Past, Present and Future: Morphology and Dynamics of Rivermouth Lagoons in Westland, New Zealand

A thesis submitted in partial fulfilment of the
requirements for the Degree of
Master of Science in Geography
at the
University of Canterbury

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Christchurch, 2009

ABSTRACT

Coastal wetlands and rivermouth lagoons are dynamic systems, which respond rapidly to sea-level, tectonic, meteorological, anthropogenic and other synergistic drivers. This research used a multi-disciplinary approach to investigate two representative West Coast lagoon systems (Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex) in order to document their present-day geomorphology and determine the development and processes acting on these systems over historical time. This information was then used to predict their future under varying climate, development and management pressures. In addition to adding to the West Coast knowledge base, the findings of this research are applicable to similar systems elsewhere in New Zealand and internationally.

This investigation used a multidisciplinary approach to investigate the dynamics, structure, development and active processes in the two study systems. Techniques to document current hydrology and topography included hydrological records of water level, temperature and conductivity, and Global Navigation Satellite Surveys (GNSS). Outlet dynamics over a decadal scale were investigated through temporal aerial photograph analysis, and sediment core analyses showed changes occurring over longer timescales.

Significant differences in morphology and dynamics were observed between Totara Lagoon and Waikoriri Lagoon, with the former being much larger, more stable, and less dynamic in terms of dune morphology and outlet migratory patterns. Hydrologically, Totara Lagoon is currently in an estuarine phase, and experiences significant tidal inflows, which demonstrates the connectivity between definitions of coastal lagoons and estuaries. Waikoriri Lagoon is freshwater, and can be described as a hapua-type system, but exhibits very different river flow and barrier composition to East Coast examples. Sediment core analyses from Shearer Swamp and northern Totara Lagoon showed little change over a decadal to centennial scale, but evidence of a change in margin dynamics in response to farming and stabilisation of adjacent dune ridges was observed in Shearer

Swamp. Results suggest landward migration of the southern end of Totara Lagoon occurred over this timeframe.

The future of these systems depends on the interaction between climate and anthropogenic (including management) factors. A conceptual model of process and response suggests three possible resultant scenarios: lagoon loss, natural lagoon, or artificially modified lagoon.

A significant finding of this research is the recognition that some systems exist on a continuum between a hapua and an estuary, switching hydrological states through time while maintaining consistent morphology. In addition, the importance of barrier permeability in hapua formation is highlighted, and the term ‘sandy hapua’ introduced to distinguish these low-flow systems with low barrier permeability from the typical mixed sand and gravel examples documented on the East Coast.

These findings enhance scientific understanding of rivermouth lagoon systems, and demonstrate the wide spectrum of conditions under which they may form. This process-based understanding is important from a coastal management perspective as concerns of human induced climate change and accelerated sea level rise grow.

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ACKNOWLEDGEMENTS

This thesis is the product of a lot of hard work, collaboration, and coffee. Thank you to the numerous people who have helped in various ways over the year, without you all this project could not have been successfully completed.

Firstly, an enormous thank you to my supervisor, Dr. Deirdre Hart. Your passion for coastal geography and perpetually willing provision of your time and energies has been greatly appreciated. Thank you also for always encouraging me to challenge myself and take hold of academic opportunities.

To Lady Diana Isaac and the Isaac Wildlife Trust, a sincere thank you. I am honoured to have been this year's recipient of the Sir Neil Isaaac Scholarship in Geography and Environmental Science, and am very grateful for the financial assistance it provided.

Thank you also to the New Zealand Coastal Society for providing research funding in the form of the NZCS Masters Research Scholarship, and for giving me the opportunity to present my research at the Coasts and Ports Conference earlier this year.

I am very grateful for the excellent support and access to field equipment provided by the Geography Department. In particular, I would like to thank Justin Harrison and Nick Key for training, field assistance, technical advice – and Nick, thanks for always being able to fix the stuff I break. To Paul Bealing, thank you for all your time and effort working with me and my huge haphazard datset in GIS. I have learnt an amazing amount from this process. Thank you also to Dr. Catherine Reid and Chris Grimshaw in the Geology Department, for the use of your equipment and for sharing your expertise.

To those awesome people who didn't mind traipsing through swamps on the West Coast to help me out with my field work – thank you: particularly Cameron Kain, Edward Wright and Simon Hall.

I am grateful for the help of the numerous friendly West Coast locals, who were very generous with both information and hospitality. From Bold Head Rd: Kathy Gilbert, Annie Hughes and Ted Brennan. Thank you to the staff of DOC Hokitika; to Don Neale and Ron van Mierlo for field information, and Jackie Breen for generously spending her time helping me with aerial photographs.

To my Masters colleagues in the Geography department, thanks for the friendship and the laughs.

I sincerely thank my friends and family for their love and support this year. In particular, Ed and Kreepa deserve a mention for putting up with me both at uni and outside of it. To Jackie, thank you for being there and for being you.

Finally, extra special thanks must go to Mum, Dad and Cameron for their unconditional love and support, and for always managing to muster some interest in ‘all this uni business’.

CHAPTER ONE

Introduction

1.1 Thesis statement

Coastal wetlands and river mouth lagoons are dynamic, active environments that can respond rapidly to changes in climate, sea level, tectonic and anthropogenic drivers. This is particularly true of those on the West Coast of New Zealand’s South Island, where a high energy coastal marine environment, extreme weather patterns and high sediment load from nearby mountains contribute to continual, and often rapid, changes in these systems. As such, it is important to understand the local coastal environment in order to effectively manage it, especially as concerns of human induced climate change and accelerated sea level rise grow.

Very little coastal process and management research has been undertaken previously on the West Coast, and consequently the coastal history and processes of the region are not currently documented or understood to the level required for making effective coastal management decisions and plans. The purpose of this research is to investigate two representative coastal systems in the West Coast region; Totara Lagoon and Shearer Swamp/Waikoriri Lagoon, with the aim of documenting their development over recent centuries and their present-day topography and dynamics. This information will then be used to predict their future under changing climate, development and management scenarios. In addition to adding to the West Coast knowledge base, it is important that the scientific and management models presented in this research are applicable to similar systems elsewhere in New Zealand and globally.

A multidisciplinary approach will be used to investigate the evolution, structure and acting processes operating in two case study lagoons. Techniques to be employed include the use of Global Navigation Satellite Surveys (GNSS), sediment core analyses, water level monitoring, temporal aerial photograph analysis, and conceptual predictive modelling. The use of these different and complementary techniques allows a robust and coherent set of results from which to construct historical and predict future evolution of these complex lagoon systems.

This chapter introduces the context of this research in terms of national and international literature on coastal lagoons and their morphodynamic evolution. Gaps in existing research are highlighted. This is followed by the definition of the specific objectives of this research and their relationship within the knowledge gaps. Finally, a synopsis of the structure of this thesis and individual chapter contents are provided.

1.2 Conceptual context

As complex, dynamic environments, coastal lagoon and wetland systems are difficult to investigate, understand and predict changes in. This project employs a multidisciplinary methodological framework to provide a comprehensive and robust documentation of changes and processes in two representative West Coast systems through historical time and the present day. A range of geological, hydrodynamic and survey techniques will be employed to achieve this. These techniques have been widely applied in previous research both nationally and internationally, and studies using these techniques individually and in concert will be reviewed as part of this project.

The coastal environment and related processes have been the subject of increasing amounts of research over the past 50 years. As technology has advanced, so too has the scope and detail of studies and hence our understanding of the coastal environment. This research has been summarised and detailed in a number of review papers published in recent decades (e.g. Thom and Short, 2006; Stephenson and Brander, 2003, 2004; Hesp *et al.*, 1999; Hume *et al.*, 1992). Textbooks dealing solely with the subject of coastal geomorphology have become common and include Kjerfve (1994), Carter and Woodroffe (1994), Komar (1998), Short (1999), Bird (2003), Woodroffe (2003), and Masselink and Hughes (2003). This chapter will provide a comprehensive overview of both New Zealand and international literature on the subtopic of coastal lagoons, their morphodynamics and their coastal evolution. In addition to published literature, many unpublished theses and reports related to coastal processes and industry exist, some of which are included and others of which are omitted from this review due to availability and access constraints.

1.2.1 **Coastal lagoons on high energy coasts**

The term ‘coastal lagoon’ applies to a wide range of coastal waterbodies that can have significant differences in morphology and dynamics. Coastal lagoons occur in micro- and meso-tidal environments worldwide, the form they take depending on the balance between marine and fluvial processes and sediment input (Cooper, 1994). The defining characteristics of coastal lagoons are therefore broad, which leads to discrepancies in estimates of lagoon spread and frequency worldwide. Estimates suggest lagoons border approximately 13% of the world’s coastlines (Barnes, 1980 p. 1).

In the context of this study, the term coastal lagoon refers to a body of water occurring at a river mouth and running approximately shore-parallel, in temperate and high latitude regions. Coastal lagoons are globally common; they can exhibit a wide range of geomorphological characteristics and structures, and can range in salinity from essentially freshwater to hypersaline (Kjerfve, 1994; Kirk and Lauder, 2000). Most lagoons are considered to be short-term features on a geological time-scale, as they form and subsequently evolve and infill within relatively short periods (Cooper, 1994). Barnes (1980) suggests the majority of lagoons exist for less than 1000 years, but that lifespan increases with size.

Coastal lagoons are different from estuaries, and Kjerfve (1994) identifies several key factors in identifying coastal lagoons: they are usually oriented parallel to the shore, separated from the ocean by a barrier while remaining connected by one or more restricted inlets, and are seldom more than a few metres deep. Most existing coastal lagoons formed during the Pleistocene or Holocene as sea levels rose and marine processes caused barriers to grow (Barnes, 1980; Kjerfve, 1994). Lagoons, estuaries and deltas are all coastal features which form at river mouths; the difference lies in the dominant process acting on the system (Hart, 2007) (Figure 1.1). Coastal lagoons form in a wave-dominated environment, estuaries are dominated by tidal cycles, and deltas by fluvial processes.

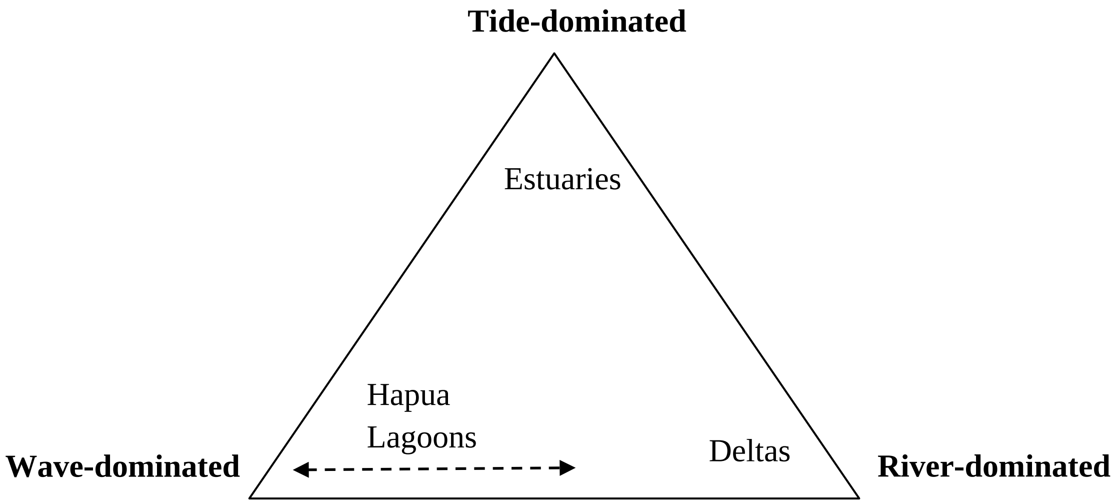


Figure 1.1. River mouth classification according to the dominant process agents of waves, tides, and rivers. *Sourced from Hart (2007),* p. 927

Early research surrounding coastal lagoons focused on understanding processes of coastal lagoon formation, identification of defining characteristics, and the development of classification schemes within which to group water bodies of similar geomorphology. Coastal lagoons were described by Phleger (1969) and defined by Kjerfve (1994 p. 2) as "*an inland body of water, usually oriented parallel to the coast, separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets, and having depths which seldom exceed a couple of metres*". This still applies in modern definitions; however, later definitions often include reference to sediment deposition and littoral drift (Kjerfve, 1986; Kjerfve, 1994; Cooper, 1994). The identification and classification of coastal lagoons is further complicated by the overlap between definitions of lagoons and estuaries, the latter being similar coastal systems but which are tidally dominated (Kjerfve, 1986). Cameron and Pritchard (1963 p. 306) define an estuary as "*a semi-enclosed coastal body of water having a free connection with the open sea and within which the sea-water is measurably diluted with fresh water deriving from land drainage*". When comparing this with the description of a coastal lagoon presented above, these are not entirely separate concepts, but rather a continuum along which the degree of ocean water exchange determines the water body type. Coastal lagoons are included as a type of estuary in some literature. Kjerfve (1986), whose coastal lagoon classification system is still the most widely used today, recommended that coastal lagoons be included as one of the major estuary types, alongside fjords and drowned river valleys. This is a particularly pertinent point in relation to Totara Lagoon, as this large system exhibits characteristics of both lagoon and estuarine definitions. In contrast, Waikoriri Lagoon experiences no tidal mixing.

Several classification schemes for coastal lagoons have been developed, the focus of which depends on the purpose of the research. Four lagoon types were identified by Nichols and Allen (1981): estuarine lagoon, open lagoon, partly closed lagoon, and closed lagoon. These are based on dominant processes. Kjerfve (1986) classified lagoons into ‘choked’, ‘restricted’ and ‘leaky’, depending on the nature of the outlet and water exchange between the lagoon and ocean. In addition to these broadly applicable categories, researchers have often subdivided these or created their own classification scheme to distinguish unique water body types in their area of interest. Cooper (2001) assessed the geomorphological variability of microtidal estuaries on the South African coast and identified three types of open estuary and two types of closed estuary, which were further subdivided according to dominant processes. Within the closed estuary group, a category of ‘river-dominated estuaries’ was included, which describes systems classified elsewhere as river mouth lagoons. Barrier lagoons are also included in a similar Australian estuarine classification scheme by Roy *et al.* (2001), and in New Zealand by Hume and Herdendorf (1988).

The most widely applied geomorphic classification scheme today is that of Kjerfve (1986, 1994), which classified coastal lagoons into choked, restricted and leaky, depending on the degree of water exchange with the ocean. ‘Choked’ lagoons occur on coasts characterised by a high energy marine environment with significant longshore drift, and generally possess only a single, narrow outlet to the sea. ‘Restricted’ lagoons are large waterbodies with two or more entrance channels, allowing a greater degree of tidal water exchange. ‘Leaky’ lagoons are dominated by oceanic processes, usually through the presence of multiple openings and greater permeability in the barrier. The two systems that are the focus of this study are of the choked variety.

In a New Zealand context, choked lagoons have been separated into two distinct types of coastal lagoon, known as ‘hapua’ and ‘waituna’, which can be identified descriptively as ‘river mouth lagoons’ and ‘coastal lakes’ (Hart, 1999; Kirk and Lauder, 2000). Waituna take the form of lake-like water bodies at the coast. They are predominantly brackish to freshwater, with only one restricted opening to the ocean, so ocean water exchange is usually unidirectional and in an outward direction, and tidal influence is minimal (Kirk and Lauder, 2000). Most waituna form in depressions left between the outwash fans of major Quaternary rivers (Kirk and Lauder, 2000). The term 'hapua' has been applied to describe the two lagoon systems throughout this study, which could also be classified as 'barrier lagoons' or 'river-dominated estuaries' according to other classification schemes.

Later research has branched out from rigid classifications of coastal systems, become more holistic and increasingly focused on drivers of change and links between formation, sediment processes and hydrology (e.g. Fitzgerald and van Heteren, 1999; Cooper, 2000; Hart and Bryan, 2008). In recent years, a more multidisciplinary approach has often been taken in coastal research, through which more robust and coherent data has been achieved (e.g. Horrocks *et al.*, 2008; Nichol *et al.*, 2007; Allard *et al.*, 2009). From these results, models of coastal behaviour have been developed to better understand processes and response. The problem of terminology remains, however, and continues to present challenges in describing complex coastal systems and their behaviour, as is the case in the present study.

