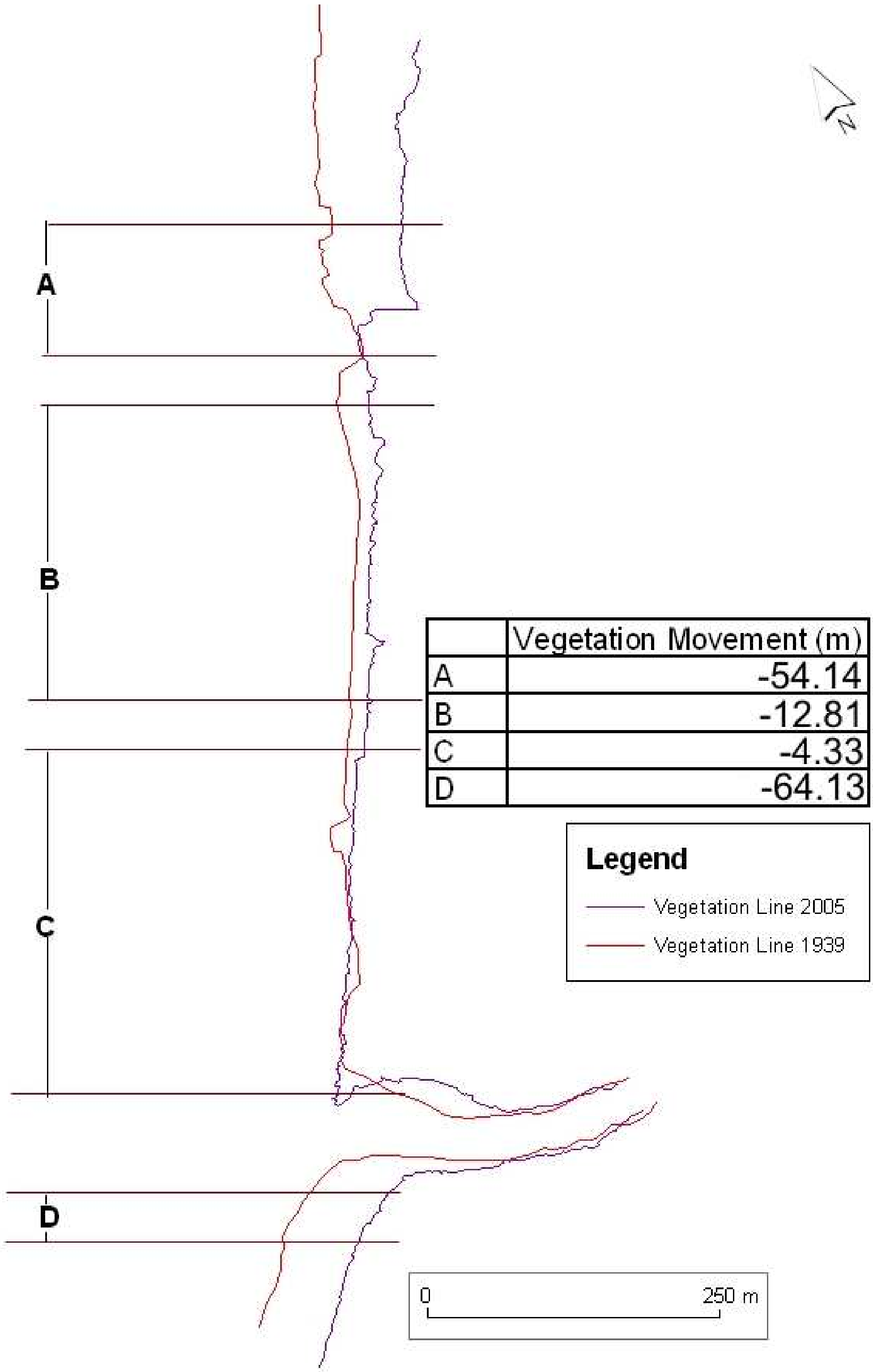
Figure 3.9 Diagram displaying lagoon location and surface area change from 1939 – 1988

3.6.2 Seaward Vegetation Line

The movement of the seaward vegetation position is used as an indicator of erosion/accretion of the shoreline. Appendix 3.8 and 3.9 display the excursion distance of the vegetation line and the excursion differences between the photographs. Appendix 3.10 displays the rate of overall movement of the vegetation line as a percentage. Between 1959 and 1970, an abnormally large proportion of change is recorded (Section A: Overall landward retreat of 51%, B: Overall landward retreat of 25% and C: Overall seaward advance of 24%).as well as between 1980 and 1988 (Section A: Overall landward retreat of 30%, B: Overall landward retreat of 39% and C: Overall landward retreat of 12%). Appendix 3.11, 3.12, 3.13 and 3.14 display the movement of the vegetation line as well as the average movement recorded in each section. The time periods displaying large amounts of change such as between 1959-1970 and 1980-1988 can be seen in further detail in appendix 3.8 – 3.14. The overall result displays large temporal variety even in a small study area as demonstrated in Figure 3.10.

The northern and southern sections (Sections A and D) display the largest amount of landward retreat, by 54 m and 64 m during 1959-1970. Section A undergoes a large amount of retreat in 1959 to 1970 as seen in appendix 3.12, due to the retreat of vegetation that was seaward of the Kaiatan mudstone cliffs retreating to the landward side of the state highway. The landward retreat is prone to this rapid movement due to abandoned and eroded Beach Road which was formerly located seaward of the cliffs. Section D is highly susceptible to the changing nature of the river mouth and this in turn leads to high retreat rates during 1970 to 1980 as seen in appendix 3.12.

Sections B and C display dynamic changes in cross shore movement, as seen in appendix 3.11-3.14. The envelope of change ranges from a seaward advance of 3.8 m to a landward retreat of 26.7 m. The vegetation in the two sections is highly influenced by the lagoon and Beach Road. For example, section B suffers the largest amount of retreat during 1980-1988 (appendix 3.13). This is due to the erosion of Beach Road, and the retreat of vegetation to the landward side of the strip of the former road. Section C was under the influence of the old lagoon, which in turn restricted seaward movement and drastic change in the boundary. The relationship between the lagoon and the vegetation line will be discussed further in section 3.7.



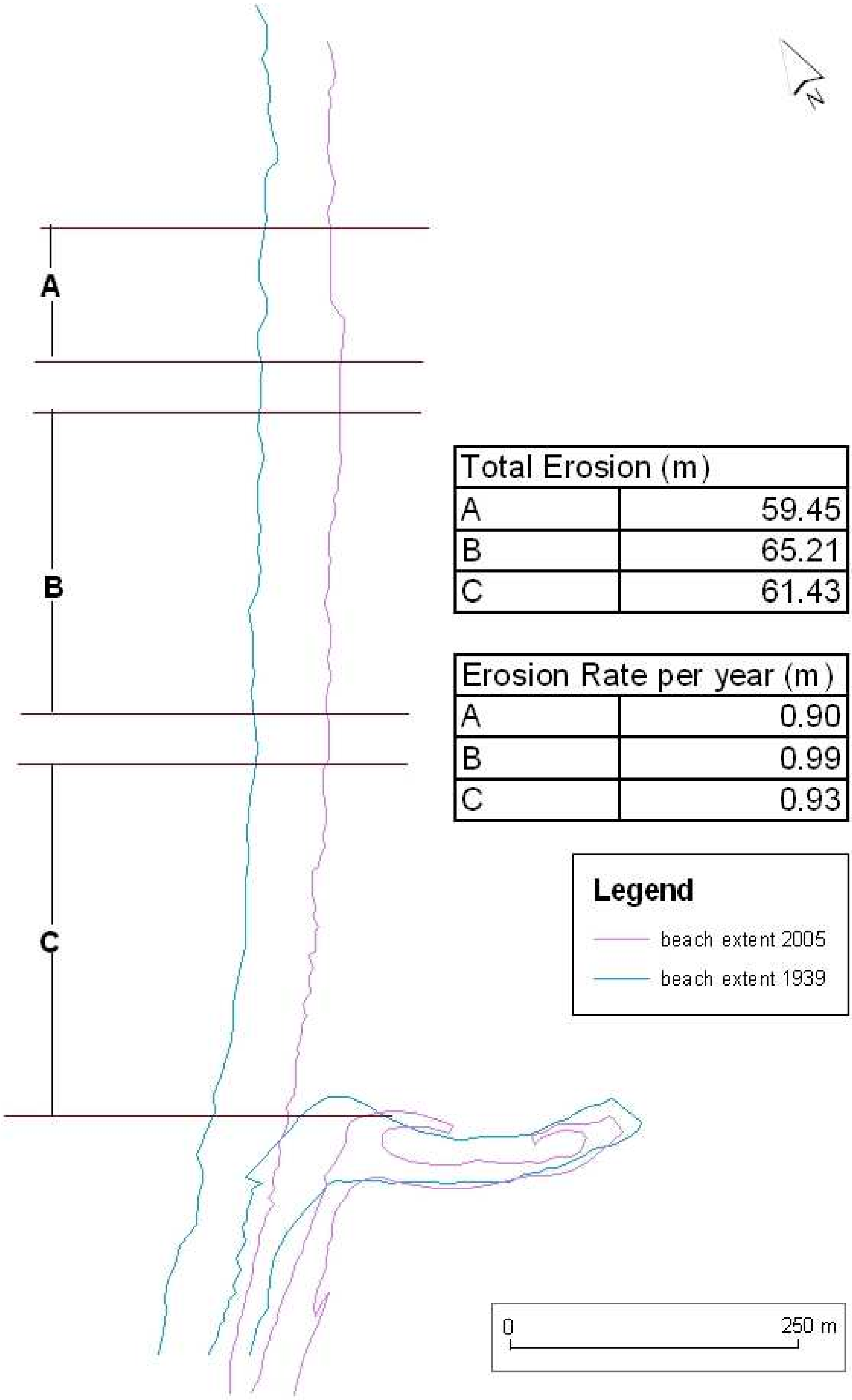
	Vegetation Movement (m)
A	-54.14
B	-12.81
C	-4.33
D	-64.13

Figure 3.10 Diagram displaying Vegetation line movement from 1939-2005 and the overall vegetation retreat (m) in each section

3.6.3 Beach Wet/Dry Line

The beach wet/dry line was the most difficult feature to identify and map. The feature was identified as the distinct tonal difference in the shoreline and the results show a general erosive trend in all 3 sections. Section D was excluded from this study as the fluvial impact does not give a true indication of movement for the southern section of coast. Appendix 3.15 displays the wet/dry line distance from the baseline, and appendix 3.16 displays the decadal excursion difference. Appendix 3.17 calculates the rate of change in metres and as an overall percentage during the time periods. The total erosion distance was similar in all the sections, ranging from 65-69m (as seen in Figure 3.11), leading to comparable annual erosion rates.

In the results in appendix 3.16, there are only two main periods of seaward movement. The first is between 1939 and 1948, where the majority of the coastline, especially in Section A and B appears to accrete by up to 7 m. This coincides with the surface area decrease of the lagoon and a slight seaward advance of the vegetation line in parts of section B. The second period of accretion is between 1997 and 2005, on a much smaller scale in comparison to the previously mentioned accretion stage, where only the southern half of section B accretes by up to 5 m. This anomaly does not seem to relate with any of the other land features. Apart from those individual cases, the remainder of the coastline appears to consistently retreating during the timeframe.



Total Erosion (m)	
A	59.45
B	65.21
C	61.43

Erosion Rate per year (m)	
A	0.90
B	0.99
C	0.93

Figure 3.11 Diagram displaying Wet/Dry line movement from 1939-2005 and the total erosion and average erosion rate per year in each section

3.7 Discussion

This discussion section combines the qualitative findings (3.5) and the quantitative results (3.6) to identify the overall trends occurring on the coastline and presents an interpretation of why. The discussion will examine the relationships between the vegetation line, lagoon and wet/dry line and how the adjustment of one feature impacts the coastline.

3.7.1 Lagoon and the Vegetation Line

In the area in front of Rapahoe Village, the lagoon acts as a boundary control for the vegetation position. When the lagoon was at its largest size in 1939, the vegetation position is restricted to the landward boundary of the lagoon. The continuous decreasing size of the lagoon allows for the vegetation to advance seaward as seen through the 1939 to 1948 and periodically in other timeframes. The seaward advance of the vegetation line indicates that the lagoon was cut off from the river, either by roll over on the southern end of the lagoon or by sedimentation from the river. When the lagoon is finally filled, the vegetation position is then controlled by the wet/dry line, anthropogenic impacts and also the beach sediment. The vegetation line advance seaward during 1938-1948 but retreats soon after during 1948-1970 due to the aggressive retreat of the wet/dry line and is then forced landward of Beach Road during 1970 to 1988.

3.7.2 Lagoon and the Wet/Dry Line

The loss of beach width was due to erosion and gravel roll over, eventually leading to the landward retreat of the wet/dry line. The main cause of the beach width loss is likely to be a change in the sediment supply combined with sea level rise. Forbes et al. (1995) states that sea level rise has been a driving factor resulting in a transgressive coastline history at Nova Scotia. The rise in sea level has resulted in a change of sediment supply, as the rate of sea level rise was not sufficient to allow access to the dominant sediment supply. This led to a lack of sediments on the beach, resulting in the transgressive movement of the gravel barriers. The gravel barriers in Nova Scotia are comparable to the Rapahoe barrier with similar characteristics, similar dominant swell conditions and comparable sediment range. The lagoon feature was a control in the wet/dry line as shown in the 1939 photograph. The lagoon restricted further landward movement by acting as a boundary between the ocean and village. Kirk and Lauder (2000) states that hapuas are capable of progressively retreating landwards while still maintaining their morphology. In this study, the lagoon was clearly not able to retreat landward due to Beach Road which acted as a boundary on the entire landward side. Therefore, the lagoon was incapable of retreating landward, and the lagoon depression was filled by the roll over process of the retreating wet/dry line. This process was evident during the 1939 to 1948 period, when the lagoon was cut off from Seven Mile Creek due to gravel roll over and the evidence of washover lobes in figure 3.3. Major periods of shoreline retreats in Sections A, B and C ranging from 18 m to 26 m occur during 1948-1959. Barrier retreat is commonly carried out through overstepping, breaching, roll over and retreat. The topography behind the barrier at Rapahoe is the former lagoon depression, therefore allowing for accelerated sediment roll over and retreat. The location of the barrier is marked roughly by the wet/dry line indicating the continuous retreat, but has been slowed down by the recently implemented rock revetment, as indicated by the erosion rates given in appendix 3.17. The decline in erosion rates are visible during the periods of 1988-1997 in Sections A and B (-6m and -7m), and further in 1997-2005 (-1m and 0.3m). Although the ripraps appeared to have slowed down the erosion, retreat is likely to continue.

3.7.3 Wet/Dry line and the Vegetation Line

The wet/dry line is an indicator of the high tide and water extent, and the vegetation line is also commonly used as an indicator of coastline movement. The wet/dry line continuously regressed landward by erosion eventually leading to the retreat of the vegetation line at Section A. The loss of the lagoon due to roll over and erosion resulted in the landward retreat of the wet/dry line in Sections B and C, in turn leading to the landward retreat of the vegetation line. The two lines can now be utilized as shoreline position and would be expected to regress or progress appropriately and consistently to shoreline change.

3.7.4 Overall Change

The overall change of the coastline in front of Rapahoe Village is summarized in Figure 3.12. The diagram displays the vast changes in the three examined features and dynamic relationship between them are outlined in the following points:

- Loss in major lagoon feature (1939-1948) lead to accelerated landward retreat of the wet/dry line (Appendix 3.18 and Figure 3.12)

- Vegetation line was influenced by the lagoon, and after the lagoon feature was lost, variable cross shore movement was observed. This was then followed by landward retreat as the wet/dry line influenced the retreat (Appendix 3.19). The wet/dry line continues to converge towards the vegetation position, reducing the beach width (Figure 3.12).

- Anthropogenic impacts such as rock revetments have had some effect in slowing down erosion in the village frontage but the retreat is clearly continuous.

- The overall coastline trend is erosive, but specific areas appear to be more prone to erosion. Section A has suffered extensive eroding throughout the timeframe, but the revetments introduced in the late 1980s have slowed down the erosion rate temporarily. Section B has experienced the highest level of erosion, directly related to the early lagoon loss and will suffer on going erosion. This is a progressive pattern for composite beaches as found on West Coast beaches. Section C follows a similar but slightly slower erosive pattern to Section B. Section D is highly influenced by Seven Mile Creek, but the general pattern is erosive and retreat due to similar reasons as stated above.

- Figure 3.12 and Appendix 3.20 demonstrates the close vicinity of the current vegetation position and wet/dry line. Therefore, features behind the vegetation will be at risk from further erosion and roll over as well as inundation during large storm events by storm surge and barrier breaching.

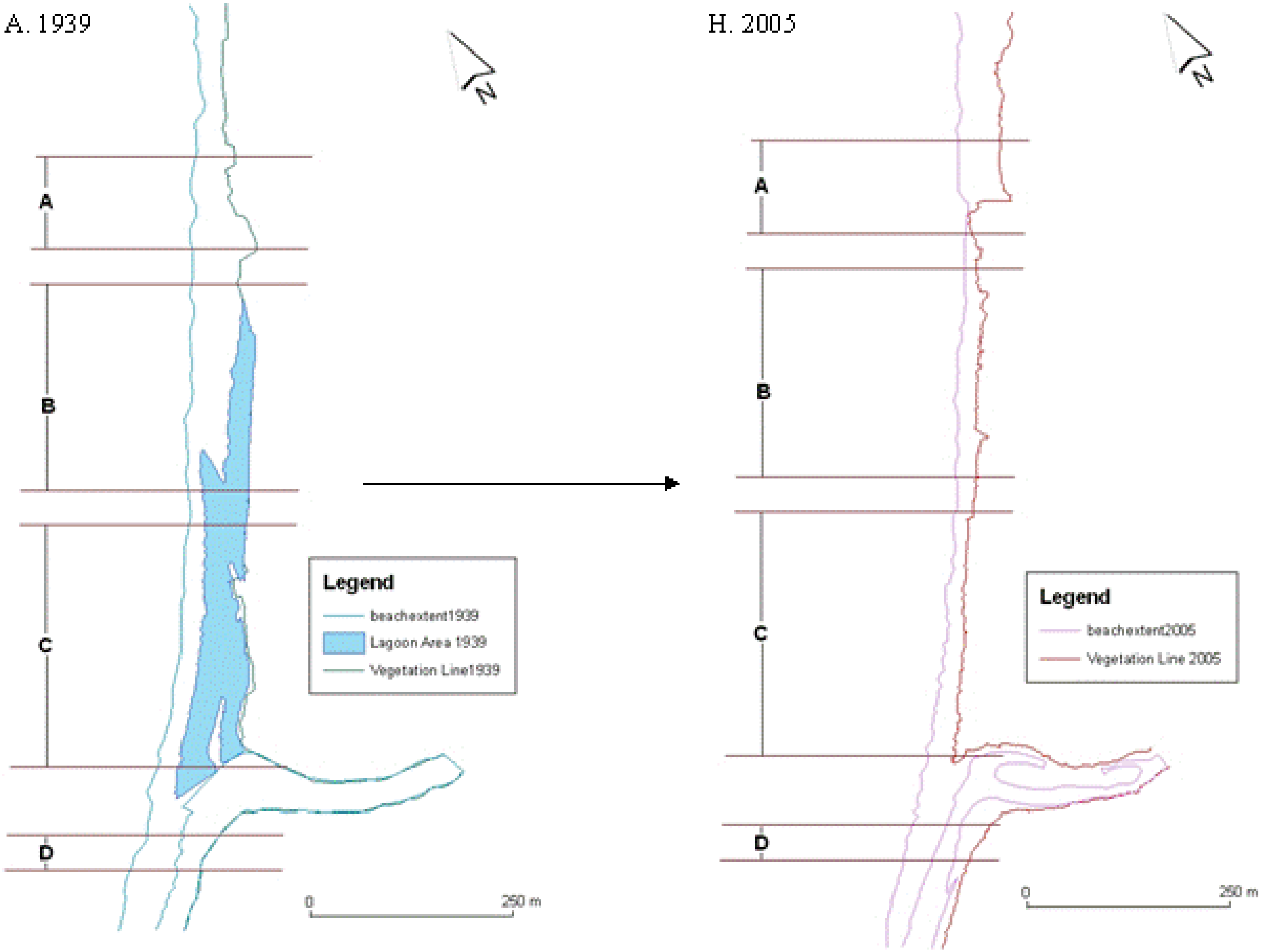


Figure 3.12 Diagram displaying the overall change of all three features from 1939 to 2005

3.8 Conclusion

This chapter has examined the coastline history of Rapahoe village through the use of 8 aerial photographs at decadal timeframes. Quantitative and qualitative methodologies were utilized to provide comparison between each photograph, to identify coastline change and provide quantitative rates and figures. This chapter concludes that the coastline has had erosive history, and appears to be going through continuous barrier retreat and coastline erosion. The interaction of the hapua and the barrier would not have occurred if anthropogenic features were not involved. The rollover and retreat was induced further by the former lagoon depression but the rate of retreat has since declined with the introduction of the riprap revetments. It is clear that the beach system is losing sediment volume through roll over and erosion. Change in sediment supply is likely to be the main reason for the increased erosion in the past, but it is important to note the erosive nature of composite beaches and barrier dynamics. This chapter is an important part of this thesis to understand the history of the coastline, and will be combined with digital elevation models and wave refraction theory to construct a conceptual model of the area.

Chapter Four: Dynamics of Beach Topography and Morphology

Figure 4.0 Photograph facing south displaying the gravel barrier and beach 26/6/07

4.1 Introduction

This chapter utilizes digital elevation models (DEMs) created in GIS computer software packages from field GPS surveys to investigate the beach topography and morphology located in front of Rapahoe Village. This chapter will carry out the following:

- Create DEMs by utilizing the field collected GPS data
- Identify the topography and morphologic features of the beach
- Identify changes in the topography and morphology over different temporal periods
- Examine the process drivers for these changes

The use of GIS related tools is common practice in coastal research. The previous chapter utilized aerial photography in ArcGIS to measure historical coastline change and movement in coastal features. This chapter uses Triangulated Irregular Networks (TIN) to create digital elevation models (DEM), which are used to examine and model the beach frontage at Rapahoe Bay. Four DEMs have been created from the field trip data to examine the spatial and temporal variations along a highly dynamic coastline. The DEMs allow for quantitative and qualitative analysis to identify change and provide an understanding of the dynamic changes along the study area beach face.

4.2 Composite Beaches and Gravel Barrier Dynamics

Composite beaches are a variation of mixed sand and gravel (MSG) beaches, sometimes referred to as mixed beaches or coarse clastic beaches. Mixed beaches are globally rare and generally found only in paraglacial or high latitude areas such as New Zealand, New England, U.K, Nova Scotia and Canada. Early literature by Kirk (1980) and Shulmeister and Kirk (1993) examine the dynamics and characteristics of mixed sand and gravel beaches, but only recent literature such as Jennings and Shulmeister (2002) have acknowledged and examined composite beaches. The differences between mixed sand and gravel and composite beaches commonly cause confusion amongst researchers, and Mason et al. (1997) identifies the two categories of ‘mixed’ beaches as opposed to pure gravel or pure sand beaches. The first description aligns and refers to Kirk’s (1980) schematic representation of a MSG beach. The second description aligns with Jennings and Shulmeisters’s (2002) schematic representation of a composite beach, provided in figure 4.1. The rarity and common incorrect categorization of this beach type with MSG has resulted in a general lack of literature examining the morphodynamics of this beach type, and the relationship to other coastal features (Mason, et al. 1997).

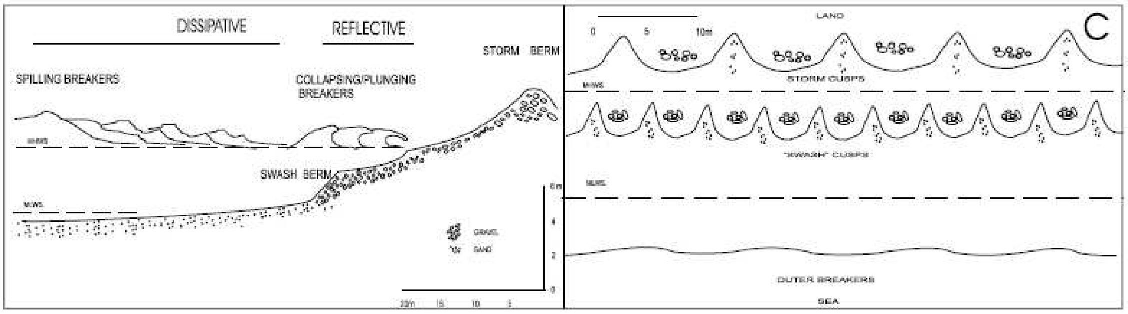


Figure 4.1 Jennings and Shulmeister’s (2002) schematic representation of a composite beach (pg224)

Key characteristics of a composite beach include profile, sediment layering and morphology. The schematic profile as represented in figure 4.1 displays a shallow, wide and sandy intertidal zone backed by a steep gravel berm. The division in sediments is a common method of identifying slope change and the distinct line separating sand and gravel is a key feature towards identifying this beach type. The variety in beach profile and tidal range modifies the impact of wave energy, ranging from a dissipative intertidal zone to a reflective state by the gravel berm. Mason et al. (1997) identifies the importance of sediment composition and beach gradient relative to the reflectivity of the beach and the implications towards sediment transport. During low tide, the ‘constructive’ spilling waves break in the sandy nearshore zone, with a strong swash and gentle backwash (Bird, 1985); therefore onshore sediment movement is assumed. However, during high tide collapsing and plunging breakers which generally have a short swash and relatively strong backwash (Bird, 1985) break in the nearshore zone or on the swash berm. The rate of reflectivity on a composite beach ranges from 20% - 85%, and high reflectivity on gravel barrier due to the slope gradient combined with local longshore currents induce gravel movement in the intertidal zone (Mason et al. 1997). Evidence of sediment movement is proven through highly developed cuspate morphology, which is also an indication of strong sediment sorting and organization (Jennings and Shulmeister, 2002). Recent research by Ishikawa (2006) at Amberley Beach, South Island, has provided an insight to gravel barrier morphodynamics and the relationship between cuspate morphology and a nearshore bar on a composite beach. The bimodal morphology represents an oscillation between the two types of morphology in the intermediate beach type.

As described in previous chapters, Rapahoe beach is backed by a single gravel barrier, which has important morphodynamic implications. Long-term trends and barrier responses have been discussed in section 3.2, and this section will focus on the morphodynamic implications of a single gravel barrier on a composite beach. Previous literature examining gravel barriers agrees that gravel barriers generally move landward even in stable sea conditions through a mixture of barrier translation, erosion and overstepping (Carter and Orford, 1984, Masselink and Hughes, 2003, Forbes et al. 1995, Forbes et al. 1991).

Forbes et al., (1995) states that a stable gravel barrier is characterized by a high, narrow, linear crest with well organized sediments, and minimal washover activity. Trends of self organization in gravel barriers occur through increasing crest height and partitioning and sorting of beach materials. This in turn results in increased wave reflectivity, as an increase of crest height induces steeper slope angles. A key note regarding sediment organization is the dependency on sediment volume and available sediment supply. A higher beach crest with little beach volume and backing may be more resistant to short term changes due to the reflectivity, but is susceptible to future destabilization which may trigger through a combination of consistent major storms, sea level rise and changes in sediment supply. (Forbes et al. 1995). Therefore, insufficient materials preclude the development of coherent structures and favour the breakdown of existing forms eventually inducing landward retreat. (Forbes et al. 1995). Major storms are known to cause irreversible change to the barrier morphology, and major wash over events combined with sediment erosion losses offshore reduces barrier volume, in turn sustaining rapid landward migration (Forbes et al. 1991). Short term changes by storm conditions include loss of sediment volume by sediment erosion and loss of volume through washover and roll over. Profile changes include loss of volume and heightened crests. Results in 4.4 will indicate if the gravel barrier at Rapahoe is responding in a similar manner suggested by Forbes et al. (1995).

4.3 Method

Coastal landforms and geomorphology have proven difficult to study in the past due to their dynamic nature, but a variety of improved modern techniques have made the task achievable (Andrews, et al. 2002). Previous methods of measuring and quantifying features involved surveying with a total station, a time consuming and labour intensive task restricted to small and specific study areas and a direct line of sight. This was followed by the use of aerial photography, which proved to be a cheap and effective method for measuring and displaying change over time in a large areal scale as seen in the previous chapter. Following aerial photography was the use of GPS equipment, resulting in highly accurate results in a small scale. The most recent methods involve the use of light detection and ranging (LIDAR) system with low flying airplanes, proving to give accurate horizontal and vertical measurements at a meso and micro scale (Andrews et al. 2002). Methods of data gathering through LIDAR, aerial photography or through GPS units allow for the creation of DEMs, a result that not only models and displays the study area, but allows for measurements and interpretation of change through visual and quantitative analysis. The increased development of coastal research methodology has addressed the need for mapping of coastal environments. Local and regional councils and government agencies have acknowledged the importance of obtaining high resolution data of coastlines and the implications of this data for coastal research and towards the management of coastal hazards. There are many methods of constructing a DEM, which vary by the method of interpolation used. Different forms include: TIN, kriging, spline and inverse distance weighting (IDW). Section 4.3.4 provides more comprehensive details as to the reason why the TIN methods were utilized as opposed to other forms of DEMs.

The methods involved in constructing the DEM are summarised in flowchart form in figure 4.2, which is adapted from Andrews et al. (2002). Each step in the flowchart is described in the following sub-sections.

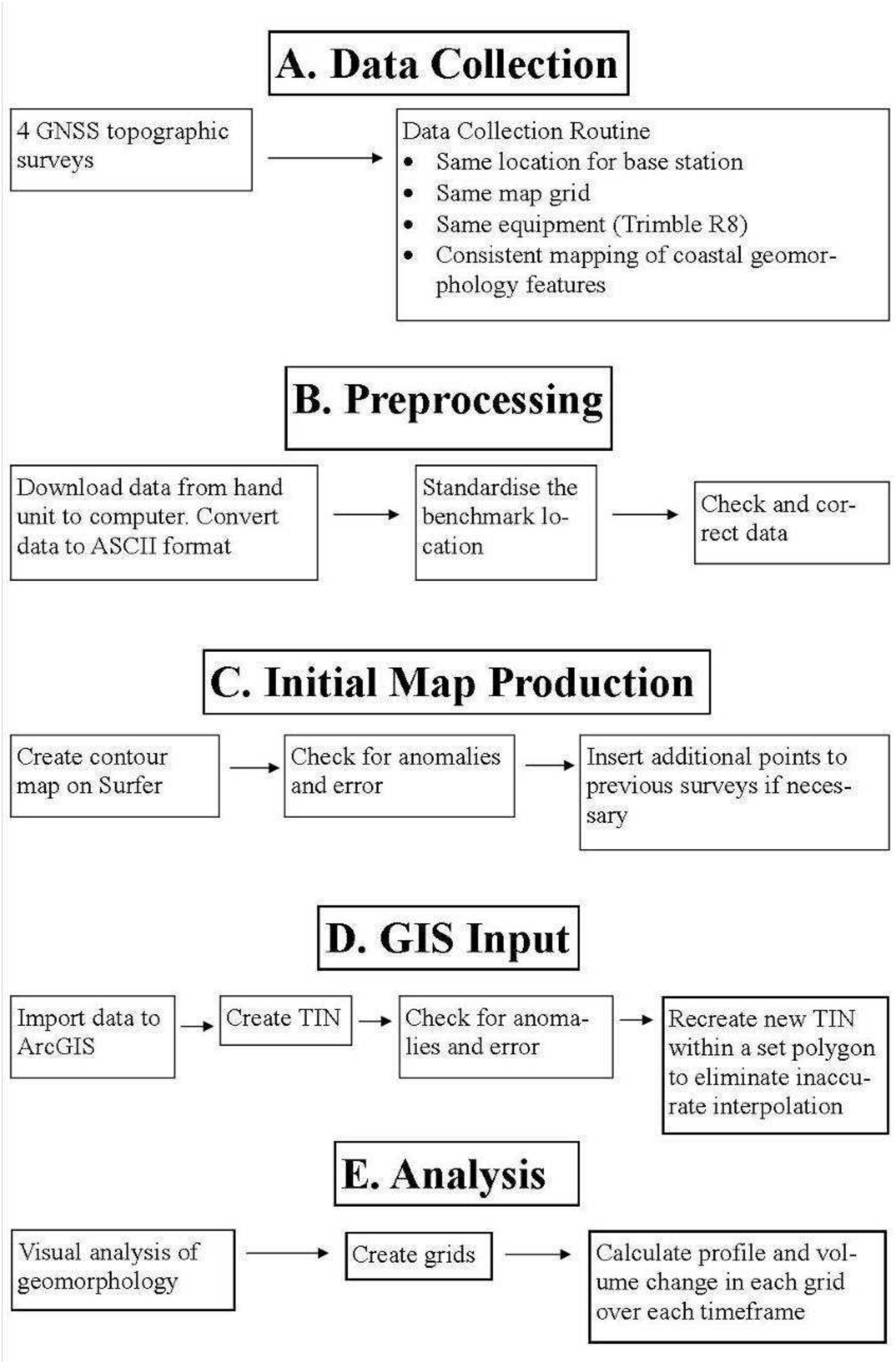


Figure 4.2 Flow chart of Method (Adapted from Andrews et al. (2002))

4.3.1 Data Collection

The quantitative and qualitative data was collected through field work carried out in four separate field visits during May, July, August and November. The quantitative data was collected through the use of the Trimble R8 GNSS(Global Navigation Satellite System) as shown below in Figure 4.3. Along with the Trimble hand unit, this GNSS system allows for the measurement of topography at an accuracy of up to ±10mm horizontally and ±20mm vertically (Trimble, 2007) through the use of the RTK (Real Time Kinematics) survey option. The qualitative data includes field observations and photographs taken throughout the field visits and this data is utilised throughout the study.

Figure 4.3 Trimble R8 and hand unit located on site above the benchmark

Field Visits

Four field visits were conducted on the following times:

- First field visit – 17th of May
- Initial equipment trial – 24th to the 26th of June – Referred to as Initial
- Winter visit – 7th to the 15th of August – Referred to as Pre-storm and Post-storm
- Summer visit – 31st of October to the 5th of November – Referred to as Summer

The first field visit was conducted to contact members of the Grey District Council (GDC) and local residents and to visit the field site. No quantitative data collection was undertaken during this visit. The data collection occurred throughout the following three visits. A GDC benchmark at 795588.6N 374730.12E (Grey Circuit 2000) located on the corner of Hawken and Morpeth Street was used as the base location for the Trimble receiver unit due to the stability and close vicinity to the beach. This benchmark is a metal peg in a concrete block and has been used infrequently in the past by local surveyors and local council to measure beach profiles. This benchmark was used throughout all of the field visits but past transect were not used for profile comparison, as the variety in data collection methods (single transect line and TIN interpolated data) would not be appropriately comparable. The NZGD 2000 Grey Circuit was the map grid used for all surveys. The Trimble R8 rover was strapped on to the researcher's backpack and the researcher walked around on the beach mapping specific coastal features, boundaries and marking beach transects. The coastal features that were surveyed include: waterline, cusp formations, river boundaries, tidal berm, storm berms, depression lines, anthropogenic features such as roads and cliff lines. GPS data capture was undertaken using the continuous topography option, which took point data measurements at 5 second intervals. On smaller features such as cusps and transect measurements, the points were taken every 2 seconds for more defined profiles.

The main focus of this study is to examine the shoreline directly seaward of the village, and therefore the Southern half of the beach (South of Seven Mile Creek) was only surveyed during the initial equipment trial and winter field visit to provide an overall DEM of the coastline. The beach in this section is directly backed by the mudstone cliff with a small amount of gravel at the base of the cliffs was found to have relatively small amounts of change between these two surveys, and will not be examined in further depth in this chapter.

4.3.2 Preprocessing

The quantitative data collected from the field was transferred from the Trimble Ranger hand unit on to a field laptop and converted to ASCII format. During the download process, the benchmark location (the location of the base station) was standardised to align the different data sets. Standardizing the base station ensures that the collected data sets are in the same coordinate systems. The downloaded ASCII format was then converted to individual shapefiles, shx files (ArcView database index) and dbf (database file). This stage also allowed for a first look at the raw collected data to check for any potential errors and anomalies.

4.3.3 Initial Map production

The converted data files were initially viewed in Surfer, a quick and simple mapping programme, which allowed for an initial visualisation of the data. The resulting contour map showed several areas of interpolation errors, especially in the areas of the northern cliffs. These areas required modification and corrections in ArcGIS as Surfer was used as a visual check of the collected data. The GPS points of the roads within Rapahoe village and on the Northern cliffs were added to the post-storm and summer files to correct inaccurate interpolations towards the landward side of the gravel barrier to allow for consistent areal extents of the DEMs. Other correction involved aligning the base station coordinates to the local circuit to confirm the data overlapped. The initial survey data is the largest as the survey extends to Point Elizabeth and the data was collected with two surveyors. Less data is gathered in the post-storm and summer data compared to the pre-storm points due to problems with the equipment and time constraints. After the files were modified and corrected, the total number of data points collected including the village and road data for each time period are as follows:

Number of GPS points recorded:

- Initial: 13693
- Pre-storm: 8836
- Post-storm: 5550
- Summer: 5627

4.3.4 GIS Input

The corrected data was imported to ArcGIS, separated and categorised to the four time periods and a DEM was created using TIN for each time period. A TIN is a vector based model which is used to display a surface model. In a TIN the data points that have been collected through the GNSS are connected by edges that form continuous, non-overlapping triangles and results in a continuous surface that represents the real world (Childs, 2004). Thiessen polygons are utilised in this method and this analysis is a quick and common method for connecting points. This method is appropriate for a small study area with large quantities of observations (Burrough and McDonnell, 2000). There are numerous other methods of data interpolation to construct a DEM such as kriging, spline, inverse distance weight (IDW), natural neighbor and point interpretation. These interpolation methods were all trialed individually with the field data and the TIN method provided the most effective and realistic method in replicating the field site. This is partially due to the high number of GNSS points recorded compared to the relatively small size of the field site, which helped to eliminate irregularities. Lo and Yeung (2006) note that ground surveys tend to have very high accuracy within a limited area coverage, using TIN is an ideal method of interpolation towards landscape visualisation. The common problems found with the other interpolation methods include, exaggerations through interpolation, unrealistic angles on natural barriers such as cliffs, river beds and depressions and smoothing of features that should not be smooth (Stockdon, et al. 2006).

Once the initial DEMs were modelled, anomalies and errors were identified and corrected. A common problem that required correcting was single GPS points excluded from other areas with high numbers of data points. For example, if the Z value of the excluded point was distinctly higher or lower than the remaining points, this would produce inaccurate interpolation when triangulated with the closest points. Therefore, solitary points were either excluded by remaking the DEM, or if there were many cases like this in one DEM, a smaller polygon was made around the DEM, excluding a large number of solitary and unnecessary points to correctly modify the DEM. The four separate grids that were constructed for analysis included some areas with unavoidable errors of interpolation. This is discussed in the 4.3.6.

4.3.5 Analysis

TIN is seen as an ideal interpolation method towards landscape visualisation, volumetric and cut and fill computation and surface characterisation due to the easily applicable vector database (Lo and Yeung, 2006). A range of qualitative and quantitative techniques are available with the use of TIN and assisted towards the analysis of the results. The initial DEM was examined to identify important morphological features along the coast. The features on the DEM were also compared with photographs taken on site to provide a comparison of the DEM and how it represents reality. The visual and qualitative analysis were mainly utilised to check and ensure that the DEM interpolated the points in an accurate manner to represent reality.

Following the visual analysis, quantitative analysis was carried out for the Rapahoe village frontage, as this is the main area of concern. Four separate polygons or grids, 200m by 40m dimensions, where created to cover the study area from the northern (just south of State Highway 6) end, south to the small river mouth spit. These grids contained the gravel barrier, immediate beach face, the intertidal zone, the buildings close to the beach and numerous morphological features. The grids were numbered as areas 1 to 4, with the Northern one (area 1) containing the Forbes residence and camp ground, area 2 containing a large depression located landward of the gravel barrier', area 3 the Rapahoe Hotel and several plots of land, and Area 4 the small river mouth spit feature. Individual DEMs were created to model the elevation and volume change for each area and timeframe. The outputs from these grids also include quantitative figures of the volume per grid, and this was utilized to calculate volume change between the time frames. The function Cut/Fill in ArcGIS was utilized for this section and the results are available in 4.4.

The four areas were also investigated for profile change. Five seaward determination lines were created in each area, the three blue lines seen in each area in figure 4.4 and the Northern and Southern boundary of each area. These determination lines were constructed and transect profiles were measured for each area and time periods. The elevations are measure in terms of the Grey Circuit (2000) datum, where 2m is classified as mean sea level. All profile and DEM have been kept in the same circuit and elevation, as a large portion of the profiles are lower than 2 m. The results from the 25 determination lines were used to calculate profile change throughout the different time periods, and are presented in section 4.4.

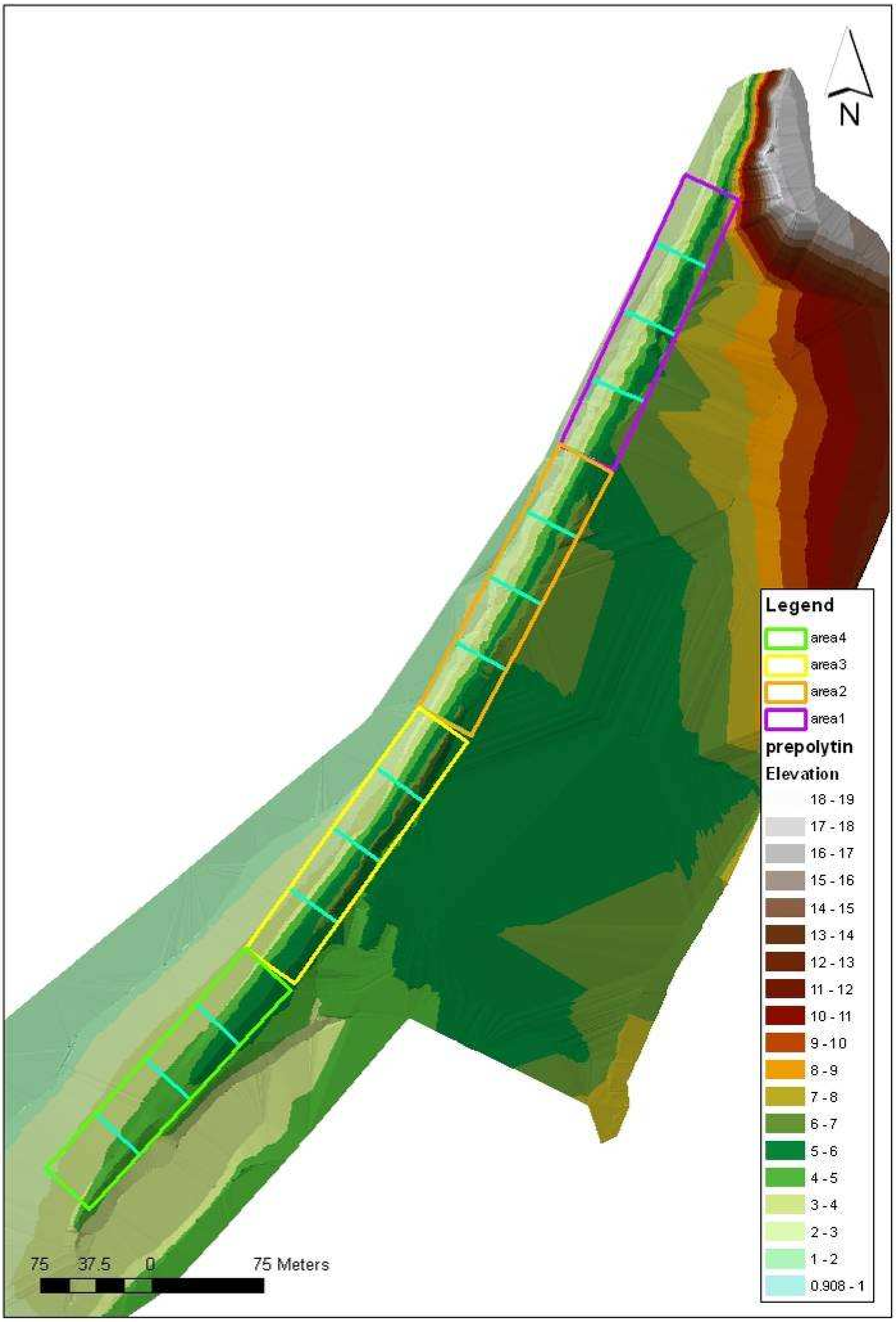


Figure 4.4 Map of Initial DEM displaying the four areas and the determination lines

4.3.6 Limitations and Error

A number of limitations and errors have been identified that may affect the results presented within this chapter. A major limitation related to the data collection, especially in regards to inadequate areal coverage of the point network. The affected sites could only be identified through the use of determination lines, and figure 4.5 displays an example of an error found in the determination lines in Area 2 of the pre-storm DEM. The top left map of the figure is the DEM produced, and the brown dots display the GPS points collected. The areal extent of the data does not include the landward sides of the grids, and therefore the DEM triangulates with the nearby road points that were collected. The red circles identify the area of inaccurate interpolation. The profile graph at the bottom of figure 4.5 show the inaccuracy more clearly, where the pre-storm and post-storm profile flatten out, which is not an accurate description of what occurred on the back of the barrier. On the right side of the figure there is an example of the cut/fill function during the two time periods, and the grey area (circled in yellow) show that there had been no change in that profile area, evidence of the inaccuracy of the interpolation. Similar errors were found in Areas 2 in the pre-storm and post-storm DEM, and Area 4 in the summer DEM, which could not be rectified in post-processing. This means than the quantitative results for profile and volume change are incomplete, which limits the interpretation of the end results. This is discussed further in section 4.4. These errors are considered to have occurred due to inexperience with field equipment and the limitation of time available out in the field.

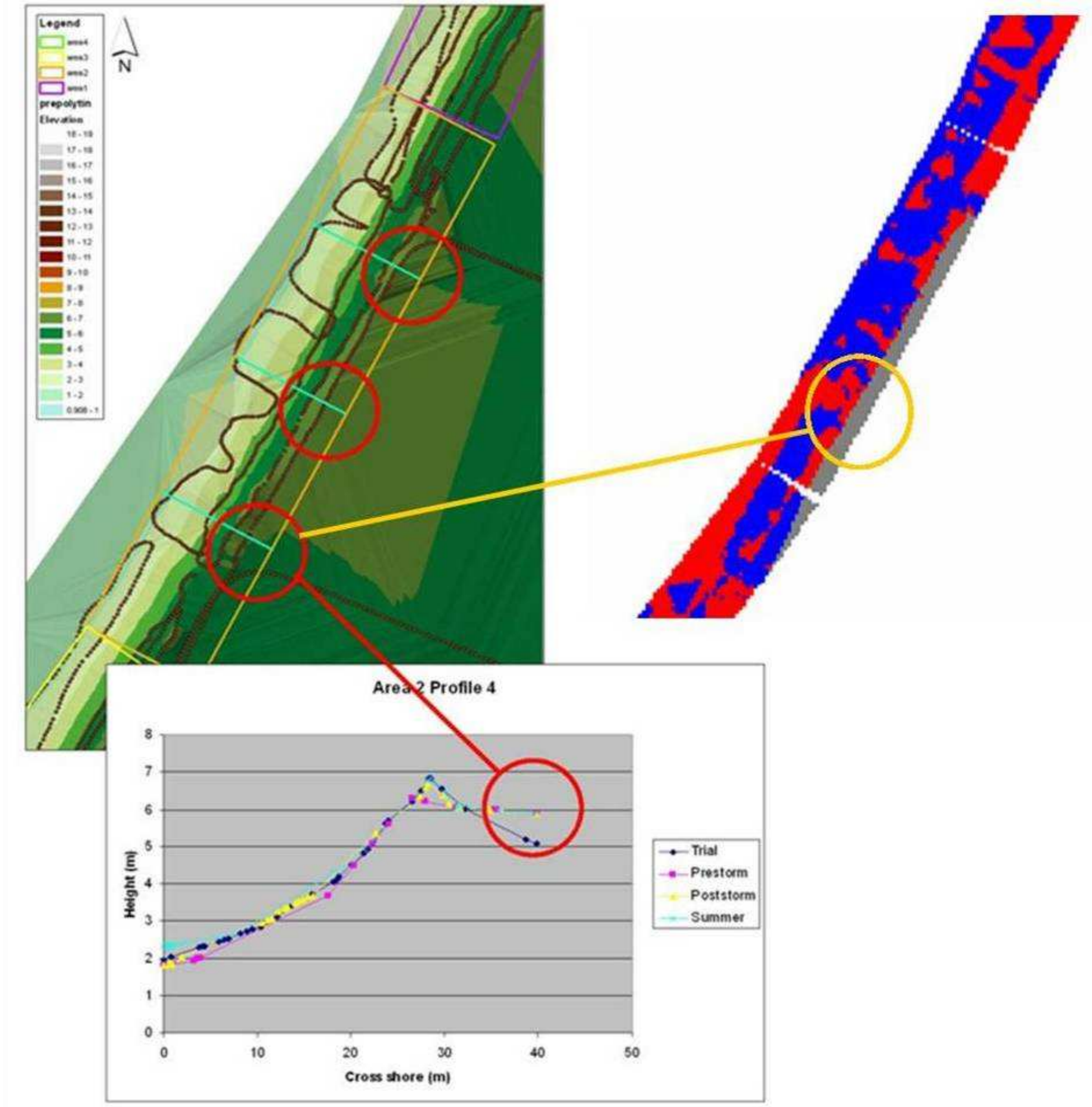


Figure 4.5 Figure displaying where errors have occurred. The top left map displays Area 2 from the Pre-Storm DEM. The bottom diagram is the Profile and the interpolation error. The diagram on the right displays the cut/fill and how the error applies to volume change.

4.4 Results

The full extent of the initial DEM seen in Appendix 4.1 covers the entire beach frontage and village area with in Rapahoe Bay. A close up of all the DEMs (Initial, Pre-storm, Post-Storm, Summer) displaying the beach frontage of the village can be found in Figures 4.6, 4.9, 4.12 and 4.15. Further profile analysis, qualitative evidence and volume change is provided in this chapter, providing a summary and comparison between each DEM. Further volume change results are available for each area in appendix 4.2 and individual beach profile results are available in appendix 4.3-4.22.

4.4.1 Initial DEM

The initial DEM contained the largest number of points and is therefore the most accurate DEM for the Rapahoe village frontage. The number, extent and distribution of GPS points present the most accurate profiles for the determination lines and areal volume. The DEM extends from the northern mudstone cliffs to Point Elizabeth as seen in appendix 4.2, but Figure 4.6 will be utilized for beach profile and barrier crest variations. The GPS points for the initial DEM were gathered over 2 days with two researchers, during low tide and field observations note that the weather conditions on each day were calm and sea conditions relatively calm with swells of 1-2 m.

After analysis of the initial DEM, it is clear that a substantial variety of profiles along the beach exist. Figure 4.6 displays four different profiles from each area in the initial DEM. Each profile was selected to represent the average slope characteristics from the individual areas in a similar manner to the cross shore profile provided by Jennings and Shulmeister (2002). The barrier crest height is highest in area 1, ranging from 8.29 to 6.15 m with an average of 7.05 m. The crest height gradually lowers towards the south, with averages of 6.56 m (area 2), 6.28 m (area 3) and 5.23 m (area 4). The topography behind the beach has a similar elevation pattern to the barrier crest, with the northern side being higher in elevation, and a gradual decrease in elevation towards the south as displayed in figure 4.6.

The variety of slope angles and shapes between the profiles is caused by a mix of revetments and sediment types. In figure 4.7, Area 1 displays a gradual slope angle, with evidence of a swash and storm berm but no evidence of a depression behind the berm as displayed in areas 2, 3 and 4. This is due to riprap revetments located seaward of the Forbes residence and the campsite as displayed in figure 4.8 A. Field notes indicate that a small portion of the foreshore area is composed of sand, and the steeper slopes represent gravel. Despite the lack of the backshore, several of the southern profiles in area 1 also align with figure 4.1. The profiles from Areas 2 and 3 and several southern profiles in area 1 display a strong resemblance to Jennings and Shulmeister's (2002) schematic representation of a composite beach as seen in figure 4.1. The angle of the slope is steeper in comparison to the area 1 profile and a prominent swash and storm berm is present. Figure 4.8 B clearly displays the shallow sand foreshore backed by the steeper gravel barrier including the swash berm and berm crest. Field notes also indicate that a larger portion of the visible foreshore is comprised of sand in area 2 and 3 compared to area 1. The elevation which peaks at a range from 6.06 to 7.01 m decreases further backshore, indicating areas where the former lagoon depression exists, combined with the natural elevation of the landward topography. Some profiles in area 3 contain riprap revetments which combine with the berm crests, as evident in figure 4.8 B and appendix 4.15 and 16. The profile from area 4 displays the shallowest slope angle, with the lowest barrier crest elevation averaging 5.23 m (ranging from 4.73 to 6.11 m). Area 4 is backed by Seven Mile Creek, and sand dominated with smaller amounts of gravel making up the barrier. The relatively small amounts of gravel restrict the build up of a barrier, resulting in shallow slope angles as seen in figure 4.8 D.

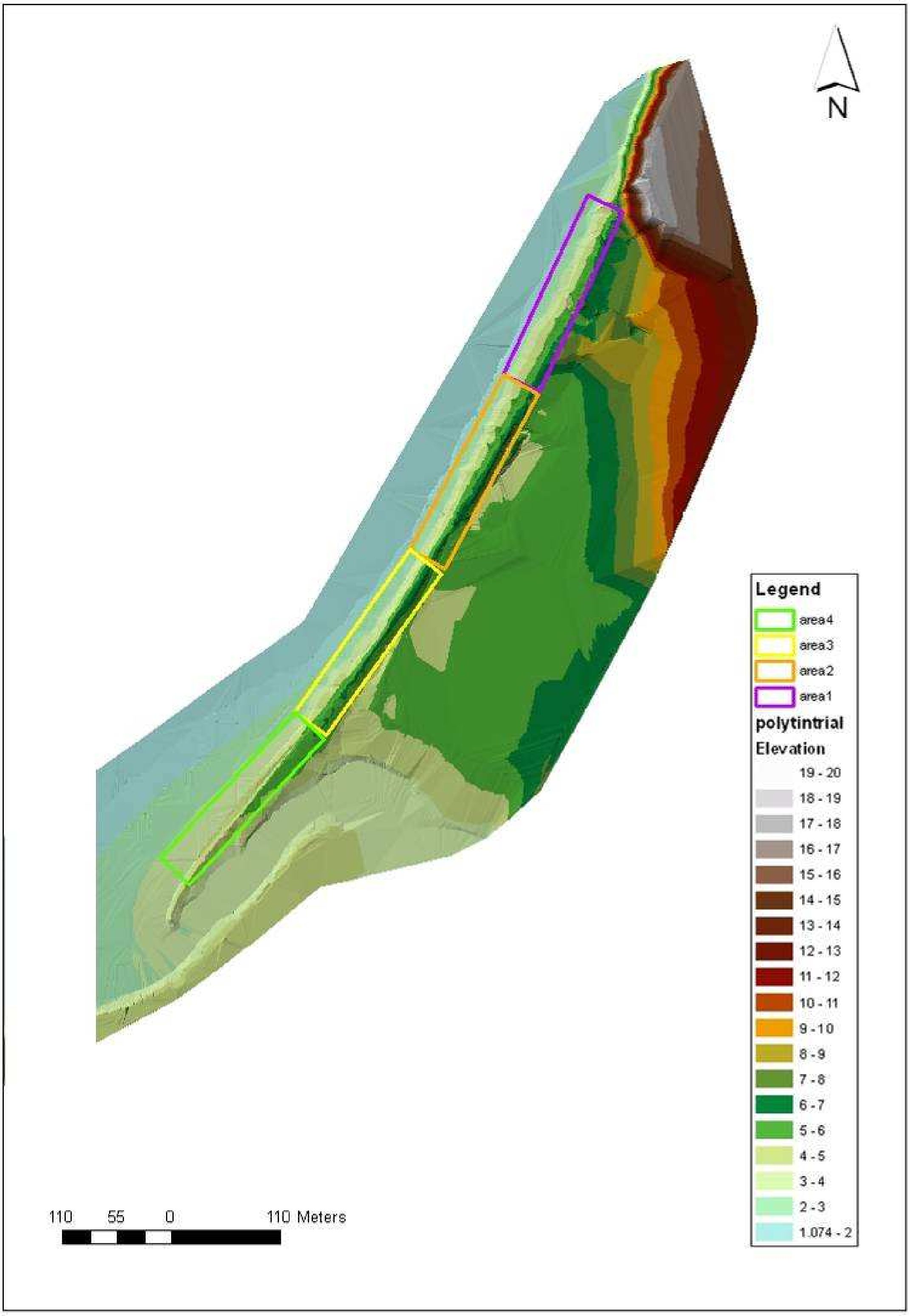


Figure 4.6 Close up of Initial DEM displaying the beach frontage

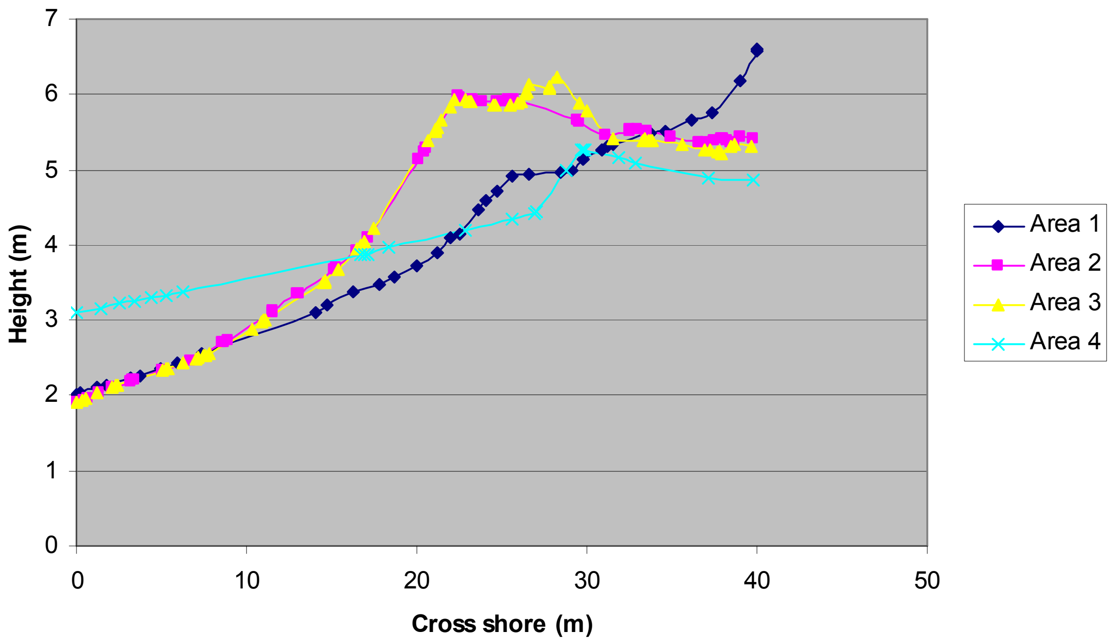


Figure 4.7 Range of Cross shore profiles in the Initial DEM

Figure 4.8 Photographs of each area A) Area 1: 17/05/07 B) Area 2: 17/05/07 C) Area 3: 17/05/07 D) Area 4: 17/05/07

4.4.2 Winter Pre-storm DEM and changes since the Initial DEM

The winter Pre-storm DEM displayed in figure 4.9 covers a similar area to the post storm and summer DEM. The data collection was completed by one researcher over 2 days. Profiles 2-4 in Area 2 of the DEM contain interpolation errors due to the lack of, and uneven distribution of GPS points, which could not be rectified in post-processing of the data. The result is that the profiles behind the storm crest and volume change between other DEMs can not be utilised due to the errors. Field observations note that the weather was calm during the two days of research with light SW winds and 1-2 m swells, but a storm from the North East passed by shortly after with 2-3 m swells and high winds. Profile analysis displays an overall decrease in average crest height by 0.05 to 0.19 m in all four areas compared to the Initial DEM. Examples of other profile change is provided by figure 4.10. The majority of profile change in areas 1 and 2 are comparable to the left hand graph in figure 4.10, displaying a loss of sediment in the intertidal zone with small gain on the gravel berm. The right hand graph displays comparable profile changes to area 3 and 4, with an overall gain in the intertidal zone and barrier face resulting in a steeper upper profile.

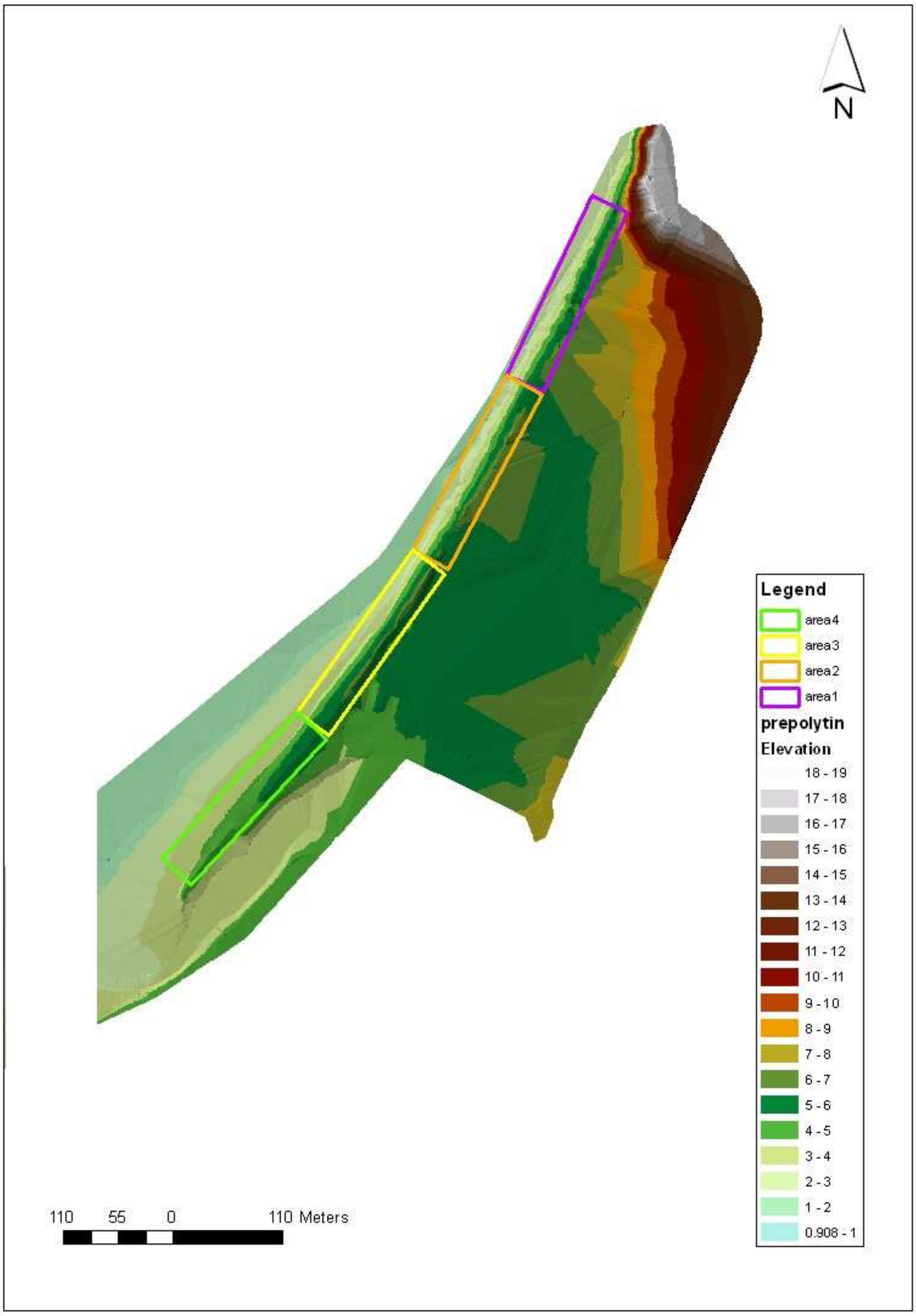


Figure 4.9 Pre-Storm DEM

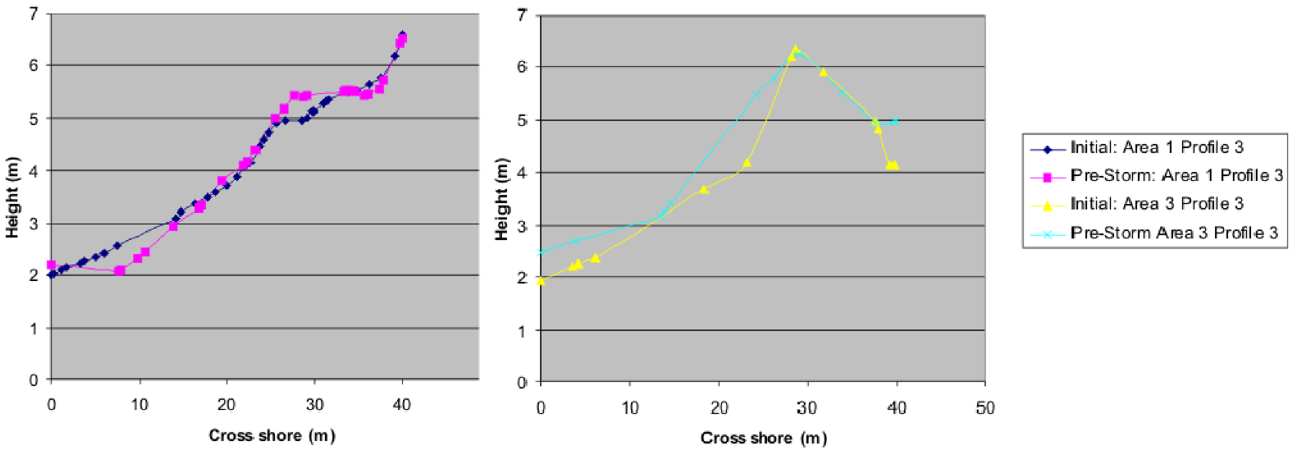


Figure 4.10 Examples of profile change between the Initial and Pre-storm DEM in areas 1 (left) and 3 (right)

Figure 4.11 displays the 4 areas in each DEM for the Initial and Winter Pre-Storm displaying profile change. Alongside the DEMs are the volume figures produced from the DEMs, and below is the cut/fill diagram showing the sediment volume change between the DEMs. Loss of sediment in the intertidal zone is identified through profiles, DEMs and the cut/fill diagram in Areas 1 and 2 (Figure 4.10, Appendix 4.3-4.12) and gain on the storm berm face is visible in areas 1 and 2 (Figure 4.10, Appendix 4.3, 4.4, 4.5, 4.7,4. 8 and 4.12). While area 1 lost -1422 m^3 (Appendix 4.2), area 3 gained 1470 m^3 (Appendix 4.2) predominantly in the intertidal zone (Figure 4.11, Appendix 4.13-4.17). Area 4 underwent similar gains in the intertidal zone profile (Figure 4.11, Appendix 4.18-4.22) despite an overall loss of sediment of 213 m^3 (Appendix 4.2). Despite interpolation errors behind the barrier in Area 2, loss of sediment is clear in areas 1 and 2 from the intertidal zone and a gain in area 3. Loss of sediment in the intertidal zone would indicate a loss of sand and gravels either out to the nearshore zone, on shore on to the gravel barrier or longshore sediment transport. The cut/fill graph clearly shows gain in the intertidal zone in area 3 and 4, therefore indicating a southerly longshore drift. Gains are also noticeable on the immediate gravel berm identifying the movement of gravels from the intertidal zone.

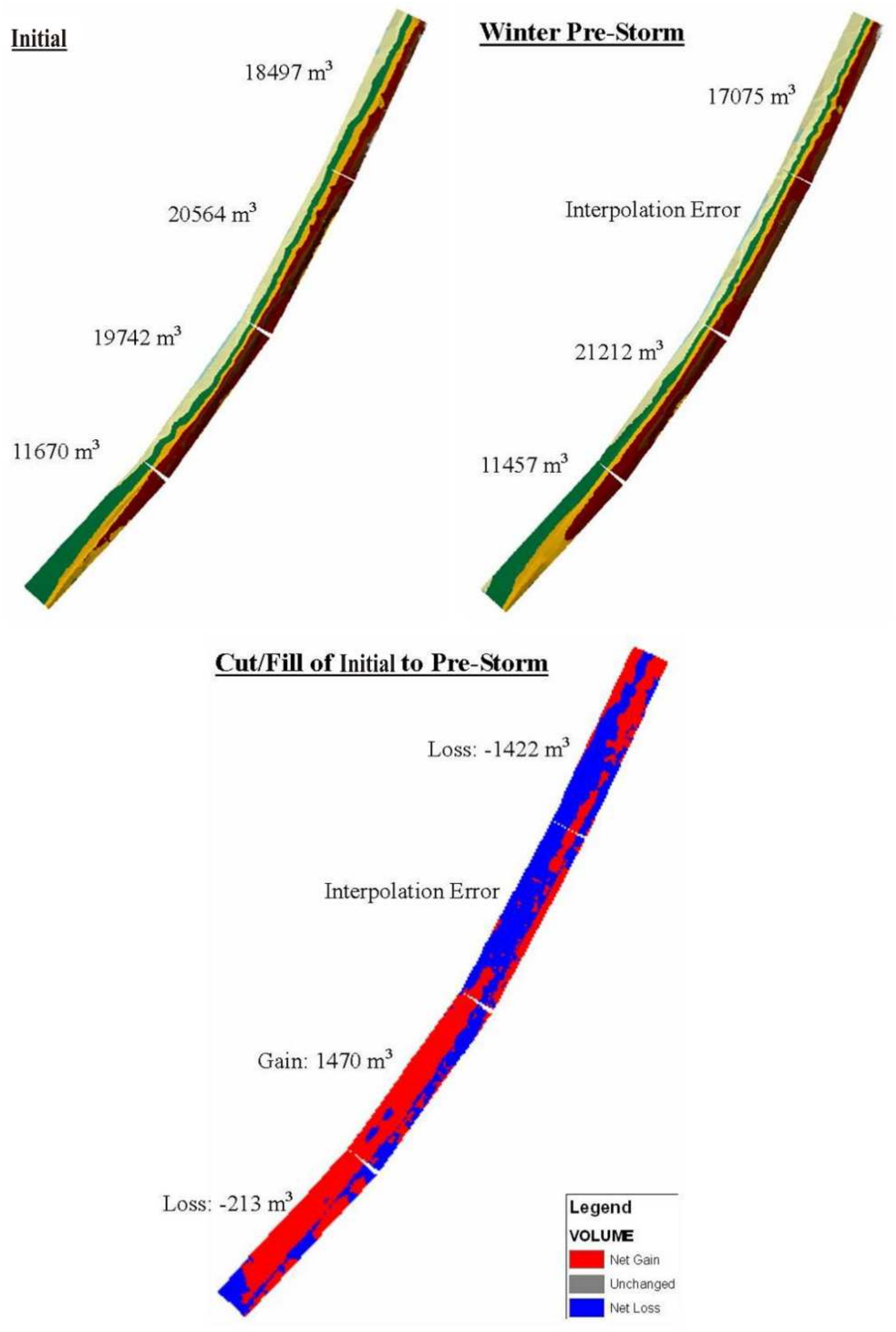


Figure 4.11 Diagram of volume change between the Initial and Pre-Storm DEM

4.4.3 Winter Post-Storm DEM and changes since the Pre-Storm DEM

The winter post-storm DEM was collected a day after the north east storm passed along the Rapahoe coastline on the 12th and 13th of August, resulting in rapid change to the beach face and foreshore. The GPS data was collected over a day, and concentrated only on the beach frontage of the Rapahoe Village. Field notes indicate change in beach profile, movements of sediment, change in sediment distribution and sorting along the beach face. Observational changes included:

- A combination of wave and rain pooled in the former depressions behind the gravel barriers which indicated barrier breach.
- Riprap revetments became exposed and gravels found on Beach road indicating the movement of gravel landward through gravel roll over.