Kirk (1991) investigates the development of the Rakaia rivermouth, a hapua-type lagoon system, and its response to changes in fluvial and marine processes, which is then applied in the context of a water resource planning model. The lagoon system was found to be very sensitive to changes in the connected fluvial and marine environments, including changes in land-use affecting catchment hydrology and sediment supply. Dramatic land-use change has occurred in the catchments of Totara Lagoon and Waikoriri Lagoon over historical time, and this model is evaluated as part of this study in Chapter 7.

Carter *et al.* (1989) assess the difference in coastal lagoon dynamics and evolution under differing relative sea level regimes using case studies from Ireland (approximately stationary relative sea level) and Nova Scotia (rapidly rising relative sea level). The Irish sequences show smooth changes, whereas the Canadian sequences fluctuate rapidly between terrestrial and marine environments. These fluctuations are not concluded to be a response to sea level oscillations, but rather evidence of 'life cycle' changes in lagoon barriers. This study highlights the importance of recognising the lagoon barriers as part of a stochastic process controlled by sea level *and* sediment supply, rather than taking these apparent changes at face value.

Following this, Orford and Carter (1995) investigated the driving forces of changes in a gravel barrier in Nova Scotia, concluding that there is an important mesoscale decadal forcing occurring, upon which the effects of microscale events (e.g. storms, tropical cyclone remnants) are superimposed. The positive feedback loop existing between relative sea level, sediment supply and barrier dynamics is apparent in this and other long term studies of morphological change and their driving factors. Another example is Jennings *et al.* (1998), who investigated the Holocene evolution of a gravel barrier, concluding that sea level fluctuations caused changes in local sediment supply and thus barrier dynamics. Once again, the interdependence is evident between different processes exerting control on lagoon geomorphology, meaning change is not only driven directly by these forcing factors, but indirectly through a complex network of feedback loops.

River mouth lagoons, and hapua in particular, have been studied intensely in New Zealand’s South Island. Kirk and Lauder (2000) compiled a report of significant coastal lagoon systems on the east coast of the South Island, and categorised these into hapua and waituna. The need for accurate data on sedimentation rates in these systems is highlighted in a management context. Kirk (1991) describes a distinctive sequence of behaviour for the Rakaia river mouth, which is a moderately sized river discharging at a wave dominated, mixed sand and gravel coast. This behaviour sequence can be applied to similar systems elsewhere and is characterised by the growth of a barrier across the river mouth in response to littoral drift, followed by freshwater lagoon development behind this coarse barrier. The lagoon mouth migrates in response to changes in river flow and sediment processes, which will be discussed further in Section 1.2.2. Further research surrounding the dynamics of river mouth lagoons on high energy, mixed sand and gravel coasts is presented by Hart (2007, 2009). Research into similar systems on sandy or other types of coasts is lacking, and it would be valuable to assess the applicability of these models to similar systems on such coastlines.

1.2.2 **Hapua**

The two lagoons studied in this project may be described as hapua type systems. Hapua usually occur at the mouths of braided, gravel-bearing rivers, and form as long, narrow waterbodies oriented parallel to the shore. They are predominantly fresh water and are separated from the ocean by a narrow barrier of coarse sediments, which forms as a consequence of strong longshore drift resulting in an offset river mouth (Hart, 1999; Kirk and Lauder, 2000). They typically form on high-energy coasts where marine processes are dominant over fluvial processes, and are thus common in New Zealand yet are not well documented in international literature (Hart, 2007). Hapua generally possess a single, semi-stable opening and are not subject to significant tidal inflows and outflows. During flood events the barrier may be breached to form new or multiple openings; however, these are only temporary (Todd, 1992; Hart, 1999; Hart, 2007).

Pre-requisite conditions for hapua formation include a microtidal regime (with tidal ranges of less than 2 m), high-energy wave climate and strong longshore drift. They occur at the mouths of ‘small’ rivers, i.e. those that carry insufficient sediment to prevent erosion by the sea of the coastline at their mouth, and usually occur on coastlines experiencing long-term net erosion but may also form on stable coasts (Kirk and Lauder, 2000). The formation of the lagoon begins with the creation of a sediment barrier along the beach in front of the rivermouth, due to erosion and reworking of cliff and river sediments by longshore currents. This occurs when waves approach sub-parallel to the beach, which moves material along it at the angle of approach, creating a longshore barrier which encloses the lagoon (Barnes, 1980). In the case of hapua, this barrier causes the rivermouth to be offset, and a depression created between the barrier and the land behind becomes the lagoon channel (Kirk, 1991; Todd, 1992) (Figure 1).

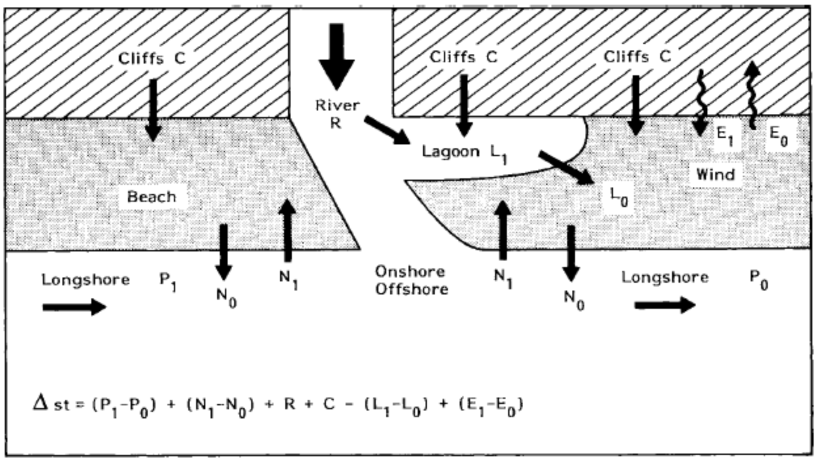


Figure 1.2. Schematic sediment budget and storage equation for a mixed sand-gravel river/beach/lagoon system such as the Rakaia rivermouth. P_1 = longshore drift into the mouth region, P_0 = drift out of the section. Onshore transport in the beaches (N_1) is distinguished from offshore (N_0) and lagoon sedimentation is divided into storage (L_1) and losses to the coast (L_0). Onshore (E_0) and offshore (E_1) sediment transport by wind are not significant on the Rakaia coast. *Sourced from Kirk (1991). p.277*

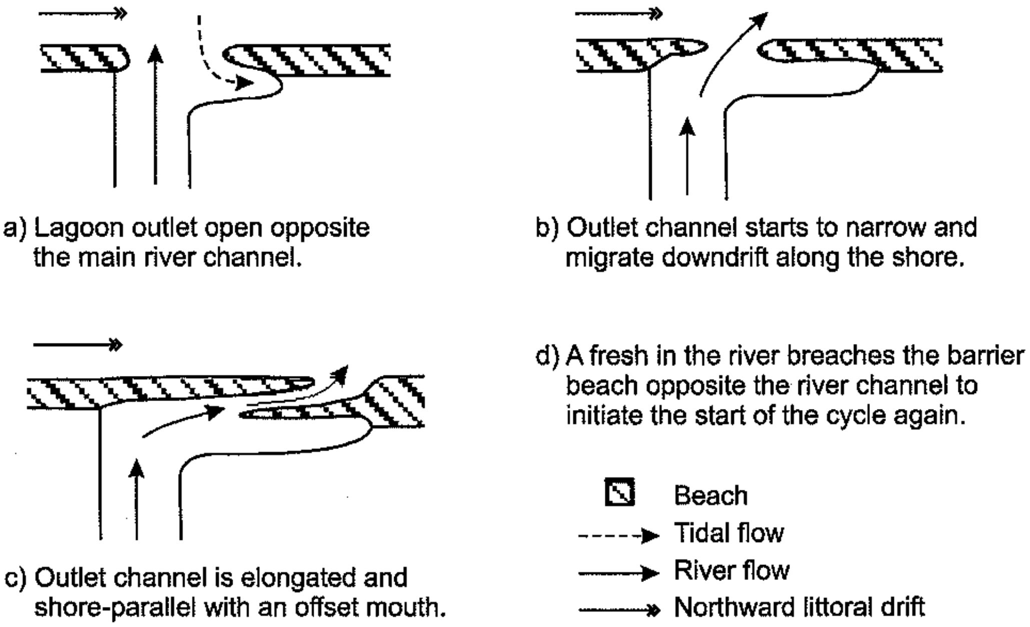
During sea-level rise and erosional phases, hapua are displaced progressively landward; however, the structure and cycle of the lagoon is believed to remain unchanged through this process (Kirk and Lauder, 2000). This is due to the fact that as the barrier is displaced through erosion, so too is the landward margin. This research does not include theory about the evolution of hapua on prograding or stable coasts.

Marine processes are dominant in hapua formation and evolution; however, change in fluvial input is the main driving factor in the timing and location of barrier breaches. Flood events and high river flows can cause breaches opposite the main river channel, which are often exacerbated by the action of high-energy waves on the barrier during storm events (Kirk, 1991; Shulmeister and Kirk, 1993; Hart, 1999). The role of waves and tides in barrier breaches is greatest in small hapua such as Waikoriri Lagoon (Hart and Single, 2004). Low river flows can result in outlet closure or channel migration. Unlike estuaries, hapua do not experience direct tidal inflows, although the water level can change in hapua in response to tides, through a ‘backwater effect’. This occurs when the drainage capacity of the lagoon opening and barrier is reduced by the higher water levels outside, and the water level inside the lagoon rises temporarily in response (Smith, 1995; Hart, 1999; Hart, 2007).

The permeability of the barrier is extremely important in hapua dynamics, as it controls the degree of throughflow between the lagoon water body and the ocean and determines the state of the outlet in response to varying river flows and wave action (Kirk, 1991; Todd, 1992; Hart, 1999). However, it is not the sole controlling factor, as the amount of throughflow between the lagoon and the ocean is also dependent on the hydraulic head between the lagoon and ocean water body. If river base flow is less than the barrier seepage capacity, there will be no outlet present. For a permanent outlet to be maintained, the base flow of the river must be many times the seepage capacity of the barrier. In between these two extremes, the outlet is more mobile and may open and close frequently in response to changes in river flow (Hart, 1999, 2007). Barrier permeability can vary widely between hapua, and at different places, levels, and conditions along a single barrier (Hart, 1999).

Models of hapua behaviour

Research into hapua dynamics and responses has centred on South Island, East Coast rivers, although the cycles and models described for these systems may be applicable to similar systems elsewhere. A distinctive process of gradual river mouth offset and lagoon development following a major flood event has emerged from these studies. Marine processes are generally dominant in hapua dynamics, but during a large flood event fluvial processes dominate and the barrier is breached adjacent to the main river channel. The flooded river injects a large amount of sediment into the system at this point, in the form of a subtidal delta (Kirk, 1991; Todd, 1992). Following the flood, marine processes once again dominate, and this sediment is pushed landward by wave action and transported by longshore drift. A barrier forms across the rivermouth, which causes the mouth to become offset and the channel becomes diagonally oriented across the barrier. As the barrier grows and becomes more stable, water becomes increasingly trapped and the size of the lagoon increases. As the water body grows, the outlet migrates in response to the changing dynamics of the system. This cycle continues until the barrier is once again breached at the river mouth by a flood event, resulting in the bypass of the existing lagoon and the start of a new cycle (Kirk, 1991; Todd, 1992). This sequence of changes is illustrated in Figure 1.3.


a) Lagoon outlet open opposite the main river channel.

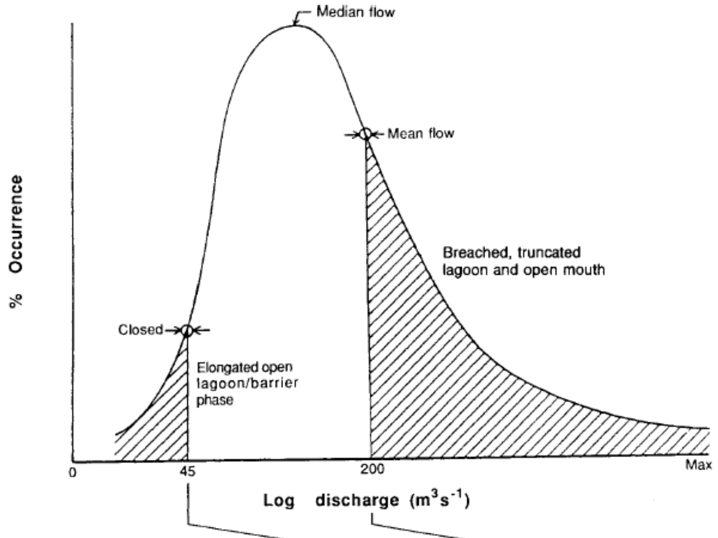
b) Outlet channel starts to narrow and migrate downdrift along the shore.

c) Outlet channel is elongated and shore-parallel with an offset mouth.

d) A fresh in the river breaches the barrier beach opposite the river channel to initiate the start of the cycle again.

Figure 1.3. Cycle of river mouth behaviour and outlet migration posited by Todd (1992, p. 212).

This sequence of events can be linked to numerical parameters of a specific system and a model created to predict the behaviour of a system at a given river flow. It is important to note that although the following model is based on river flow, marine processes remain the dominant driving factor of lagoon formation, and fluvial processes dominate solely during large flood events in the initiation of barrier breaches at the river mouth. A resource management model for the behaviour of the Rakaia River mouth is presented in Figure 1.4. For this particular system, the outlet is closed at low river flows, and possesses a single, migrating opening at more typical river flows. The threshold for a breach at the river mouth is defined as the mean annual flood flow (200 m3 s^{-1} for this particular system), resulting in lagoon truncation and the injection of a large sediment flux at the coast. Although this model is designed specifically for this system, the general dynamics are transferable to other hapua. Not all stages may occur in every hapua, and other stages which are not described here may occur (Hart and Single, 2004).



River flow	Low	Moderate	High (floods)
Throughflow	Minimal	Low	High in breach phase
Mouth stability	Closed	Open to sea. Mouth migrates northward	New mouth formed by breaching. Sometimes multiple mouths
		Offset either south or north, usually to north	Deltas formed to seaward by injection of gravels to lagoon
Lagoon	Closed	Open to sea; elongates northward	Truncated. Much of low flow lagoon becomes backwater
Sedimentation	Siltation in closed lagoon (sink)	Reworking of fines sink for coarse sediments	Active source of coarse sediments to lagoon and beach
		Source/sink of fines	Scour of land adjacent to channels

Figure 1.4. Descriptive model of mixed sand and gravel lagoon/spit/barrier processes. Threshold values are set for the Rakaia as functions of river discharge. *Sourced from Kirk (1991), Figure 6.* p. 285.

Hart (1999) presents a descriptive model of hapua dynamics in terms of both fluvial and marine processes (Figure 1.5). This three dimensional model recognises the effect of wave height (y-axis) and river flow (x-axis), either separately or in concert, on the barrier. Thresholds for changes in outlet morphology or hapua behaviour are recognised and identified through dashed lines present on the diagram. Different types of breaches and the processes driving each are depicted, which include flood-induced breaches. Storm-induced breaches, a combination of the two, and secondary breaches induced by floods where flows are not sufficient to induce a direct breach. Storm breaching occurs when large storm waves close the existing outlet of a barrier, yet continue to overtop the barrier and increase water levels inside the lagoon. This rise in water level increases the hydraulic head between the lagoon and the sea on the outgoing tide, and thus a new breach is initiated (Hart, 1999).

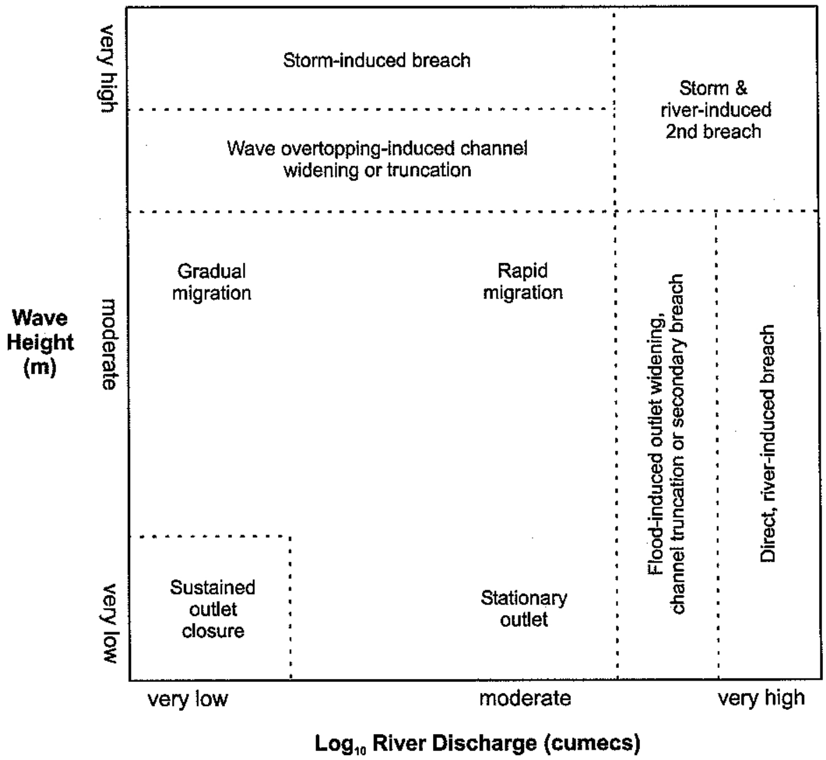


Figure **1.5.** Descriptive model of hapua behaviour illustrating the relationship between marine and fluvial driving forces. Thresholds are depicted for lagoon closure, outlet channel migration and different types of river-induced, storm-induced and combined barrier breaches. *Sourced from Hart (1999),* p. 198.

The models presented by Kirk (1991) and Hart (1999) are both able to explain the pattern of outlet offset observed by Todd (1992) (Figure 1.3), but do not consider all factors in concert. Kirk (1991) excludes the influence of waves on barrier morphology, which is addressed by (Hart, 1999). Neither model is able to factor in the effect of sediment supply, but it is acknowledged in both cases.

1.2.3 Evolution and development of coastal lagoons

Coastal lagoon evolutionary processes and histories have been well documented for specific areas of the South Island’s coastline over recent decades, in particular around the Canterbury region (e.g. Hemmingsen, 1997; Hart, 1999; Kirk, 1991; Neale, 1987; Shulmeister and Kirk, 1993; Soons *et al.*, 1997). An important recurring theme throughout this research is the balance between fluvial sediment input and sea-level changes (i.e. *relative* sediment input) as a driver for which evolutionary path a given coastal feature takes and its inherent lifespan. Where the sedimentation rate exceeds sea-level rise in a lagoon, it will infill within a short time span; whereas if the opposite occurs the lagoon will deepen and water volume will increase (Kirk and Lauder, 2000). This has important implications for the management of coastal areas; for example, catchment land use change may accelerate coastal infilling and lagoon loss, or river mouth dredging and modification may have the opposite effect. As such it is critical to understand the processes occurring in each individual setting in order to effectively manage it. For example, catchment land-use change may accelerate coastal infilling and lagoon loss, whereas river mouth dredging and modification may slow infilling.

Changes to features in the coastal environment occur on a variety of timescales, from seconds to millennia (Figure 1.6). These changes are driven by a set of drivers which interact with each other in a network of complex feedback loops (Figure 1.7), making it difficult to understand and predict coastal response on a detailed scale. The timescales involved in evolution of different features and the feedback loops involved are introduced by Wright and Thom (1977) and enlarged upon by Cowell and Thom (1994). The feedback loop involving topography, fluid movement and sediment transport is of primary importance in coastal morphodynamics and evolution. Schwarzer *et al.* (2003) applied this in their investigation of coastal evolution of the Pomeranian Bight at timescales from storm events to millennia. In this case, changes wrought by storm events remained visible on a decadal scale, while those that occurred in response to the long-term processes of sea level change and tectonics were unable to be accurately measured. The interaction between changes on these different timescales was observed, and consequently it was suggested that any coastal evolution investigation requires study of changes on all of these timescales to provide a comprehensive understanding of large-scale behaviour. A study of long-term changes in a coastal dune system was undertaken by Clemmensen *et al.* (2001), who used stratigraphy to assess long-term evolution, from which changes were attributed to climatic and storm factors. Historical records of change over recent centuries suggest an anthropogenic influence exists in later changes, interacting with other more natural variables.

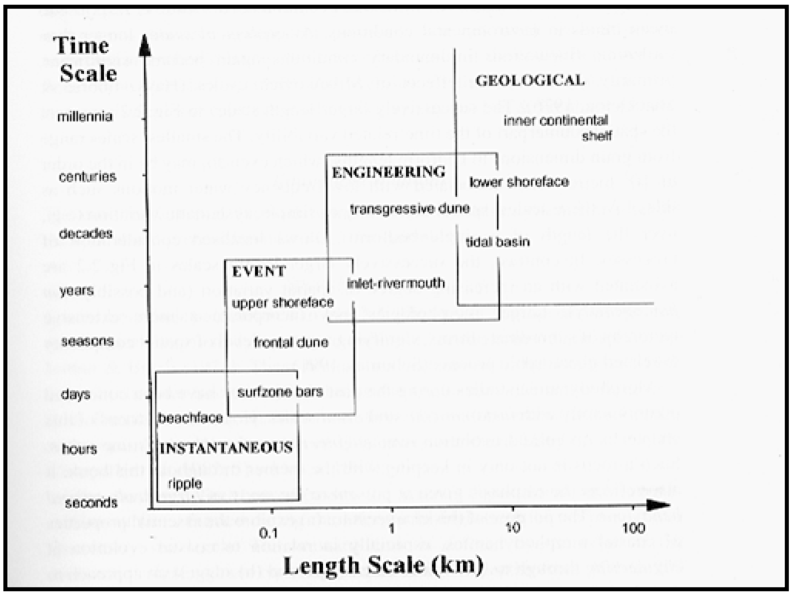


Figure 1.6. Definitions of spatial and temporal scales involved in coastal evolution. *Sourced from Cowell and Thom (1994).* p. 35

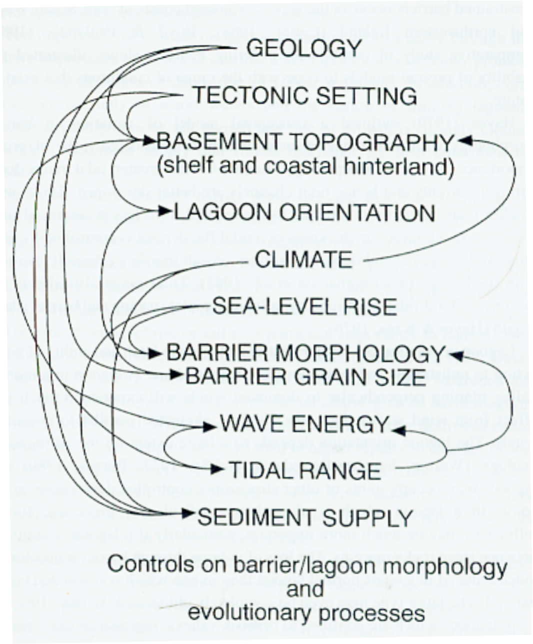


Figure 1.7. The complex interaction of processes which control evolutionary processes in a lagoon. The arrangement is broadly hierarchical but feedback between different variables renders the interaction complex. *Sourced from Cooper (1994),* p. 247

As a consequence of the enormity of the timescales and factors involved, research generally focuses on a single timescale or driving process, while recognising the importance of multiple processes and long-term change in a modelling and management context. Many such studies have been performed both internationally and within New Zealand. Studies which have focused on millennial-scale changes include Shulmeister and Kirk (1993), Meadows (2001) and Hemmingsen (1997). Shulmeister and Kirk (1993) investigated the evolution of a mixed sand and gravel barrier in Canterbury, New Zealand through Holocene sea level fluctuations and by stratigraphic analysis, determined the coast's rivers were trapped behind a barrier that was emplaced as sea level rose. The authors suggest this scenario is likely in other transgressive contexts where coastal sediment is generally unconsolidated, rather than being restricted to barriers of mixed sand and gravel type.

Meadows (2001) uses case studies from southern Africa to study the relationship between environmental changes during the Quaternary and evolution of coastal features during that period. Landscapes in this study were influenced not only by the dynamic climate, but by the impacts of human interference, the authors noting that it can be difficult to distinguish which is the dominant forcing factor. They concluded that the paleoenvironmental insights into solely climate induced change allowed later anthropogenic influence to be identified, which is very useful from a coastal management perspective.

Process-focused approaches to coastal evolution assessment and prediction potentially provide a more useful perspective on coastal changes, as by studying a key process rather than the individual factors driving it, a more complete record of change is gained. As the processes of sediment transport and hydrodynamics are part of the feedback loop influencing topography and form (Cooper, 1994), these are the two primary foci of this type of research. Cooper *et al.* (2001) use a sediment budget approach to predict coastal evolution in southern England, which is achieved through defining discrete littoral cells and identifying sediment sources, inputs and outputs, and sinks. The authors suggest this 'top-down' approach to modelling coastal geomorphology is a superior approach to other physical and hydrodynamic modelling techniques, which work on inputs of small scale process data (i.e. 'bottom-up'). With this approach, links are maintained between the interacting coastal processes on many spatial and temporal scales, allowing a variety of management scenarios to be trialled.

A large volume of research exists surrounding decadal scale shoreline and coastal changes in response to sea level, sedimentation and anthropogenic drivers. Understanding changes and processes on this scale is enormously important for coastal resource management and developmental planning. In addition to changes in sediment supply and relative sea level, coastal changes have been documented to respond to decadal-scale climate oscillations (e.g. El Niño Southern Oscillation Index, ENSO). Documentation of shoreline change using remote sensing and aerial photographic techniques has been popular and applied in a variety of settings. Romagnoli *et al.* (2006) assessed shoreline change over a 60 year period on an active island volcano, where new sediment was frequently supplied from eruptions. From these shoreline changes, spatial and temporal trends of erosion and accretion were identified and sediment redistribution paths were inferred. The need for concurrent data regarding nearshore currents was highlighted, as it is required to explain and understand transport processes leading to spatial trends of erosion and accretion. In this case, no direct current related data was available, but processes and direction were inferred from coastal morphology and meteorological data.

Battiau-Queney *et al.* (2003) performed a similar shoreline analysis to assess the sediment budget and mobility on a sandy coast in France over a 50 year period. In addition to the decadal-scale shoreline evolution, topographic surveys and profiles over much smaller timescales were also considered. In some cases along this coast, unusual patterns of erosion and accretion occurred, which could be explained by the depletion of sand reserves that had accumulated during the marine transgression following the LGM (Paskoff, 1998). Once again, this demonstrates the interplay between processes on a variety of timescales, which must be considered holistically if a complete picture of changes and operational processes is to be gained.

Solomon (2005) mapped shoreline change over a 49 year period to assess coastal hazard zones, calculate sediment budgets, and investigate the spatial and temporal variability of these changes in a Canadian delta. A database of coastal retreat rates was constructed, which was then used for coastal management and development purposes. Importantly, several areas exposed to heavy winds were identified as stable, which was due to the effects of increased sediment supply creating protective bars and mudflats.

The relationship between sea level rise and sediment supply in a salt marsh was investigated by Hastlett *et al.* (2003). No increase in vertical accretion occurred despite increased sediment supply; rather the extra sediment was deposited on the fringes of the marsh in the form of lateral accretion. This is believed to reflect general trends in salt marsh response to sea level and sediment drivers. Similarly, the spatial and temporal scales of change in inlet geometry and morphology in a Russian estuary were investigated by Behrens *et al.* (2009), including the response of the estuary to ENSO induced climate oscillations. These large scale climate oscillations were shown to have a significant indirect effect on inlet morphology, by affecting meteorological patterns and thus hydrodynamics and sediment transport patterns. In addition, inlets that were more curved were found to have a much higher risk of closure at all times.

Allard *et al.* (2009) investigated millenial-scale variability in a wave-dominated estuary (which could also be termed ‘coastal lagoon’), using a thorough combination of cores, high-resolution seismic and bathymetric surveys. Initially, an open estuary was present, which then became progressively more enclosed and infilled. This was related to changes in sea-level over the Holocene, and subsequent changes in sediment supply, wave and tidal energy further exacerbated the infill process. This is an important study in terms of estuary-lagoon dynamics, as it demonstrates the continuum between the two states: in this case, a decrease in tidal energy and an increase in wave energy meant this system moved from a tidally-dominated estuary to a wave-dominated system, contributing to the formation of the lagoon. Once again, the interaction and feedback loops between a variety of driving factors on differing timescales (sediment supply, marine environment, and sea level) is apparent in the evolution of this system.

1.2.4 **Hydrology of coastal lagoons**

By definition, coastal lagoons are not tidally dominated (Barnes, 1980; Hart, 1999; Kjerfve, 1994; Kirk and Lauder, 2000), and in particular; hapua, according to their strictest definition, experience no tidal influxes or salinity gradients. There may, however, be variations in salinity and water quality derived from land drainage and evaporation processes (Kjerfve and Magill, 1989). Circulation and water exchanges in coastal lagoons are driven by a complex set of factors, including weather, wind, sea level and heat and water exchange with the atmosphere (Kjerfve and Magill, 1989). Typically, coastal lagoons are shallow, with depths of only a few metres. Consequently, the water column is generally well mixed and no vertical stratification of temperature or salinity occurs (Barnes, 1980; Smith, 1981; Kjerfve and Magill, 1989). The main geomorphological factors influencing the hydrology of a lagoon are inlet size and shape, water depth and lagoon orientation to prevailing winds (Smith, 1994). The balance between freshwater (fluvial or rainwater) input and marine influence is the primary control in the case of the systems studied here.

A large volume of research surrounding hydrology of coastal water bodies has been undertaken globally, although much of this relates to estuaries or deltas rather than coastal lagoons specifically. Despite this, some of these findings can be applied to coastal lagoons, especially in the case of Totara Lagoon, which currently experiences a substantial degree of tidal influence, so perhaps could be described as being in an estuarine phase.

The degree of tidal influence occurring in an estuary, the form and behaviour of the tidal wave, and the depth to the saltwater intrusion penetrates depends heavily on channel morphology and river flow. Blanton *et al.* (2002) investigated the tidal current dynamics in a long, shallow estuary, finding that the tidal waves were distorted and asymmetrical. This finding is in agreement with earlier studies (Speer and Aubrey, 1985; Wang *et al.*, 1999) all of which recognise the relationship between channel morphology and current flow. Slope of the channel bed can also cause tidal current asymmetry, as the energy required for the current to move upstream on the incoming tide is greater than required on the down-hill outgoing tide in this type of situation. Tidal intrusion also relates to river flow, as described by Vaz *et al.* (2005), who modelled salinity and temperature gradients, matched with field data inputs, in an estuarine channel. Results showed that in periods of low river flow, the channel was tidally dominated, but was dominated by freshwater flow in periods of high river volume. The tidal wave also changed shape as it propagated up the channel, becoming distorted by channel geometry and bathymetry.

The relationship between saltwater penetration, mouth morphology and river flow is further illustrated in the case of the Senegal River delta (Isupova and Mikhailov, 2008), which was a large delta that became blocked off by longshore drift and formed an estuary, part of which is now becoming a lagoon. The construction of a dam upstream decreased the flow reaching the river mouth, which is now subject to greater tidal influence than previously experienced. This saltwater propagation is exacerbated by the low gradient of the river surface. Although these changes in morphology were generated by human-induced change upstream, this is a good example of the flow-on effect that was wrought by a decrease in river flow. This affected longshore sediment deposition and hydraulics of the river mouth, consequently altering the local morphology.