The results are displayed in figure 4.12 and has a similar error to the Pre-storm DEM with profiles 2, 3 and 4 in Area 2, therefore the profile behind the gravel barrier and beach volume and change in volume are not reliable. The weather had calmed during the day of the data collection, with fine weather and 1-2 m swells.

Analysis from appendix 4.3-4.22 display the changes since the pre-storm DEM in crest height and cross shore profile. Gains in crest height in Area 1 (+0.17m) and Area 2 (+0.14m) align with literature by Forbes et al. (1995) regarding short term crest height increases after storm conditions. On the contrary, crest height loss was experienced in Area 3 (-0.07m) and Area 4 (-0.33m), the cause suggested to be through washover and erosion. Forbes et al. (1995) states that low crest, poorly organized barriers experience frequent washover, resulting in poor sorting in the backshore. Observations included poor gravel sorting in the majority of the southern sections of the study area, and distinct patterns or similarly sorted sediment slugs were not observed. Roll over evidence was also noted with substantial amounts of gravel found on Beach road in area 3.

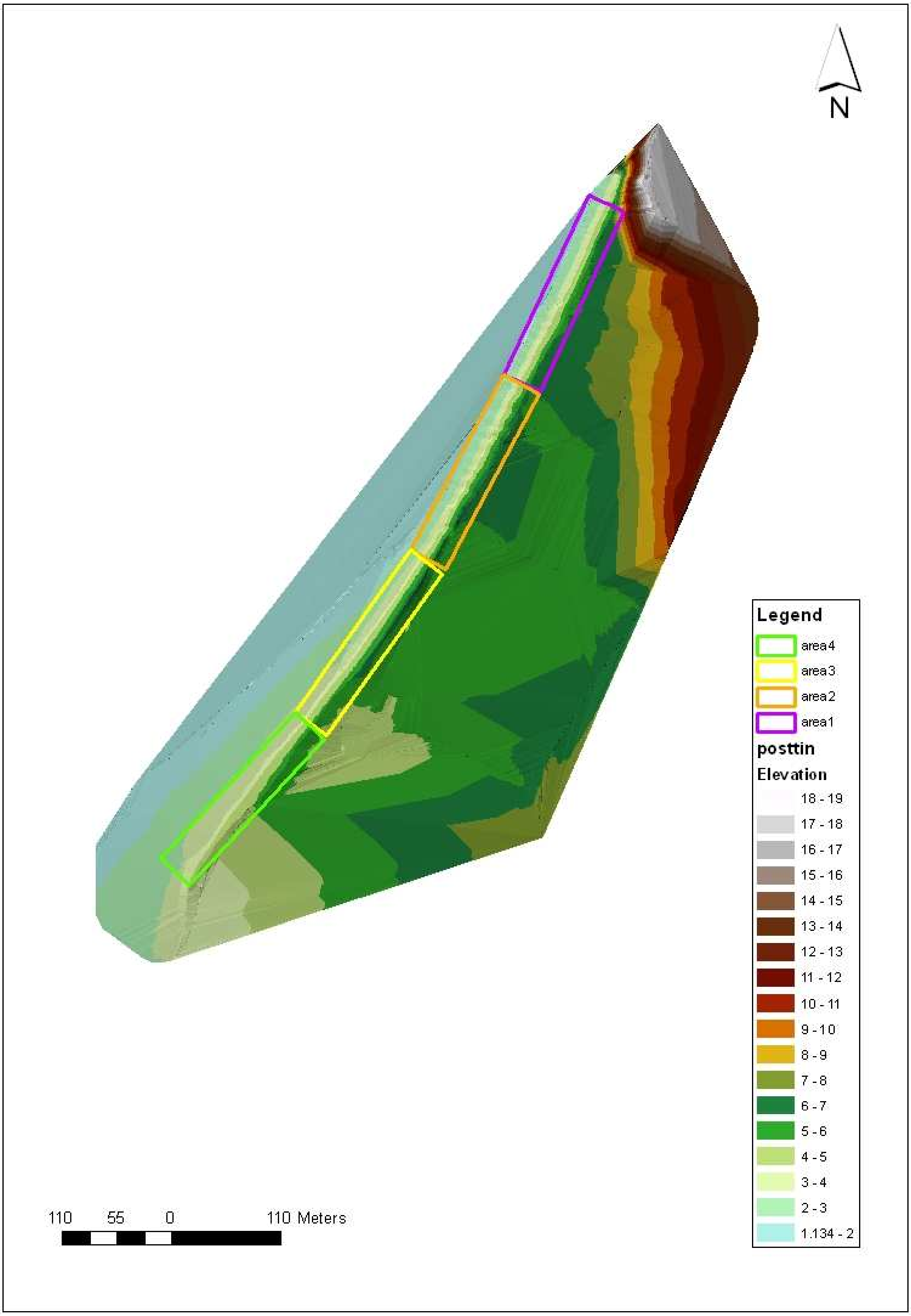


Figure 4.12 Post-Storm DEM

Figure 4.14 displays the changes between the Winter Pre-Storm and the Winter Post-Storm DEMs. Interpolation errors affected the backshores of Area 2, and there is a clear loss of sediment volume in Areas 3 and 4. The profiles from areas 1 and 2 indicate a loss in the intertidal zone and increase in gravels on the berm face, providing gravels for crest height gain as shown in Appendix 4.5, 4.6 and 4.7. Area 1 undergoes a gain of 2476 m^3, a substantial gain in a short period of time. This appears to be a short term gain due to the change of wave conditions associated with the storm. Whereas the dominant swell from the South-West induces strong southerly transport direction due to the refraction caused by Point Elizabeth, North-Easterly storms result in un-refracted wave energy directed onshore as Point Elizabeth is no longer an obstacle, and hence southerly transport is reduced (Refer to section 5.5 and figure 5.8). Swash aligned gravel barriers are dominated by movement up and down the beach (Forbes et al. 1995), and the direct wave energy on the shoreline results in gravel movement on to the gravel barrier (Areas 1 and 2) resulting in crest height increase. The gain in crest height was expected but the source of the gravel is unknown, as the intertidal zone which lost sediment during the storm was mainly comprised of sand. Field observations indicate that very little gravel was found under the sand, therefore the gravel must be sourced from the nearshore zone. This would indicate the possibility of a nearshore bar comprised of gravel, which was lost due to the high wave energy and change from the predominant wave direction, resulting in the onshore sediment movement. A similar scenario was found during a study on Amberley beach, a composite beach on the East Coast of the South Island (Ishikawa, 2006). Results showed a close interaction and oscillation of sediment between the beach and nearshore zone, with the formation and destruction of prominent beach cusps and a nearshore bar.

The barrier on the southern end of the beach experienced extensive breaching and rollover as displayed in figure 4.13 within Areas 3 and 4 due to lower crest heights, suggesting that the barrier is less stable then the northern half. The stability of the barrier is related to the hinterland, where areas 1, 2 and 3 are backed by land, area 4 is predominantly backed by Seven Mile Creek resulting in constant changes in the barrier. Areas 3 and 4 undergo extensive volume losses, as evident in the profiles (Appendix 4.13-4.22).

Area 3 and 4 has a higher wash over potential due to the low barrier crest height and this storm resulted in complete washover of the southern end of the spit as seen in figure 4.16B. The washover explains the overall loss of sediment in area 4. Profile change is summarized by an overall loss from the intertidal zone to the barrier and a decrease in crest height. Overall sediment volume loss is evident in the study area, and despite some small gains on the crest on the northern half, the loss of sediment through rollover, erosion and wash over is a direct result of the storm.

Figure 4.13 Photographs displaying evidence of roll over (14/8/07)

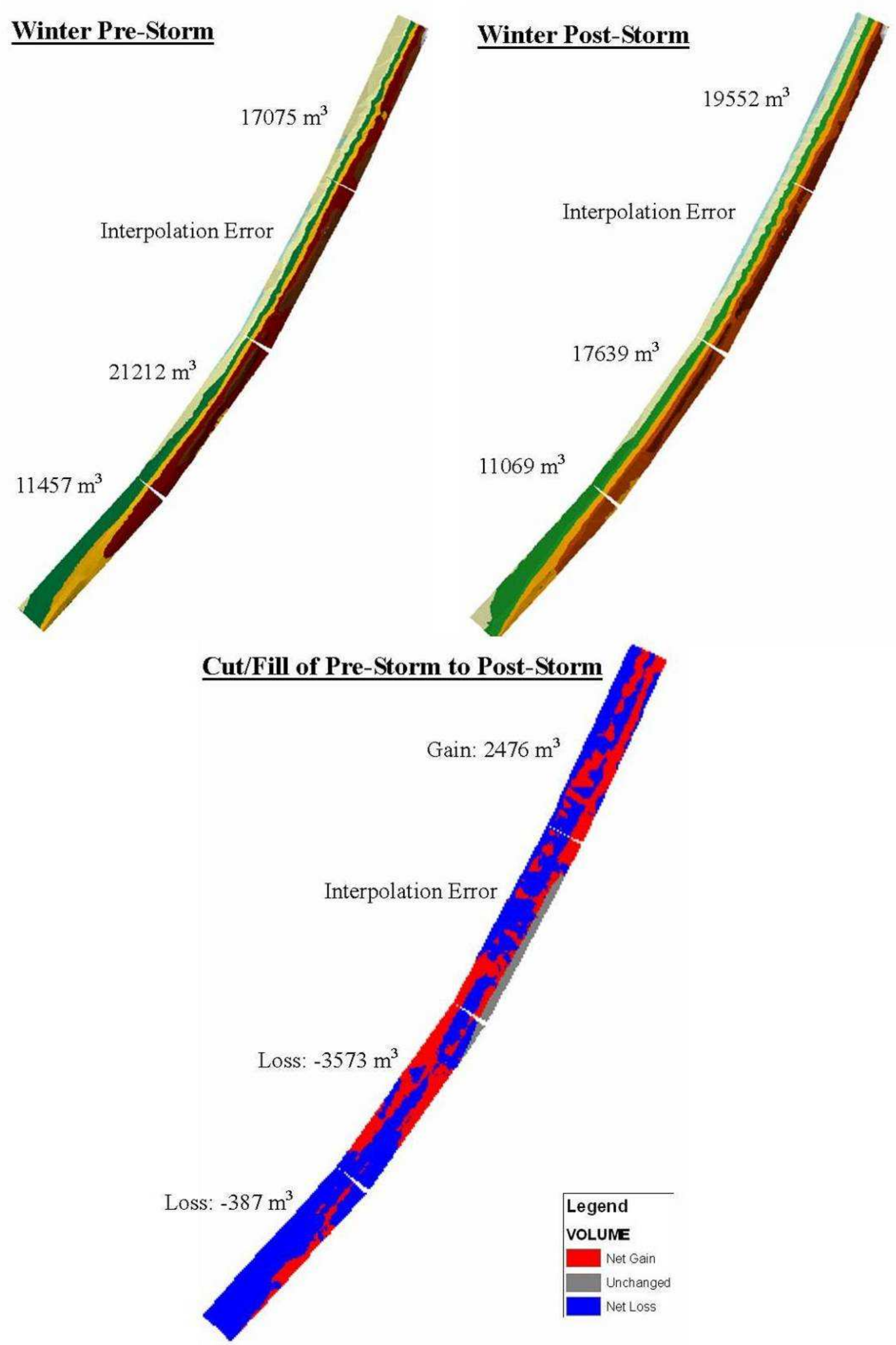


Figure 4.14 Diagram displaying volume change between Pre-Storm and Post-Storm DEMs

4.4.4 Summer DEM and changes since the Post-Storm DEM

The summer DEM was collected over 3 days and the results are displayed in figure 4.15. Problems with the equipment resulted in a sparse distribution of data on the Southern end of the Rapahoe frontage. Profiles 2-5 in Area 4 have interpolation errors and the profiles and beach volume figures are not reliable. The remaining sections of the beach have adequate GPS points and can be utilized for analysis. Swells were recorded to be 1-2 m in height and the general weather conditions were fine with patches of rain and light winds from the South West. Profiles from appendix 4.3-4.22 display very little change in crest height averages ranging from + 0.02 m to – 0.04 m in areas 2-4. In contrary to this trend, Area 1's crest height decrease by 0.56 m, mainly in the most northern profile. This profile is seaward of the Kaiatan mudstone cliffs, causing the gravel barrier to be highly dynamic. As rollover in not an option in this profile, the gravel is highly dynamic with the offshore and onshore movement, providing an answer to the unusual crest elevation change. The remaining profiles show very little overall change, with the majority of profiles shadowing the post-storm profiles.

Figure 4.16 displays the changes from the Winter Post-Storm DEM to the Summer DEM. Despite the interpolation errors, overall loss of sediment is apparent from the gravel barrier through roll over but the intertidal zones in area 1 and 2 display an increase in volume. The increase of the intertidal zone in area 1 and 2 is assumed to be a recovery of sand lost during the post-storm period. The short term volume and crest increase in Area 1 from the Pre to Post-storm phase has been lost with the decline in volume by 2830m^3 mainly on the storm berm. Interpolation errors due to the lack of GPS points results in inaccurate figures for the backshore of Areas 2 and 4 but the loss of beach sediment is evident through the profiles in appendix 4.13-4.17 and 18-22 on the gravel barrier. The profiles in Area 3 display overall volume loss of 758 m^3, predominantly in the intertidal zone with slight gain in volume on the barrier. The accretion on the gravel berm suggests introduction of fresh gravels from the dominant southerly transport. Field observations concluded the improvement in sediment sorting in comparison to the Post-storm period, with distinct sediment slugs on the lower berm and improved sorting on the barrier and backshore. The self-organisation indicates the recovery of the beach from the storm period.

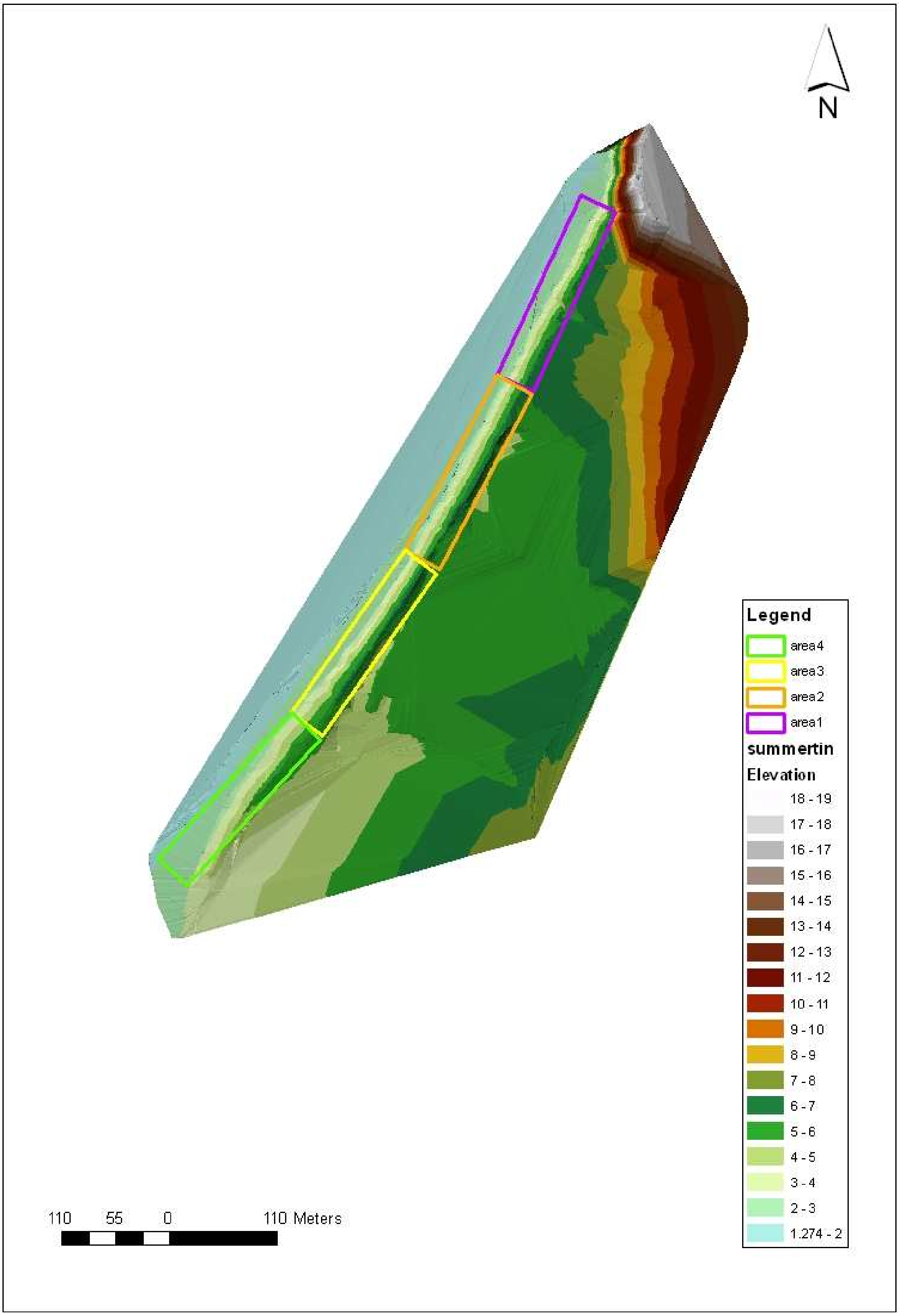


Figure 4.15 Summer DEM

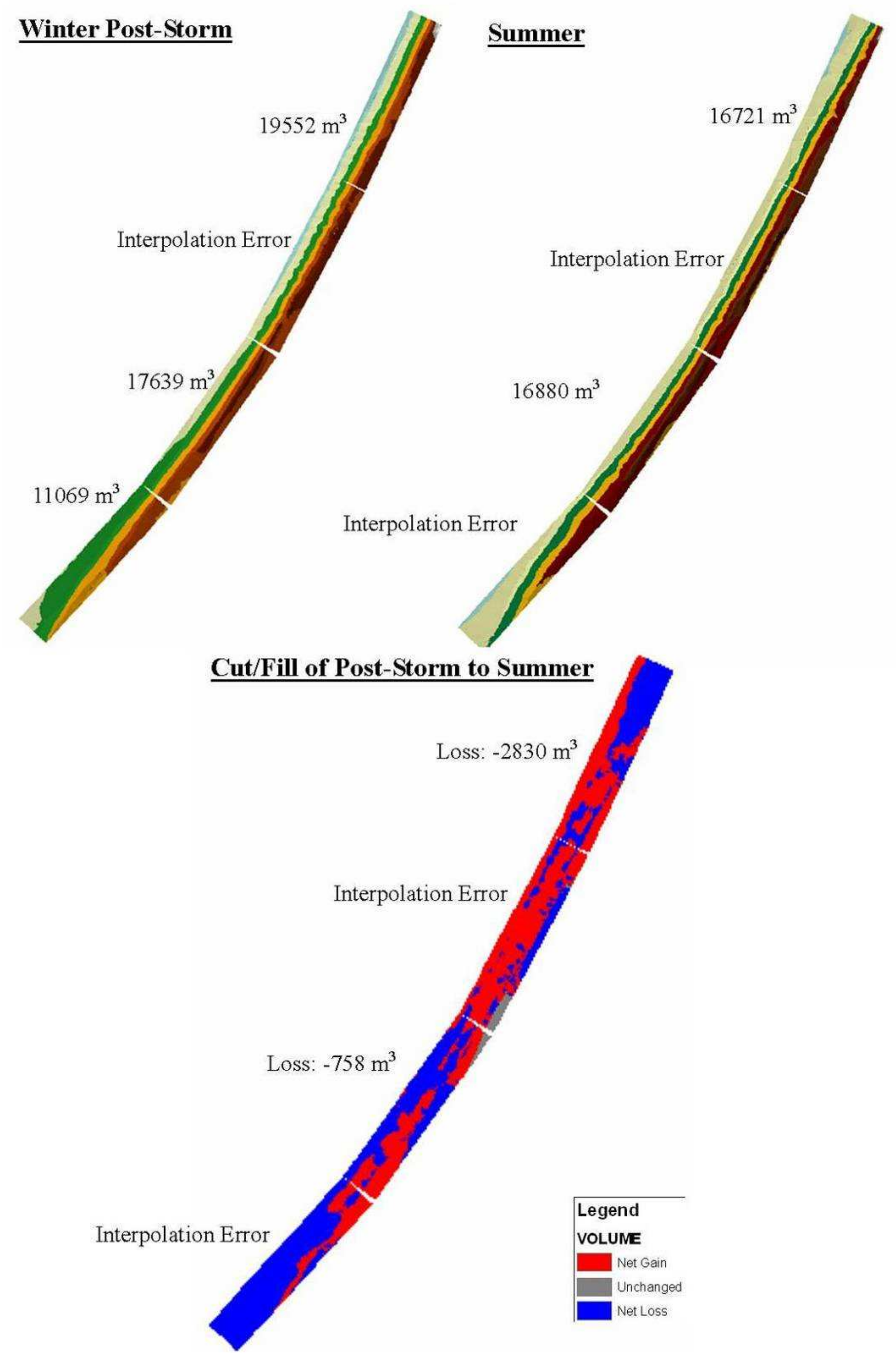


Figure 4.16 Diagram displaying volume change between Post-Storm and Summer DEMs

4.5 Discussion

The results from the 4 DEMs, profiles and cut/fill graphs have provided a number of key results towards the study of the Rapahoe coastline. Important results include the spatial variety in beach and morphological profile, cross and longshore movement of sediments and overall change in beach profile during the study.

The spatial variety in beach and morphological profile along the Rapahoe frontage can be classified through barrier crest, beach profile and hinterland. The most northern section (Area 1) displays a steep beach gradient with a barrier crest elevation ranging from 9.53-5.89m (Appendix 4.7-4.10, Figure 4.7). This section is partially backed by the Kaiatan mudstone cliffs and also by the Forbes property and the campground. Areas 1 and 2 also contain riprap revetments which modify the beach profile shape and sediment movement. Areas 2 and 3 display profiles similar to the schematics representation in figure 4.1, with a shallow intertidal zone comprised of sand and a steep gravel berm crest ranging from 7.03-5.93m (Area 1) and 6.56-5.31m (Area 2), backed by Beach road and depressions from the former lagoon. Area 4 is backed by Seven Mile Creek, and displays the shallowest profile gradients. Sediment layering is visible with a very wide, shallow and sandy intertidal zone and a small gravel barrier, with the crest ranging from 6.11-3.77m.

There is a gradual decrease in barrier peak height from North to South, and a common trend throughout the study has been the general decrease in all of the average crest height in each section. The exception to this trend is immediately after a storm period, where the Post-Storm DEM displays and an increase in crest height for areas 1 and 2. A similar pattern of crest elevation change is examined by Orford et al. (1996) through a gravel barrier in Nova Scotia where the increase in crest elevation is a response to the greater range of wave break induced through a storm, and this process is termed ridge consolidation. The increase of wave energy and distance of wave run up by the storm explains the short term increase in crest elevation. The overall decrease in crest elevation is explained by landward movement of the barrier requiring further sediments (which are not available due to change in sediment supply) to sustain the barrier. As landward retreat continues, the crest elevation decreases resulting in an increase in overtopping, overwash and rate of transgression as displayed with field evidence in figure 4.17. The rate of barrier transgression was enhanced with a lagoon backshore as seen in chapter 3 during the period of 1939-1988, but is now slowing down with the recent placement of riprap revetments. Results from Appendix 4.15, 4.21, 4.22 display the changes in barrier crest elevation and Appendix 4.5,4.11,4.12,4.15,4.16 show overall transgressive landward movement of the barrier crest.

Figure 4.17 Photographs displays barrier overwash (A) and washover of the spit and barrier (B) (14/8/07)

Changes in the beach profile relate directly to wave conditions, barrier crest and sediment supply. The general beach profiles align with the schematic profile of a composite beach (Figure 4.1) apart from the northern sections in area 1 (profile 1 and 2) and area 4 (profile1-5). The reason for the variety in profile is due to the hinterland backing the northern half of area 1 and in area 4. Profiles 1 in area 1 is backed by the mudstone cliff and the remaining profiles are backed by the Forbes residence and riprap revetments, confining the gravel sediments on the beach frontage. The steep gravel based profile loses sediment overall (Area 1: -1776 m^3) though the movement of sediments are a result of:

- Beach erosion leading to the offshore loss in sediments through the backwash.
- Gravel rollover resulting in sediment loss from the beach system. ,
- Cross shore sediment movement, mainly due to the southerly longshore sediment transport as the barrier morphology is not capable of sustaining itself through transgression.

- Loss of sediment within and between the riprap revetments which can not be recovered.
- The potential existence of the nearshore bar which leads to a dynamic bimodal oscillation of sediment and dynamic formation and destruction of morphology as found by Ishikawa (2006).

Seven Mile Creek backs the majority of Area 4, which is a composite layered spit. Mixed spits are highly dynamic and influenced by the wave environment, river discharge and sediment transport from the river as well as longshore (Woodroffe, 2003). The complexity of the morphology due to the variety of involved parameters makes the phenomena difficult to study, but through field observations and DEM results the following conclusions can be made.

- The profile is different from the figure 4.1 due to southerly sediment transport and discharge from the river, resulting in a very shallow and sandy outlet region backed by a small gravel barrier.
- The low elevation of the barrier and large tidal extent results in frequent overtopping and overwash resulting in chaotic sediment sorting and radical losses of sediment (Forbes, 1996) as observed in the field during the pre and post-storm period and displayed in figure 4.9 B.
- Evidence of transgression of the barrier crest is evident in appendix 4.19 and 4.20, though previous research would indicate that this section of the barrier would be in the barrier breakdown phase (Forbes et al., 1996) with the difference of hinterland backing compared to areas 1, 2 and 3 and the consistent discharge from Seven Mile Creek restricting area where the barrier can transgress.

Figure 4.18 displays an overall loss in sediment volume (Area 1: -1776 m^3, Area 3: -2862 m^3) and that provides a general reflection of the barrier backed by the township. The profiles similar to figure 4.1 undergo a general trend in change as loss of gravels on the lower berm and intertidal zone, and gains in the upper berm, and backshore as displayed in the majority of Appendix 4.5-4.17. The inter-tidal profile gradients are steeper from the Northern cliffs and shallower on the South. The inter-tidal zone is prone to regular wave action and the composite layering was clearly visible at low tide. The only exception to this was during the post-storm field study, when the layering was not clear and sediment sorting was poor. This provides evidence of the sediment movement resulting in ridge consolidation and also the latter process of self-organisation. Jennings and Shulmeister (2002) note that the steepest beach faces were of gravel and clastics of the gravel barrier and ridges, and this aligns with the results found in this study. The lower beach face is of shallower gradient, mainly comprised of sand and smaller gravels. This dynamic cross shore movement extends landward of the barrier and observational evidence of overtopping and movement of the barrier crest supports the transgressive barrier movement and proves the continuous landward retreat pattern in areas 1, 2 and 3.

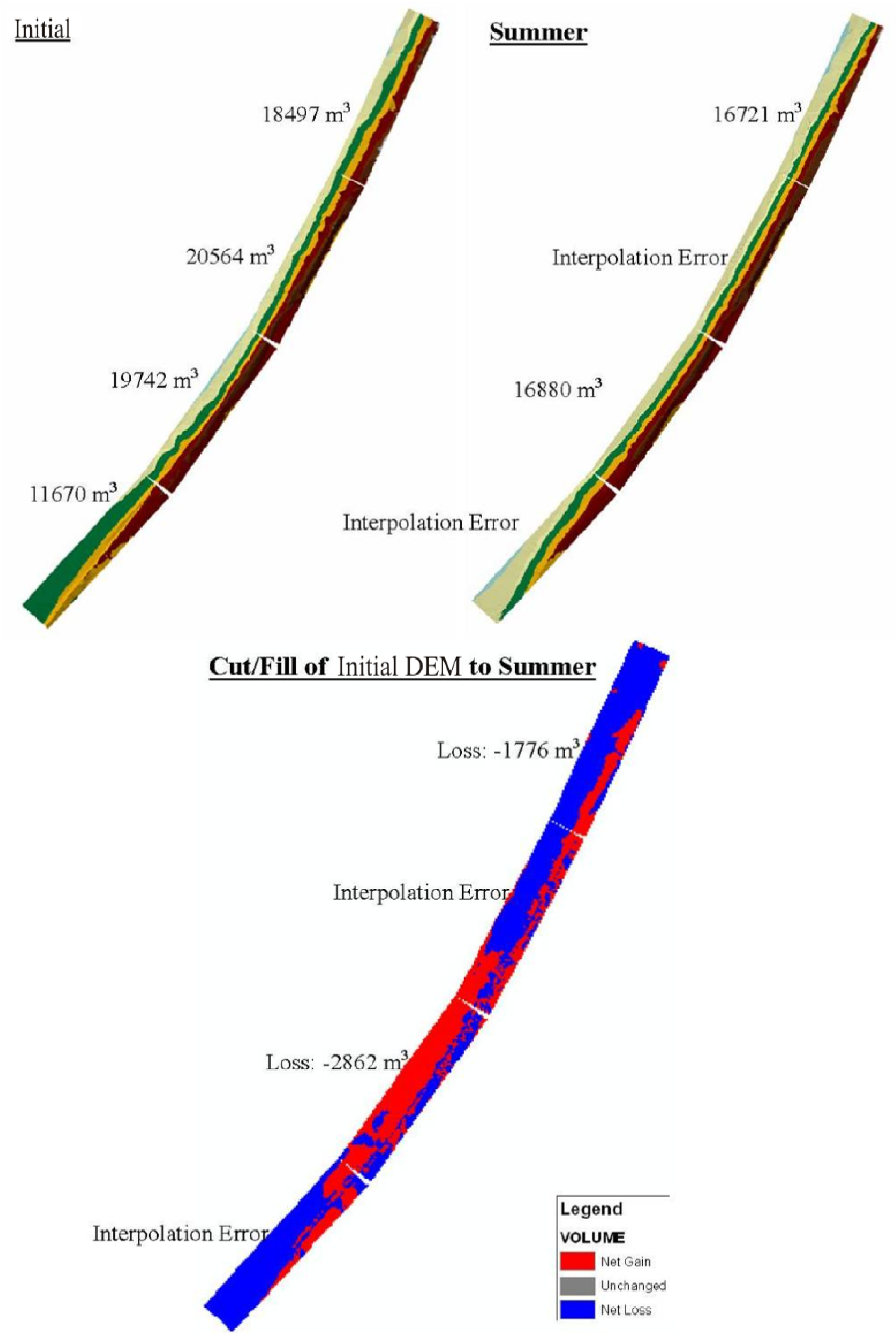


Figure 4.18 Overall Change displaying the Initial DEM and the Summer DEM

4.6 Conclusion

This chapter has investigated the beach frontage at Rapahoe Village through the use of numerous quantitative and qualitative methods. Field observations and GPS points were collected and generated four main DEMs from the separate data collection periods. These detailed models of the coastline showed the dynamic changes of the beach face and coastal morphology in a temporal and spatial approach. The results concluded that the northern half of the beach is of transgressive nature, with storm conditions resulting with an increase in crest height. The overall result displays landward retreat through gravel rollover and washover. The southern half of the beach is undergoing similar processes, and area 4 with the backing of creek is highly dynamic but evidence points to possible destruction of the spit feature in the future, resulting in a large modification of the fluvial impacts on the coastline and may induce erosion on southern parts of Rapahoe Bay. Sediment supply is considered to be the major control of gravel barrier morphology and the overall transgression of the barrier implies the lack of sediment supply on the beach aligning with the mentioned literature.

Chapter Five: Wave Processes and Sediment Transport

Figure 5.0 Photograph facing West from the village frontage 26/6/07

5.1 Introduction

In the field of coastal research, identifying wave processes and quantifying longshore transport is essential towards understandings the history of coastline movements, wave processes effecting the current coastline and the future prediction of the coastline. This chapter examines the wave processes that occur in Rapahoe Bay through the use of 20 year wave hindcast data obtained through the WAM model. Wave refraction theory is applied to obtain the wave field of the shoreline in Rapahoe Bay, to quantify the longshore transport direction, and to estimate the longshore transport volumes. The aims of this section are as follows:

- Analyse the 20 year wave hindcast data to identify wave conditions which effect the coastline of Rapahoe Bay.
- Apply the wave refraction theory to analyse the wave processes occurring in the embayment.
- Examine the refraction results and identify, and quantify the potential longshore transport direction and volume.

5.2 The WAM Model and Hindcast Data

5.2.1 The WAM model

Gorman et al. (2003a and b) examines and clarifies the wave generation model (WAM) in a New Zealand context. The WAM model generates 3-hourly wave parameters around the New Zealand coast from 20 years of wind data from 1979 to 1998 calculated by the European Centre for Medium-Range Weather Forecasts (ECMWF). The created WAM data was verified against data from eight representative sites along the New Zealand coastline, and was found to provide satisfactory wave simulations. Lagrangian approach used in the calculation of WAM hindcast data is seen as appropriate for field situations on a scale of 20-30km with a water depth of no less than 20m, allowing the WAM model to provide valuable data to an otherwise poor wave data coverage history of the New Zealand coastline and the data base has proved to be an important asset to coastal scientist and researchers in New Zealand. However, the effectiveness of these models in shallow water has been argued and these models can not always be applied to supply accurate wave conditions in beaches (Cooper and Pilkey, 2004).

Figure 5.1 displays the deep water significant wave height in the New Zealand region from Gorman et al. (2003a). Wave heights progressively decrease towards the North, with typical wave height on the West Coast of the South Island being between 2 -3 m. Seasonal variations can be seen in Gorman et al. (2003b), with the lowest significant wave height being during the summer and increase during Autumn and Winter. Figure 5.2 displays the WAM results focusing on wave energy transport direction. It is important to note the dominance of the prevailing Westerlies, refracted in a general North-Easterly direction along the West Coast of the South Island. Figure 5.2 indicates the general wave and transport direction in a national scale but the limits of WAM does not provide any details of wave changes in local irregularities such as headland, lee shadow areas and small bays. This is the case at Rapahoe, where previous literature describes the possibility of the change in the local transport direction due to the topography, thus the application of wave refraction is applied manually to examine the wave processes in a smaller study area.