Hapua, and choked lagoons in general, experience very little or no tidal influence, acting as a true river outlet. Thus, the hydrology of these lagoons is driven by river flow (Kirk, 1991; Hart, 2007). This is due to their structure, which is typically a single, narrow channel through which they exchange water with the ocean (Barnes, 1980; Fernandes *et al.*, 2004). This channel acts as a hydraulic filter, which dampens or eliminates tidally driven water level oscillations within the lagoon (Kjerfve and Magill, 1989; Fernandes *et al.*, 2004). This effect is explored by Fernandes *et al.* (2004), who combined hourly measurements of water elevation with a tidal simulation model in a choked lagoon in Brazil. Findings suggested that the narrow channel limited the amplitude of tidal oscillations within the lagoon to between 1 and 11% of those in the outside ocean, and the ability of the channel to filter these fluctuations varied seasonally and in response to volume of river flow. Lower frequency sub-tidal oscillations (on an approximately fortnightly period) occurred in response to synoptic forcing, and these tended to propagate further into the lagoon than the higher frequency tidal oscillations. As well as enhancing understanding of tidal hydraulics in choked lagoon systems, studies such as this can provide important data that can contribute to predicting future changes in lagoon morphology.

Changes in water temperature and salinity structure can occur on a variety of different timescales in response to storm events or increased evaporation. Smith (1981) investigated heat exchange in a Florida lagoon, concluding that during summer, the dominant forcing factor is the absorption of solar radiation controlled by cloud cover. The temperature of the water responded to various other meteorological forcing factors throughout the other seasons. Temperature results presented by Vaz *et al.* (2005) showed that water temperature in the system studied was closely related to spring/neap tidal cycles and river flow, exhibiting a strong horizontal gradient with water transport.

This is likely to be absent or less pronounced in systems that exhibit a greater degree of mixing.

1.2.5 Morphodynamics in the coastal environment

This research is based on the fundamentals of morphodynamics and conceptual modelling of hapua dynamics. The study of coastal environments can be performed either directly, through real time measurements of the acting processes, or indirectly through the study of topographic features, structures, and sediment textures (Carter and Woodroffe, 1994). The term morphodynamics refers to the use of these two approaches in concert, thus relating process and form within a single study (Carter and Woodroffe, 1994), and is the approach used in this study. Morphodynamic theory as it relates to coastal evolution is thoroughly discussed in several key coastal textbooks (e.g. Cowell and Thom, 1994; Masselink and Hughes, 2003; Woodroffe, 2003).

Coastal morphodynamics can be defined as *“the mutual adjustment of topography and fluid dynamics involving sediment transport*” (Wright and Thom, 1977 p. 412), and results in the processes and changes described as coastal evolution. These evolutionary changes operate through a series of feedback loops which exist between the topography of the system and the influence of fluid dynamics on sediment transport, which in turn results in morphological change (Carter and Woodroffe, 1994). The morphodynamics approach allows each component or process involved in a system (e.g. a coastal lagoon) to be studied individually, yet the context of each within the system as a whole is maintained. This is a particularly useful concept for studies of rivermouth lagoon environments, due to their complexity of processes and related response (Figure 1.7).

The evolution of coastal features is complex and does not follow a specific formula or respond in a linear fashion to forcing factors. Each system is constrained by boundary conditions and the cycle of evolutionary changes taking place is bound by the principle of Markovian Inheritence, by which the product of previous changes (i.e. antecedent topography and hydrology) provides the initial conditions upon which future evolutionary processes build (Cowell and Thom, 1994). Coastal landforms can evolve on timescales of hours to millennia, in response to the highly varied time periods of forcing factors, such as weather events, climate changes, tectonic forcing, and sediment supply (Carter and Woodroffe, 1994) (Figure 1.6). The interaction and interdependence between the processes, resultant landforms and timescales makes predicting the future of a given coastal system extremely difficult through traditional numerical and statistical models. Consequently, this study will employ an approach which is primarily conceptual, avoiding total reliance on numerical inputs and outputs.

The study of a given coastal landform cannot be restricted solely to the feature of interest, as the spatial boundaries of a morphodynamic system extend beyond the physical limits of the current system to include the area occupied by the system as it evolved through the Quaternary (Cowell and Thom, 1994). This is necessary, as by the principle of Markovian Inheritance, it is these past changes that provide the framework around which current evolution occurs. Process boundaries of a system refer to the extent of external controls exerted on a system, such as geology, climate, and oceanic forcing, which affect the sediment throughput and fluid flow as well as defining the physiographic setting of the area (Cowell and Thom, 1994).

The application of morphodynamic theory to coastal lagoons specifically is not a simple matter. Lagoons form in many different ways in response to differing environmental conditions and forcing factors, and thus can display substantially different morphologies (Carter and Woodroffe, 1994). Long-term lagoon evolution and morphodynamics has not been widely studied and most existing models apply only to a specific type of lagoon. In addition, the definition of the boundary conditions of a lagoon system is a complex matter, as lagoons respond and form in response to a diverse combination of factors – including fluvial, marine and terrestrial processes (Figure 5).

An important challenge in modelling coastal behaviour is relating the short term transport and hydrodynamic processes, which can be measured, to long-term morphodynamic changes, of which only the products can be observed. As pointed out by de Vriend *et al.*(1993), Nicholson *et al.* (1997) and Roelvink (2006), this causes these models to perform poorly in providing detailed predictions. Varying approaches to morphodynamic modelling and methodological considerations are discussed and applied in illustrative examples by Roelvink (2006). The tide-averaging approach uses wave, current and transport data over a tidal cycle to calculate the expected change in seabed during this period, which is continually corrected over longer time periods. The RAM approach uses initial transportation and sedimentation rates to calculate seabed changes, which is faster than the use of a full morphodynamic model, although much less accurate. However, neither of the aforementioned methods perform well with varying input conditions. The parallel online approach recognises that input conditions may vary substantially, and thus performs several simulations using different conditions simultaneously, updating the bathymetry from an average of these simulations.

Hart (2009) deals specifically with morphodynamics of river mouth lagoons on high energy coasts, which is of particular interest to this study. Rather than numerically modelling changes in particular systems, a conceptual model of interactions between hydrodynamics, sediment supply and transport, and drivers of barrier morphology is presented.

A problem highlighted in all research pertaining to morphodynamic modelling is that of accuracy and verification of results or predictions arising from the numerical calculations. The nature of modelling to predict future change means that until the predicted change takes place, or otherwise, the model cannot be deemed ultimately accurate. The use of models to explore and simulate the operation of contemporary processes in natural science can be an important tool if used wisely, and while accounting for limitations and quality of data required for parameterisation. However, the extent of their value as a predictive tool is still under debate (e.g. Oreskes *et al.*, 1994; Cooper and Pilkey, 2004a, 2004b).

Morphodynamic study of a given coastal area does not have to rely solely on numerical models, although without these the result produced is conceptual (but potentially more honest and appropriate) rather than a quantified prediction of rate and volume of change. Povilanskas *et al.* (2009) describes the morphodynamic trends of a Russian dune ridge through the Holocene, concluding that the dune ridge has flattened over time in response to exhaustion of sediment supply, vegetation loss and human intervention. While not a quantified measure of change, these sorts of observations are hugely important for coastal management decisions.

Integrated models are another form of conceptual models that are popular in coastal management literature, as they encompass the dynamic and multi-influence nature of the coastal environment. The development and implementation considerations of using an integrated model is described by Capobianco *et al.* (1999), and will be discussed further in later sections. Cooper and Pilkey (2004a, 2004b) discuss the problem of the numerical model inaccuracy and point out several workable alternatives to the use of these models. Alternatives to the mathematical modelling of beaches are presented in these papers, and in particular aspersions are cast on the use of the Bruun Rule to predict shoreline retreat in response to sea level rise. Although these papers pertain specifically to models for beaches, the principles of the alternatives presented can be applied to the modelling of other coastal features as well. These include looking at changes on neighbouring beaches with similar characteristics, using past experience on the beach in question, using a composite approach, ‘go slow-go soft’ management strategies (i.e. gently experiment), and to predict nothing (Cooper and Pilkey, 2004b). The authors highlight the importance of recognising that future sequences of events are unique, and thus predictions based on past and present observations may not be valid.

1.2.6 Reconstructing past environments in coastal settings

Coastal lagoons are believed to be short-lived features on a geological timescale (e.g. Cooper, 1994) and much research has focused on documenting changes in these sensitive systems in order to understand changes in climate, sea level and other driving factors. This usually entails a multidisciplinary study of the environment in question, and may include studies of stratigraphy, sedimentology and ecology from cores, bathymetry, hydrology, geophysical profiling and surveying. From the study of sedimentology and microfossils in coastal sediment cores, the environment at the time of deposition can be inferred. Changes in the system over time can be constructed, and conclusions made regarding the processes responsible for this change. This can be applied to studies of relatively recent change (in the order of decades to centuries), or longer term change (centuries to millennia). Changes in coastal environments are particularly useful in studies of paleoseismology, as changes in relative sea level can be used to infer vertical displacement (either through subsidence/uplift or sedimentary compaction) resulting from a seismic event (Cochran *et al.*, 2007). Although the aim of this project is not specifically to assess seismic activity, the goal is still to investigate and document environmental change over time and the techniques are applicable in multiple research contexts. In addition, the coastal plain upon which Shearer Swamp and Totara Lagoon are situated is subject to large-scale tectonic disturbance associated with the nearby Alpine Fault.

International studies that have used these techniques to assess landscape evolution and morphology in the coastal zone include Clemmensen *et al.* (2001), Haslett *et al.* (2003) and Allard *et al.* (2009), all of whom applied a multidisciplinary and holistic approach. Clemmensen *et al.* (2001) investigated the evolution of a coastal dune system in Denmark over the Holocene period, and the interaction between natural and anthropogenic drivers on its development. Changes in the dune system in response to climate change were documented from stratigraphic analysis of sediment cores, and a clear signal of human-induced change in dynamics was identified following increased habitation of the area. Haslett *et al.* (2003) assessed changes in salt marsh sedimentation in western France over a 120 year period, and related patterns of depositional/erosional change related to specific driving factors. The findings of Allard *et al.* (2009), discussed in section 1.2.3, are also pertinent here.

Paleoseismological studies and those relating to relative sea level have been undertaken in coastal environments worldwide, which highlight regional tectonic climate and seismic events as important drivers of change in the local coastal environment. Mathewes and Clague (1994) investigated relative sea level changes associated with co-seismic subsidence and uplift in British Columbia. Microfossil analysis was able to show periods of rapid change in salinity (and thus relative sea level), related to large earthquakes. This technique can detect small amounts of change that leaves no lithostratigraphic signature, which demonstrates the sensitivity of the coastal zone to changes in relative sea level, and would also be valuable in contexts outside of seismology. Similarly, Zong *et al.* (2003) used analysis of sediment cores from a salt-marsh to assess land subsidence. In this case, gradual subsidence had caused a bog environment to be flooded by the sea, creating a salt-marsh environment. The authors point out the possibility that other drivers might cause a coincident change in relative sea level, and that factors such as sediment mixing and hydrological change may also cause changes in microfossil assemblages. This is in agreement with Yabe *et al.* (2004) and Sawai *et al.* (2004), both of whom used similar processes to document paleoenvironmental changes along the Japanese coast and pointed out the considerable difficulty in breaking down the individual causes of that change and quantifying the effect of each. Nelson *et al.* (1998) investigated the history of relative sea level change in an American estuary, and also challenges the assumption that every large change in a microfossil assemblage reflects local subsidence. The authors posit that instead, some of these horizons could be related to hydrodynamic changes in the estuary or tsunami deposits. It could be suggested that some of the uncertainty surrounding studies such as these would be lessened by further research into the local hydrodynamics and sediment supply, such as the techniques being employed in this study.

There has been a significant volume of research undertaken in New Zealand using coastal environments for paleoenvironmental reconstruction, detection of seismic events and to document the tectonic history of an area. This research has focused on mainly tectonically active areas of the North Island. Chague-Goff *et al.* (2002) and Hayward *et al.* (2004) used microfossil analysis primarily to detect seismic events and associated tsunamics.

Several studies aiming to document climatic change and coastal system development over the Holocene have been undertaken elsewhere in New Zealand. Horrocks *et al.* (2000a, 2000b) used sedimentological and microfossil analyses from cores taken in a coastal swamp environment to document the development of that swamp throughout the Holocene sea level and climate changes. The changes inferred from these analyses were consistent with the New Zealand sea level curve presented by Gibb (1986). Hicks and Nichol performed a similar analysis of a wetland, documenting the succession from a transitional-marine environment, to brackish, to freshwater swamp. Changes in depositional energy are apparent in this transition, and there are clear indications of human impacts in terms of vegetation change related to deforestation. This research has direct relevance to the study of Shearer Swamp, which formed during the same period and was likely subject to similar processes. These studies are significant in terms of documenting sea level change throughout the Holocene, as well as providing insights into the development of coastal wetlands that can be applied to similar systems in less advanced stages of infill.

The environmental history of Okarito Lagoon, a large estuarine inlet situated in Westland to the south of Shearer Swamp (Figure 1.8), was documented by Goff *et al.* (2001) and the geomorphology deemed to be controlled by local seismic activity. Goff *et al.* (2004) and Nichol *et al.* (2007) used a multidisciplinary approach, similar to that of this study, to document the changes in the lagoon over recent geological time and detect possible tsunami inundation horizons. This work is particularly significant, due to the proximity of Okarito Lagoon to the field sites in this project, and the fact that they too are subject to large-scale tectonic disturbance from the nearby Southern Alps. Results of this research suggest the area experienced two large tsunamis in recent geological time (one in 1826, and another dated at 630-455 years before present), corresponding to known ruptures of the neighbouring Alpine Fault. The findings of Nichol *et al.* (2007) are subject to some debate, as some researchers believe these may be storm deposits rather than tsunami deposits (Professor James Shulmeister, University of Canterbury, *pers. comm.*). In addition, the inherent problems with interpreting and connecting results, and extrapolating them outside of the immediate sampling area are highlighted.

Also in South Westland, Wells and Goff (2009) investigated dune ridge formation in the area to determine the history of seismic events in the area. Findings suggest that a period of coastal progradation occurred within 50 years of each large tectonic disturbance in the area over the past 800 years. Individual earthquake events resulted in the delivery of a sediment pulse to the coast, which then contributed to the formation of coastal features in the region.

It is clear from this collective research that a multidisciplinary approach, or at least the use of more than one technique is preferable to a single-analysis study, and provides the most complete and complementary record of environmental change.

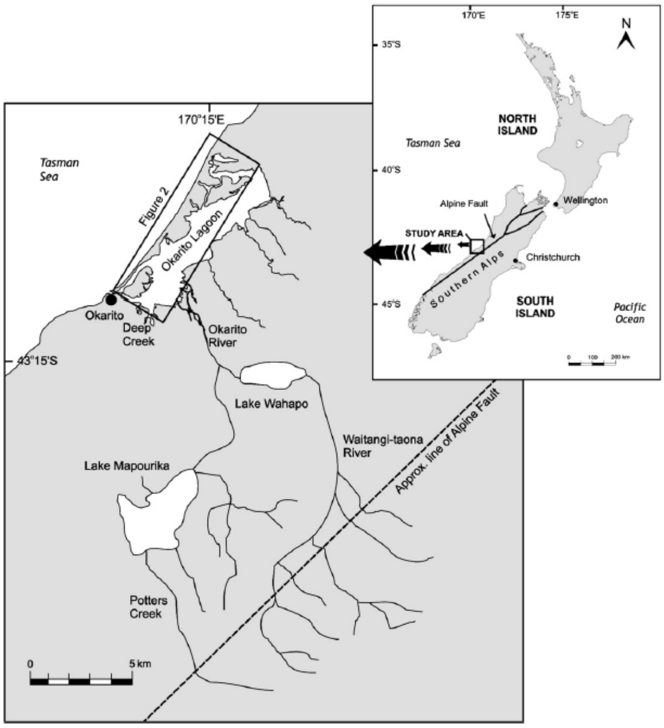


Figure 1.8. The Okarito Lagoon locality. Okarito Lagoon is a large coastal lagoon situated approximately 50 km south of Ross township. *Sourced from Nichol et al. (2007, Figure 1).*

1.2.7 Coastal management

The connectivity of fluvial and marine environments at the coast and the dynamic nature of this interface have become increasingly important from a coastal management perspective. The coastal zone is subject to intensive human activity, including recreation, habitation, industry, fishing and transport. An overview of literature surrounding the management of river mouth zones is presented here, along with a synopsis of New Zealand coastal management structure. Anthropogenic influence and management on the West Coast, including issues specific to Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon complex, are discussed in Chapter 7.

The resources of the coastal environment are diverse and are crucial to the economies of many countries and settlements along its borders. As such, it is important to understand the processes acting in a local environment in order to assess the potential impact of human activities in the area. As population grows, the management and preservation of these resources becomes more important and more difficult as conflicting viewpoints emerge. The concept of ‘Integrated Coastal Management’ is what drives management strategies and resource division in most developed countries, and aims to balance the different needs of the public, industries and developers in the coastal zone. This concept is reviewed in an international context by Nichols (1999), who concludes that this system is likely to result in degradation of the environment at the expense of economy (and has already occurred in some areas), and that alternative resource management systems need to be explored.

Internationally, management of dynamic coastal features is moving increasingly away from engineered structures (so called ‘hard-protection’ measures, such as sea walls and jetties) to ‘soft-protection’ works in order to prevent erosion of the coastline or undesirable river mouth migration. This involves techniques such as artificially redistributing sediment to renourish an eroding area, or creating a barrier breach to move the outlet of a lagoon or estuary. These measures are viewed as less damaging to the environment as they do not constrain the processes of nature, but modify the environment to work with these processes, or at least reduce their undesirable effects.

This approach was discussed by Gao and Collins (1995), which they termed the ‘design with nature’ principle. The equilibrium between different active processes and characteristics of the coastal system needs to be understood, from which a workable management strategy is constructed that does not interfere with this equilibrium. Two criteria are stated to manage human impact on the system: human impact must not destroy the processes through which equilibrium is maintained, and the rate of any human-induced change must not exceed the rate at which this type of change would occur via long-term, natural processes. This principle can work well in areas that have a long history of monitoring and which are inherently relatively stable, but it is difficult to apply in very dynamic systems that display a large range of behaviours and are not well researched. In addition, this does not account for factors such as sea level rise, which may render historical observations of system behaviour obsolete for the purpose of predicting long-term system response.

In terms of estuaries and lagoons, outlet position and morphology is the primary characteristic of concern to coastal managers. As well as directly affecting access, river flow and water volume, the outlet character affects water quality and ecology of the water body. Vila-Concejo *et al.* (2004) follow the artificial relocation of two large estuarine outlets in Portugal. In order to maximise success of any artificial opening or relocation, the choice of new outlet location is paramount. Factors that must be taken into account include historical observations of outlet migration, hydrodynamic regime of the system (and whether this has changed), and morphology and dynamics of the barrier (Figure 1.9). The authors stress the importance of comprehensive environmental impact studies, including geomorphology, ecology and hydrology, and the need for post-relocation monitoring. The examples presented here were very large-scale; however, the principles remain applicable to smaller coastal lagoons such as those studied here.

Sea level rise is of concern to coastal managers worldwide, as coastal systems are very sensitive to the changes in energy dynamics that occur when water level rises (Pethick, 2001). In response to a medium to long-term transgression, coastal landforms migrate landwards, while maintaining their relative position to adjacent landforms. This is a natural process, but one which is often considered undesirable to coastal dwellers and landowners, often resulting in measures to halt this geomorphic response. Pethick (2001) discusses the tradeoff that must be made in the future management of this process. If managers continue to act with static, short-term measures designed to halt or slow the process, radical change in coastal landforms will result as a consequence of ‘coastal squeeze’. In contrast, the character and safety of the coastal environment can be maintained by assessing rates of change and accepting the sacrifice of coastal land where it is viable to do so. This approach has become known in the United Kingdom as ‘managed retreat’, and has been trialled at two estuaries in the UK (Emmerson *et al.*, 1997; Pethick, 2001). In the case of the Blackwater Estuary (Emmerson *et al.*, 1997), existing hard structures have been removed in places to allow the restoration of natural salt marshes, which are a key part of the coastal system ecologically and in terms of dissipating marine energy.

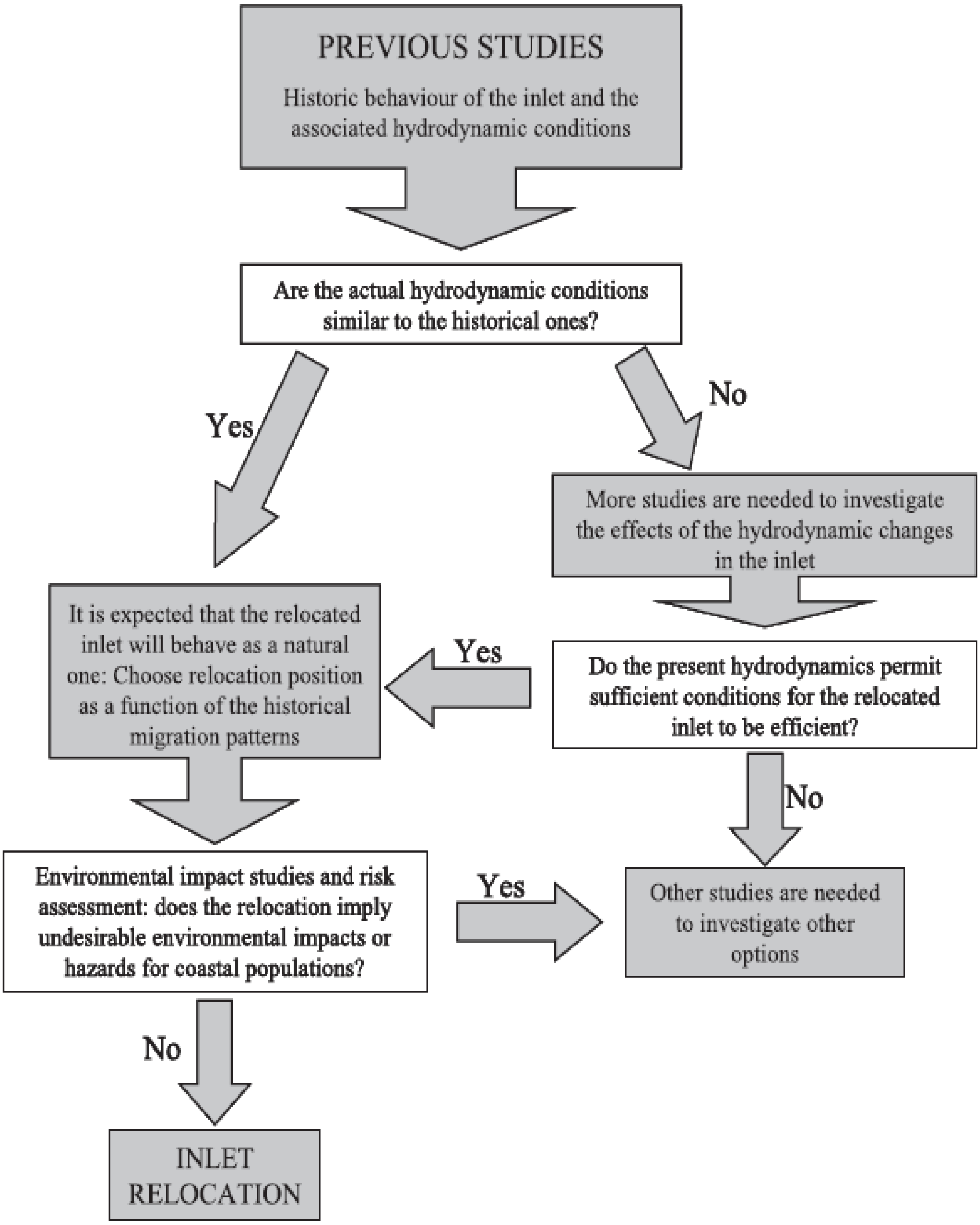


Figure 1.9. Schematic representation of theoretical practices recommended by Vila-Concejo *et al.* (2004) when assessing the impact of inlet relocation. *Sourced from Vila-Concejo et al. (2004, Figure 14* p. 987).

In a New Zealand context, coastal management is extremely important, due to the country's large coastal perimeter. Hart and Bryan (2008) use case studies of two very different types of coastal systems, which experience different wave and sediment conditions, to highlight the need for system and area-specific management strategies and associated background information of processes and form. In terms of coastal lagoon management, researchers commonly recognise the importance of connections between the lagoon and the adjacent marine area and river catchment, both of which must be considered when assessing potential environmental impact (Kirk, 1991; Hart and Bryan, 2007; Hart, 2009b). The greatest issue surrounding hapua management relates to artificial opening of the lagoon mouth, either to protect neighbouring communities from flooding, or to promote recreational use (Kirk and Lauder, 2000). Further discussion of coastal management in relation to hapua is presented in Chapter 7.

Management framework in New Zealand

Coastal management in New Zealand is directed by a hierarchy of statutes ultimately controlled by the national Resource Management Act 1991 (RMA) and working down to local council level. The RMA was designed to provide guidelines surrounding the management of natural resources and promote their sustainable use and development. This applies to coastal, catchment and atmospheric environments, and was introduced to standardise environmental management in New Zealand and replace numerous separate overlapping and, therefore, confusing pieces of legislation. The natural character of coastal environments and their surrounds, including rivers and wetlands, is recognised as an issue of national importance.

Alongside the RMA, the New Zealand Coastal Policy Statement (NZCPS) was introduced in 1994, which pertains specifically to the coastal zone and acts as a link between the RMA and regional coastal management plans which have been formulated to work in conjunction. The NZCPS provides more practical, detailed information surrounding the application of RMA guidelines in regional coastal plans and the enforcement of local laws in the coastal environment. Below the national level, the regional council is responsible for managing the natural resources of the area, which is usually performed separately for the coastal area, catchment zone and other areas. The management hierarchy structure for the Canterbury region is detailed in Hart (2009b) (Figure 1.10), and is more complex than that of the West Coast region. This regional management scheme is not well integrated, and Hart (2009) points out that the potential is there for a regional governing body to develop an integrated scheme if they choose. For hapua and coastal wetlands this would be the ideal scenario, as often these systems are influenced more by processes in their connected catchment or marine area than by those acting in the immediate area (Kirk, 1991; Hart, 2009).

Figure 1.10. Flowchart showing the hierarchy of management of the coastal environment in New Zealand under the RMA. *Sourced from MfE (2008b), Figure 6.1* pp. 61

1.2.8 **Research gap**

Coastal research as a discipline has advanced hugely in recent decades, both nationally and internationally. Hapua-type coastal lagoons have been reported to be rare globally yet common in New Zealand and existing research is centred mainly on the east coast of the South Island. As such, there is enormous scope for further research into these systems elsewhere, to gain a greater understanding of their dynamics and the processes that form them. This knowledge is necessary for the purpose of management and development of coastal areas, and for issues such as water resource management and concerns of climate change and sea level rise. There is also a necessity to investigate the parallels between hapua-type lagoons and other types of lagoons, in particular those defined as estuaries or estuarine lagoons.

The West Coast region represents a major research gap in terms of New Zealand coastal research, and consequently the processes and coastal history of the region are not documented or understood to the level required in making coastal management decisions. The coastline of the West Coast is particularly dynamic due to the extreme climate and sedimentation processes in the region and, as such, there is a lot of scope to investigate these processes and draw from the results implications of major benefit to local government and management organisations.

Research surrounding coastal geomorphology and management has been sadly lacking on the West Coast, primarily due to budget and access constraints. Much of the existing research was undertaken by government organisations or private companies or individuals, often as part of consent applications or land and industry development and is thus not readily available. The Department of Conservation (DOC) and West Coast Regional Council (WCRC) have commissioned much of the coastal research to date. The majority of river mouth outlets and coastal wetlands in the region have been generally documented and classified (e.g. WCRC, 2000); however, few have been studied in depth.

1.3 Research objectives

Arising from this literature review, the primary objective of this thesis is to explore the geomorphology of two rivermouth lagoon systems in the West Coast region and determine their historical development, present day structure and dynamics in order to predict their future under changing climate, development and management scenarios. In addition, to advance New Zealand and international understanding of rivermouth lagoon systems by producing scientific and management models that are widely applicable to this type of environment.

These aims can be broken into several distinct objectives applicable to both field areas, which are as follows:

- To document their current topography and structure,
- To explain their current hydrology,
- To understand their development through historical time and relate this to the current state of each system,
- To analyse the processes driving these changes in geomorphology,
- To explore factors likely to influence changes in these systems over the following 100 years and determine how each system might respond to these drivers individually and collectively,
- To develop a conceptual model of process and response that can be used to predict future changes of each system and which is applicable to similar settings elsewhere.

1.4 Thesis structure

The purpose and objectives of this research have been presented in this chapter, along with a conceptual context and theoretical background to the study. Previous research was presented and discussed. Research was reviewed and divided according to the objectives of this project, with research pertaining to present day coastal processes and form presented first, followed by paleoenvironmental research. There are significant gaps in this research body, which have been identified and form the rationale for this particular project.

Chapter 2 provides a comprehensive overview and background of the study area and setting: explaining regional climate, hydrology, geology, sediment supply and a review of previous local research and history. This is important background and context, and provides a reference point for interpreting the developmental history of these systems and making predictions regarding future system geomorphology.

The following chapters present the methodology employed in the project and the subsequent results achieved. Chapter 3 is dedicated to methodology, and Chapters 4, 5 and 6 present the results. These chapters are sectioned by time period and field site. Current geomorphology (Chapter 4) is investigated through the use of GNSS topographic surveys and water level records are used to investigate the hydrology. Past changes of these sites are determined through the analysis of sediment cores for sediment character and texture, the results of which are presented in Chapter 6. Interpretations of these results are presented at the end of each chapter.

Chapter 7 is dedicated to an integrated discussion of these results. The present geomorphology and hydrodynamic functioning will be interpreted with reference to existing models of hapua dynamics, and linkages between past process and present form will be explored. Linkages between driving factors and form will be discussed and these systems will be classified in the context of coastal lagoon and estuarine literature. From these results, a conceptual model of lagoon process and response will be applied to these systems and their future will be explored and compared under different climate and management scenarios. Issues currently faced by the local and regional authorities in managing these important areas will be identified and discussed.

The main findings and implications are summarised and reviewed in Chapter 8, the final chapter. Also presented are limitations to the application of results from this study, and limitations of the methodological approaches employed. Areas for further research are identified.

CHAPTER TWO

Study Area

2.1 Introduction

The physical and climatic environment of the West Coast region is profoundly impacted by the location and orientation of the New Zealand landmass (Sturman, 2001). A comprehensive understanding of this environment is necessary to provide a context for changes which occur in the coastal environment in response to physical or climatic forcing factors. This chapter will describe the environment and climate of the study areas and the West Coast region in more detail, and place this in a New Zealand context. As well as setting a general physical context for the study of these lagoons, it seeks to highlight aspects which are pertinent to understanding the processes operation on the lagoons and driving changes in their morphology. After descriptions of the wider region, the chapter then focuses on the physical settings of the two study sites, Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex.

The West Coast Region is a 600 km length of coastline situated on New Zealand's South Island, and is a very dynamic environment that can respond quickly to environmental forcing factors. The open coastline is highly exposed to the prevailing westerly weather systems of the 'Roaring Forties' and thus experiences very high energy wave action (Salinger, 1980; WCRC, 2000). The coast is aligned northeast – southwest, which causes the waves to arrive sub-parallel to the coast, and their energy is further enhanced by the fact that the continental shelf drops off a relatively short distance from the coast, particularly in the south (Stanton, 1976; WCRC, 2000).

In addition, the coast receives high rates of sedimentation due to the large suspended sediment load transported by the rivers from the nearby Southern Alps (Neale et al., 2007). The beaches are commonly made up of mixed sand and gravels, and there is a mixture of long beach shorelines interspersed with pocket beaches and rocky headlands where the coast comes into contact with the exposed rock of the mountains.