Initially, this chapter attempted to utilise the shallow water wave analysis (SWAN) model, a nearshore model developed and verified by the Fluid Dynamics team at Delft University in the Netherlands (Booji et al. 1999, Ris et al. 1999 and SWAN Team, 2007). Local case studies found SWAN to be effective in nesting in to WAM results and modelling wave refraction and to quantify sediment transport (Gorman et al. 2002, Gorman and Neilson, 1999, Reynolds-Fleming and Fleming, 2005). The SWAN was run on the study area simulating average conditions, but the results were found to be incompatible with observations and exported results. Therefore, manual calculation of wave refraction and sediment transport was utilised as an alternative.

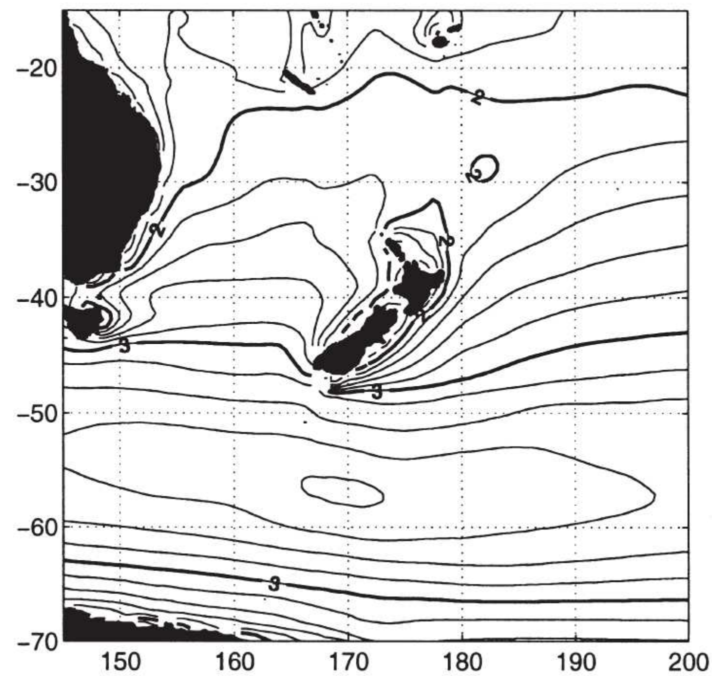


Figure 5.1 Map displaying the significant wave height in the New Zealand Region (Gorman et al. 2003b pg594)

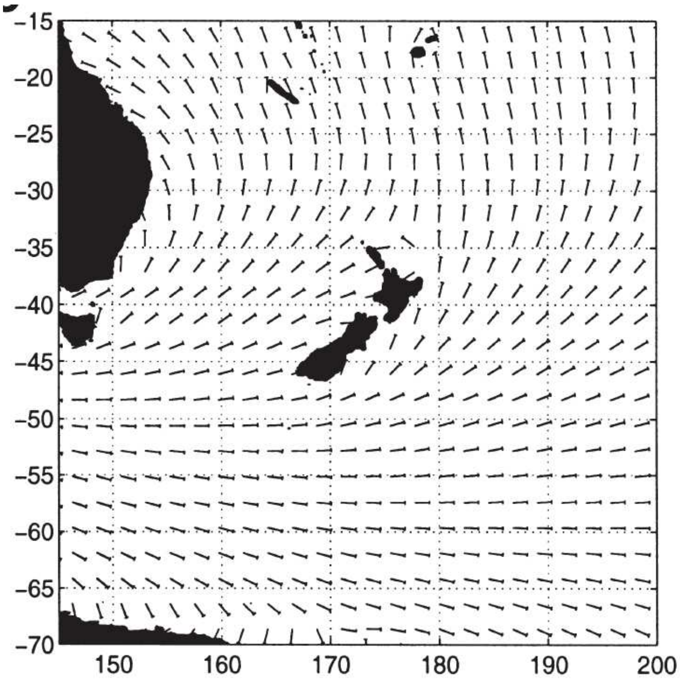


Figure 5.2 Vector map displaying the averaged net wave energy transport direction (Gorman et. al., 2003b pg594)

5.2.2 WAM Hindcast data

The 20 year WAM hindcast data was obtained from NIWA through the Geography Department at the University of Canterbury for use in student research. The data is projected through WAM for Site 5, displayed below in Figure 5.3 and the wave data has been transformed from the original deepwater node point to the 10 m contour by the process of 'parallel contour refraction' by NIWA. This site was selected due to its vicinity to the study area (roughly 4 km SW from Point Elizabeth), and because the field site is on the leeward side of the dominant swell. The model hindcast data provides 32 projected wave parameters every 3 hours from 1979-1998 including wave height, direction, frequency, period, spread, wind speed and direction and a variation of energy parameters such as magnitude and direction. The results provide realistic and accurate wave conditions within the study area, where in the past Pfalhert (1984) considered the area to be lacking in reliable long term wave and current data. The wave data is then sorted and calculated in averages and overall statistics for various time periods.

Figure 2.4 in chapter 2 displays a rose graph of significant wave height and mean direction over the total 20 year period, an example of the outputs available from the data. The wave rose shows that over 60% of the dominant deep water swell direction is in the range of 34-79°, hence originates from 216 - 289° (SW). A further 31 % originates from 260 – 304° (West) while only a small portion of 8% originate from 305 – 350° (NW). These wave directions represent 99.8% of the conditions, and the average direction from each section (236°, 281° and 326°) are utilised for refraction modelling with the following deep water parameters in table 5.1.

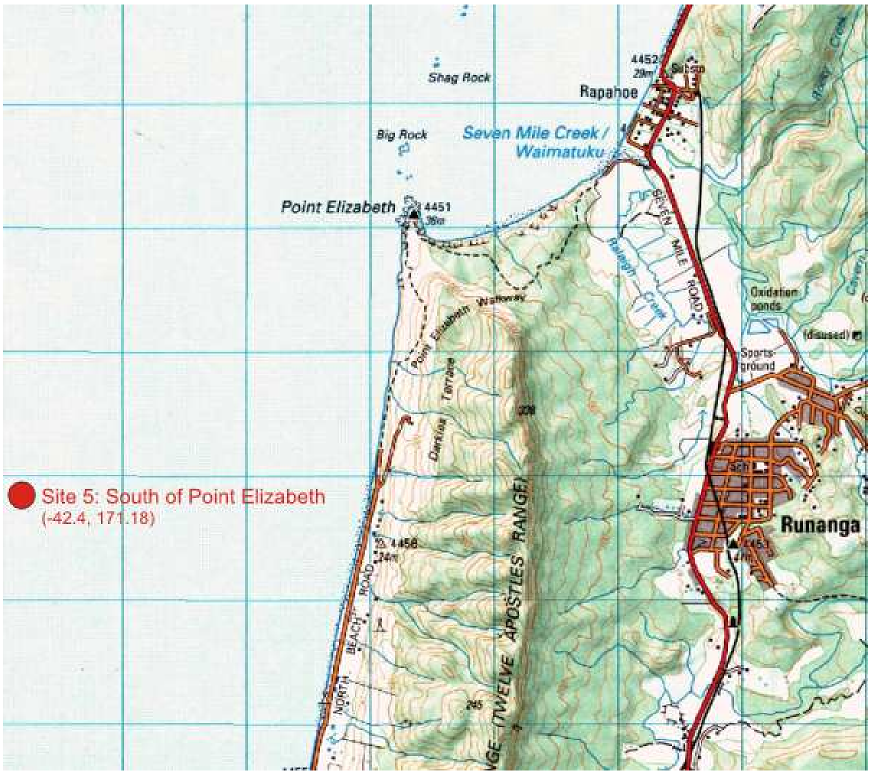


Figure 5.3 Map displaying Site 5

Table 5.1 Data utilised for Refraction Diagrams

Figure	Direction (From) (Deg)	Directional Spread (Deg)	Frequency Occurrence (%)	Hs (m)	Period (s)	Length (m)
5.7	236	33.75-78.75	61.40%	2.08	8.3	107.47
5.8	281	78.75-123.75	30.90%	2.03	7.37	84.73
5.9	326	123.75-168.75	7.50%	2.07	7.07	77.98

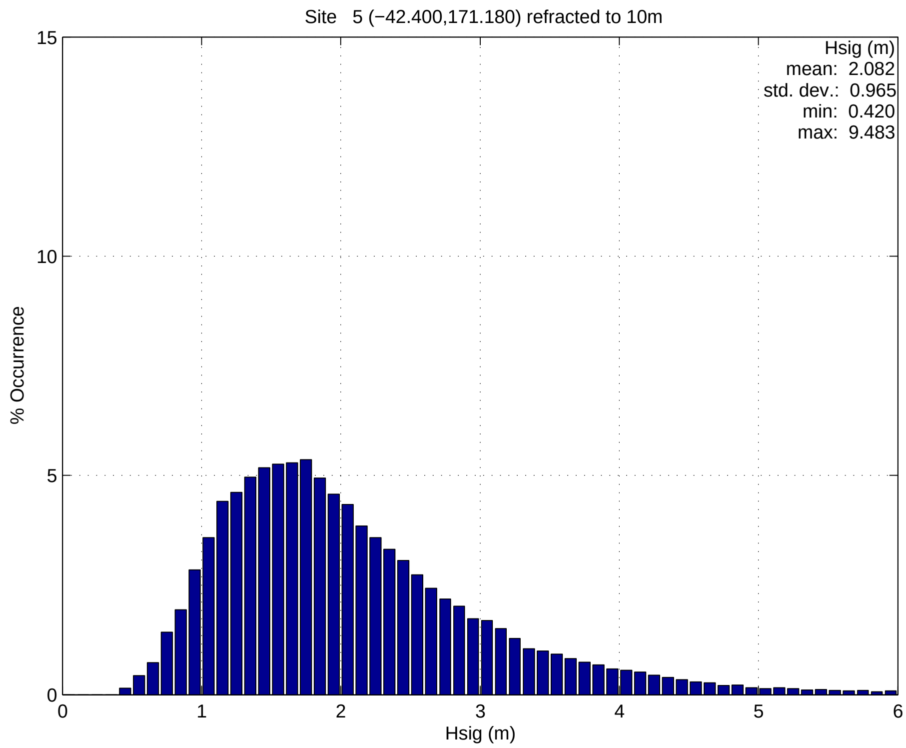


Figure 5.4 Percentage of significant wave height occurrence at site 5

Figure 5.4 displays the percentage of significant wave height occurrence at site 5. This displays a skewed normal distribution curve with the highest occurrence at 1.7 m. The monthly average of the hindcast showed that the average significant wave height ranged from 1.716 – 2.298 m. Hs illustrated a seasonal pattern, with higher Hs during the winter seasons (2.093 – 2.298 m) and subdued heights in the summer (2.014 – 1.716 m). The 1% and 10% exceedance height was from 5.29 m (1% exceedance). For the refraction diagram, deep water Hs will be utilised as the refraction diagrams initiate from 50 m depth being the limit of the $L_0/2$ criteria. Using the Hs bins with direction, the Hs utilised for each diagram are 2.07 m (236° wave source), 2.03 m (281° wave source) and 2.07 m (326° wave source) as shown in table 5.1.

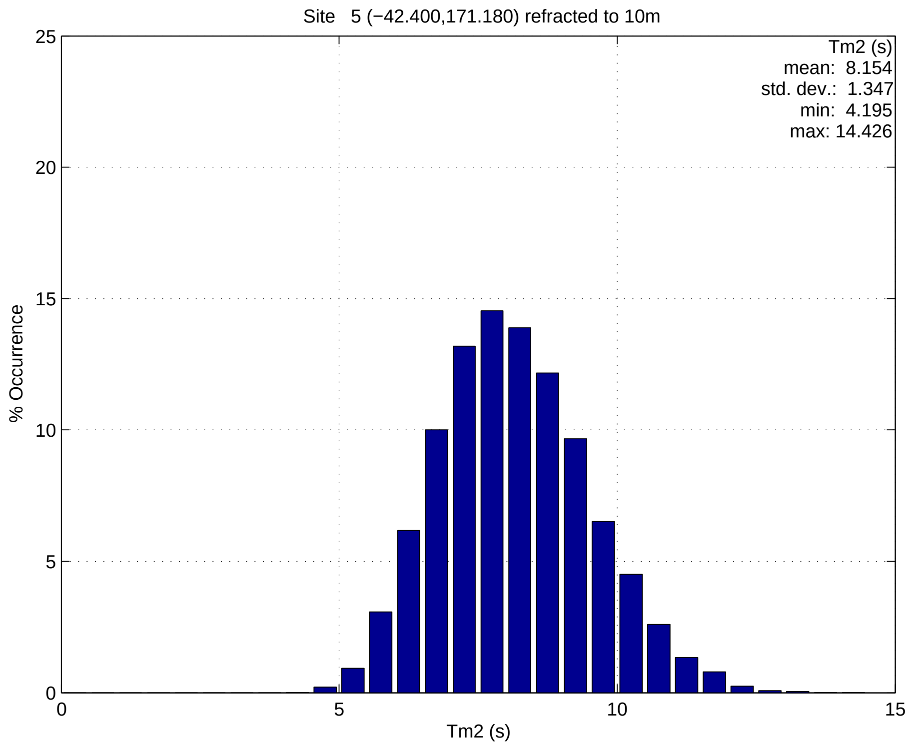


Figure 5.5 Percentage of period (T) occurrence

The distribution of wave period is presented in figure 5.5 The mean period is 8.154 s, with a range of 4.195 – 14.426 s. Once again, the deep water statistics are utilized for the refraction diagram and sediment transport calculations. The wave periods utilized were 7.92 s (236° wave source), 7.37 s (281° wave source) and 7.07 s (326° wave source) as shown in table 5.1.

5.3 Method

5.3.1 Refraction Diagram

Wave refraction is the process of waves bending to parallel the contour lines as waves approach a coastline (Woodroffe, 2003). The bending occurs when the orbital motion wave cycles undergo friction as the bathymetry shallows, resulting in the waves bending, commonly aligning with the coastline (Bird, 2000). Figure 5.6 displays the wave bending process to parallel the contours and shoreline. Wave orthogonals are perpendicular to the wave crest, commonly used to identify areas of wave focus. Swell waves are known to refract more than locally generated winds, and the refraction is important towards identifying the dominant longshore transport direction (Woodroffe, 2003). CERC (1984) gives several reasons why understanding the wave refraction is important, including:

- Determining the wave height assists to identify wave energy distribution on the coastline. Wave energy is directly proportionate to wave height, consequently the breaker height that results from refraction is relevant towards quantifying energy and sediment transport.
- Refraction can result in areas of concentrated wave energy, thus affecting the erosional or depositional state of a beach and bottom topography.

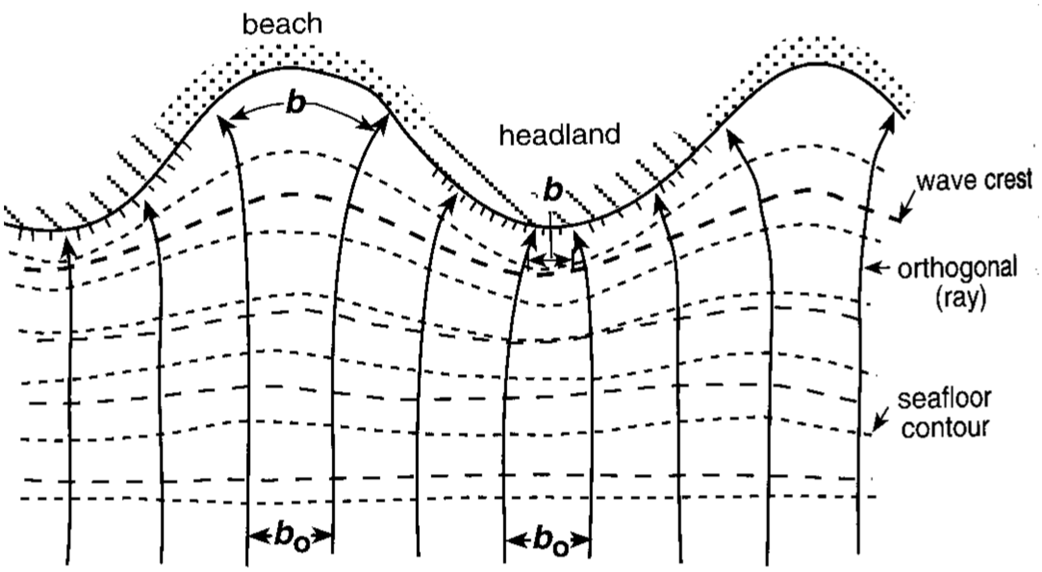


Figure 5.6 Diagram displaying wave refraction (Woodroffe, 2002 pg110)

The method provided in the Shore Protection Manual (CERC, 1984) is utilized to map the wave refraction in the study area. The validity of this approach has been verified through studies by Chien (1954), Ralls (1956) and Wiegel and Arnold (1957) as noted by CERC (1984). The fundamental theory behind this method is based on Snell's law where wave velocity and angle of wave crest is calculated between different contours.

Three refraction diagrams have been illustrated manually using the CERC template provided, then presented on the bathymetric charts provided by LINZ sheet NZ7142. The wave angles utilized have been previously discussed in 5.2.2, to represent 99.8 % of the average wave conditions through the hindcast data. The wave refraction diagrams were drawn starting from the 50 m contour, as L_0 range from 97.9 – 78 m and $L_0/2$ is where refraction begins. Therefore, the deep water wave directions were applicable for this method. The refraction diagrams were illustrated in three different scales of the bathymetric chart to accurately map the refracted orthogonals. The results include figure 5.7, 5.8 and 5.9.

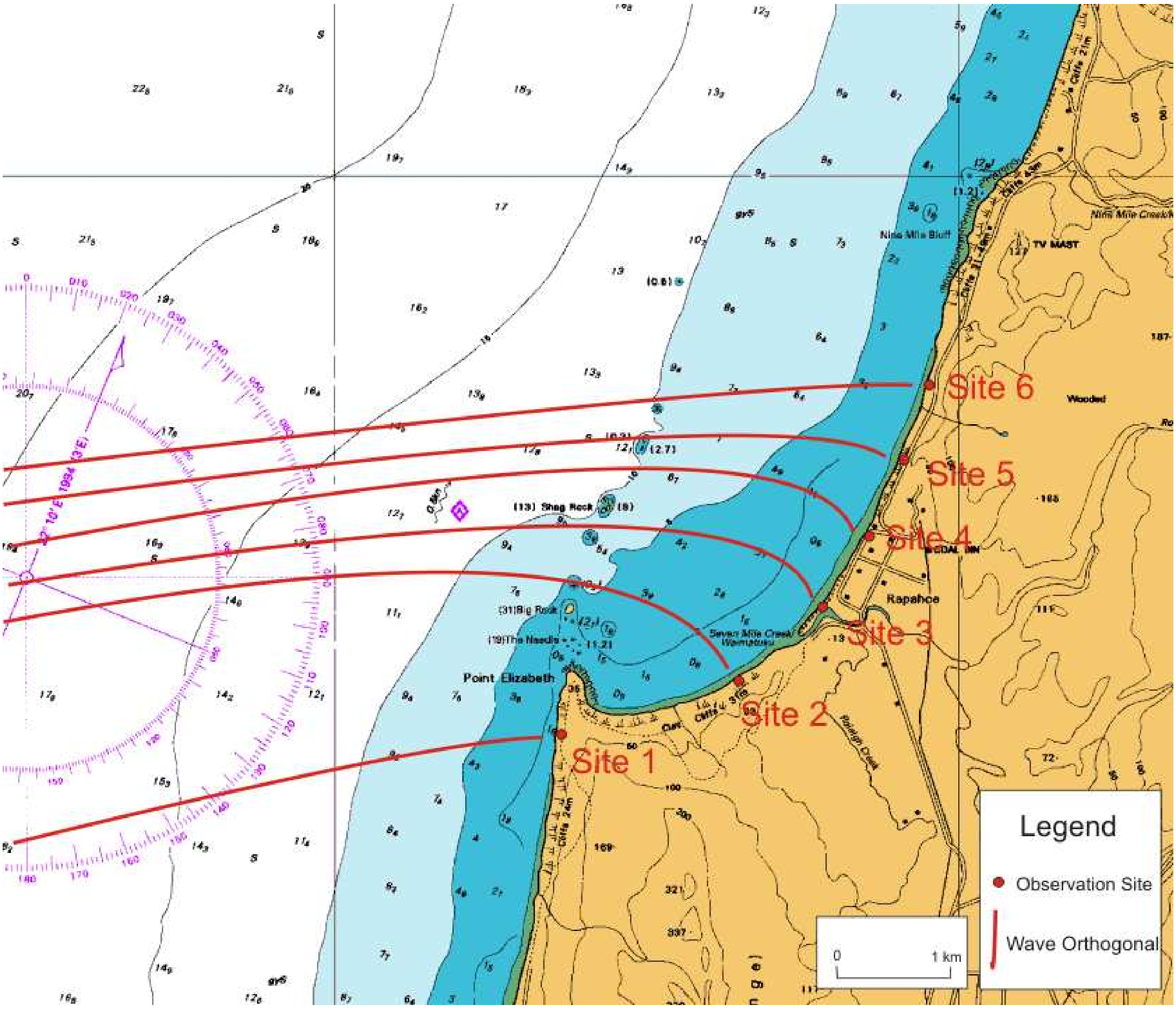


Figure 5.7 Refraction diagram with swell directions from 236° (61.4% occurrence)

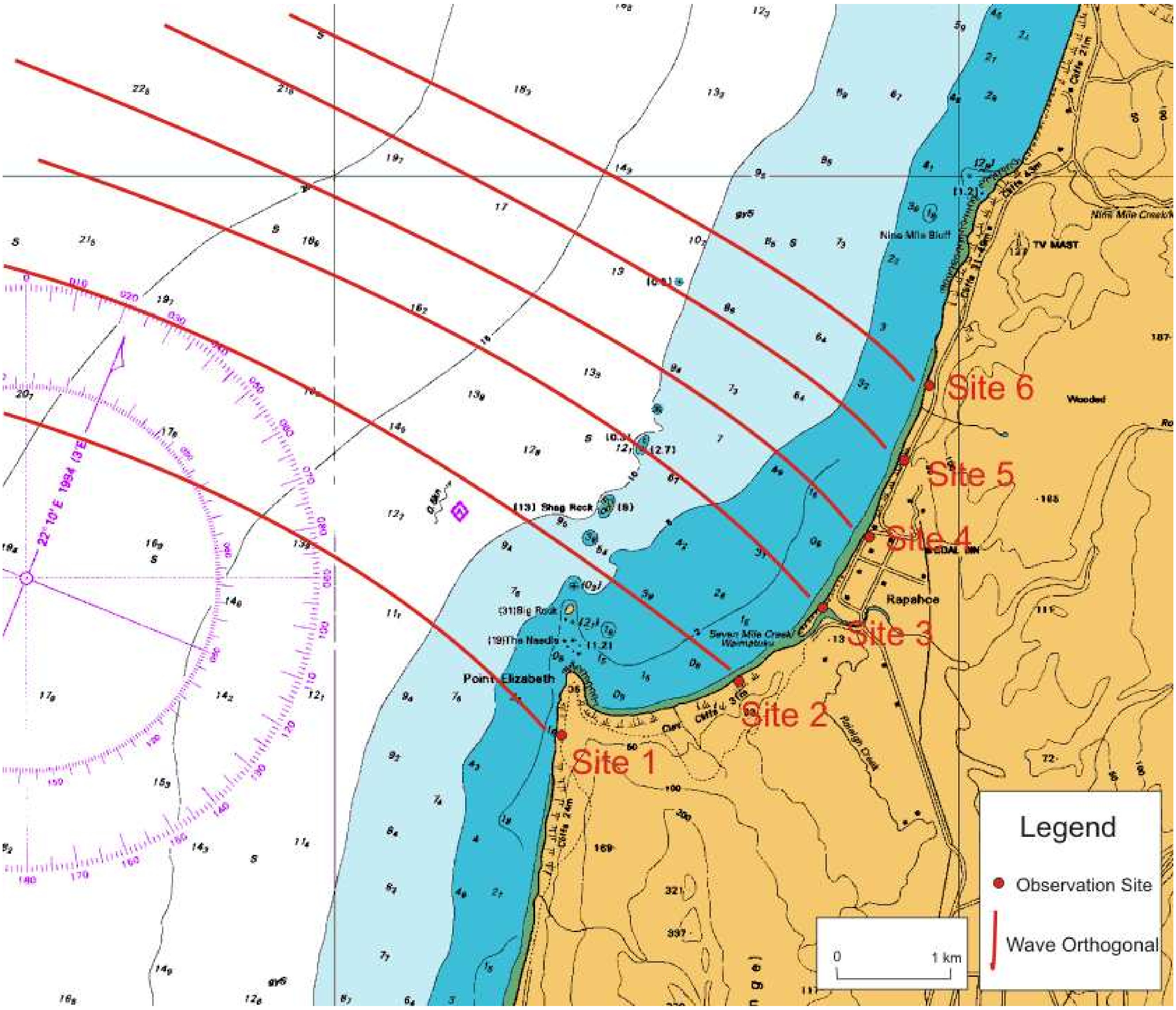


Figure 5.8 Refraction diagram with swell directions from 281° (30.9% occurrence)

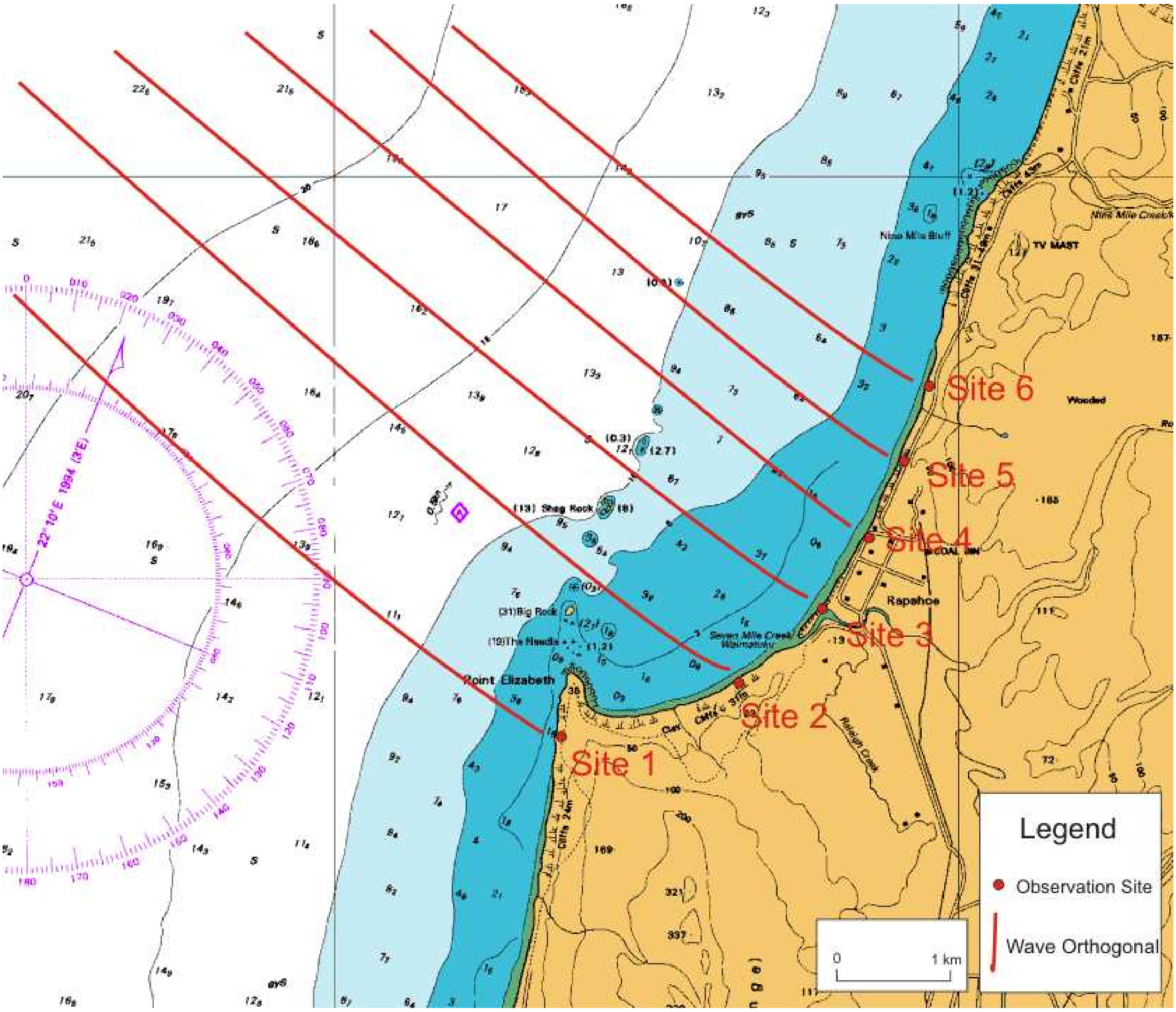


Figure 5.9 Refraction diagram with swell directions from 326° (7.5% occurrence)

5.3.2 Identifying and quantifying sediment transport

The method for identifying and quantifying sediment transport was undertaken in two steps. The initial step involved further analysis of the refraction diagrams and the second step involves the input and calculations of the potential sediment transport.

The orthogonals were mapped to intersect with six sites along the Rapahoe coastline. The six sites are clearly identified in the results (Figure 5.7-5.9). This was illustrated to identify the refracted wave orthogonal relative to the shore orientation. This step allows for quick identification of wave transport direction at each site, displaying the variety along the coastline. The angles were inputted in to a spreadsheet with further formulas provided by CERC (1984) along with other required deep water wave parameters including significant wave height (Hs), period (T), wave direction, wave length (L_0), wave celerity (C_0). The refraction coefficient Ks/Kr was manually quantified through a monograph from CERC (1984) and the calculated results include wave group speed at breaker (Cgb), wave breaker height (H_b) and rates of sediment transport potential for sand (m^3/yr). The quantified results are displayed in figure 5.10 representing the sediment transport direction and quantities over 99.8% of time per annum.

5.4 Limitations and Errors

The major limitations and sources of potential error involve human interpretations and accuracy in mapping. As the refraction diagrams involved human interpretations of mid contours and angles through the use of a clear plastic template, the complexity of the bathymetry proved difficult when contours became closer. To mitigate this problem, maps were enlarged to achieve more accurate results. The accuracy of the bathymetric chart is unknown, and the amount of error from this can not be quantified. The complexity of the coastline also proved difficult to map the orthogonals, as the rocky islets north of Point Elizabeth induces a complex system of diffraction and refraction, an investigation beyond the scope of this research. Therefore, the orthogonals are drawn as going directly through some of the islets. Although this is not completely accurate, the orthogonal indicates the general direction of wave energy. Shore angles were measured with the use of a protractor, as well as angles between the orthogonal and shoreline, and shoreline orientation.

5.5 Results

The results from figure 5.7, 5.8 and 5.9 display the wave orthogonals that represent 99.8% of the wave conditions and figure 5.10 presents the total sediment transport potential. The refracted orthogonal induce the change in potential sediment transport direction and quantity. Observation site 1 displays an overall sediment transport of 2.81 x 10^6 m^3/yr to the north. In comparison to other quantified sediment transport rate, very little research has been undertaken and the majority of reports refer back to Pfahlert's review (1984) on Furkert's research (1947). Furkert concluded that approximately 47.5 x 10^6 m^3/yr of sediment was being transported to the West Coast, where 25% of this would be sand and coarse sediments that were deposited on the coastline. From this, one-third of the sediments were assumed to be transported north. This means that approximately 3.95 x 10^6 m^3/yr of sediment is estimated to transport north. The difference between the rates is 1.14 x 10^6 m^3/yr and the accuracy of Furkert's results are widely debated. Therefore, it can be assumed that these results quantify a realistic quantity of potential sediment transport at observation site 1.

Figure 5.7 identifies the hinge point that is referred to by Neale (2000), Westlake (2000) and Ramsay (2006), located between observation site 5 and 6. This is quantified as the sediment cell between site 4 and 5 experiences a potential sediment loss of 4.93 x 10^6 m^3/yr. Shown in figure 5.10, this hinge point does not occur around 38% of the time as the figure 4.8 and 4.9 indicates a southerly drift in sites 3, 4 and 5 but figure 5.10 indicates the overall existence of the hinge point due to the dominance of the SW deep water waves.

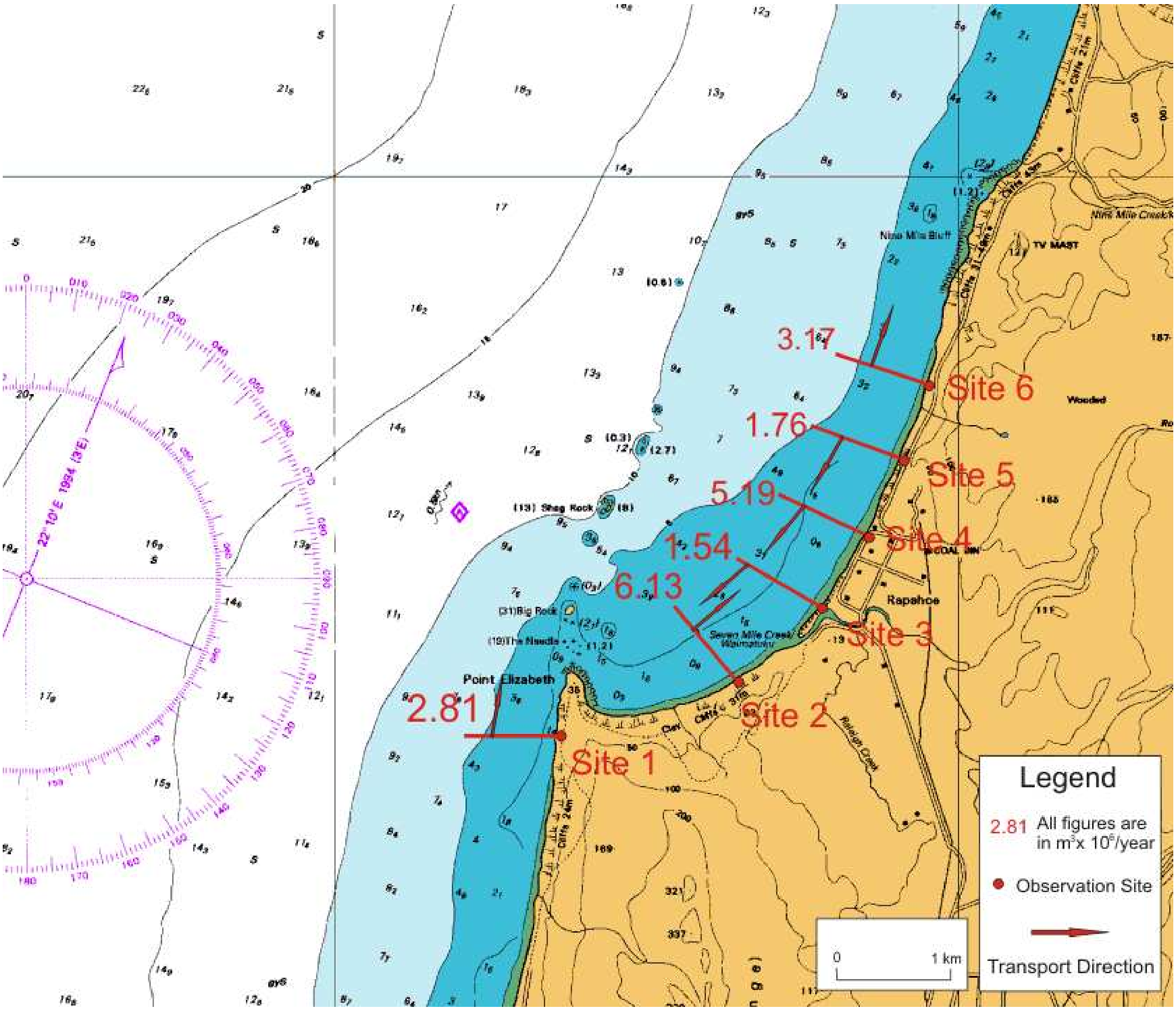


Figure 5.10 Diagram displaying sediment transport direction and volume (99.8% occurrence)

Table 5.2 Potential sediment transport results. A positive number quantifies potential northerly transport and a negative number quantify potential southerly transport.

	Wave Direction: 245	Wave Direction: 281	Wave Direction: 326	Annual Transport Potential (99.8%)
Observation Points	million m^3/yr	million m^3/yr	million m^3/yr	million m^3/yr
1	10.17	-6.48	-0.89	2.81
2	2.43	2.74	1.56	6.73
3	-3.35	0.59	1.22	-1.54
4	-2.50	-2.18	-0.51	-5.19
5	5.88	-6.93	-0.71	-1.76
6	12.09	-8.05	-0.87	3.17

Observations site 2 and 3 have concluded with some unusual results as the sediment cell between the site potentially gains sediment by 7.67 x 10^6 m^3/yr. The accuracy of this is questionable as the rocky islets north of Point Elizabeth results in a complex interaction of refraction and diffraction. The sediment cell of interest is a wide, shallow dissipative zone, where the Seven Mile Creek outlet is located. Sediment gain on the beach face has not been experienced throughout this study in this area, and as a result the potential sediments are assumed to be either lost offshore through backwash and currents or the sediment causes a biomodal morphology exchange. The sediment exchange results in the interaction of a nearshore bar and beach cusps and the cross shore movement of sediment have been observed at composite beach on the East Coast (Ishikawa, 2006). The general southerly transport directions observed in sites 4 and 5 in figure 5.10 correlates to the sediment losses experienced on the village frontage in chapter 4. This has major management implications that will be assessed further in 5.6

5.6 Discussion

The results discussed in 5.5 have identified and quantified the potential sediment transport rates in Rapahoe Bay. These rates have reiterated the potential for coastal hazards on the coastline and major implications towards future coastal hazard management.

Figure 5.11 Kaiatan Cliff base undergoing revetment work at high tide

Observation site 5 is identified on figure 5.11 as the Kaiatan mud-cliffs with State Highway 6, located just North of the Forbes residence. Previous literature such as Ramsay (2006), Neale (2000), Westlake (2000) and Pfalhert (1984) mention the hinge point and Ramsay (2006) illustrate schematic plots of the beach, longshore transport movement and the possible location of the sediment transport hinge point. Results from figure 5.10 have proven and justified the need for coastal protection along the village frontage and Kaiatan mudstone cliffs. Over time, the rising sea levels and anthropogenic impacts have resulted in a change of sediment supply. Cliffs fronted by riprap revetments have restricted cliff erosion on relatively soft geology, changes in fluvial flow and available sediments have reduced supply and decreased the sediment availability for the bay. This has lead to shoreline erosion and landward retreat, as proven through change in coastline history in chapter 3. The requirement of coastal protection has been acknowledged on the village frontage by the local residents and district council and riprap revetments have been placed on the village frontage and seaward of the Kaiatan mudstone cliff (State Highway 6) by Transit NZ.

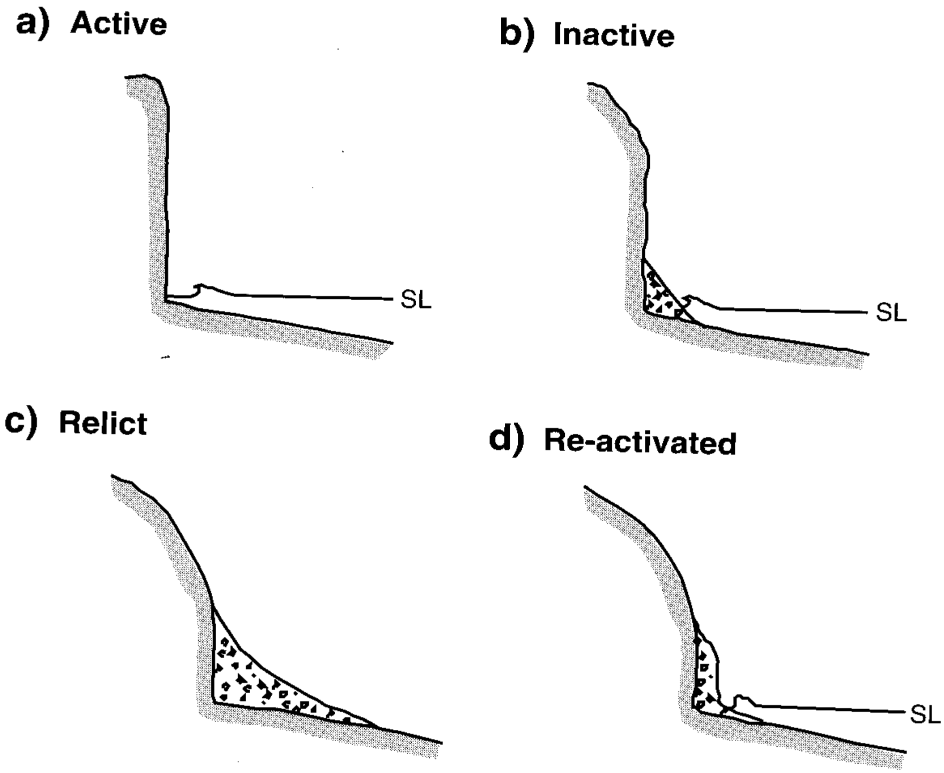


Figure 5.12 Cliff types in terms of activity (Based on Emery and Kuhn, 1982) adapted from Woodroffe, 2003 pg145)

Site 5 displayed in figure 5.11, is a cliff based area with heavy revetments in the form of rip raps. During high tide, the water level reaches the base of the cliff as seen in figure 5.11 and dynamic movement of sediment has been observed in field observations. Figure 5.12 displays four major cliff types in terms of activity (Woodroffe, 2003). Results from chapter 3 indicate that in the past, the mudstone cliffs at site 5 were not directly influenced by the tide. Therefore the cliff would classify as a relict type (C). With the continuous erosion along the coastline, the cliffs ranged within the tidal zone, and the hinge point by the refraction lead to sediment starvation of the frontage. Site 5 would now classify as an active cliff type (A).

The consistent exposure to the high energy swells mixed with the mudstone's relatively low resistance to erosion, starved sediment supply by the wave refraction and the lack of a gravel barrier frontage. This means that site 5 is highly prone to erosion. Figure 5.13 displays the erosive patterns of a soft rock cliff. Evidence of planar slide is visible in figure 5.13 and evidence of rotational sliding has been noted from observation from the post-storm period. Transit NZ has continuously attempted to protect the highway based on the cliffs through ripraps but it is evident that unless further evasive protection methods are implemented, the erosion through wave process and weathering will eventually lead to the erosion of the state highway along the mudstone cliffs.

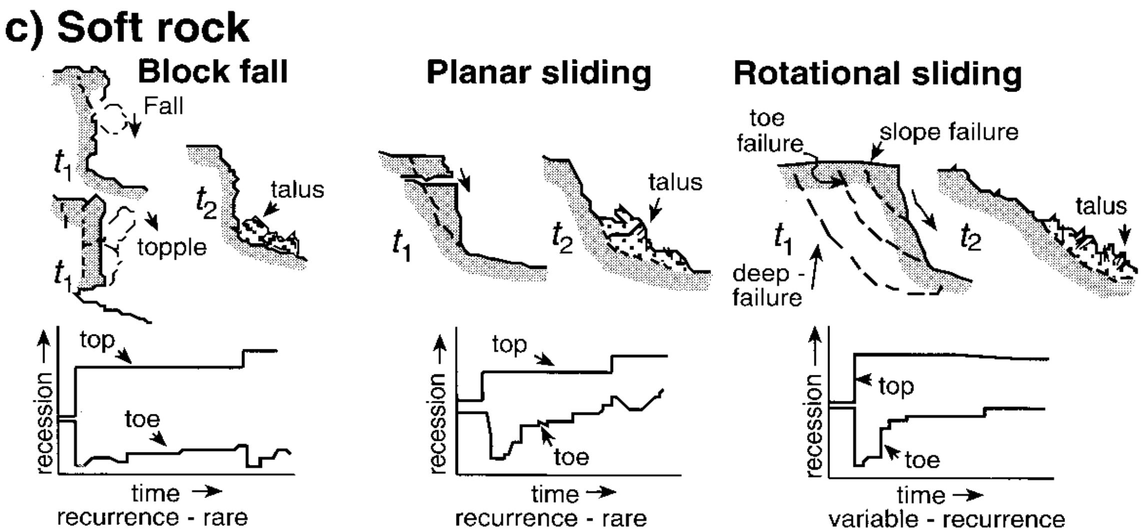


Figure 5.13 Recession of soft-rock cliffs (based on Sunumara, 1992) replicated from Woodroffe, 2003 pg184)

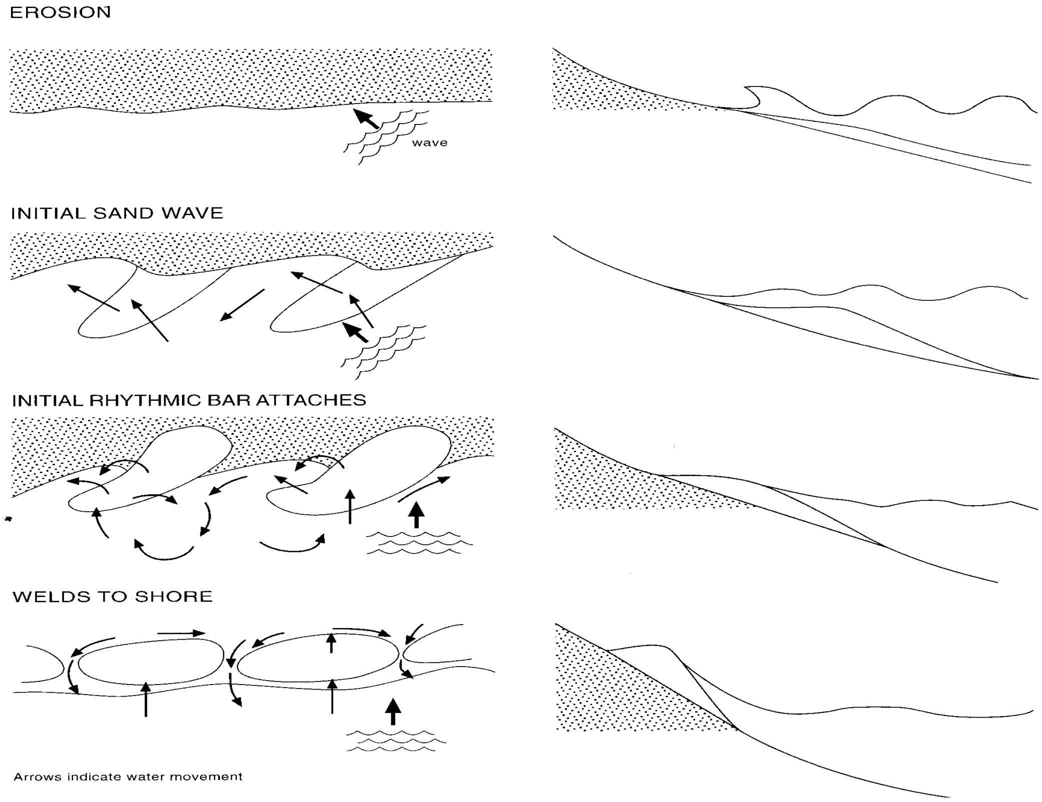


Figure 5.14 Sequence of three-dimensional beach cycle involving the formation and shoreward migration of rhythmic bars (Modified from Sonu (1973) replicated from Short, 1999 pg175)

The southerly transport due to the refraction leads to a complex mixture of a range of sediment transport and an eddy effect with in the embayment. As identified in figure 5.10 and in the previous section, the nearshore bar formation is a morphological feature that is not commonly associated with composite beaches. This bar was noted in field observations in the areas of site 2 and 3 at low tide, and is likely to be based from a mixture of sediment transported south from the hinge point and sediment output from Seven Mile Creek. Figure 5.14 displays the sequence of events involved in the movement and development of a rhythmic nearshore bar. The coastline with in the embayment has showed morphological evidence of a nearshore bar and beach cusps, and these features require environments including a gentle bed slope and downdrift transport, inducing potential for phase coupling of bars and shoreline rhythms (Short, 1999). The required parameters fit the description for Rapahoe Bay, and the consistent supply of finer sediments from Seven Mile Creek mixed with the southerly transport is likely to be the source for the bar. The shoreward migration of sediments was observed during the pre and post-storm periods on the Southern end of Rapahoe Bay in a similar was to the right hand side of figure 5.14. These findings mixed with previous work by Ishikawa (2006) continue to acknowledge the growth and loss of morphology through cross shore sediment movement. The nearshore bar formation induces wave break further from the beach, dissipating wave energy on the nearshore zone and reducing erosions from the Seven Mile Creek and southern cliffs area.

5.7 Conclusion

This chapter aimed to apply a wave refraction diagram to the Rapahoe Bay coastline incorporating 20 year hindcast data. Several wave refraction diagrams were constructed to represent 99.8% of the conditions on the field site to identify the main wave processes occurring in the region. The main results show the variety of longshore transport direction as a result of wave refraction in figure 5.10. This identifies the sediment starvation in the hinge point area, located just north of the Forbes property and a potential sediment accumulation area between observation site 2 and 3. A nearshore rhythmic bar as a result of the southerly drift from site 3 and northerly from site 4 is confirmed through field observations. Figures 5.8 and 5.9 represent wave direction that is not sourced from the general conditions which induce a variety in longshore sediment transport direction. The refraction diagrams and the use of the 20 year hindcast data proved successful in identifying the coastal processes in the area and quantifying potential sediment transport. These rates were previously not available, and are valuable for coastal management and protection considerations.

Chapter Six: Zeta Planform Coastline

Figure 6.0 Photograph facing South from the Kaiatan mudstone cliffs located north of the Forbes property 17/5/07

6.1 Introduction

This chapter will incorporate the results from the previous chapters and incorporate the zeta coastline theory to investigate the planform shape of Rapahoe Bay. The zeta theory investigates the headland beach planform shape to identify if the beach has reached a state of static equilibrium and identify areas that may undergo change in the future. The use of this theory has important management implications, as well as predictions of further beach morphodynamics. This chapter will conclude with the integration of results to identify the main relationships between the morphology and processes investigated in Rapahoe Bay relative to the zeta planform shape. The aims of this chapter are as follows:

- Test the applicability of zeta shoreline shape to the actual shoreline configuration at Rapahoe Bay.
- Identify controls involved in planform shape.
- Examine the coastal management implications with the projected shoreline change.

6.2 Zeta Planform Coastlines and Applications

Crenulated coastlines are common along swell exposed coastlines. These coastlines are categorized by a variety of names, such as headland bay, crenulate shape bay, half-heart shaped, curved or hooked bay and zeta or pocket beach (Woodroffe, 2003). The curvature of these headland beaches is characterized by a strongly hooked shadow zone and a relative straight coastline to the fixed downcoast control point. The curvature is a result of the angle of approach on a swell dominated coastline and corresponds to an eventual equilibrium formation (Quevauiller, 1987). The application of this theory was first introduced as a logarithmic spiral equation by Krumbein (1944) and the development of the improved equations have been tested in laboratory scenarios (Ho, 1971, Vichetpan 1969 in Hsu et al. 1989a) and applied to natural beach experiments, case studies, perturbations and man made beaches in national and international scenarios (Yasso, 1964, Finkelstein, 1983, Quevauviller, 1987, Gonzalez and Medina, 2001, Dai et al. 2004, Mclean, 1967, Hsu et al. 1989a, Hsu et al. 1989b, Iglesias, et al. 2002, Hsu et al. 2008).

Static equilibrium refers to the state of a beach where dominant wave approach points directly onshore and offshore, resulting in no further littoral drift. Therefore zero longshore sediment transport exists, and a state of final equilibrium is reached (Hsu et al. 1989). The application and analysis of a range of headland beaches through the zeta planform theory have displayed characteristics of a static embayment (Dai et al. 2004, Gonzalez and Median, 2001) as well as beaches undergoing dynamic accretion or erosion (Dai et al. 2004). The basic equation for calculating the static equilibrium of zeta beach involves two control points and the wave crest line. Developed from the early work by Krumbein (1944), Yasso (1964), Hsu et al. (1989) provides the most comprehensive explanation towards the application of the equation and figure 6.1 displays the basic definition sketch to apply the theory. Assumptions made for the application of this equation are provided below and are followed in this chapter.

- The tangential section downcoast is parallel to the wave crest approach
- Wave refraction and refraction occur in to the bay, resulting in simultaneous wave break.
- There will be no longshore component of breaking wave energy, hence no littoral drift.
- The model does not take any concern towards the height and period of wave action, as the wave will undergo refraction and diffraction equally to the final shoreline position.

The use of aerial photographs, hydrographic charts and satellite images are commonly used to apply the planform shape and previous methods of calculating the equilibrium involved hand calculations and tracing on the images. Recent development in planform shape research has introduced MEPBAY (Model of Equilibrium Planform of BAYed beaches). Developed by Klein et al. (2003), MEPBAY provided a computerized visual assessment of bayed beaches and

MEPBAY has been tested and applied since (Lausman et al. 2006). MEPBAY was not obtainable for this research, and the basic formula provided by Hsu et al. (1989) will be applied through manual calculations and the use of ArcGIS to supply precise distances and the presentation of the results.

Beach sediment type is not thoroughly examined with the application of the zeta planform theory. The headland control point is commonly accepted as consisting of a rocky outcrop, headland or man-made structure (Hsu, et al. 2008 and Dai et al. 2004) but very little literature comment on specific sediment type or size. Hsu et al. (2008) and Eliot et al. (2006) notes that the majority of beaches that have been tested for planform shape have been sandy beaches as they have either recreational or economic value and is of interest to developers, government organisations and scientists. Local examples of planform investigations such as McLean (1967) along the East Coast of the South Island and Healy (1980) have mentioned beach sediment range from boulders to fine sand but are not specific and fail to identify beach types. Therefore, considering the relative rareness and recent research on composite beaches, this thesis provides some primary research on the application of zeta planform on a composite beach.

6.3 Method

The zeta planform shape was measured and applied to the Rapahoe coastline through a combination of manual calculations and ArcGIS. The procedure provided by Hsu et al. (1989) was followed. The 1997 aerial photograph supplied by LINZ (2007) was aligned with the J31 map sheet from the NZ50K maps supplied by the Geography Department at the University of Canterbury. The two images were converted to a common projection, the New Zealand Map Grid (GD-1949) projection and all lines and point shapefiles mapped were in the same projection. The upcoast control point was estimated at the most logical choice, the northern tip of Point Elizabeth and the downcoast control point was established as the northern point of the bay where the beach meet with the cliffs at Nine Mile Bluff. The control line $R_{0,}$ was drawn between the control points and length was measured. The wave crest line was represented by paralleling the visible wave crests as suggested by Hsu (et al. 1989) and measured at 22° allowing for β (angle between the wave crest line and R_0) to be quantified for manual calculations of the two variables, R and θ.

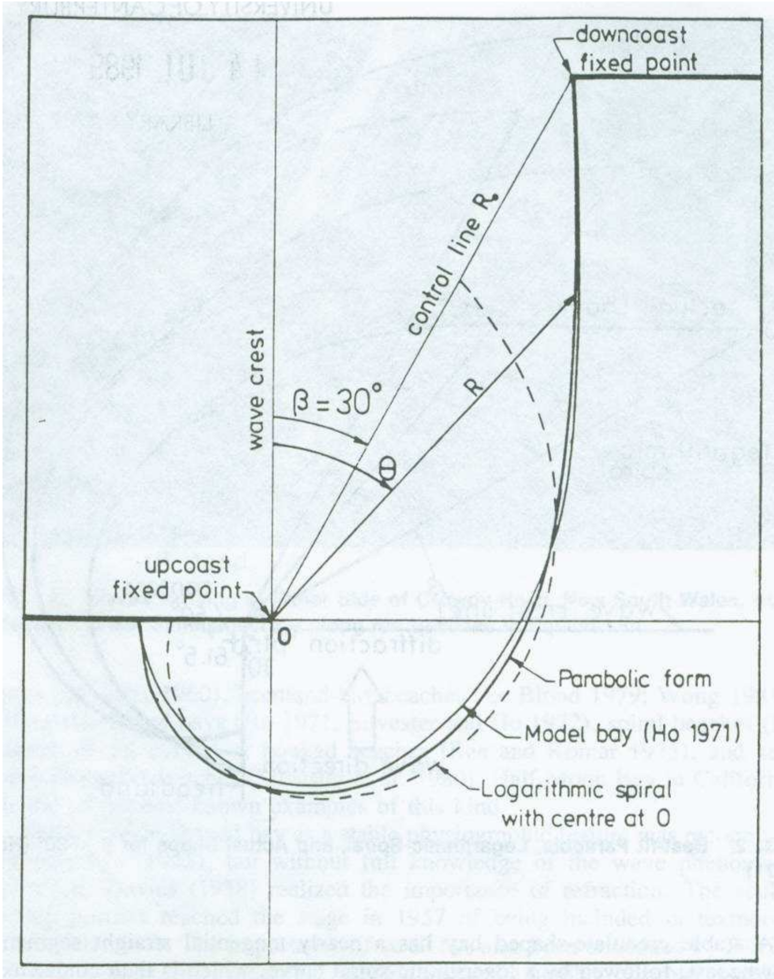


Figure 6.1 Definition sketch for a bay in static equilibrium (Hsu et al. 1989. pp288)

- Upcoast fixed control point – Northern Tip of Point Elizabeth
- Downcoast fixed control point – The southern tip of the cliffs by Nine Mile Bluff
- Control Line (identified as R_0) – Line connecting the two control points
- Wave crest line – normal to wave direction
- β – angle between wave crest line and R_0
- Two variables: R (variable of R_0) and θ (angle of R)

$$\frac{R}{R_0} = \frac{0.81\beta^{0.83}}{\theta^{0.77}}$$

Equation 6.1 Formula to calculate zeta curvature

Hsu et al, (1989) advised the calculations of R with a range of θ from 30-120°. Equation 6.1 was applied and calculated manually to quantify R varying θ by 10° each time. The quantified R lines were then mapped, and the results are displayed in figure 6.2. Gonzalez and Medina (2001) examines a beach with multiple diffraction and refraction points under a consistent swell with a variety of control points. As figure 6.2 did not display an ideal zeta curve for the southern half of the beach, several other upcoast control points were experimented as Gonzalez and Medina (2001) undertook and the results were illustrated under the same methods. Big Rock, the largest nearby islet located roughly 450m north of Point Elizabeth proved to be the most ideal control point as the zeta curve was the closest shape to the coastline and the results are presented in figure 6.3.

Several limitations were apparent with the utilized methodology. Human interpretation of the control points required numerous experiments to fit the zeta curve with the beach. The study area is regarded as complex, and the numerous rocky islets and the river outlet is not seen as an ideal scenario for fitting the zeta curve (Gonzalez and Medina, 2001, Hsu et al. 1989). Finding the exact control point was extremely difficult due to the numerous points of diffraction and refraction, and the best curve result was found to be on the northern point of Big Rock. Evidence from bathometric charts show that the relatively low bathymetry around Big Rock and the islets named the Needles act as an extension to the headland, thus Big Rock is the most appropriate upcoast control point. Further experimentation was trialed with the modification in the downcoast control point to the Kaiatan mudstone cliffs located just north of the Forbes property, and the results are seen in figure6.4.

Another potential interpretation error includes the wave crest line, which was estimated by aligning the visible refracted wave crests within the bay. The zeta curve is commonly utilized to identify impacts and equilibriums of hard engineering structures such as groins, tombolos, and breakwaters (Hsu et al. 2008). There is little literature observing the impacts and effects that riprap revetments may have, as is the case for this field site. Therefore, the impacts the ripraps may have towards the future coastline is assumed as slowing down the rate of coastal erosion.

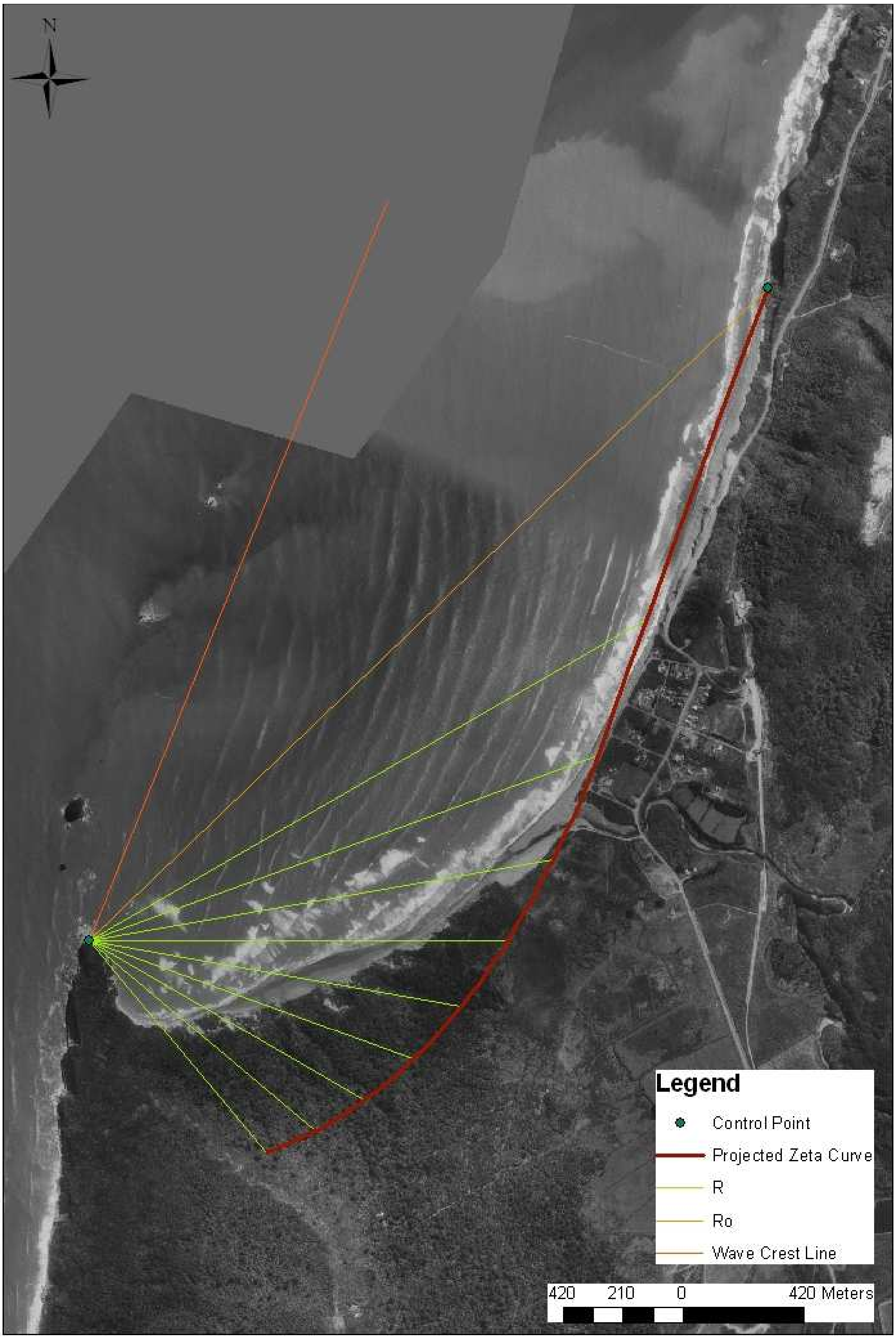

N
Legend
Control Point
Projected Zeta Curve
R
Ro
Wave Crest Line
420 210 0 420 Meters

Figure 6.2 Results when Point Elizabeth was used as the upcoast control point. $\beta = 25°$, $R_0 = 3293$ m

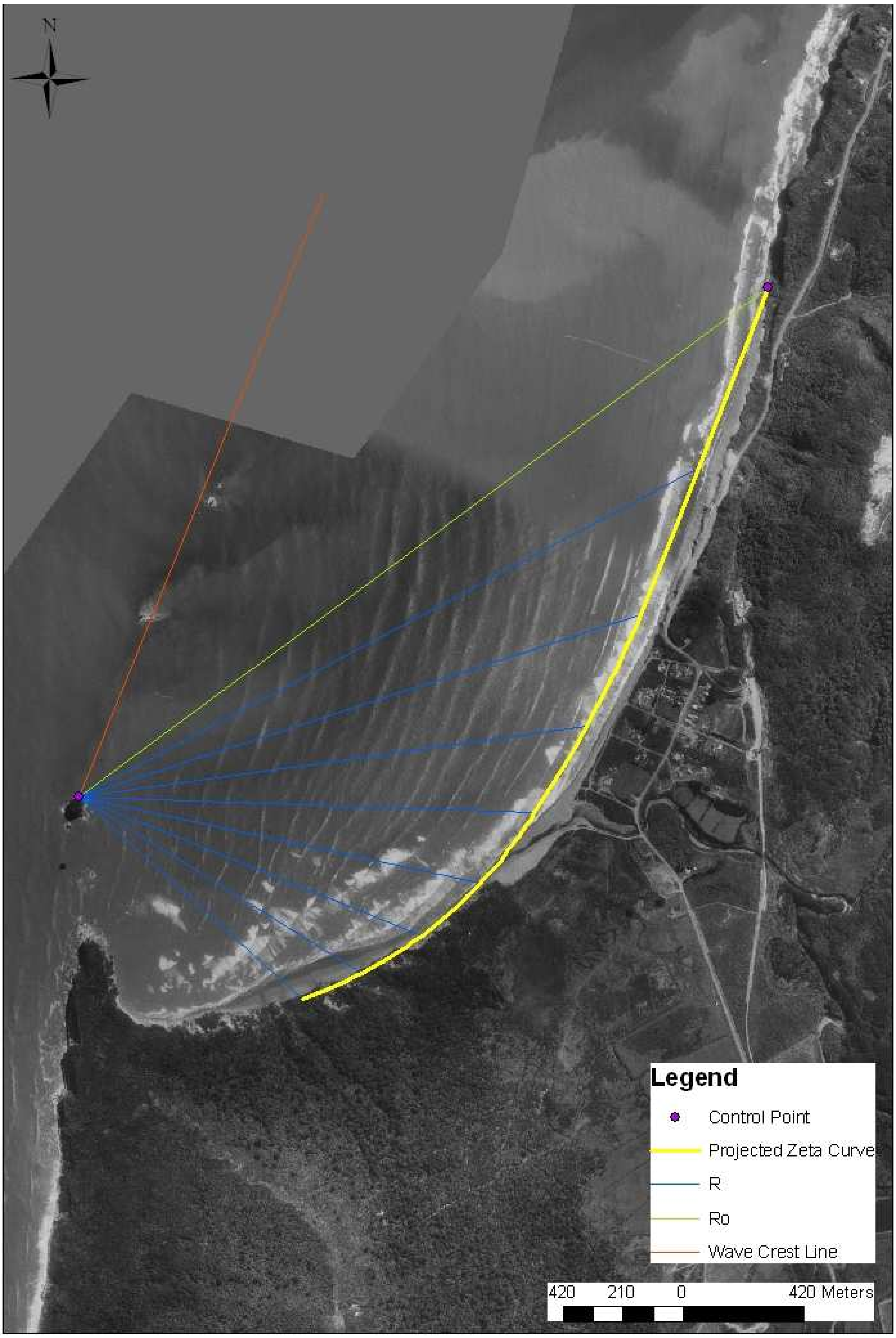


Figure 6.3 Results when Big Rock was used as the upcoast control point. The zeta curve displays the best fit with the

current shoreline. β = 31°, R_0 = 2995 m

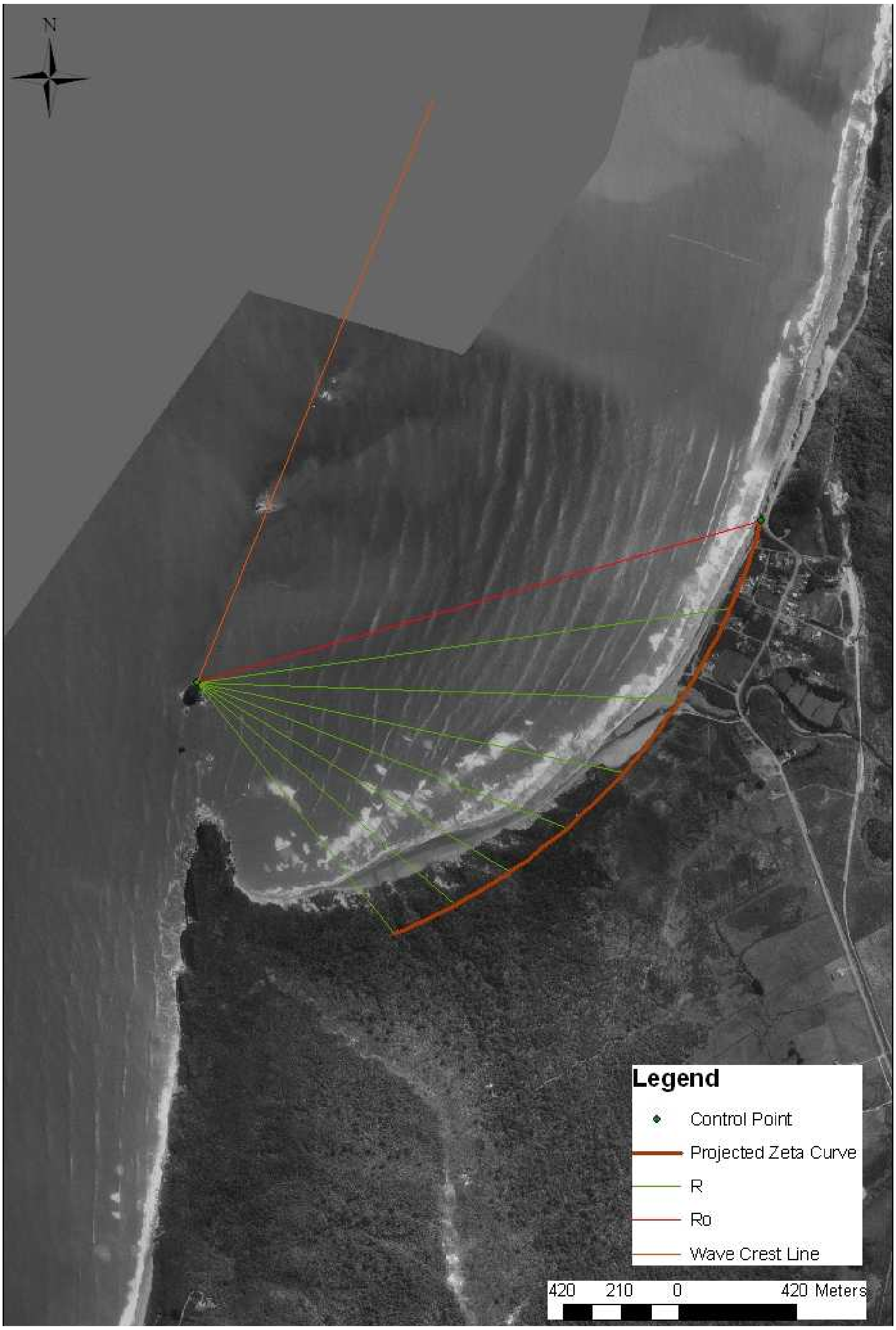


Figure 6.4 Results with Big Rock as the upcoast control point and the Kaiatan mudstone cliffs as the downcoast control point. $\beta = 52.5°$, $R_0 = 2116$ m

6.4 Results and Discussion

The results from this chapter have tested the applicability of the zeta planform shape on a composite beach and provide future scenarios of coastline change and static equilibrium of Rapahoe Bay.