The West Coast region is situated in the transition zone where sub-tropical waters meet the colder waters of the sub-Antarctic Southern Ocean. The predominant direction of littoral drift is northwards, although at times this is offset by southward drift from Southern Ocean currents and storm events (Stanton, 1976; Bradford, 1983). This northward current transports sediment which is then deposited on the Challenger Plateau to the north of the region, although much sediment is transported off the continental shelf and out of the system via two large offshore canyons situated to the south of the region (Stanton, 1976; Bradford, 1983; Neale et al., 2007). The physical environment of each study area is described in the following sections.

The two sites of interest differ hugely in size, structure, and dominant processes. Both are situated on a narrow coastal plain in Westland, on either side of the township of Ross (Figure 2.1).

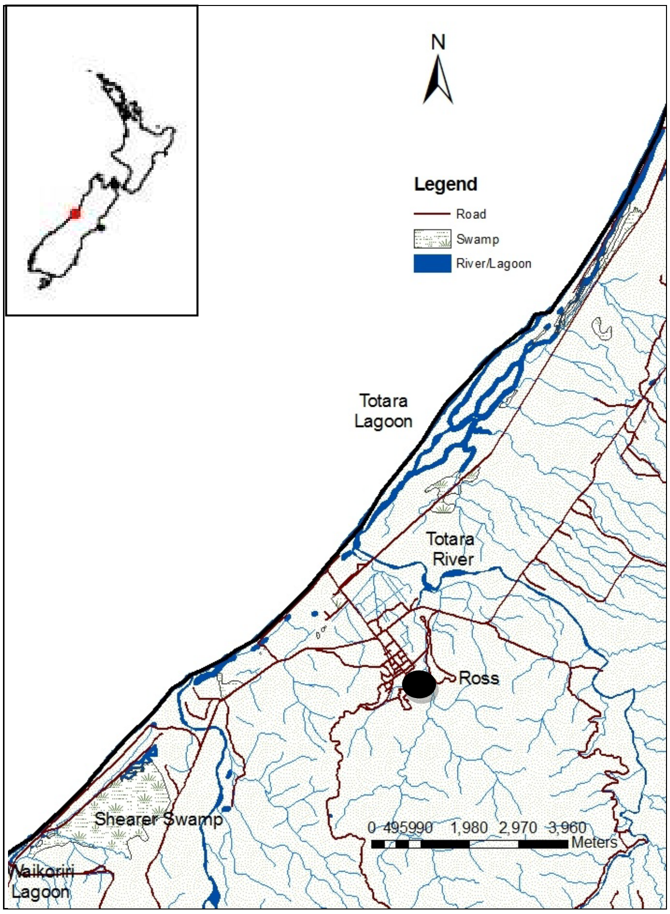


Figure 2.1. Location map showing the study sites in relation to New Zealand, each other and the township of Ross.

2.2 Geology and soils

The geology and geomorphology of an area are the present imprint of past processes and the base upon which future processes act and landforms develop (Cowell and Thom, 1994). The West Coast is an area of high tectonic activity due to the close proximity of the Alpine Fault system and the Southern Alps, which are the result of the oblique convergence of the Australian and Pacific tectonic plates (Suggate *et al.*, 1978; Goff et al., 2001). The Australian Plate is being subducted obliquely beneath the Pacific Plate in New Zealand's southwest corner (the Puysegur Subduction Zone) and the opposite is occurring to the East of the North Island (Hikurangi Subduction Zone) (Figure 2.3). The Alpine Fault system connects these two zones and runs the length of the South Island in a single, right-lateral oblique slip fault. Consequently, the adjacent Westland region is subject to significant, ongoing tectonic disturbance (Goff et al., 2001; Neale et al., 2007). The Southern Alps consist largely of easily erodible schists, which are subject to intense compression and shear along the Alpine Fault. Uplift rates of approximately 6-7 mm.yr^{-1} and horizontal displacement of 30-40 mm yr^{-1} interacting with large and frequent rain events leads to heavy erosion of these schists and a large sediment flux to the coast (Suggate *et al.*, 1978; Goff et al., 2001).

The basement geology of the West Coast region is between 300 and 450 million years old and formed as part of the ocean sediments of Gondwana (Marton, 2004). These are exposed in occasional places, but are generally overlain by younger, sedimentary sequences. The specific area surrounding Totara Lagoon and Shearer Swamp is dominated by glacial outwash fans and moraine belts, remnants of the last glacial period (Suggate *et al.*, 1978; DOC, 2003; DOC, 2007). The Otiran Glaciation occurred in the region between 12 000 and 22 000 years ago, during which time sea level was between 100 and 200m lower than present and glaciers extended well beyond the present coastline south of Hokitika (Soons and Selby, 1992).

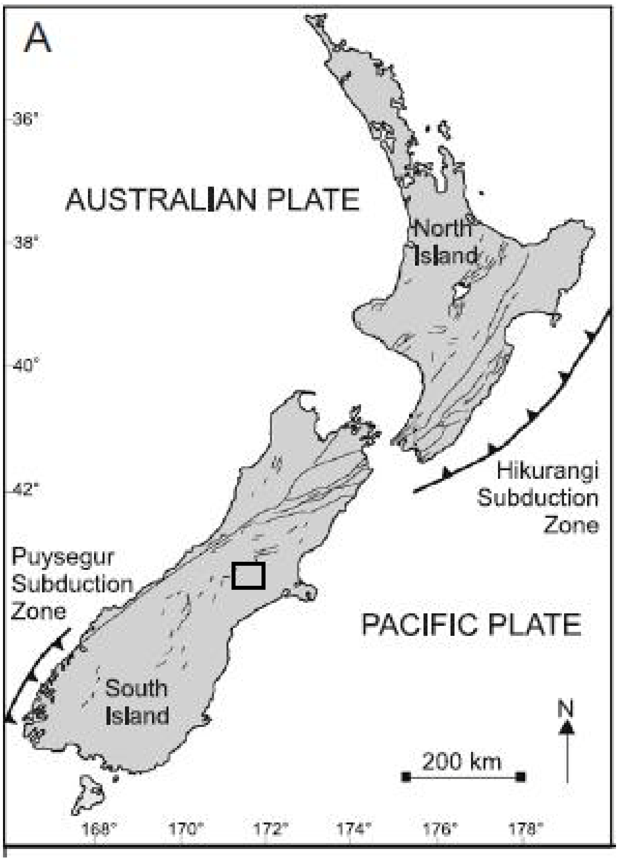


Figure 2.2. The tectonic setting of New Zealand. The alpine fault can be seen running the length of the South Island, and Westland is situated north of the Puysegur Subduction Zone. The study area is depicted by the black square. *Modified from Cochran et al. (2007), Figure 1, p. 1131*

Shearer Swamp is situated upon a coastal plain comprised of fluvio-glacial gravels and sands related to the Otiran glaciation, and coastal deposits (DOC, 2003). Following the glacial retreat at the end of the Otiran Glaciation and subsequent sea level rise, the existing low-lying land was drowned during the early Holocene. The resulting coastal embayment has been subject to uplift events and infilling, leading to the development of the current swamp and lagoon system (Hart and Single, 2004). The current coastal plain is very narrow, and is bounded by the Rangitoto Range to the east, and smaller hills to the north and south. Bold Head, a distinctive moraine bluff, lies at the southern boundary of the system. The deposits of this plain are poorly consolidated and easily erodible, and the sediments consist of schists, greywacke, granite, quartz and serpentinite, brought down from the nearby Southern Alps (Suggate *et al.*, 1978). Soils have been identified as mostly Kini organic soils, with more recent Karangarua gley soils to the south of Waikoriri Creek (DOC, 2003). Peat deposits of the coastal plain upon which Shearer Swamp lies are estimated at a total volume of six million cubic metres (Davoren, 1978), and overlie blue-grey silt in the east, and coarse brown sand in the west.

The area surrounding Totara Lagoon is also dominated by glacial features as well as coastal and fluvial deposits. At the southern end of the lagoon, the river mouth itself is comprised of alluvial deposits from the Totara River, and further up the valley are glacial tills and outwash deposits known as the Moana Formation. These were deposited towards the end of the Otiran Glacial period, between 17 000 and 14 000 years ago. At the northern end of the lagoon, the plain consists of coastal deposits of sand and silt, river-gravels, and swamp deposits (Suggate *et al.*, 1978; DOC, 2007). The most prominent feature of the landscape to the east of the lagoon is the Loopline lateral moraine, which is composed of glacial till and outwash gravels deposited during the Otiran Glacial period, approximately 22 300 – 18 000 years ago (Suggate and Moar, 1970). The terminal moraine of the Loopline Glacier is not present; however it would have extended beyond the currently coastline and included the majority of the Totara Lagoon area (Suggate *et al.*, 1978). Soils around the entire lagoon have been classified by the New Zealand Department of Scientific and Industrial Research (NZDSIR) as “hygrous Mahinapua yellow-brown sands” (DOC, 2007 p. 7).

2.3 Climate

New Zealand is a relatively small landmass, which is oriented northeast-southwest and situated between 34 and 47 degrees of latitude. The West Coast region lies approximately between 42 and 44 degrees of latitude, which coincides with the boundary between the cold subantarctic waters and warmer subtropical waters of the Pacific Ocean (Stanton, 1976; Bradford, 1983; Neale et al., 2007). This oceanic front circles the globe and gives rise to strong westerly weather systems, thus known as the ‘Roaring Forties’ (Figure 2.3).

The climate of the Westland Region is temperate, moist and relatively mild. The region is subject to extremely high levels of precipitation, with an average of 2500 mm annually along the piedmont, increasing to over 12 000 mm in the mountains (Salinger, 1980). The close proximity of the Southern Alps and narrow width of the plain causes an orographic rain shadow effect east of the Alps, leading to extreme precipitation levels in the upper western catchments. These events are often intense and short-lived in nature and, consequently, the number of regional sunshine hours approaches the national average despite the high precipitation levels. There is seasonal variation in precipitation, with significantly more events in spring and summer and relatively dry winters (Garnier, 1958). Temperature also varies seasonally, although summers are cooler and winters milder than expected by latitude alone (Garnier, 1958). Hokitika temperature records taken by the National Institute of Water and Atmospheric Research (NIWA) between 1971 and 2000 recorded maximum and minimum temperatures of 30 and -3.4 °C respectively, with a mean temperature of 11.7 °C over this 29 year period (NIWA, 2009).

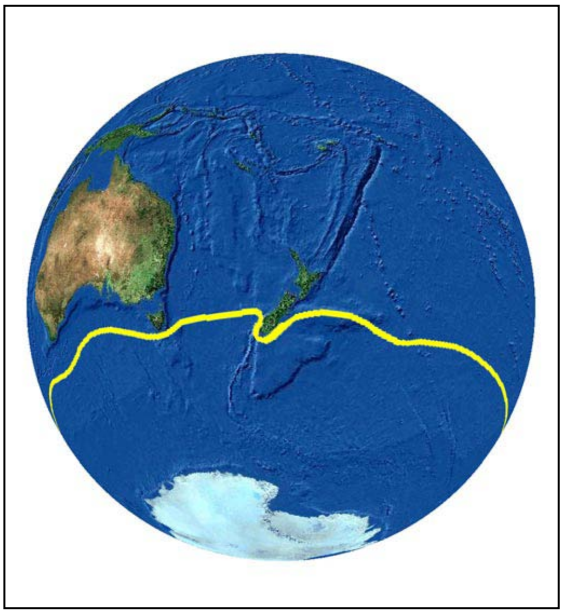


Figure 2.3. The approximate location of the subtropical convergence. *Sourced from Neale et al. (2007, Figure 2.3 p. 12)*

2.4 Marine environment

The West Coast marine environment is intense and extremely dynamic, as a result of the location and orientation of the coastline. The subtropical convergence zone marks the boundary between the cold sub-Antarctic water mass and the warmer sub-tropical waters of the Pacific Ocean, and is situated just south of the Westland region. The cooler, sub-Antarctic water mass to the south of this zone does not directly impact the West Coast and the ocean currents of the region are mainly driven by the warmer, subtropical water mass of the Tasman Sea (Stanton 1976; Bradford, 1983; Neale et al., 2007). The influence of this zone of disturbance on local weather is huge as the coast is directly exposed to the prevailing westerly weather systems, which cause the region's wave climate to be extremely dynamic and high energy.

The continental shelf off the West Coast is situated very close to shore (less than 20 km offshore in places), particularly towards the south (Figure 2.4). The water coming in from the Tasman is forced to divert around this obstruction, with the coastal currents of the region being primarily wind-driven (Stanton, 1976; Bradford, 1983; Neale et al., 2007). The most important feature of the seabed topography off the coast of the study area is the presence of the Hokitika Canyon, which is one of a large network of offshore submarine canyons in South Westland. The Hokitika Canyon begins adjacent to the Mikonui Rivermouth and extends into the coastal marine area (Figures 2.4 and 2.5). These canyons act as sediment sinks; draining much of the shelf sediments from longshore drift (Neale et al., 2007).

The predominant direction of current flow along the entire coastline is northwards, known as the Westland Current. The region is also subject to southward flowing 'coastal-trapped waves', which are very long waves of only a few centimetres in height that are imperceptible to all but the most sensitive instruments. These waves do not directly affect the coastal environment of the area but act to either slow down the prevailing northward current, cause it to change direction, or accelerate a southward running current (Cahill et al., 1991). The ocean currents affecting the West Coast region are detailed in Figure 2.6.

The tidal cycle on the West Coast is the same as that of the rest of New Zealand; a 12.4 hour cycle (LINZ, 2009a). The section of coast relating to this study experiences spring tide ranges of approximately 2.1 m with southerly and westerly swells dominant (LINZ, 2009a). Surface water temperatures are relatively warm; ranging from approximately 16.5° C in the summer to 12° C in winter months (DOC, 2004). Close to the shore this tends to be less, due to the influx of cooler freshwater from rivers combined with the influence of the Westland Current (Moore and Murdoch, 1993).