The results have proven the applicability of the zeta curve on to a composite beach despite the lack of tests on other composite beach types. In general, the zeta curve is applicable with most sandy shorelines (Hsu et al. 2008 and Eliot et al. 2006) but the applicability on a composite beach was unknown. The corrected control points in figure 6.3 displays a zeta curve projection that suitably aligns to the 1997 coastline. The precise beach line is difficult to identify due to tidal variations and waves, but it is evident that the seaward vegetation line and village frontage from the downcoast control point south to the southern end of the village parallels the projected curve on the landward side by a small distance. South of Seven Mile Creek, the projected curve aligns with the vegetation line precisely.

As parts of the shoreline are not situated on the zeta curve, future adaption of the coastline would naturally be predicted. The assumed planform response would be a coastal realignment and Dai et al. (2004) provides schematics examples of shorelines that will experience erosion, accretion or is at a state of equilibrium. To align the coast to the curve, the village frontage that parallels the coast should have experienced accretion in the last 10 years. This is not the case as concluded in chapter 4, with continuous erosion occurring since 1938 to 2005. Therefore, there are other controls on the coastline which has provoked its current planform shape.

The local geology has been discussed previously in chapter 2, and the variety of geology on this discordant coastline is the control causing the variance of planform shape. Appendix 2.1 provides a geological map of the area, and the variety between the weak, erodible sediment base of the township (marine and river gravels) and by Coin Creek compared to the remaining coastline formed of Kaiatan mudstone, island sandstone, grey calcareous mudstone and limestone. Therefore, the areas based on marine and river gravels are prone to more rapid erosion in comparison to the other areas of comparatively harder geological base. The vegetation line south of Seven Mile Creek aligns with the curve as the geology is constant in that area. This would indicate that further erosion is expected, as the coastline is expected to align with the zeta curve. This area is visually deceptive, as the shallow, sandy nearshore zone lacks a developed gravel barrier, consequently the waves reach the cliffs at high tide. This indicates the location of the shoreline at the cliff base. Despite the geological controls comprised on this shoreline, the application of the zeta shoreline was successful. Erosion of the beachfront is restricted as the gravel barrier has highly reflective characteristics, thus depleting the impacts of wave energy on the coastline (Mason et al. 1997). Therefore, despite the variety in geology, the relatively softer mudstones and gravel barrier on the beach front has paralleled the planform shape. Composite beaches consist of mainly sand with a gravel barrier and the sandy beach front has responded in a similar description to May and Tanner's (1973) littoral power gradient.

The continuous landward retreat of the shoreline on the village frontage has lead to the conclusion of the geological differences on the coastline resulting in variant rates of erosion. From a management perspective, this is important as this would indicate that extreme landward retreat that has occurred in the past is not predicted in the future of this coastline. Evidence in chapter 3 has shown that landward retreat rates have decreased in the last decade (1997-2005 period shows erosion rates of 0.53 m/yr) and the relative alignment of the village frontage with the zeta curve indicates that the beach is close to reaching a form of positional equilibrium.

Another concern that has been identified is the modification of the control point. There is very little beach and barrier on the frontage of the Kaiatan mudstone cliffs north of the Forbes property. What if the mudstone cliff was to act as a new control point for the Southern half of the beach? Another zeta curve was projected in this scenario with the mudstone cliffs as the downcoast control point. The results are illustrated in figure 6.4, projecting further erosion of the village frontage and the southern cliffs. Under this future scenario, the village frontage will experience further landward retreat through erosion and rollover of the gravel barrier. Measurements concluded that from the wet/dry line from the 1997 photograph to the projected zeta curve, future landward retreat ranging from 75 m at the Rapahoe Hotel, 58 m in front of the campsite and 34 m in front of the Forbes property could be expected. This modification of control point would provide an answer to why the village frontage has continued to erode beyond the zeta curve in figure 6.3. Composite beaches are known to have erosional characteristics but this scenario provides a valid explanation to the continuous erosion on the village frontage. The zeta curve also impacts Seven Mile Creek where the small spit future is likely to be eroded away. The southern cliffs which parallel Seven Mile Creek currently aligns with the projection, so little change would be expected, but further south, the mudstone cliffs would be expected to erode to align the zeta curve.

The results from figure 6.4 identify the potential coastal hazard on the village frontage. The areas of immediate risk are the people, property and infrastructure on the immediate coastline. This includes the Forbes property, the campsite, the Rapahoe Hotel and what is left of Beach Road. Chapter 3 has discussed the loss of the Northern half of Beach Road, and evidence shows that further loss is predicted. The processes that will induce the coastline change will be constant to the processes described in chapter 4. Gravel roll over of the barrier is a constant sign of retreat as evidence displayed in chapter 4 and the barrier is likely to continue to recede or lose sediment through erosion. High seas are likely to induce coastal inundation and overwash in areas of lower elevation. The Forbes property has been at risk for sometime and unless the house is retreated, further hard engineering solutions will be required to slow down the coastal erosion. These hard engineering solutions have been proposed by Ramsay (2006) in schematic representations of the coastline, and these may slow down the erosion process, but are unlikely to prevent inundation from high waves.

6.5 Conclusion

This chapter investigated the zeta planform curve and the applicability to the field site. Little was known of the applicability of the zeta curve on composite beaches, and this chapter validated the use of the theory on this beach type. The control points were identified and a zeta curve was illustrated. Modification of the upcoast control point to Big Rock concluded that Point Elizabeth is not the main control of the embayment shape. The complexity of the field site attributed to some areas where the zeta curve did not align with shoreline but rather ran parallel. Geological control was identified as the main reason why the beach on the village frontage did not align as successfully, due to the weaker geological base in comparison to the mudstone cliffs flanking the village. Another zeta curve was constructed using the mudstone cliffs as a future downcoast control point, and this predicted further coastline retreat on the village frontage. The management implications of these results have been discussed and if the scenario in figure 6.4 occurs, action will need to take place to mitigate the risk of coastal hazard to the village.

Chapter Seven: Conclusion

Figure 7.0 Photograph displaying the Forbes property and riprap revetments 24/6/07

7.1 Summary of Main Findings

This chapter will summarise the main findings to fulfill the initial research aims set in chapter one. Each chapter will be summarised to indicate the process drivers and parameters involved in the historical shoreline change and beach morphodynamics on Rapahoe Beach.

1. Investigate the coastal environment of the study area and relevant past literature

The study in to the field area and relevant past literature in chapter two provided an important basic background for further research. Past literature proved that very little study has been done on a regional context on the West Coast (Pfalhert, 1984) and the majority of recent studies were undertaken in a qualitative method through visual analysis and personal communication with local residents with virtually no quantitative results (Neale, 2000, Westlake, 2000 and Ramsay, 2006). Pfalhert's (1984) work is considered to be the most comprehensive study on the immediate study area, but the accuracy of the results have been widely debated by the recent studies (Neale, 2000, Westlake, 2000 and Ramsay, 2006) and thus highlighted the requirement of a more extensive investigation of the area.

Chapter 2 provided a wide range of background information which proved as essential research towards each chapter including the geological history and conditions (referred to in chapter six), beach and sediment movement (referred to in chapter three and four), atmospheric and oceanic influences (referred to in chapter five) and anthropogenic history (referred to in chapter three to six).

2. Identify and quantify the historical coastline change and the responsible processes

The historical coastline change was investigated in chapter three through the use of aerial photographs. Qualitative assessment examined the visible changes of the beach morphology, the most important discovery involving the hapua located landward of the gravel barrier in 1939. The seaward vegetation line, wet/dry line and lagoon area was mapped to provide quantitative figures of shoreline change. The results provided a range of quantitative results and insight in to the interactions between gravel barriers, hapua, seaward vegetation line and the impacts of anthropogenic features. The lagoon features as seen in 1939 acted as a buffer between the village and gravel barrier back. Gravel roll over that occurred after 1939 on the southern end of the beach resulted in the northern half of the hapua cut off from Seven Mile Creek river system. The former lagoon feature provided a depression inducing further gravel roll over. From 1939 to 2005 the rate of landward retreat by the wet/dry line was quantified ranging from 59-65 m along the village frontage with overall retreat rates of 0.90 – 0.99 m per year. The loss of the lagoon resulted in the high rate of retreat of the wet/dry line but recent aerial photographs shows the decline in retreat rates to 0.53 m per year during 1997-2005 as the gravel barrier has reached the seaward boundary of the township at Beach Road. The riprap revetments as identified in chapter 3.4.6 have also been identified as a key feature towards slowing down the rate of erosion as proven by the decreasing retreat rate of the wet/dry line. The movement of vegetation line is initially restricted by the lagoon feature, and the loss of the feature allows for a short period of seaward advance during 1939-1959. The initial seaward advance is then stopped by the receding wet/dry line through gravel rollover and the vegetation line retreats behind Beach Road by 1980.

The interactions between coastal features and anthropogenic features were the key to identifying and quantifying the historical shoreline change at Rapahoe Bay. The loss of the lagoon was due to Beach Road forming a boundary on the landward perimeter. Therefore, when the lagoon attempted to retreat with the coastline, the restrictions resulted in the roll over separating the lagoon from Seven Mile Creek. This induced the fast rates of retreat, as gravel roll over process is promoted when a depression is located behind the barrier. The retreating vegetation line indicates the back of the barrier and rollover is inducing further retreat. The riprap revetments have succeeded in slowing down landward retreat, but roll over has already destroyed the northern half of Beach Road, and appears to continue on the southern half of Beach Road.

3. Examine and map the seasonal and short term changes in the beach profile in particular gravel barrier dynamics.

Chapter four investigated the seasonal and short term variations in the beach profile through the use of DEMs. The data was collected manually over three field visits to represent seasonal varieties. TIN was used to create the DEMs and the results displayed the spatial and temporal varieties along the study area coastline and village area. Gravel barrier morphodynamics were investigated throughout this chapter.

Spatial varieties along the beach included a variation in crest height, variety in profile gradients and hinterland. The northern side of the beach by the Forbes property had the highest barrier crest elevation backed by the Kaiatan mudstone cliffs. The elevation ranged from 9.53-5.89 m and decreased towards the southern end to the lowest point on the spit by Seven Mile Creek. The spatial variations acted as controls that induced profile change throughout the surveys. Areas with higher crest elevations experienced an increase in crest height and barrier gradients became steeper. This was identified as ridge consolidation, further evidence of future gravel barrier retreat. Areas with lower crest elevation experienced gravel roll over and in some cases overwash (Area 4). The hinterland is identified as a control to barrier dynamics, as areas with higher elevations (Areas 1 and 2) experienced less roll over and was also better protected by anthropogenic influences (riprap revetments). Decreases in overall beach volume indicated loss of sediments from the intertidal zone and behind the barrier.

The results from chapter four highlighted the processes involved in composite beach and gravel barrier morphodynamics. The high energy swell conditions induced frequent change to the barrier and shore profile. The transgressive nature of the beach is evident even during the short study period through DEM analysis and observations. The morphodynamic behaviour of the composite beach and barrier align with the results from chapter 3, involving the gravel roll over and transgressive movement of the barrier resulting in the loss of hapua.

4. Identify and quantify coastal processes operating in Rapahoe Bay and the impacts on beach dynamics.

Chapter Five identified and quantified the coastal processes operating in the study area. The 20 year hindcast data from NIWA was analysed and utilized to construct three refraction diagrams. The diagrams represented 99.8% of the wave conditions that occur in the study area, and were utilized to calculate potential sediment transport rates. Direction of sediment transport followed the general West Coast northerly direction, but refraction with in the bay results in a eddy creating a sediment hinge point just north of the Forbes property. The sediment cell adjacent to Seven Mile Creek experiences potential gains from both transport directions. This area does not show signs of beach accretion but observations have reported a nearshore bar feature, also identified in chapter 3. The morphology is theorized to interact with the beach cusp formations on the coast, but sediment is eventually lost offshore.

The general loss of sediment aligns with the results from chapter 3. The historical coastline change displayed a landward retreat, and this is induced through the wave processes. The combination of gravel roll over, coastal erosion and change in sediment supply is clearly the cause of the historical coastline change. Change in sediment supply through a combination of anthropogenic, fluvial and sedimentary influence has lead coastal erosion and retreat. Gravel barriers are known to respond to change in sediment supply through a transgressive movement, and gravel roll over has further caused the landward retreat.

5. Examine the planform shape of the coastline compared to the zeta model planform literature

Chapter 6 applied the zeta planform theory to the study area. Following the methods provided by Hsu et al. (1989a), two control points and the dominant wave crest line was determined. The upcoast control point was modified to Big Rock, resulting in the coastline aligning with the theory. Geological controls were identified as determining future movement in the coastline and another zeta curve using the Kaiatan mudstone cliff as the downcoast control point. The results show that under this scenario, the future shoreline change on Rapahoe village frontage is expected to experience further retreat through erosion as identified in chapter 5 and gravel roll over as identified in chapter 4. These results have important management implications as well as proving the successful testing and applicability of the zeta shoreline curve on to a composite beach type.

7.2 Final Conclusion

A variety of methodologies was utilized to examine the historical coastline history and beach morphodynamics at Rapahoe Bay. The results from each method aligned together to identify the driving factors behind the historical coastline change. The examination of the nature of the beach morphodynamics on a composite beach conclude that the main controls that determine change are the sediment supply, wave processes, geological variety and planform shape. This study also validates the use of a variety of different methods to examine the coastline change and dynamics of a composite beach type. This thesis has succeeded in answering the research questions provided in chapter 1. The morphodynamic behaviour of composite beaches was examined through DEM and wave refraction diagrams. The controls that have induced historical shoreline change have been identified in chapter 3-6. Finally, the application of the zeta shoreline curve proved valid on a composite beach and has provided a potential future scenario for coastal management.

7.3 Recommendations for Future Research

This thesis has provided a range of quantitative and qualitative results on Rapahoe Beach and explored the historical shoreline change and beach morphodynamics on the field site. Due to the relative lack of research on composite beaches, this thesis has contributed towards a better understanding of the morphology and process drivers involved. Future research regarding composite beaches would prove valuable for academic contributions and have important implications for coastal management. As the distribution of composite beaches along the West Coast, this is especially important in a management context. Some potential future research questions include:

- Why are there so many composite beaches on the West Coast and not on the East Coast, when both coasts are exposed to similar high energy environment? What controls guarantee a composite beach?
- Is the zeta planform shape applicable to all composite beaches? A study on the West Coast would provide a large number of composite beaches under similar swell conditions towards identifying other controls involved in composite beaches.
- Can other sand related models be related to composite beaches to predict future change?
- Can the sediment transport on the entire West Coast be quantified?

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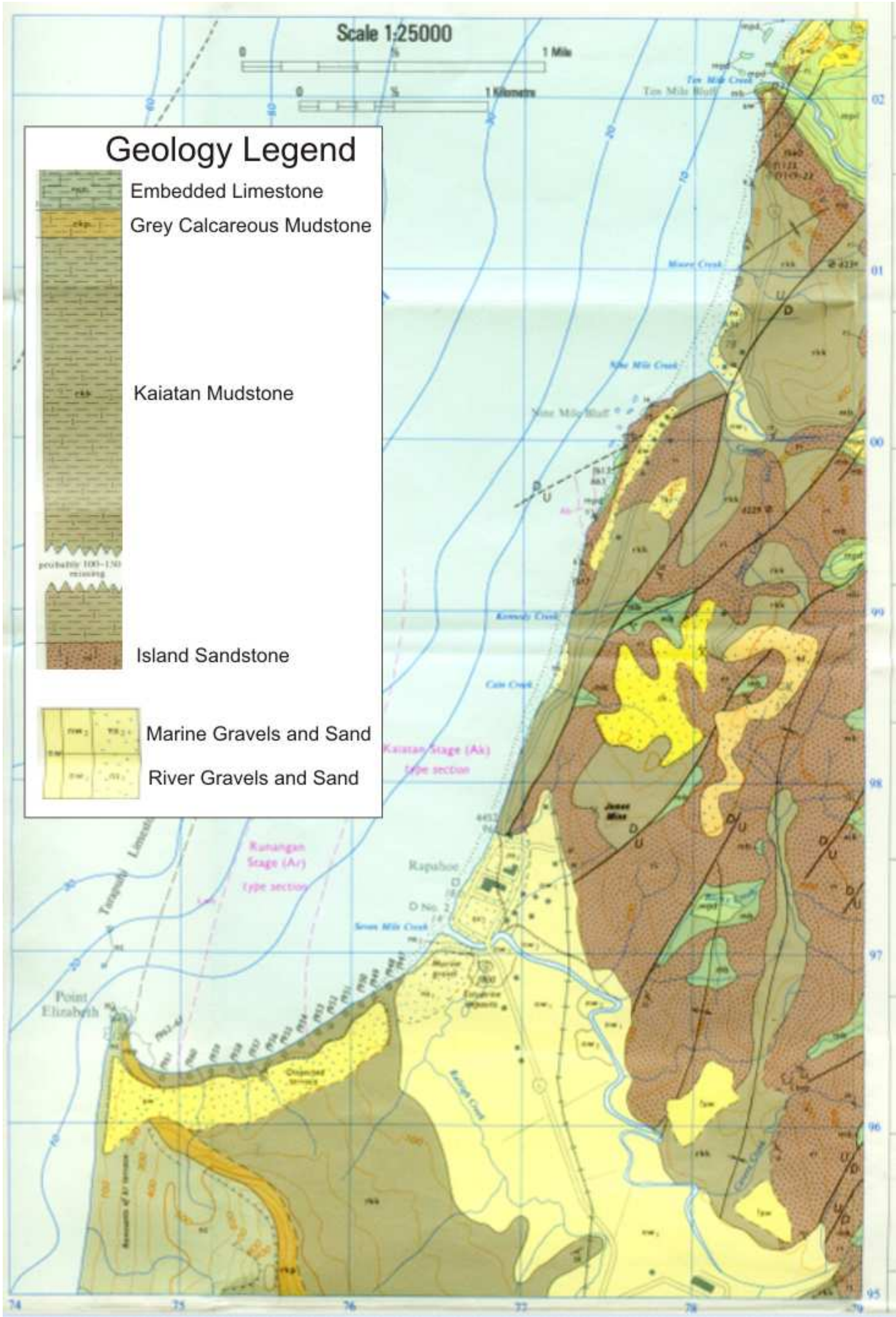
Appendix: Chapter 2

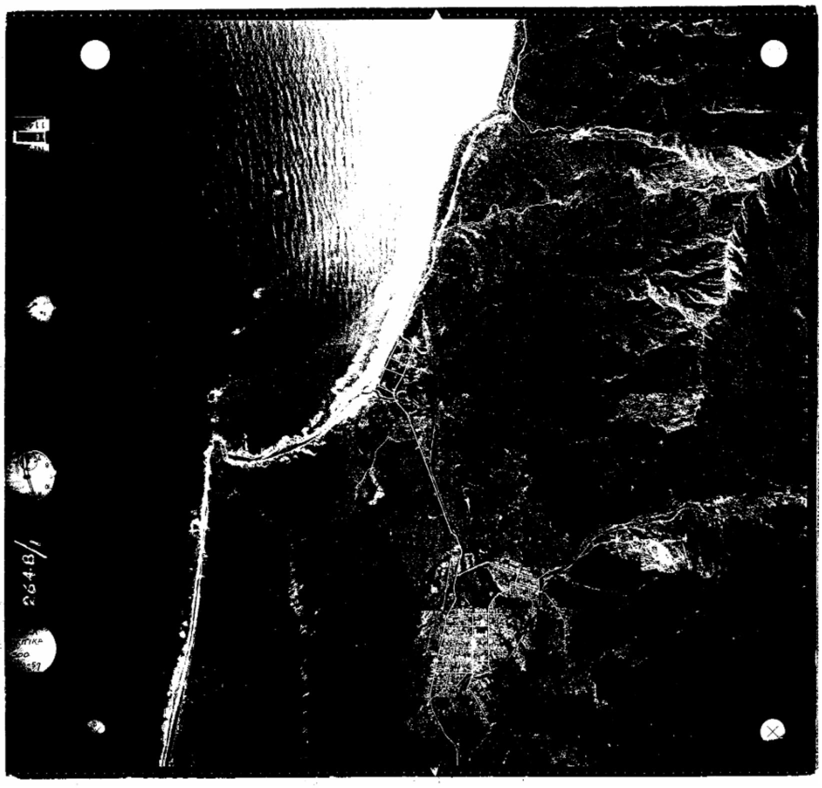


Appendix 2.1 Geological map of the Study Area (Department of Scientific and Industrial Research (1978), Sheet S44)

Appendix: Chapter 3

Survey Number	Run and Frame	Flying Date	Original Neg Scale
109	3/1	05/04/1939	1:10000
265	1473/2	01/04/1948	1:16000
1067	2648/1	07/10/1959	1:44000
3221	4320/3	19/03/1970	1:24000
5782	G/4	28/12/1980	1:10000
8922c	A1/2	18/02/1988	1:15000
9641	G/1	28/03/1997	1:50000
50498c	12/16	13/03/2005	1:8000

Appendix 3.1 Aerial Photograph Details from NZAM



Appendix 3.2 Copy of Original Aerial Photograph (1959)

Appendix 3.3 Snapshot of ArcGIS displaying the process of measuring the perpedicular transcets line for the vegetation line (2005).

Appendix 3.4 Qualitative Observational Results

1939	
River	Appears to be high flow in the river, river banks are not visible and 'the bend' is full flowing. River widens near outlet and splits North to a lagoon and South down the beach and eventually out to sea
Lagoon	Strong presence of some form of lagoon or heavy flooding on the Northern End. Lagoon does not appear to be connecting to the ocean on the Northern half. Northern Extent is by the Forbes house.
Beach Sediment and Width	Some layering of sediment present on the Northern parts of the beach. Beach width in front of Forbes property as wide as the Southern Extent.
Vegetation	Distinct vegetation lines seaward of the Forbes property that head south east. Some vegetation present seaward of Beach road.
Ocean	Rough seas, with distinct breaker lines showing wave refraction. Areas of rips can been seen.
Anthropogenic	Very small number of buildings. Rapahoe Pub, Forbes Property and the Railway building are the prominent structures. Beach Road extends north in front of the cliffs, in front of the Forbes Property.
Rip Raps	Not Present
1948	
River	Decrease in river flow compared to 1939. River flow heads south, and thins out when the river approaches the beach gravel. River banks are visible suggesting that flow has decreased since the 1948 photo. 'The bend' has dried up and no flow is visible through it. There is also a distinct creek by the bridge draining in to the main river, and this suggests high water flow.
Lagoon	No longer connected to the river. Main lagoon area is located seaward of Beach Road, from Morpeth Street heading towards the Forbes Residence. Small patches of wet sediment on the Southern end of the lagoon, headed south towards the river.
Beach Sediment and Width	Layering of sediment is visible. Rhythmic topography (beach cusps) present, mainly on the northern extent of the beach up to the northern end of the river. Beach width still appears to be even throughout the beach.
Vegetation	Large vegetation area still present on the seaward side of the Forbes residence, appears to be unchanged since 1939. Some vegetation present on the seaward side of the Beach Road north of the Forbes residence.
Ocean	Calmer conditions compared to 1939. Waves are breaking closer

	in shore, and refracting of waves can be seen. Some water discolouration suggests sediment suspension.
Anthropogenic	Increase in building numbers and roads.
Rip Raps	Not present.
1959	
River	Further decrease in river flow, river banks are more visible and distinct. The river flow has headed strait out to sea, instead of south. This suggests that either the longshore drift of sediment headed south has decreased allowing for the river to head directly out. There is a small delta like formation in the area as the waves are breaking earlier by the river outlet. The river 'bend' is now overgrown.
Lagoon	Decrease in lagoon size and extent, and the main lagoon has split in half by Morpeth Street.
Beach Sediment and Beach Width	Beach sediment layering is not as distinct as pervious photographs but there is still some evidence of composite layering. The beach width appears to be decreasing especially at the northern end of the beach.
Vegetation	Increase in vegetation is visible on the southern side near the Rapahoe pub. Vegetation is more dense north of the lagoons.
Ocean	Cusp features are no longer present, but interesting areas of white capping in line with beach. This may suggest the presence of a offshore bar. Wave breaking is further offshore by the river, suggesting shallower areas, possibly due to a delta formation.
Anthropogenic	Beach road is no longer used and the State Highway (SH) is introduced on the cliffs above the Forbes property. Slight increase in building numbers and road improvements.
Rip Raps	Not Present.
1970	
River	Increase in river flow, and the river outlet is headed further south (increase in longshore sediment?). Distinct formation of a delta. The river banks have appeared to build up as well. Water discolouration suggests either sedimentation or very low water levels by banks. Sediment build up by outlet.
Lagoon	Decrease in lagoon size. Two main lagoons are present.
Beach Sediment	Sediment layering is present as well as driftwood. Sediment build up by river outlets, and the formation of the delta makes much shallower contours on the southern end of the beach. Beach width appears to be decreasing by the highway.
Vegetation	Increase in beach vegetation on the seaward side of Beach Road.

	The vegetation is mainly around the lagoons and parallel to beach road.
Ocean	Some water discolouration is present. Distinct wave break area by the delta.
Anthropogenic	Further increase in buildings and road improvements.
Rip Raps	Ripraps are not present but seaward cliffs by SH show distinct lines where water would have travelled through.
1980	
River	Change in river flow and build up of river banks. Delta is still distinct.
Lagoon	Very small body of water apparent near the pub. All other lagoons are no longer present.
Beach Sediment	Distinct layering, and a silt like layering forming some formations, possibly rhythmic topography, but unclear.
Vegetation	Heavy loss in vegetation along beach front.
Ocean	High wave energy apparent with heavy wave breaking. Distinct form of local circulation or large rip. Delta present.
Anthropogenic	Further development in houses and some roads. Campground development.
Rip Raps	Introduction of ripraps by Transit by SH.
1988	
River	Dynamic changes in river. Change in river banks and flow pattern. The river has also tried to go further south but did not reach the ocean.
Lagoon	One small body of water existent by the pub. No water bodies north of it.
Beach Sediment	Beach layering still present, appears to be a decrease in width in al parts of the beach, but especially on the northern parts by SH.
Vegetation	Large decrease in vegetation, probably due to gravel retreat. Very little vegetation seaward of Beach Road.
Ocean	Wave lines are very distinct, once again signs of whitecapping in certain areas further from shore, suggesting a possible formation of a offshore bar. Delta area is very shallow.
Anthropogenic	Beach road is probably compromised and may not be used any longer. Further increase in building and road upgrades.
Rip Raps	Ripraps present by SH.
1997	
River	Increase river flow. The outlet is headed further south and the river is much wider. River banks still visible. Delta area present,

	with wave break visible on the shallower regions.
Lagoon	Not present.
Beach Sediment	Layering present, with a large decrease in beach width on the northern regions.
Vegetation	Decrease in vegetation, mainly thinning in the middle and northern ends (forbes)
Ocean	Areas of wave break apparent further offshore (bar?). Water discolouration.
Anthropogenic	More roads and houses. Beach road gone in from Morpeth to Forbes.
Rip Raps	Increase in ripraps by Transit at SH. Ripraps introduced (white by GDC) seaward of beach road and Forbes.
2005	
River	Dynamic changes, in river and width of 'spit'.
Lagoon	Not present.
Beach Sediment	Composite layering visible. Width of beach decrease especially up north and Beach road area.
Vegetation	Difficult to judge change
Ocean	Distinct rips areas and delta wave breaking. Offshore wave break not apparent.
Anthropogenic	Further developments, Beach Road in more trouble.
Rip Raps	Increased ripraps by Transit, in front of Forbes, and additional ripraps in front of beach road.

Lagoon Results						
Distance from Base Line						
Line Number	1938	1948	1959	1970	1980	1988
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	75.63	0	0	0	0	0
7	78.42	0	0	0	0	0
8	81.79	75.47	69.85	65.53	0	0
9	85.78	78.06	74.68	64.06	0	0
10	117.36	76.92	73.92	0	0	0
11	114.45	76.26	73.76	0	0	0
12	110.25	75.62	73.74	0	0	0
13	111.33	67.35	0	0	0	0
14	107.28	0	0	0	0	0
15	108.06	0	0	0	0	0
16	110.98	0	0	0	53.93	0
17	114.65	0	0	0	0	0
18	121.32	0	0	0	0	0
19	129.24	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0

Appendix 3.5 Lagoon Seaward Transect Boundary

Lagoon Results						
Difference						
Line Number	1938 - 1948	1948-1959	1959-1970	1970 -1980	1980-1988	1938 -2005
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	-75.63	0	0	0	0	-75.63
8	-78.42	0	0	0	0	-78.42
9	-6.31	-5.61	-4.32	0	0	-6.31
10	-7.72	-3.37	-10.61	0	0	-7.72
11	-40.44	-2.99	-73.92	0	0	-40.44
12	-38.18	-2.49	-73.76	0	0	-38.18
13	-34.63	-1.87	-73.74	0	0	-34.63
14	-43.97	-67.35	0	0	0	-43.97
15	-107.28	0	0	0	0	-107.28
16	-108.06	0	0	53.93	-53.934	-108.06
17	-110.98	0	0	0	0	-110.98
18	-114.65	0	0	0	0	-114.65
19	-121.32	0	0	0	0	-121.32
20	-129.24	0	0	0	0	-129.24
21	0	0	0	0	0	0

Appendix 3.6 Lagoon Seaward Transect Difference (m) between each photograph

	Lagoon Surface Area (m^2)		Change in Surface Area (m^2)
1939	140.77	1939 - 1948	-116.90
1948	23.87	1948 - 1959	-8.52
1959	15.35	1959 - 1970	-11.76
1970	3.58	1970 - 1980	-2.91
1980	0.67	1980 - 1988	0.43
1988	1.11	1988 - 1997	-1.10
1997	0	1938 - 1997	140.77

Appendix 3.7 Lagoon Surface Area per photograph and difference between each photograph

	1939	1948	1959	1970	1980	1988	1997	2005
1	98.01	97.51	95.66	48.67	50.11	43.00	36.22	32.92
2	98.91	98.06	93.37	37.54	57.09	38.46	31.36	32.97
3	86.97	87.02	83.61	80.08	68.46	26.37	24.62	17.48
4	77.74	79.82	77.13	68.45	67.51	63.59	64.39	61.70
5	59.45	76.78	77.50	64.56	64.77	59.63	56.58	54.05
6	61.26	75.70	75.64	65.91	59.54	58.21	46.59	46.13
7	58.71	72.87	76.24	68.00	59.62	48.51	47.86	47.16
8	59.04	58.20	75.03	57.95	56.21	50.00	48.49	48.49
9	59.56	56.87	57.78	58.41	57.86	48.96	49.30	46.67
10	59.51	58.52	61.21	58.83	57.24	43.29	44.81	41.20
11	58.76	57.09	56.98	58.96	55.69	47.70	46.08	42.93
12	58.95	57.89	58.39	60.72	57.72	47.54	48.26	45.64
13	57.16	56.86	54.92	58.91	57.19	54.83	56.53	52.01
14	65.91	54.00	64.36	57.72	55.54	54.01	52.39	53.07
15	55.81	54.74	66.39	69.65	55.32	53.43	51.75	51.78
16	45.49	46.71	47.31	48.91	48.94	51.13	51.38	51.28
17	50.65	48.44	43.88	48.92	50.88	51.85	52.00	54.62
18	56.49	59.11	51.40	55.41	53.00	52.10	52.76	51.75
19	0.00	0.00	0.00	0.00	0.00	56.50	55.18	55.58
20	76.15	67.92	52.46	52.41	36.28	38.18	0.58	10.24
21	96.17	84.01	73.86	73.52	40.65	40.77	29.28	33.81

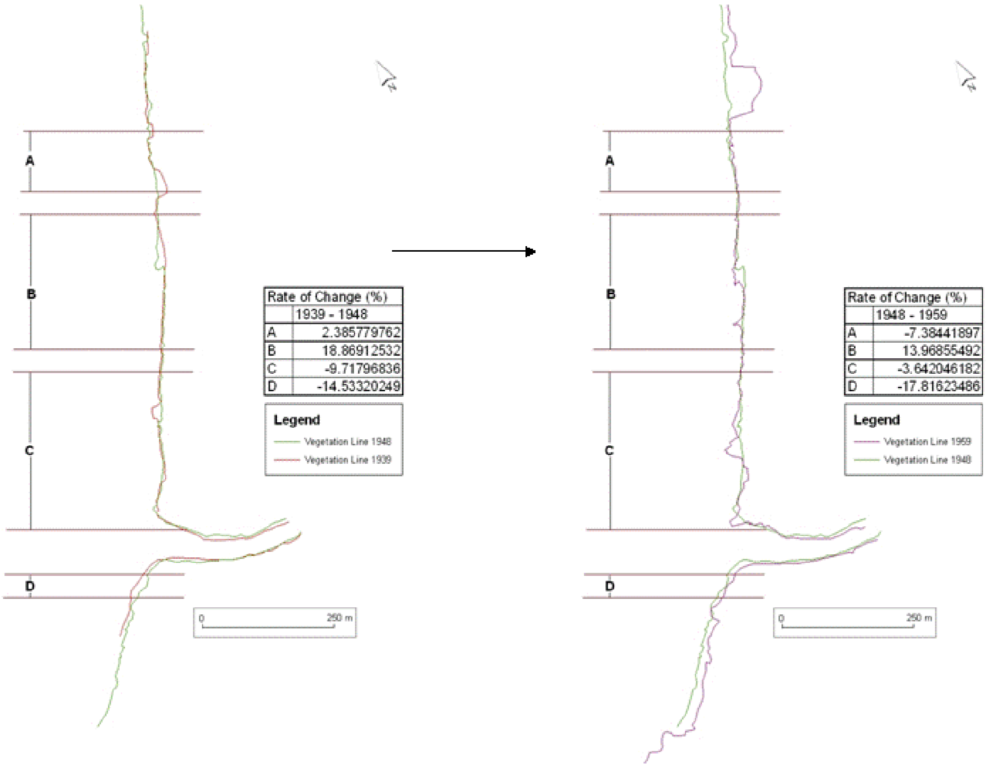
Appendix 3.8 Distance of Seaward Vegetation line from the baseline (m)

	1939-1948	1948-1959	1959-1970	1970-1980	1980-1988	1988-1997	1997-2005	1938-2005
1	-0.51	-1.85	-46.99	1.44	-7.12	-6.78	-3.30	-65.09
2	-0.85	-4.69	-55.84	19.55	-18.63	-7.10	1.60	-65.94
3	0.06	-3.41	-3.53	-11.62	-42.10	-1.75	-7.14	-69.49
4	2.08	-2.69	-8.68	-0.95	-3.91	0.80	-2.69	-16.04
5	17.33	0.73	-12.95	0.22	-5.15	-3.05	-2.53	-5.40
6	14.44	-0.06	-9.74	-6.37	-1.33	-11.61	-0.46	-15.13
7	14.15	3.38	-8.25	-8.37	-11.11	-0.65	-0.71	-11.56
8	-0.83	16.83	-17.08	-1.74	-6.21	-1.51	0.00	-10.55
9	-2.69	0.91	0.63	-0.55	-8.90	0.35	-2.63	-12.89
10	-0.99	2.69	-2.38	-1.59	-13.95	1.52	-3.61	-18.30
11	-1.67	-0.11	1.98	-3.27	-7.99	-1.62	-3.15	-15.83
12	-1.06	0.49	2.33	-3.00	-10.18	0.72	-2.63	-13.32
13	-0.31	-1.94	3.99	-1.72	-2.36	1.70	-4.52	-5.16
14	-11.92	10.36	-6.64	-2.18	-1.53	-1.61	0.68	-12.84
15	-1.07	11.65	3.26	-14.33	-1.89	-1.68	0.03	-4.03
16	1.22	0.59	1.60	0.03	2.18	0.25	-0.10	5.78
17	-2.21	-4.56	5.03	1.96	0.97	0.15	2.62	3.97
18	2.62	-7.72	4.02	-2.41	-0.90	0.66	-1.01	-4.74
19	0.00	0.00	0.00	0.00	56.50	-1.32	0.41	50.23
20	-8.23	-15.46	-0.05	-16.13	1.90	-37.60	9.65	-65.91
21	-12.16	-10.15	-0.34	-32.86	0.11	-11.49	4.53	-62.36

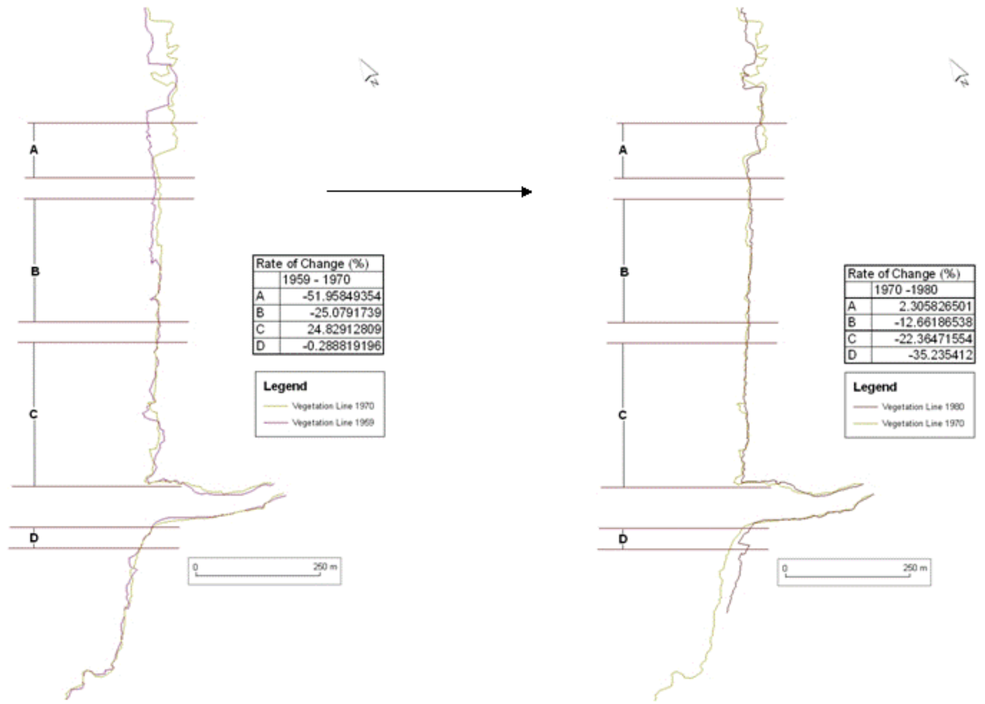
Appendix 3.9 Vegetation Line Change between photographs (m)

	1939 - 1948	1948 - 1959	1959 - 1970	1970 -1980	1980-1988	1988-1997	1997-2005
A	2.39	-7.38	-51.96	2.31	-30.17	-4.76	-6.95
B	18.87	13.97	-25.08	-12.66	-39.53	-8.58	-10.41
C	-9.72	-3.64	24.83	-22.36	-12.90	3.31	-9.94
D	-14.53	-17.82	-0.29	-35.24	1.34	-33.47	9.78

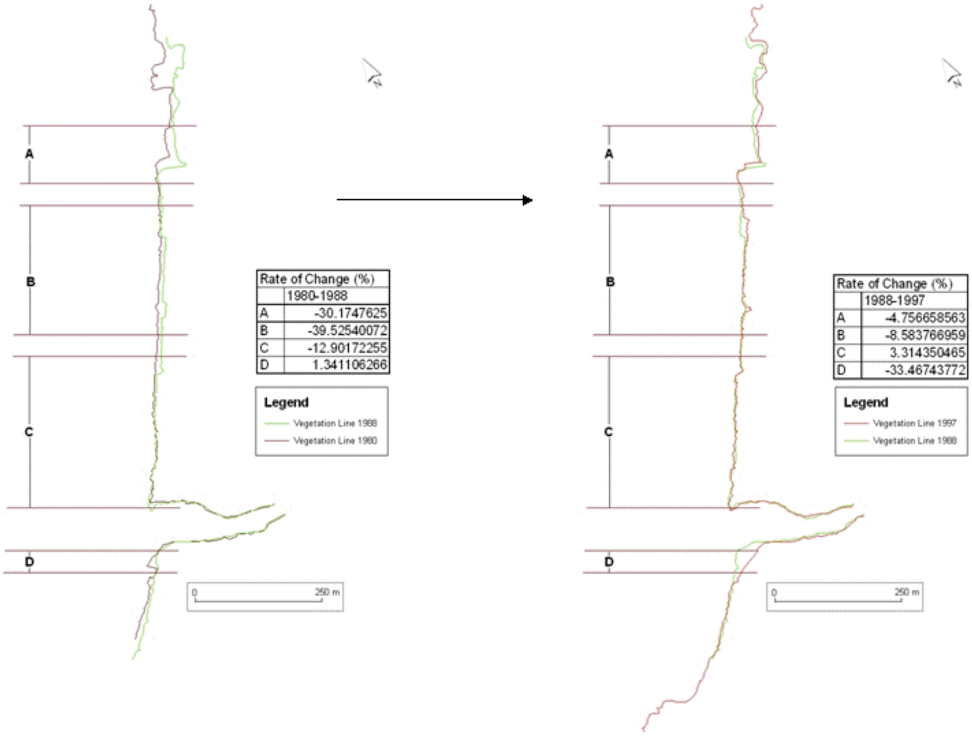
Appendix 3.10 Vegetation Rate of Change in percentage in each section



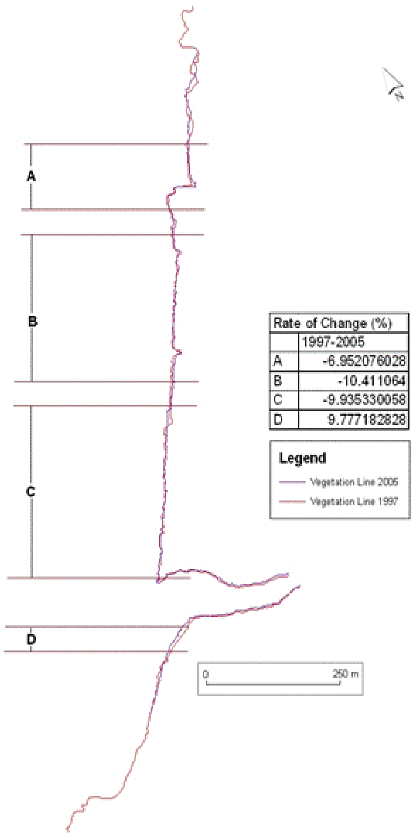
Appendix 3.11 Change in vegetation between different photographs (Left- 1939-1948, Right- 1948-1959)



Appendix 3.12 Change in vegetation between different photographs (Left- 1959-1970, Right- 1970-1980)



Appendix 3.13 Change in vegetation between different photographs (Left- 1980-1988, Right- 1988-1997)



Appendix 3.14 Change in vegetation between different photographs (1997-2005)

Distance from baseline (m)

	1939	1948	1959	1970	1980	1988	1997	2005
1	138.39	145.83	125.82	108.94	105.05	93.04	84.79	84.04
2	142.16	142.14	122.34	105.28	102.04	91.10	82.43	80.98
3	134.44	138.36	120.60	106.55	103.67	79.85	75.86	73.32
4	134.44	138.36	120.60	105.80	103.66	79.85	75.86	73.32
5	136.91	140.96	119.80	105.48	99.05	76.54	74.23	69.30
6	136.58	142.46	117.13	103.40	99.08	77.13	74.30	68.50
7	132.42	139.76	113.10	99.02	92.77	76.56	67.54	65.55
8	134.00	137.36	113.62	99.72	87.85	78.75	64.88	69.14
9	130.83	133.49	106.33	100.41	85.28	76.64	65.42	71.06
10	137.85	132.70	99.16	96.74	86.58	75.04	67.53	71.99
11	133.15	132.07	102.46	97.58	89.03	75.15	68.57	69.70
12	130.92	127.46	104.38	96.60	94.38	76.26	68.16	68.30
13	127.44	128.00	109.09	98.75	88.30	75.14	68.64	67.91
14	131.91	129.48	107.71	98.75	86.77	71.93	71.36	65.95
15	130.79	130.13	111.04	95.62	86.67	73.61	71.13	70.38
16	131.26	127.20	113.32	97.89	85.84	76.93	72.99	72.53
17	133.04	133.20	117.62	102.77	83.21	79.27	79.71	72.45
18	137.84	138.32	118.36	104.32	93.20	83.68	82.37	75.66

Appendix 3.15 Distance of Wet/Dry Line from baseline

Rate of Change (m)

	1939-1948	1948-1959	1959-1970	1970-1980	1980-1988	1988-1997	1997-2005
1	7.44	-20.01	-16.88	-3.89	-12.01	-8.25	-0.75
2	-0.02	-19.81	-17.06	-3.23	-10.95	-8.67	-1.44
3	3.92	-17.77	-14.05	-2.88	-23.82	-3.99	-2.55
4	3.92	-17.77	-14.80	-2.13	-23.81	-3.99	-2.55
5	4.04	-21.15	-14.32	-6.43	-22.51	-2.31	-4.93
6	5.88	-25.33	-13.73	-4.32	-21.95	-2.83	-5.80
7	7.34	-26.66	-14.08	-6.25	-16.21	-9.02	-1.99
8	3.37	-23.74	-13.91	-11.86	-9.11	-13.87	4.27
9	2.66	-27.16	-5.92	-15.13	-8.64	-11.22	5.64
10	-5.16	-33.54	-2.42	-10.16	-11.55	-7.50	4.45
11	-1.07	-29.61	-4.89	-8.55	-13.88	-6.58	1.13
12	-3.46	-23.08	-7.79	-2.21	-18.13	-8.10	0.15
13	0.55	-18.91	-10.34	-10.45	-13.16	-6.50	-0.73
14	-2.43	-21.76	-8.97	-11.98	-14.84	-0.56	-5.41
15	-0.66	-19.09	-15.42	-8.95	-13.07	-2.47	-0.75
16	-4.06	-13.88	-15.42	-12.05	-8.91	-3.94	-0.46
17	0.16	-15.59	-14.84	-19.56	-3.94	0.44	-7.25
18	0.48	-19.96	-14.04	-11.13	-9.52	-1.31	-6.71

Appendix 3.16 Change of Wet/Dry Line distance between photographs

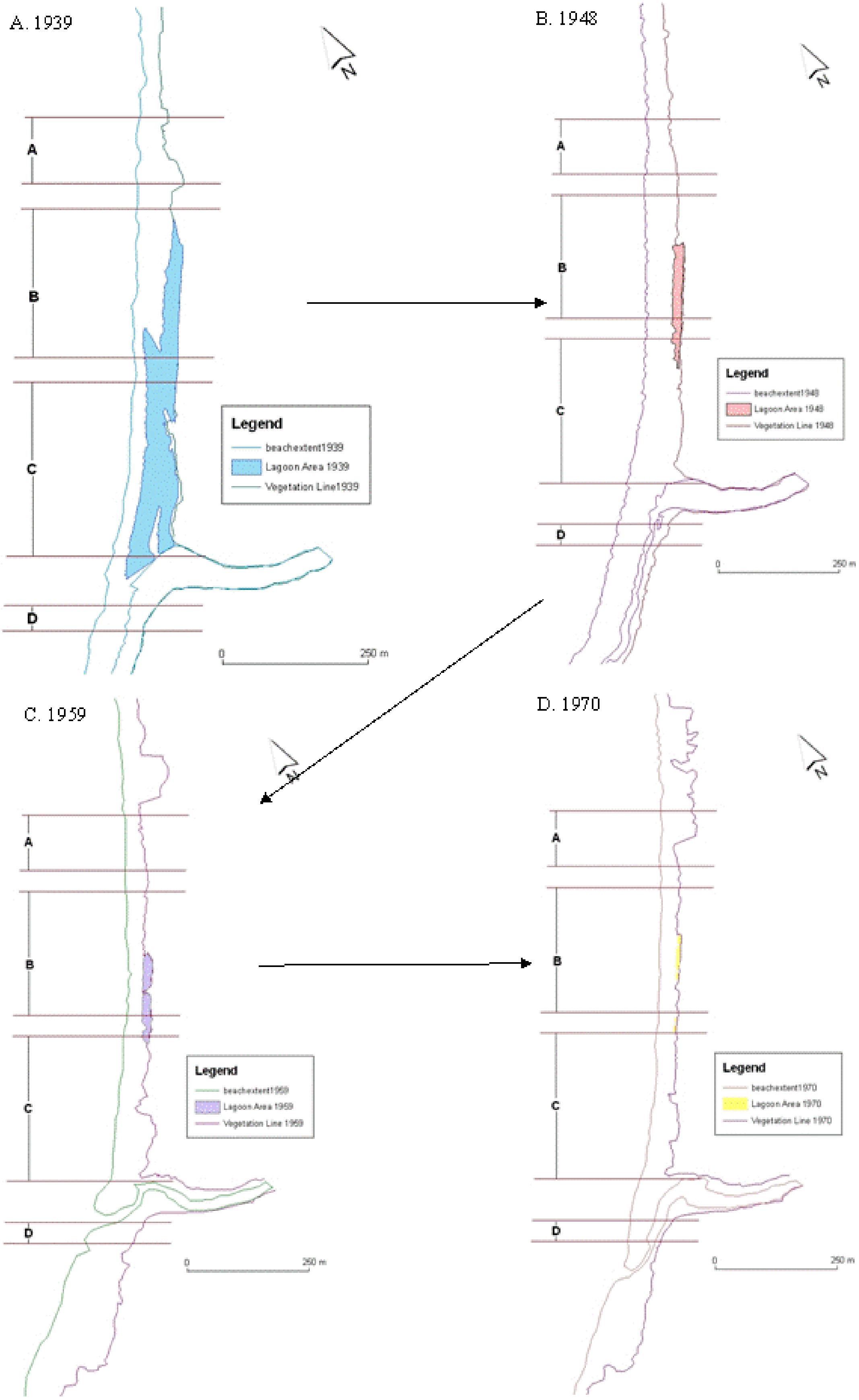
Rate of Change (m)

	1939-1948	1948-1959	1959-1970	1970-1980	1980-1988	1988-1997	1997-2005
A	3.81	-18.84	-15.70	-3.04	-17.65	-6.22	-1.82
B	2.44	-26.74	-9.89	-8.96	-14.83	-7.62	0.40
C	-1.35	-18.90	-12.40	-10.90	-11.65	-3.21	-3.02

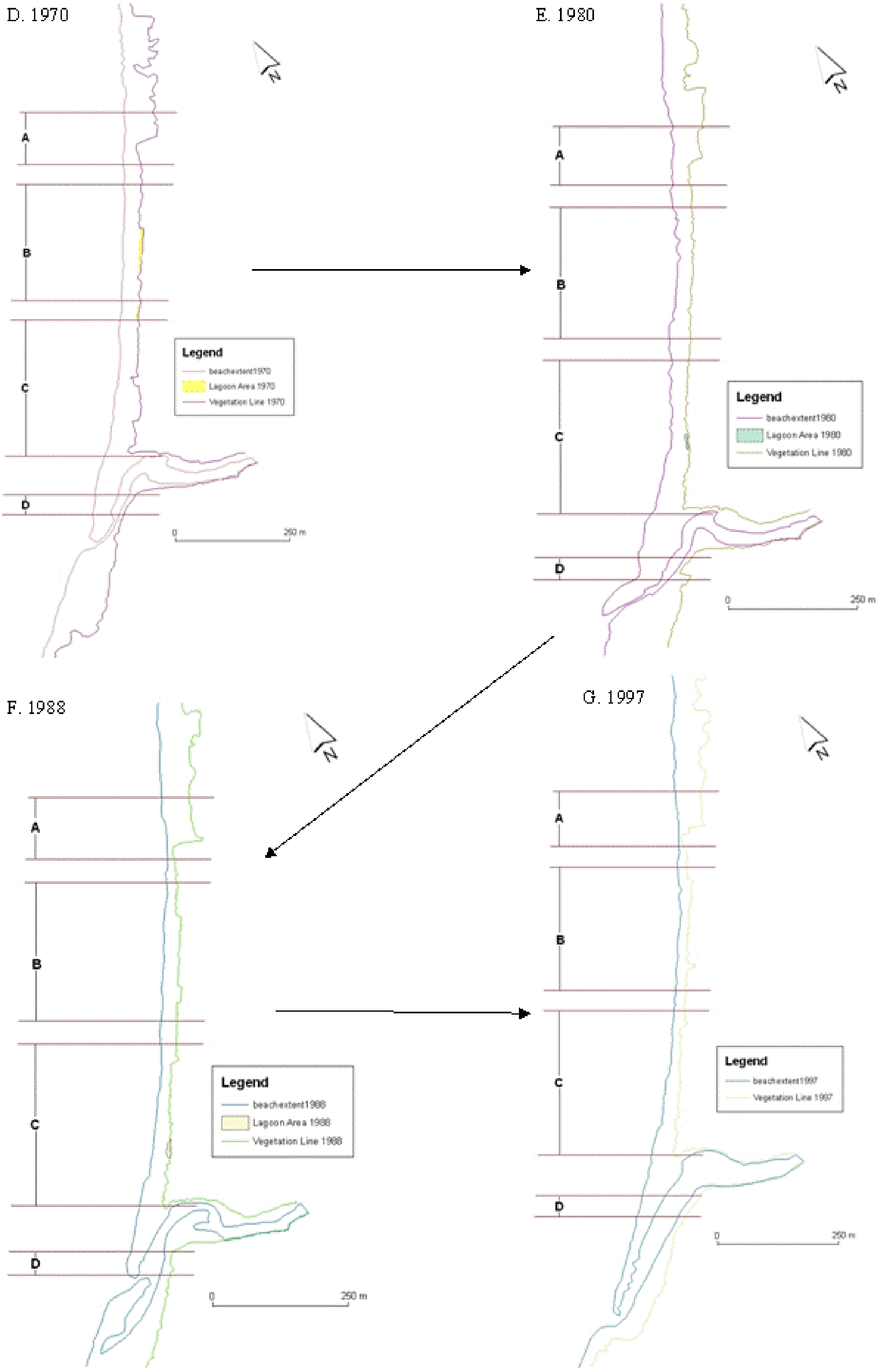
Rate of Change (%)

	1939-1948	1948-1959	1959-1970	1970-1980	1980-1988	1988-1997	1997-2005
A	-1.75	-28.19	-24.65	-21.32	-14.62	-3.04	-6.17
B	2.18	-10.76	-8.97	-1.73	-10.08	-3.56	-1.04
C	2.44	-26.74	-9.89	-8.96	-14.83	-7.62	0.40

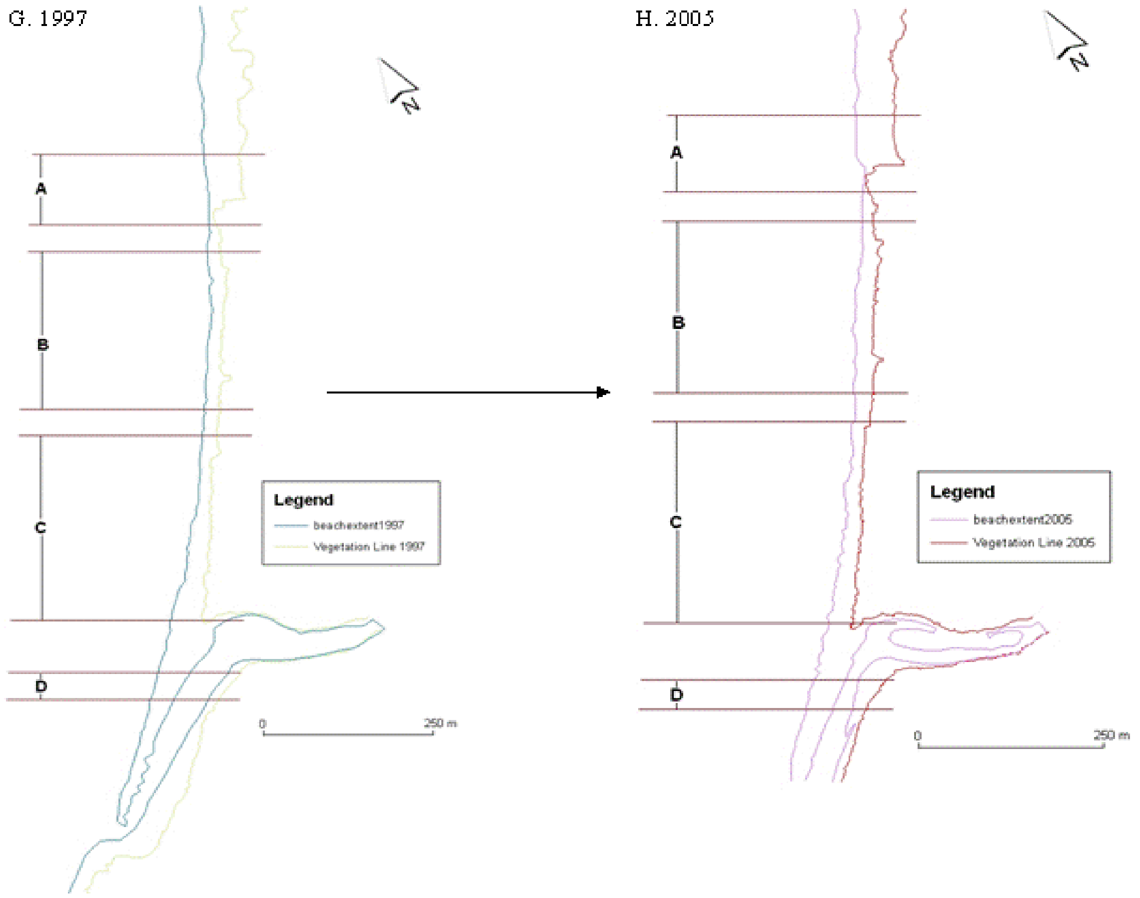
Appendix 3.17 Change of Wet/Dry Line distance between photographs in each area



Appendix 3.18 Diagram displaying the overall change of all three features from 1939 to 1970

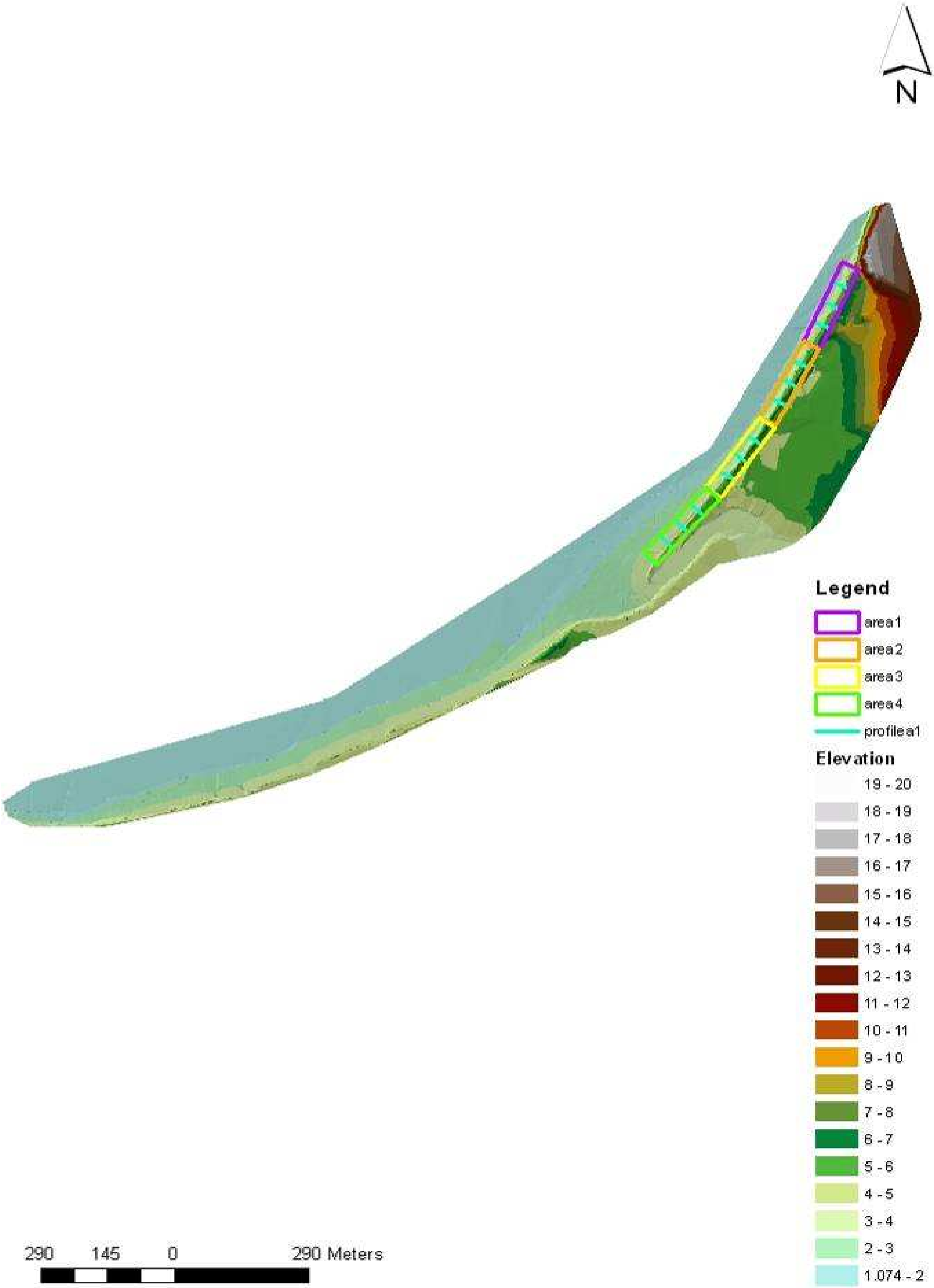


Appendix 3.19 Diagram displaying the overall change of all three features from 1970 to 1997



Appendix 3.20 Diagram displaying the overall change of all three features from 1997 to 2005

Appendix: Chapter 4



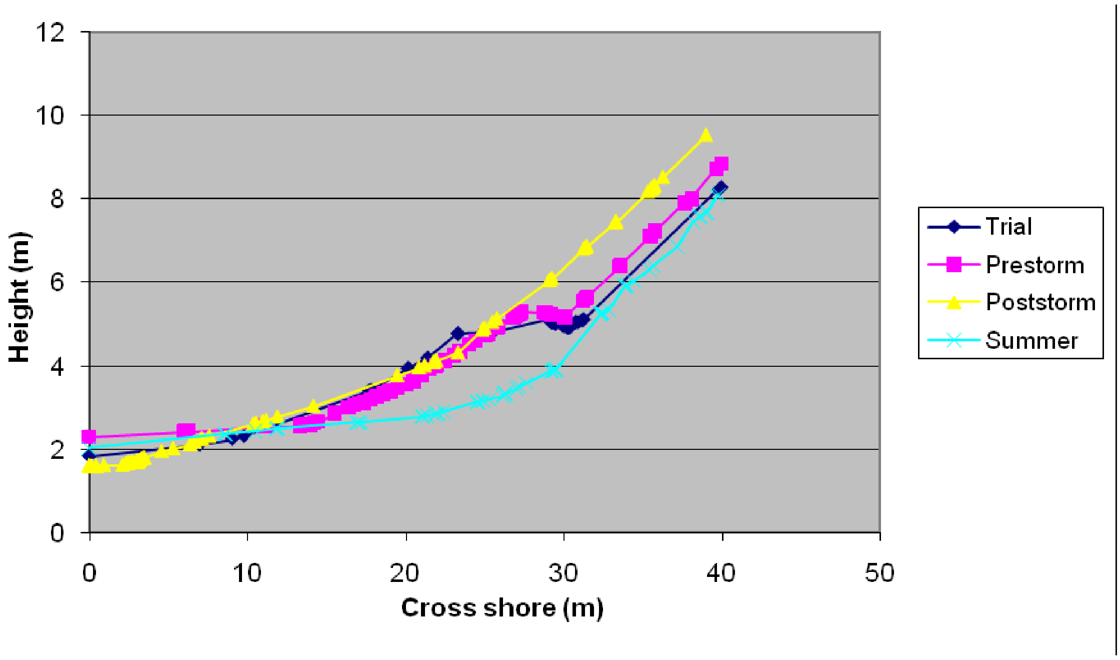
Appendix 4.1: Full Extent of the Initial DEM

	Area	Volume (m^3)
Initial	Area 1	18498
	Area 2	20565
	Area 3	19743
	Area 4	11670
Pre-storm	Area 1	17076
	Area 2	Interpolation Error
	Area 3	21213
	Area 4	11457
Post-storm	Area 1	19552
	Area 2	Interpolation Error
	Area 3	17639
	Area 4	11069
Summer	Area 1	16721
	Area 2	Interpolation Error
	Area 3	16881
	Area 4	Interpolation Error

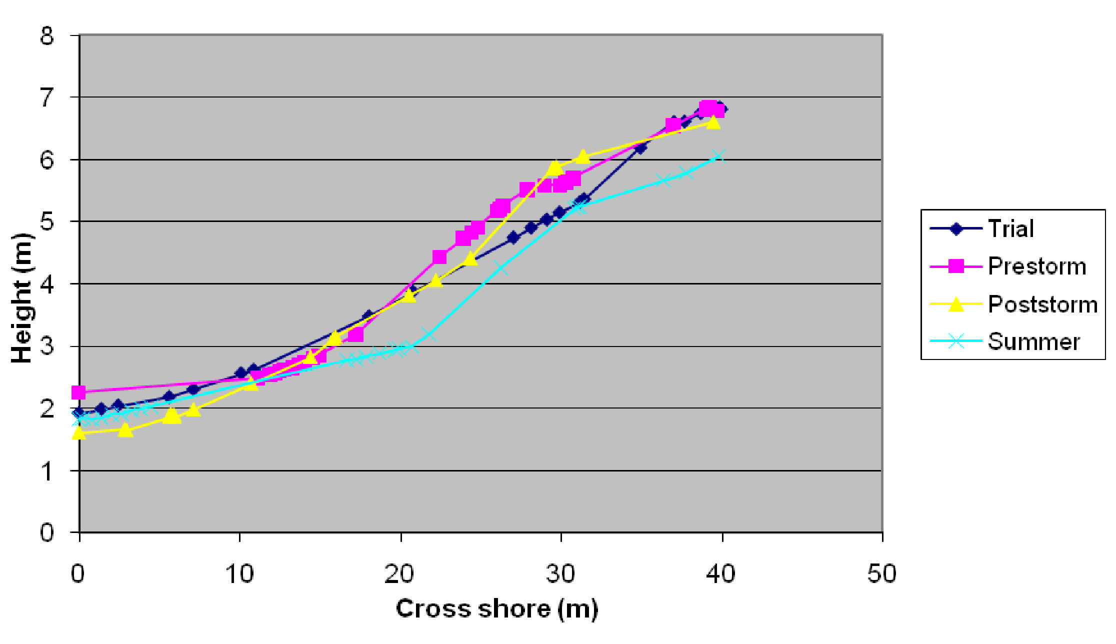
Appendix 4.2A: Volume Change Results

	Initial to Pre-Storm	Pre-Storm to Post-Storm	Post- Storm to Summer	Initial to Summer
Area 1	-1422	2477	-2831	-1776
Area 2	Interpolation Error	Interpolation Error	Interpolation Error	Interpolation Error
Area 3	1470	-3574	-758	-2862
Area 4	-213	-388	Interpolation Error	Interpolation Error