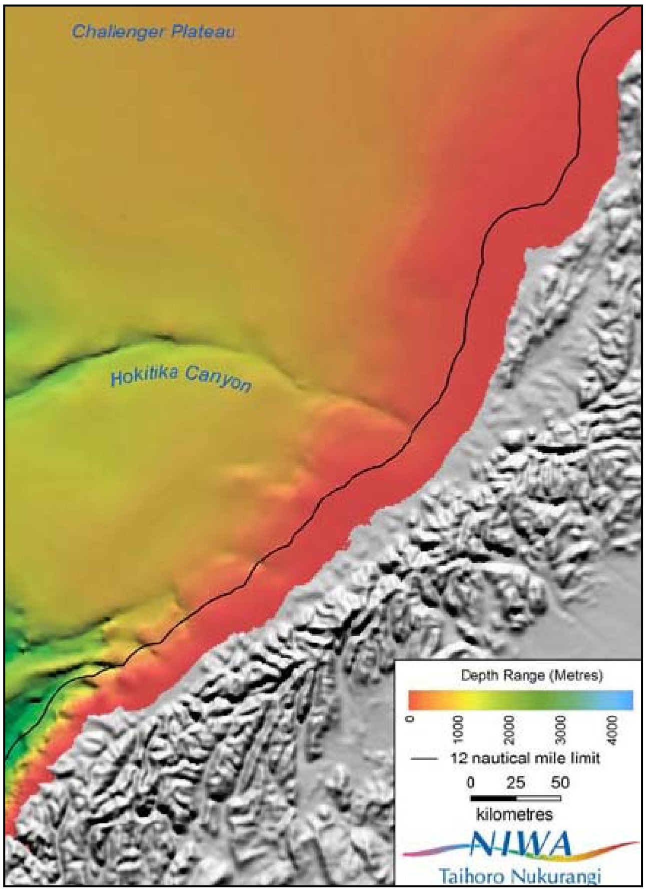


Figure 2.4. Undersea landform features of the West Coast. The width of the continental shelf can be seen to decrease dramatically southwards along the coastline. *Sourced from Neale et al. (2007), Figures 2.7 and 2.8 p. 20*

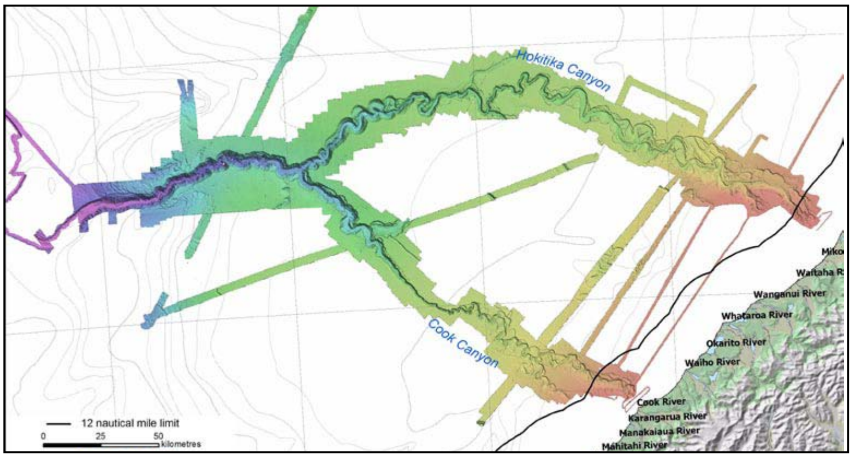


Figure 2.5. The structure of the canyon network off the coast of Westland. The Hokitika Canyon is adjacent to the Shearer Swamp-Waikoriri lagoon Complex. *Sourced from Neale et al. (2007), Figure 2.8 p. 20*

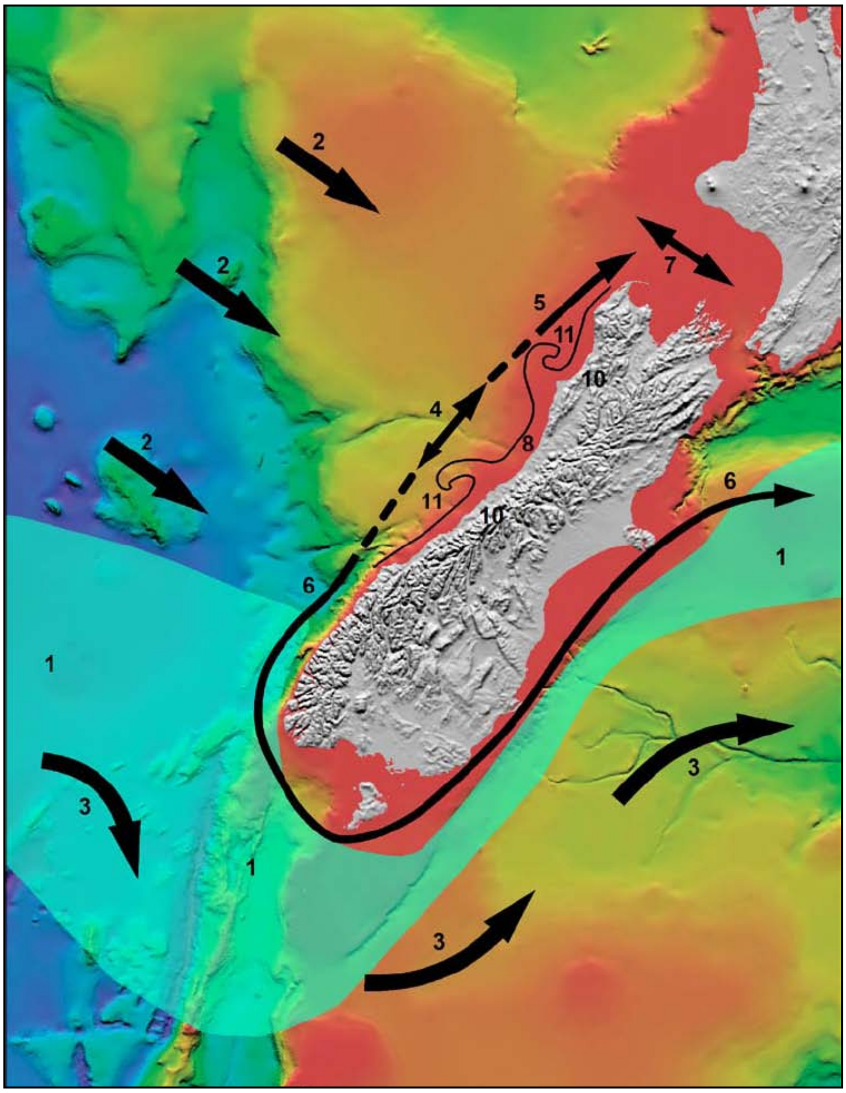


Figure 2.6. The ocean currents of the West Coast region. Numbers refer to features described in the text, as follows: 1 = Subtropical Convergence, 2 = Tasman Current, 3 = Antarctic Circumpolar Current, 4 = West Coast shelf surface currents, 5 = Westland Current, 6 = Southland Current, 7 = Wind-generated oscillations in Cook Strait, 8 = West Coast inshore zone, 9 = Upwelling (not depicted), 10 = Freshwater inflows, 11 = “Squirts”. *Sourced from Neale et al. (2007), Figure 2.3 pp. 15*

2.5 Sediment supply

The nature of West Coast weather systems and geology mean that southern and central West Coast rivers have extremely high sediment loads, which have been placed amongst the largest in the country by NIWA suspended sediment discharge models. This high sediment load causes large amounts of sediment to accumulate on the beaches and the continental shelf. In the area surrounding these sites, much of the sediment reaching the continental shelf is captured and removed from the system via the Hokitika canyon system. The coastline is oriented south-east to north-west in this region, and the net drift direction is northwards. The net rate of this transport is calculated at 240 000 ± 10 000 m^3 yr^{-1}, of which 93% is sand and gravel (Gibb, 1987).

Swamps act as natural sediment sinks, and over geological time are inclined to infill (Woodroffe, 2003). Shearer Swamp is consistent with this, and a large volume of sediment is deposited in the system from the catchment area of the contributing streams. Most of the sediment originates from large slips that have occurred in the upper catchment and washed down tributary streams in recent years. This process is accelerated through the removal of this sediment and creation of unconsolidated stop-banks from landslide debris to protect farmland, which are then disturbed and remobilised by subsequent flood events.

2.6 Site descriptions

2.6.1 Totara Lagoon

Totara Lagoon is a much larger, more permanent lagoon system than Waikoriri, and stretches 10 km northwards from the Totara rivermouth at Ross (Figure 2.7). It is a long, narrow, hapua-type lagoon, with the water surface covering approximately 100 ha (Neale et al., 2007; DOC, 2007). It is fed predominantly by the Totara River, which currently discharges at the southern extremity of the lagoon, although the mouth has been displaced varying distances along the 10 km long channel at times. There are also a number of smaller creeks which feed into the lagoon further north, which are: Gows Creek, Woolhouse Creek, Rocky Creek and Camp Creek. There is a significant tidal influence in this waterbody, extending several kilometres up the channel. Totara Lagoon is separated from the sea by a sandy beach and low sand dunes, which become steeper and more heavily vegetated towards the north end of the lagoon. There is evidence of dune blowouts in many places along the barrier, up to and for a distance past the current northern extremity of the waterbody.

2.6.2 The Shearer Swamp-Waikoriri Lagoon Complex

Shearer Swamp is a large, freshwater wetland that occupies 135 ha on a narrow coastal plain south of the township of Ross (Figure 2.7). The Department of Conservation (DOC) have classified the swamp as a combination of wetland classes, including fen, swamp, bog, pakihi, and coastal lagoon (DOC, 2003). It is low-lying (less than 3m above sea level) and slopes from east to west, making the western edge closer to the water table (Hart and Single, 2004). The wetland is bounded by two small streams: Granite Creek and Waikoriri Creek on the southern and western sides, and by Ferguson's Bush (through which State Highway 6 runs) on the northern side. These two creeks meet at the south-west corner of the swamp, approximately 100m inland from the sea, and drain through Waikoriri Lagoon. Shearer Swamp is heavily vegetated with flaxes and *coprosma* shrubs, with large pockets of well developed *podocarp* trees along the southern and eastern margins. Sediment in the swamp area consists of muds and peat, the latter being recorded to a maximum depth of 3.5 m (Davoren, 1978).

Waikoriri Lagoon is part of the same system as Shearer Swamp, and forms the outlet to the sea that drains the wetland (Figure 2.7). It is a small hapua-type lagoon, which extends up to 4 km northwards from the confluence of Granite and Waikoriri Creek. The lagoon occupies a swale behind the beach and foredune, and is separated from Shearer Swamp by a series of low-lying sand dunes. On the seaward side of the lagoon, the barrier is between 20 and 80 m wide, and consists predominantly of coarse sand with a small percentage of gravel and fine sand (Hart and Single, 2004). Waikoriri Lagoon is not a stable, permanent feature, being constantly in a state of change ranging between its maximum extent of approximately 2 km to being present as an empty channel at the back of the beach. The causes of this variability are a combination of natural processes, such as storm events, and anthropogenic influence and management. Marine processes (i.e. wave energy acting on the barrier and outlet) are the dominant factor in this lagoon, as the Westland region has an extremely high energy marine environment, and there is relatively little fluvial input from Granite and Waikoriri Creeks.

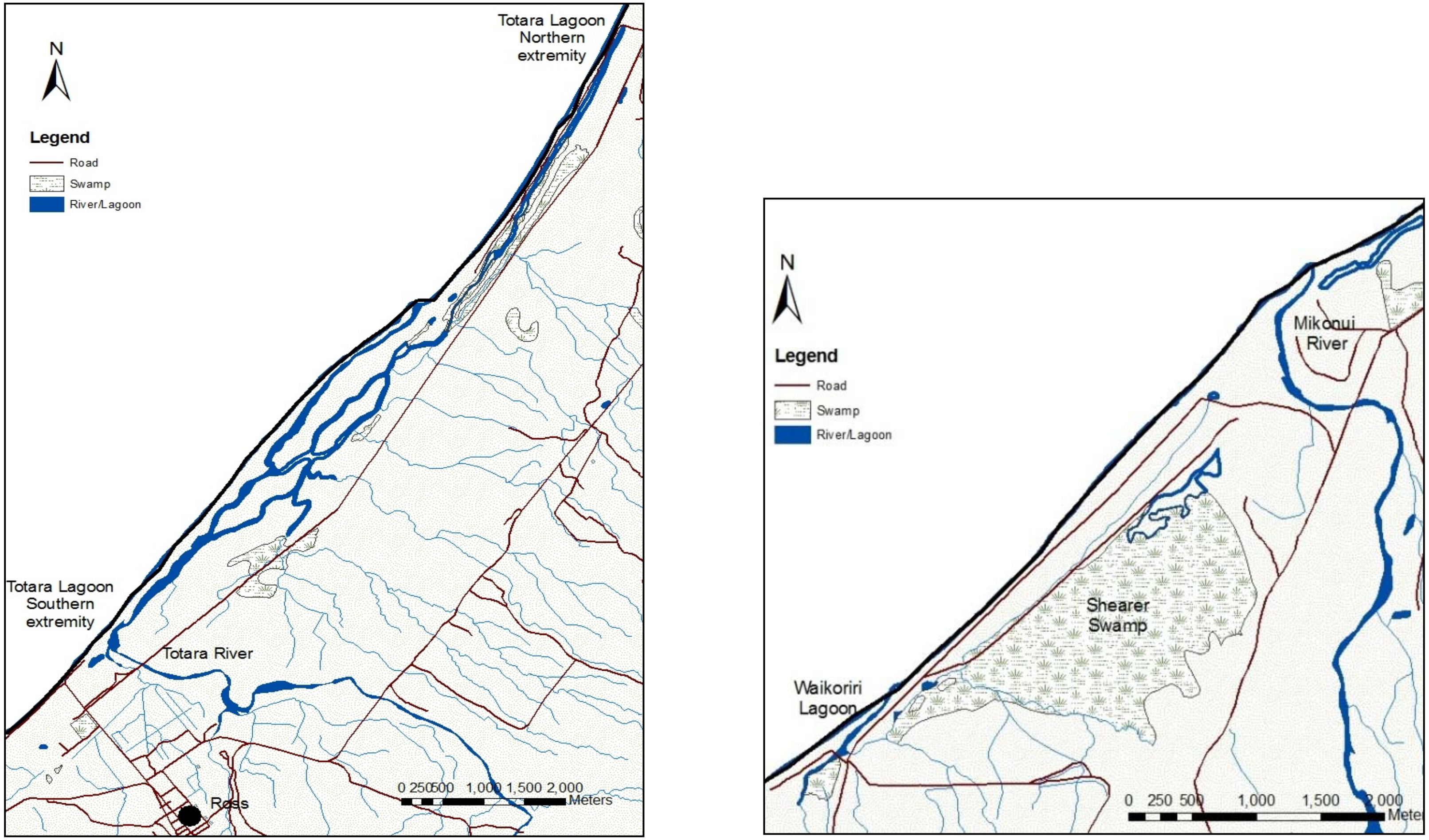


Figure 2.7. Location maps showing Left: Totara Lagoon and Right: Shearer Swamp-Waikoriri Lagoon complex.

2.7 Hydrology

Totara Lagoon is a very large system and as such, exhibits complex hydrology. The catchment area of the lagoon itself is approximately 13 563 ha, of which forty percent lies at an altitude of less than 100 m (DOC, 2007). The main water source for the lagoon is the Totara River, which currently discharges at the southern extremity of the lagoon but the opening of which can migrate up to several kilometres northwards from this point. Seven streams have been identified and mapped by DOC as contributing to the middle and northern reaches of Totara Lagoon, including Gows Creek, Stenhouse Creek, Woolhouse Creek, Camp Creek, and Rocky Creek. These streams drain an area of private land in the hills to the east, and their margins are now well vegetated with flax and gorse (DOC, 2007). In addition, water enters the system through numerous smaller streams and seepage zones from adjoining swamps to the west. The water in Totara Lagoon is brackish, as a result of tidal influence at the river mouth which extends several kilometres up the channels. This results in long residence times for water in the northern end of the Totara Lagoon system.

The hydrological regime of Shearer Swamp and Waikoriri Lagoon is not fully documented or understood and, in particular, questions surround the degree of hydrological connectedness between the northern and southern ends of the swamp. Water enters the main swamp system from rain and streams or subsurface flow (namely Dickey Creek, Granite Creek, and Ferguson’s Creek), which bring water from the hills to the east and north of the swamp. Water is also brought from the south by Waikoriri Creek and Pearn Brook, although these do not travel through the main area of the swamp. The swamp drains from east to west, into Waikoriri Creek (the western boundary of the true swamp), which then flows south and discharges into the sea through Waikoriri Lagoon. At the northern end of the swamp a now-blocked channel formerly provided drainage into the Mikonui Rivermouth, particularly during floods. It has been posited that rather than a single drainage network culminating in discharge through Waikoriri Lagoon, the swamp may be separated into two distinct hydrological areas by a topographical divide, with the southern areas draining through the lagoon, and the northern areas draining into the Mikonui River (DOC, 2003). This is supported by field observations following a recent barrier breach event, when water levels remained high in the northern area although they dropped dramatically to the south. The natural hydrology of this system has been influenced by farming and development in the surrounding areas and higher in the catchment, and through artificial openings of the Waikoriri Lagoon barrier. These will be discussed further in the following sections.

Marine processes are clearly the dominant process agents in Waikoriri Lagoon. There is a small fluvial outflow from the mouth of Waikoriri Creek, which discharges into the high energy West Coast marine environment. It is suggested that the Waikoriri Lagoon barrier is of low permeability (due to the abundance of fine sediment and lack of gravel), which would allow an outlet channel to be maintained at most times despite the small fluvial outflow (Hart and Single, 2004).