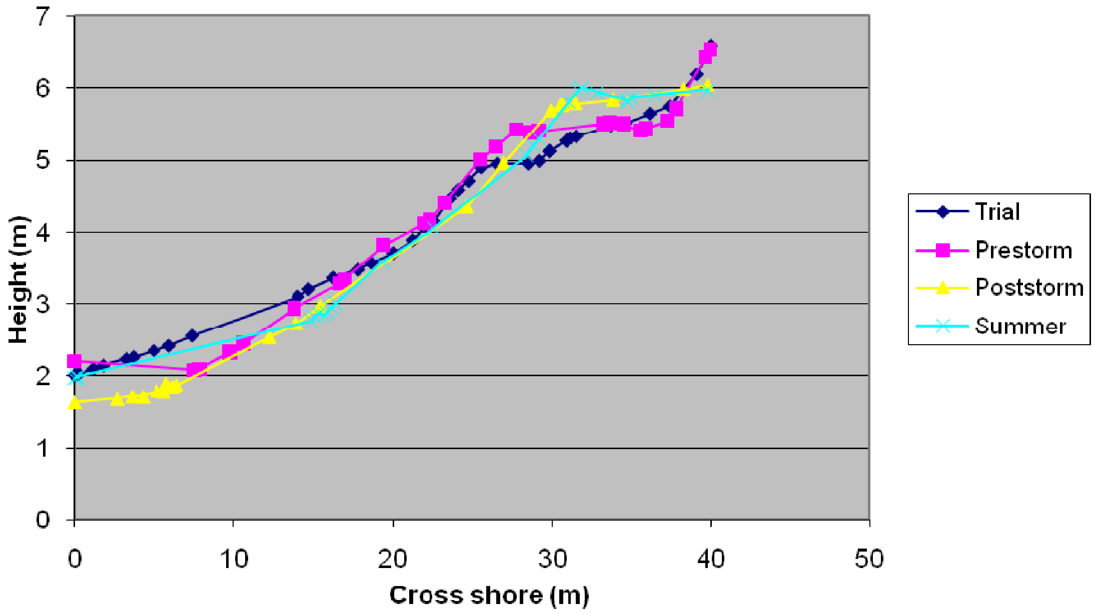
Appendix 4.2B: Volume Change Results



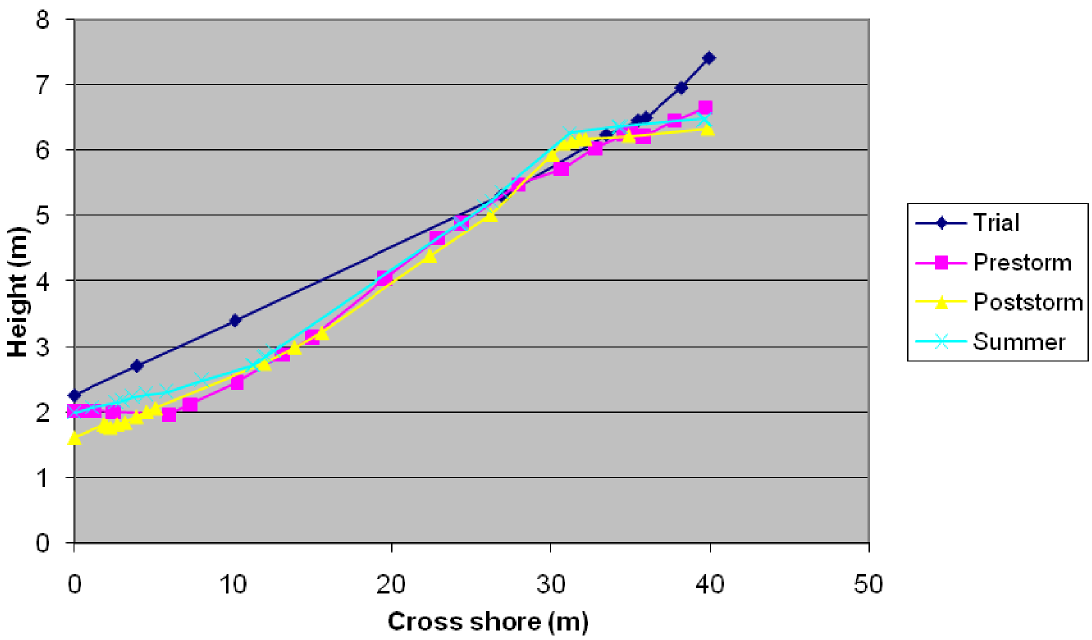
Appendix 4.3: Area 1, Profile 1



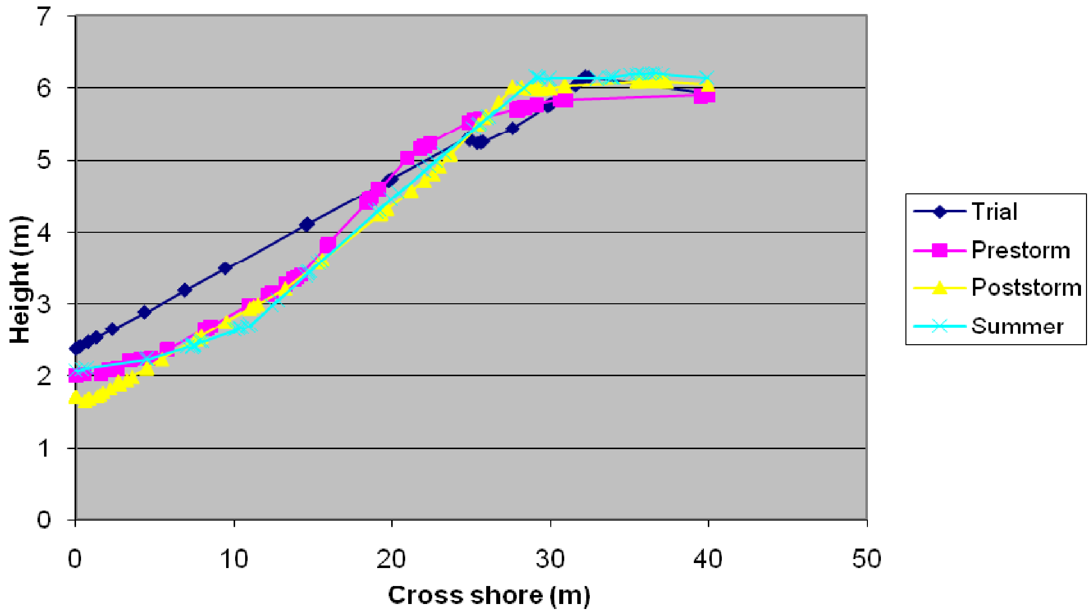
Appendix 4.4: Area 1, Profile 2



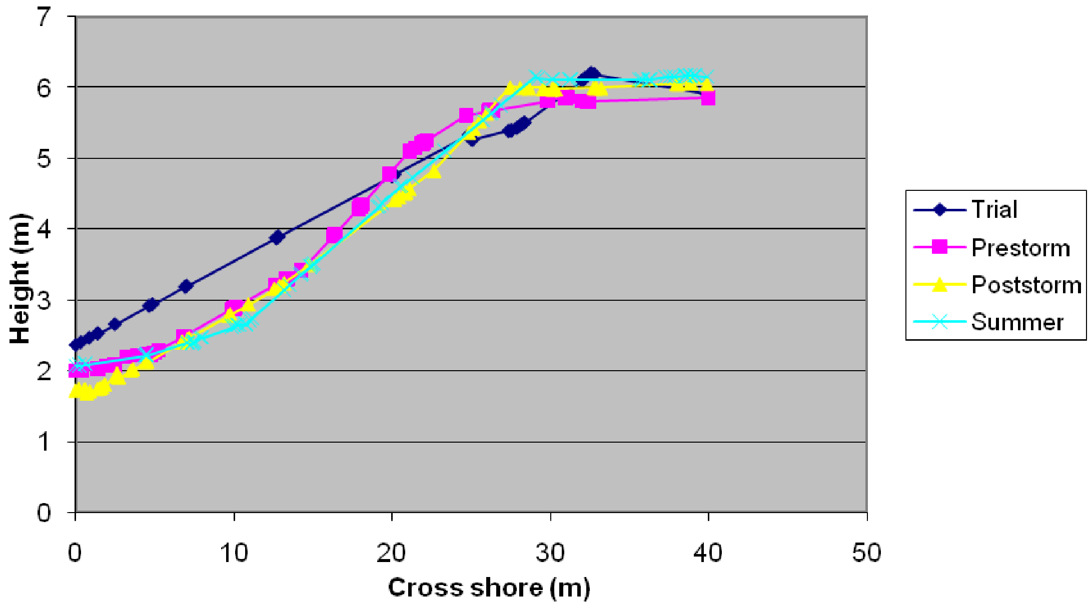
Appendix 4.5: Area 1, Profile 3



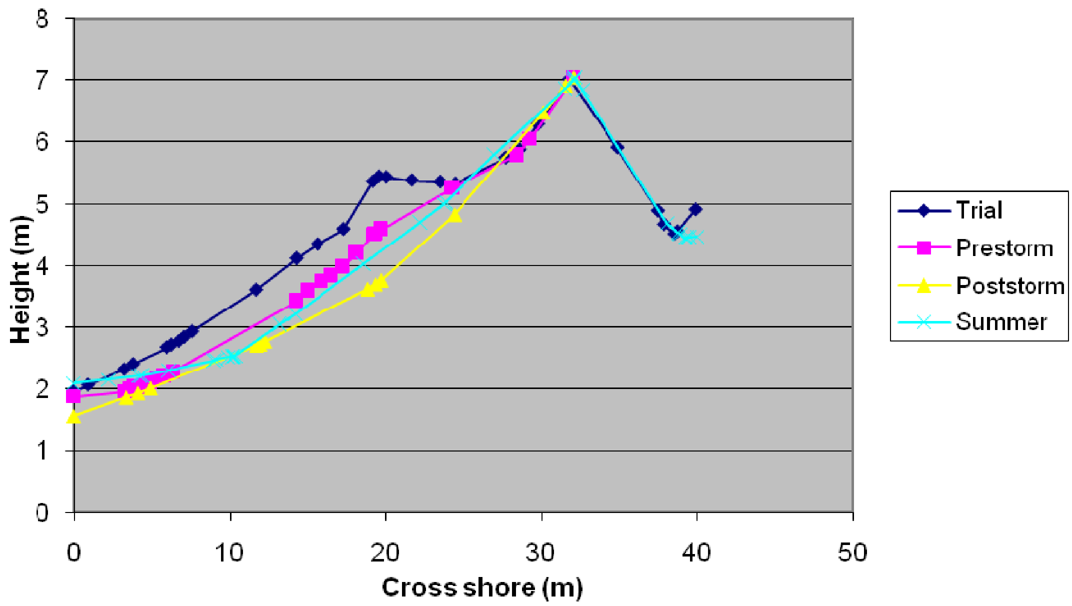
Appendix 4.6: Area 1, Profile 4



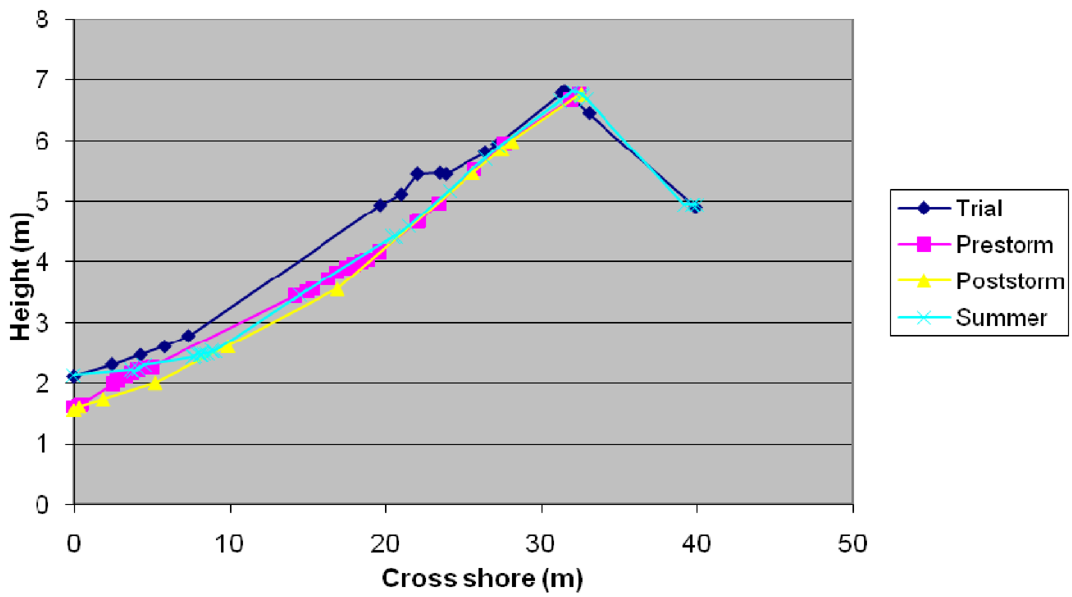
Appendix 4.7: Area 1, Profile 5



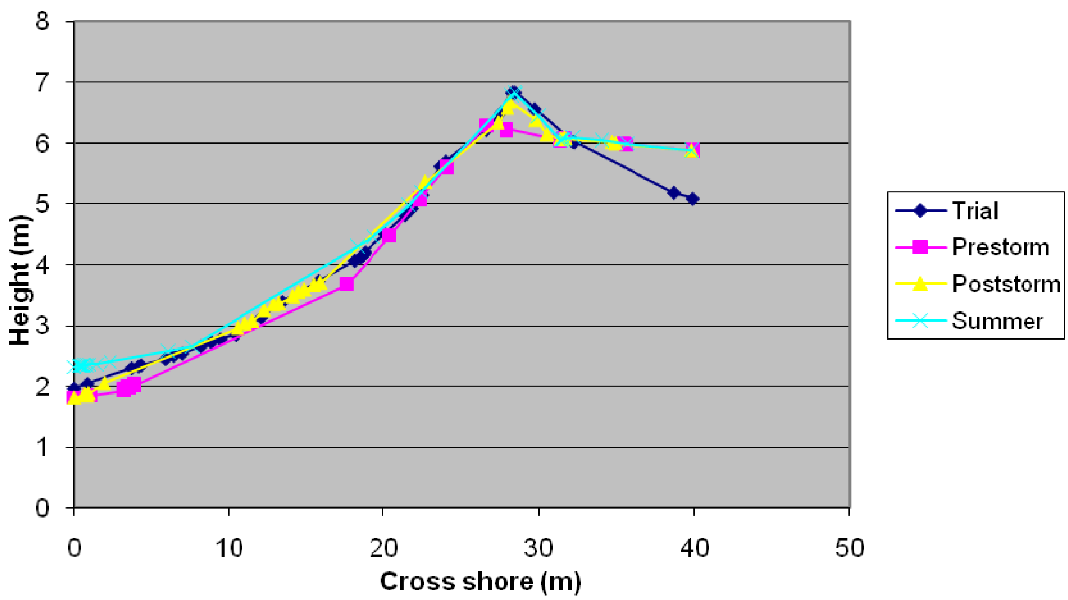
Appendix 4.8: Area 2, Profile 1



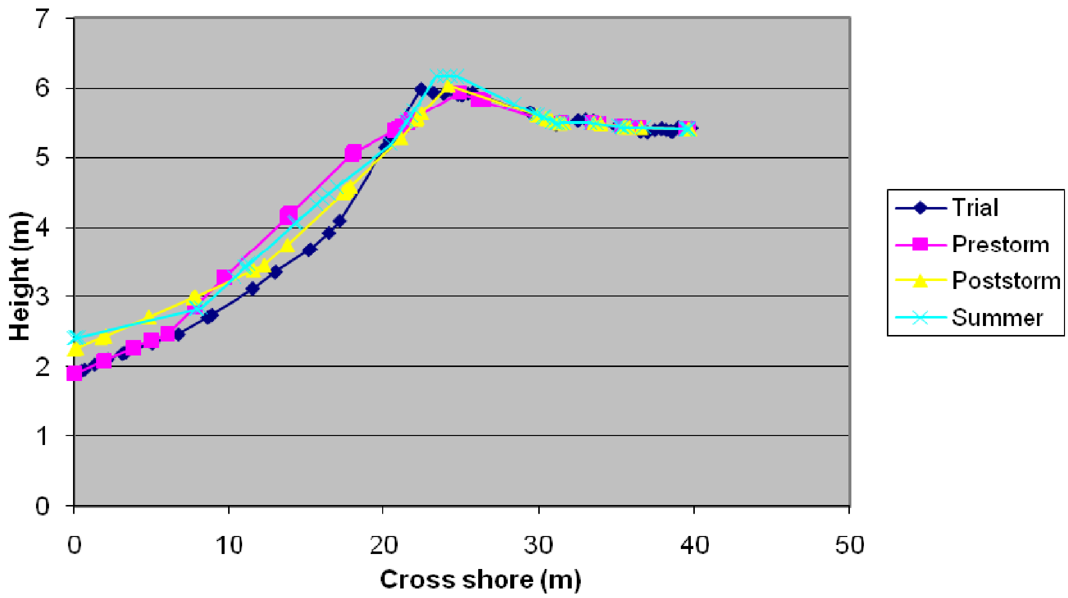
Appendix 4.9: Area 2, Profile 2



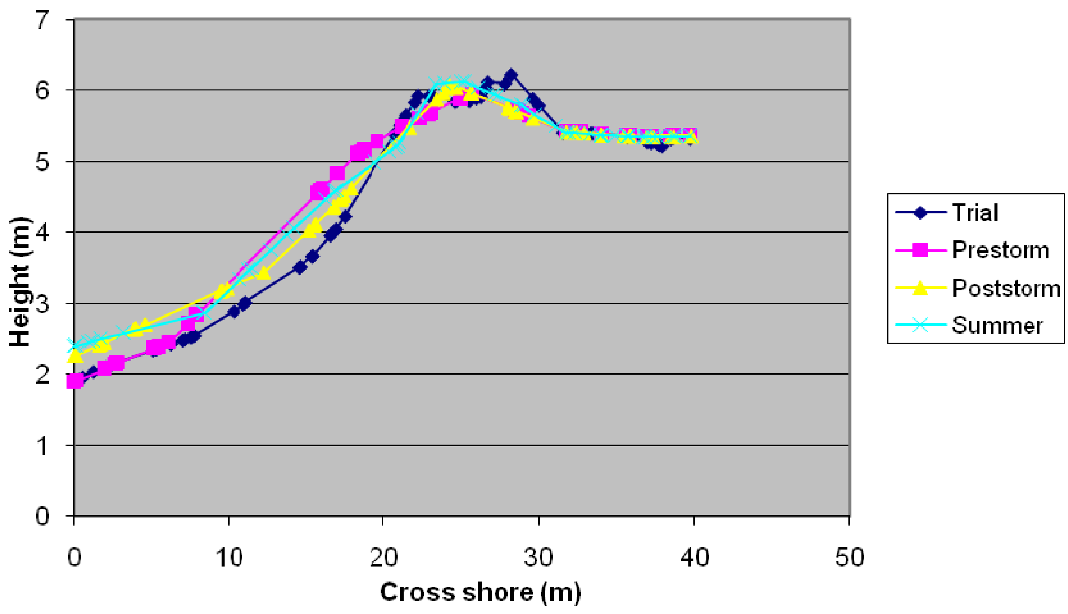
Appendix 4.10: Area 2, Profile 3



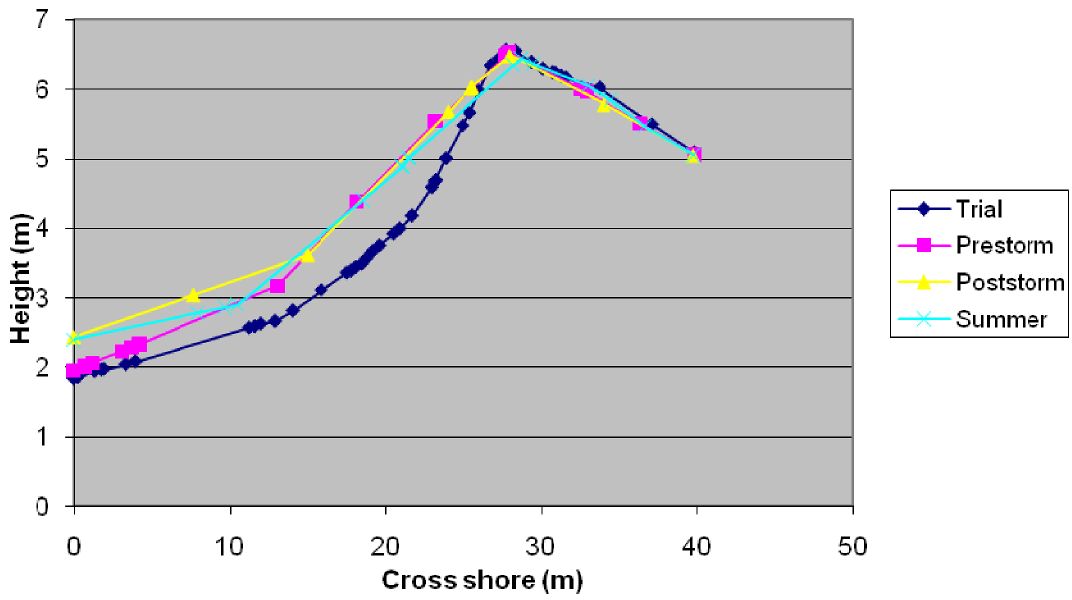
Appendix 4.11: Area 2, Profile 4



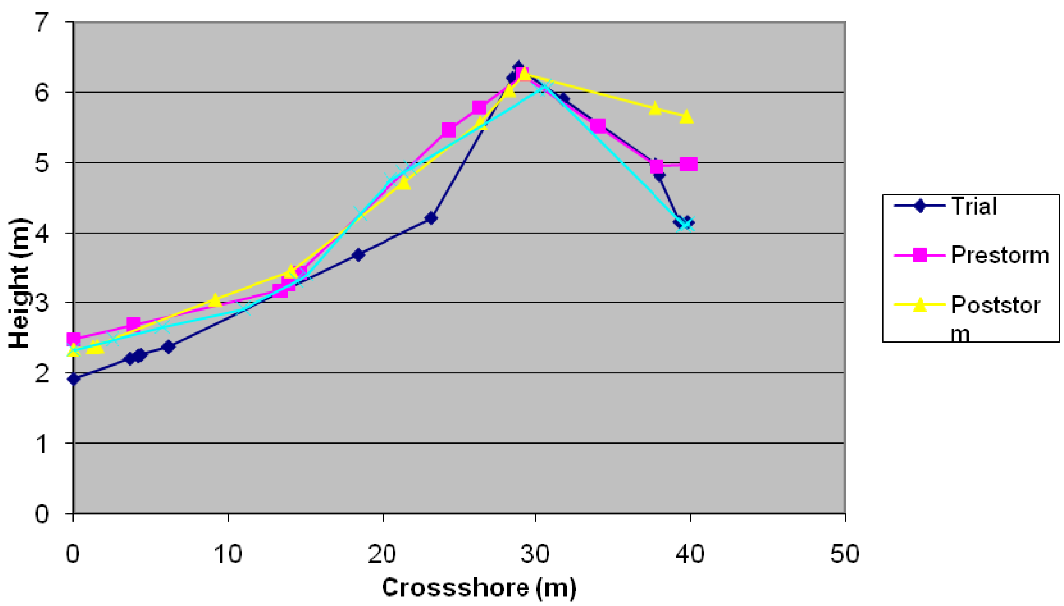
Appendix 4.12: Area 2, Profile 5



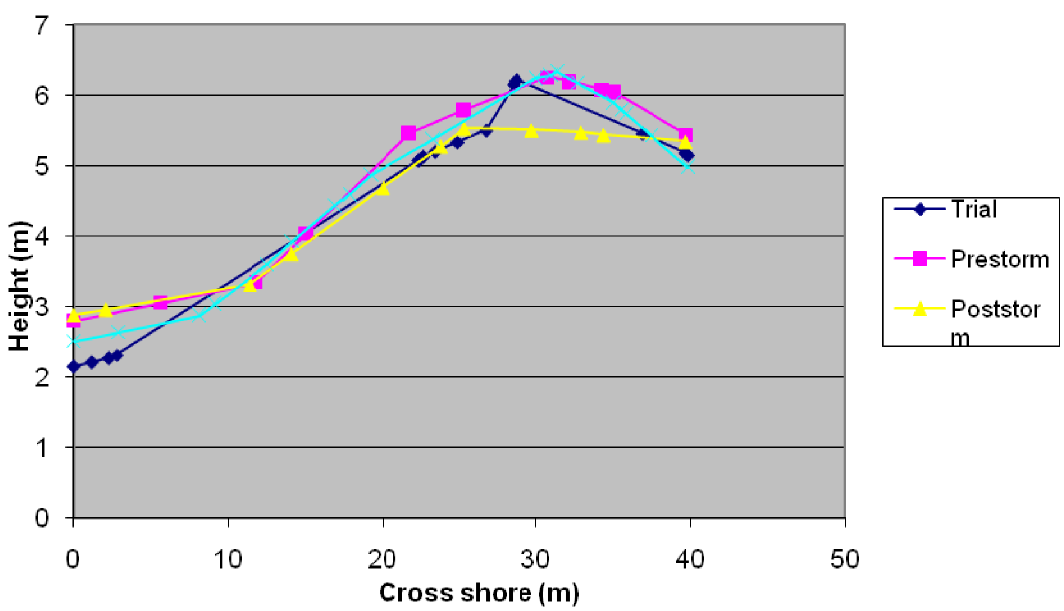
Appendix 4.13: Area 3, Profile 1



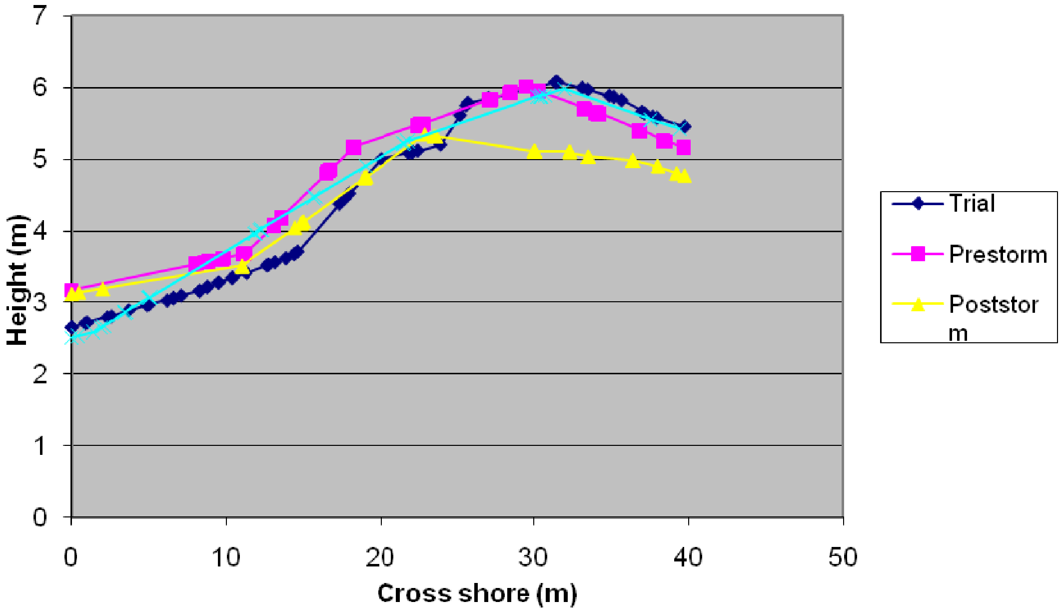
Appendix 4.14: Area 3, Profile 2



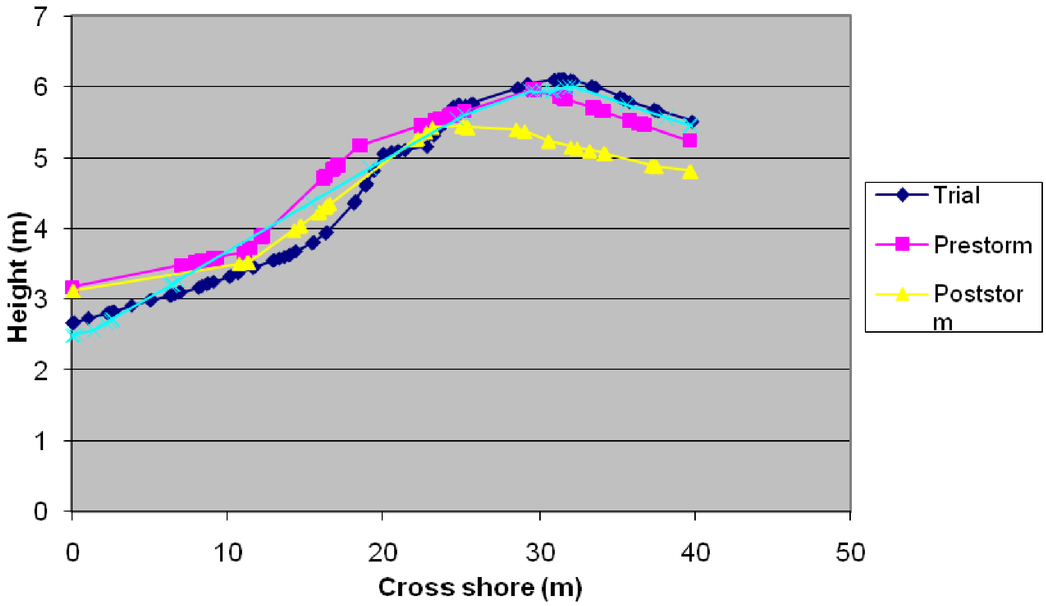
Appendix 4.15: Area 3, Profile 3



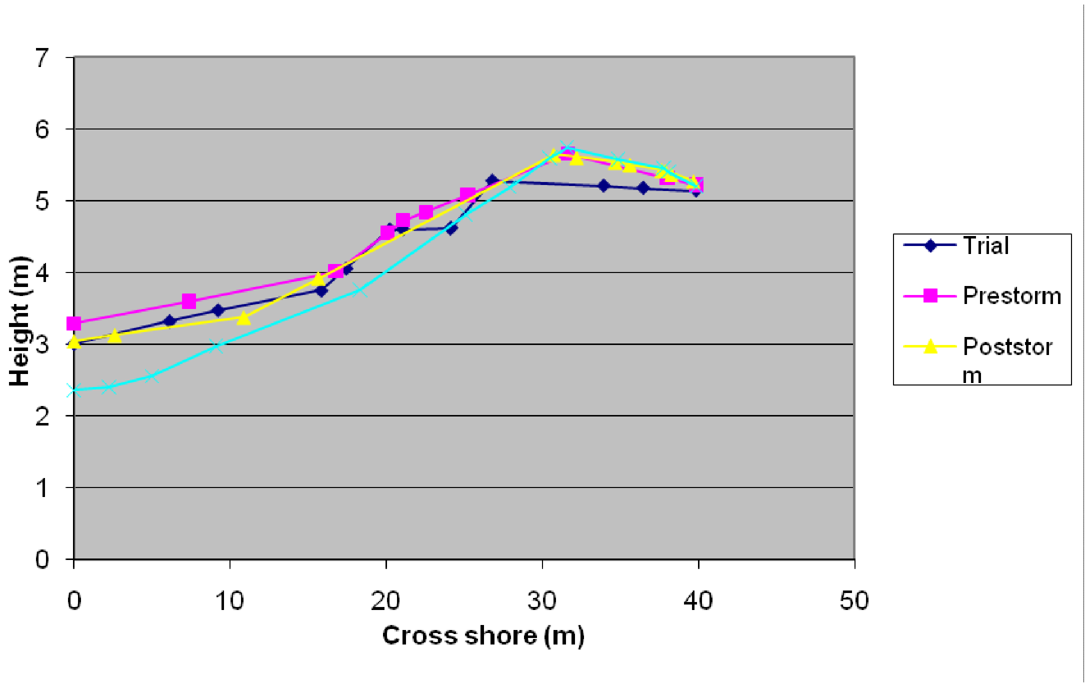
Appendix 4.16: Area 3 Profile 4



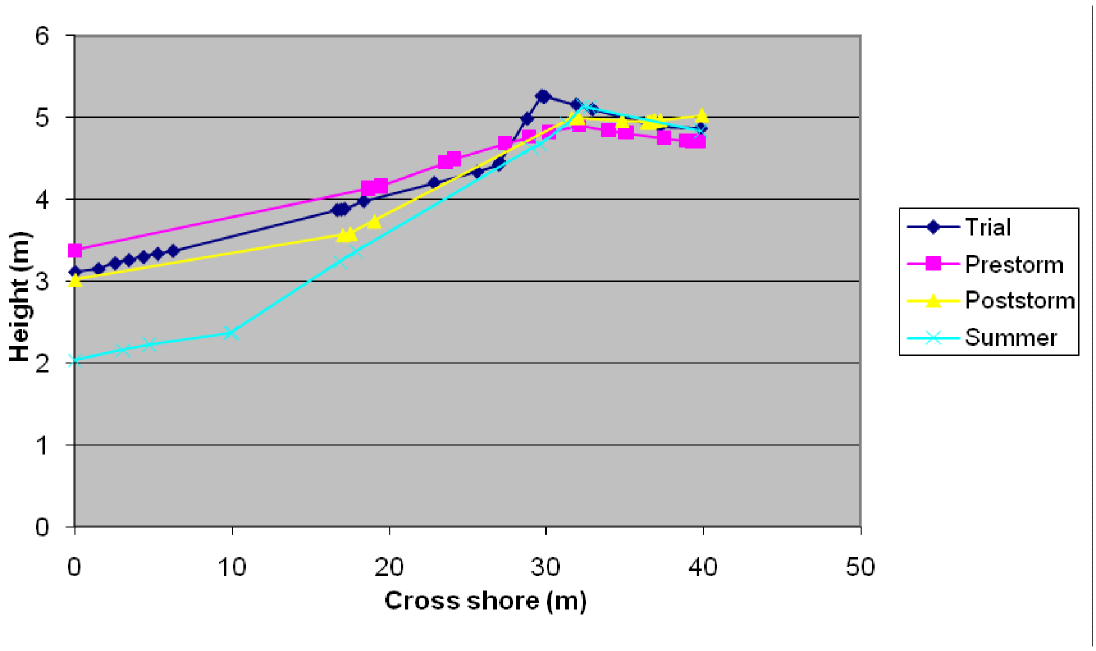
Appendix 4.17: Area 3, Profile 5



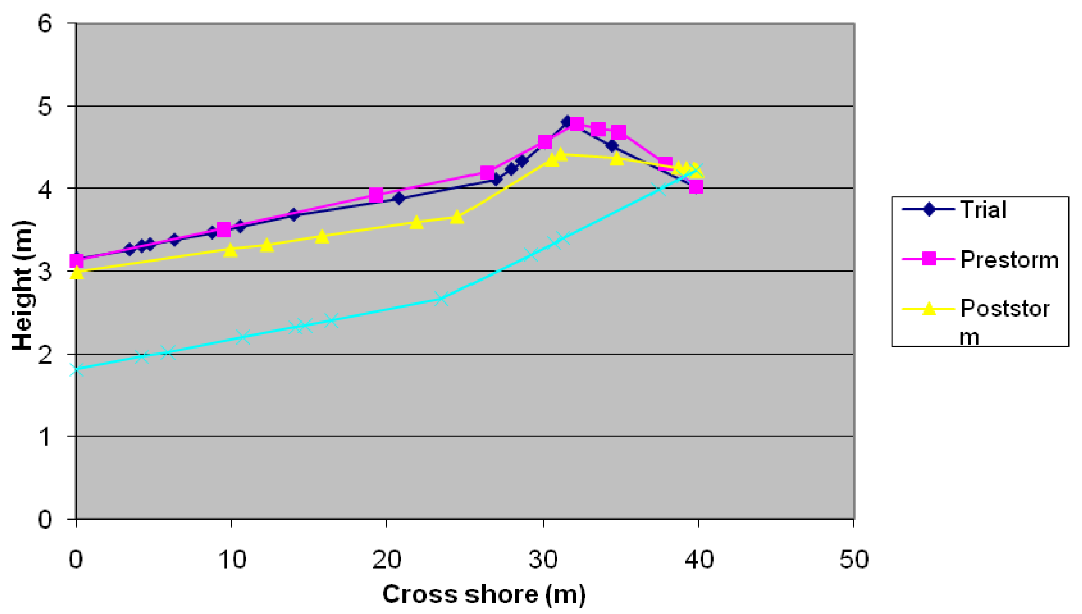
Appendix 4.18: Area 4, Profile 1



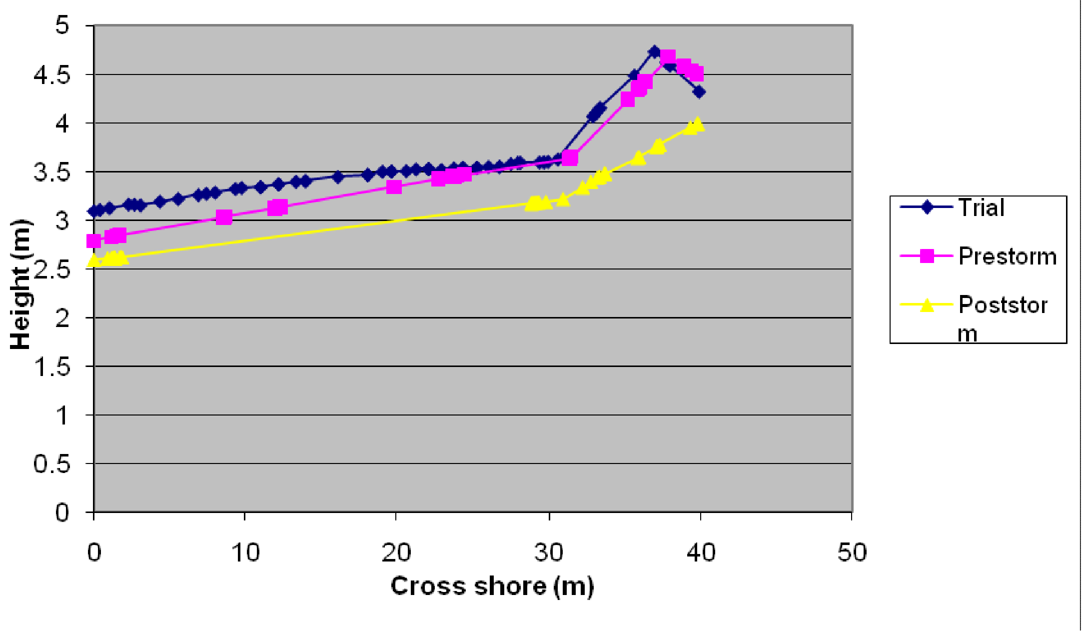
Appendix 4.19: Area 4, Profile 2



Appendix 4.20: Area 4, Profile 3



Appendix 4.21: Area 4, Profile 4



Appendix 4.22: Area 4, Profile 5