2.8 Anthropogenic influence and management

Totara Lagoon has also been subject to significant anthropogenic influence throughout historical times. There is no historical documentation of Maori use of the area, but it is likely that the wealth of food sources and natural resources were put to use. Since March 1983, the lagoon area has been owned and protected by the New Zealand Wildlife Service and the Wetland Acclimitisation Society, through the formation of the ‘Totara Lagoon Wildlife Management Reserve’. The area is now managed by DOC, although some islands, such as Frenchies Island and Tui Island, are privately owned. The adjoining land to the west is also farmed, as is a thin strip of land on the eastern bank of the waterbody’s northern reaches.

Totara Lagoon’s long history of significant anthropogenic disturbance dates back to the 1870s. Prior to the construction of a highway between Ross and Hokitika (1871-1873), a boat down Mahinapua Creek, then overland, followed by another boat down the lagoon was the main route of transport between the two towns. From 1865, a small settlement was situated at the northern end of the lagoon to service this route, and another appeared at the southern end (DOC, 2007). In addition to the large-scale mining operations occurring in Ross during the gold-rush years of the 1870s, mining occurred in the areas adjoining the lagoon. The glacial outwash terraces on the eastern side of Totara Lagoon were mined in parts, and the beach sands in direct line with these areas to the west of the lagoon were also mined for gold between 1872 and 1878 (DOC, 2007). Mining of the black sands on the beaches to the west of the lagoon has continued intermittently until the present day. A modern mining company is currently operating southeast of the Totara River mouth, and at times discharge from this operation causes mineral output and staining of the rocks at the river mouth/southern end of the lagoon.

Clearance and drainage of the adjoining land for farming has modified the natural hydrology of the lagoon, particularly in the north, where large areas of swamp have been, and continue to be, drained. The presence of cattle grazing up to the lagoon edges in some places has caused degradation of the vegetation and sediments at the margins, and accelerated dune erosion (DOC, 2007). Dune erosion is also exacerbated by recreational motorcyclists and four wheel drive enthusiasts who make frequent use of the beach, particularly at the northern end. In addition, the lagoon area is popular for whitebaiting, fishing, and game bird hunting. Like Waikoriri Lagoon, historical anecdotes suggest that the lagoon has been subject to artificial opening of the mouth at the southern end to facilitate whitebait migration. The mouth of Totara Lagoon is currently situated directly opposite the main coastal river channel, where it has been artificially maintained via sediment removal over recent years.

Like Totara Lagoon, Shearer Swamp and Waikoriri Lagoon have been the subject of significant anthropogenic influence over historical times. The main body of Shearer Swamp north of the Waikoriri Creek boundary is currently Crown owned land and managed by DOC. Farmland to the west of the swamp and south of Waikoriri Creek is privately owned, and is bounded to the north by Ferguson’s Bush Scenic Reserve. Shearer Swamp itself is recognised and listed as a wetland of national importance by DOC. Prior to European settlement, the swamp was of significance to local Maori for hunting and gathering (DOC, 2003). In historical times the surrounding hills were heavily logged for native timbers, which took place until the late 1960s, and a tramway to service this industry was constructed on the seaward (western) swamp boundary (DOC, 2003) (Figure 2.7). The remains of this tramway are still present today, with deep channels running either side. It is accessible to the public and functions as a walkway. This logging and subsequent sediment disturbance and change in catchment characteristics hugely impacted the sediment supply and modified the natural hydrology of the swamp, as did the development of the surrounding areas as farmland. The construction of Bold Head Road, which runs alongside the swamp between the seaward and anterior dune ridges, does not directly affect the swamp or adjoining creeks/lagoon system, but the creek is potentially somewhat constrained by the Waikoriri Creek bridge in the southeast corner of the swamp. Similarly, the construction of power pylons on the farmed dune ridges seaward of the swamp had little or no effect on the system.

Land clearance and channel realignment in Granite Creek north and west of the swamp occurred during farming development, and drainage of these areas has led to a build up of sediment in the lower reaches of Waikoriri Creek (Hart and Single, 2004). However, this has been partially buffered by high water levels in Waikoriri Creek/Waikoriri Lagoon, and a large margin of *podocarp* and *coprosma* vegetation along the creek. The removal of sediment from Granite Creek to create stop-banks, thus accelerating the transport of large volumes of sediment to the coast, has had the effect of accelerating the formation processes of Waikoriri Lagoon (Hart and Single, 2004). At the northern end of the swamp, the natural drainage channel into the Mikonui River mouth has been blocked by a causeway to access power pylons. Until relatively recent times, this was still open via a culvert beneath Bold Head Road; however, this is no longer the case. During the early part of the 20th century, a drainage channel known as 'The Causeway' was constructed and linked Shearer Swamp with Waikoriri Lagoon through the seaward dune system. This no longer functions, although the channel still exists as far as Bold Head Road (Figure 2.8). In addition to this work, farmers of the time planted flax along the seaward dune ridge, to the east of the road, as a stabilising measure.

The most heavily investigated and debated form of anthropogenic influence in this area surrounds the position of the Waikoriri Lagoon opening, and the question of whether or not it should be artificially controlled. Historical accounts of this issue suggest the barrier was at times breached artificially in response to high water levels threatening roads and farmland, and to facilitate recreational activities such as whitebaiting. This dilemma was particularly evident during a flood event in January 2004, when elevated water levels persisted for six days without a natural breach occurring and it was decided to artificially open the lagoon. As a result, the water levels in the swamp and creeks rapidly decreased and the lagoon drained. This had catastrophic consequences for the affected ecosystems, and the need for and optimum position of any subsequent openings related to flood mitigation is an ongoing debate.

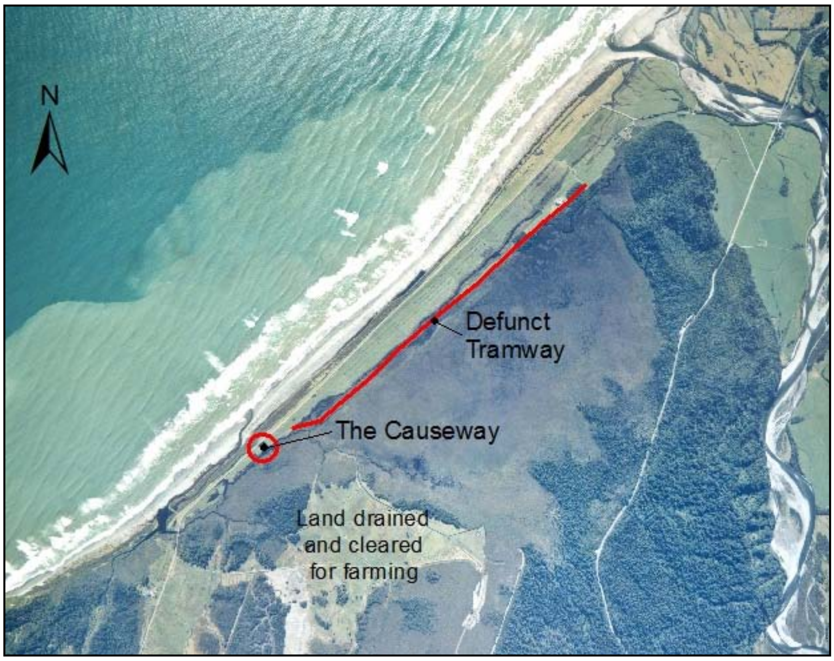


Figure 2.8. Aerial photograph of the Shearer Swamp-Waikoriri Lagoon complex (taken 2002), showing the location of the old tramway and the artificial overflow channel known locally as 'The Causeway'.

2.9 Observational site descriptions and field conditions

2.9.1 Totara Lagoon

Totara Lagoon is a very long, well developed system which varies significantly along its length in terms of dune morphology and channel characteristics. At the southern end of the 10 km long system, the Totara River forms the entrance to Totara Lagoon, and the outlet is currently situated at this location also. Figure 2.9 shows photographs illustrating the conditions at the Totara Lagoon field site.

The first 2 km length of Totara Lagoon consists of a single wide, shallow channel that experiences significant variations in water level in response to tides. The channel sediments are a mixture of sand and gravel in most places, interspersed with large, flat areas of mud. There is a lot of stranded debris in the channel and along its margins. To the seaward side of the channel the dunes are low, rounded and sparsely vegetated with marram grass. In some places along this dune ridge there is evidence of wave overtopping, where the vegetation has been washed away and debris has been deposited. On the landward side, the lagoon is bordered by farmland that is cleared of vegetation in most places. At the southernmost extremity, there is erosion of this farmland occurring, and a large scarp marks the border of farmland and lagoon. Further upstream, evidence of erosion lies in two dilapidated buildings, which have fallen off the edge of the land onto the mudflat.

The central and northern reaches of the lagoon are much less dynamic. The central reaches of the lagoon bifurcate, and there is still significant current occurring in response to tides. The inland and island margins of the channels are swamp in this area, which is heavily vegetated with flax, reeds and other swamp vegetation. The sediment beneath the vegetation is mud, of which the channel bed is also composed. Field work in the central reaches was undertaken in the most landward of the major channels, and the terrain was very flat in this area. Vegetation on the central island was very well developed, including several large trees.

In the northern reaches, the lagoon once again becomes a single channel, which is very choked with vegetation and is stagnant. Sediment on the channel bed is very deep, thick mud and organic sludge, which is impossible to walk on and through which solid ground could not be found. High dune ridges constrain the lagoon on both sides, which are heavily vegetated. On the seaward side, this vegetation consists mainly of scrub and marram grass, and the dune ridge is very steep. Evidence of dune blowouts is present periodically along the dune ridge. Landward of the lagoon, the steep, high dune ridge is completely covered in vegetation, mainly consisting of flaxes. Beyond the northern extremity of the lagoon body, the swale between these two ridges extends as a grass covered basin before pinching out a few hundred metres further north. There are also relic dune ridges in the farmland behind this part of the lagoon, which change orientation, becoming sub-parallel to the active dune ridge.

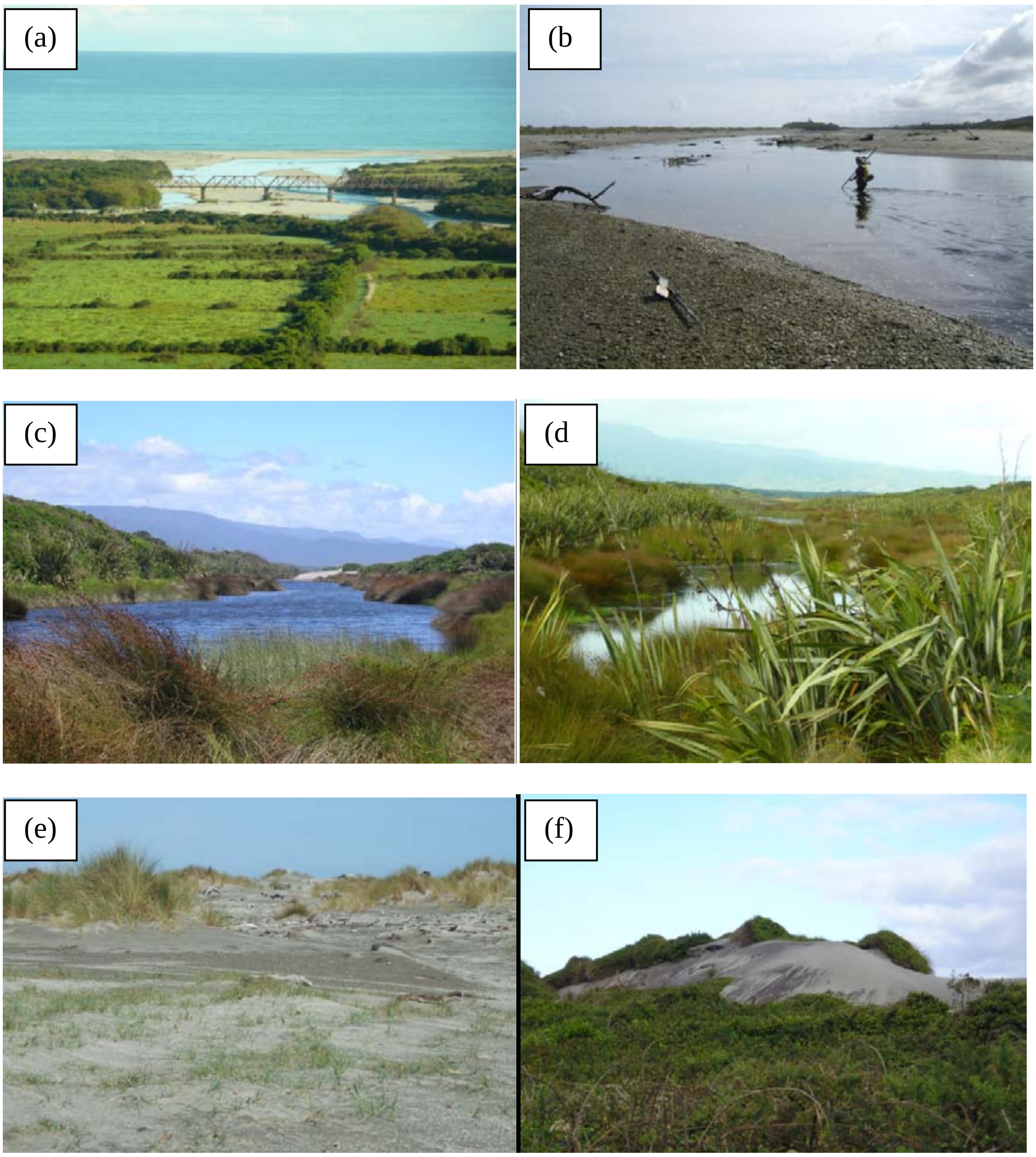


Figure 2.9. The conditions surrounding Totara Lagoon. (a) The Totara River mouth. The lagoon entrance is at the very right of this photograph, as is the outlet, which is very narrow and diagonally cut through the barrier. Photograph taken March 2009. (b) The channel at the rivermouth end of Totara Lagoon. The waterbody is very wide and shallow, and flanked on either side by large expanses of mud or sand and gravel. (c) The northern extremity of the Totara Lagoon waterbody. On either side of the channel are heavily vegetated, steep dune ridges. (d) The Totara Lagoon channel towards the northern end. The channel is very choked with vegetation and there is not a lot of water movement. (e) The seaward dune ridge at the southern (rivermouth) end of Totara Lagoon. The dune ridge is low and rounded, and sparsely vegetated with marram grass. (f) The steep, well vegetated seaward dune ridge at the northern end of Totara Lagoon.

2.9.2 Shearer Swamp-Waikoriri Lagoon complex

The conditions in the interior of Shearer Swamp meant that the swampland itself was inaccessible. The swamp is surrounded by creeks which are very deep, muddy and choked with vegetation in parts, creating access problems. Beyond these, the swamp is mostly covered with tall flaxes and grasses, making navigation difficult. In the northern section of the swamp, a large expanse of water covers the area, which is open in some places (making travel by boat possible), and choked with reeds or covered by thick moss in other places. It is a very hazardous environment, as at times what appears to be solid ground is in fact a mat of vegetation covering very deep water. In the higher, eastern areas of the swamp, the ground is harder and scrubby vegetation has developed. The environment of Shearer Swamp is depicted in Figure 2.10 (a) – (c).

Waikoriri Lagoon is a much smaller, more dynamic system that Totara Lagoon. The outlet is much more mobile, and is currently situated at the southern end of the system. The rapid movement of this outlet is evident in the scarps cut into the beach, and the outlet was observed at several different positions over the study period. The lagoon channel is narrow, and is situated between a very low, rounded barrier on the seaward side, and a taller dune ridge on the landward side. The floor of the channel is composed mostly of the same sand as the beach, with some mud and gravel. The beach itself is covered by a lot of debris (evidence of the high energy wave environment) and the barrier seaward of the lagoon is mostly bare of vegetation. Some patches of marram grass are apparent, but these are not well developed; even less so than the dunes at the southern end of Totara Lagoon. The landward dune ridge is very stable and heavily vegetated, to the point where access across it is constrained to several paths maintained by locals. Between this ridge and the swamp edge is farmland, and the sand of the relic dune ridges beneath can clearly be seen in the paddocks in places. Photographs of Waikoriri Lagoon are presented in Figure 2.10 (d) – (f).

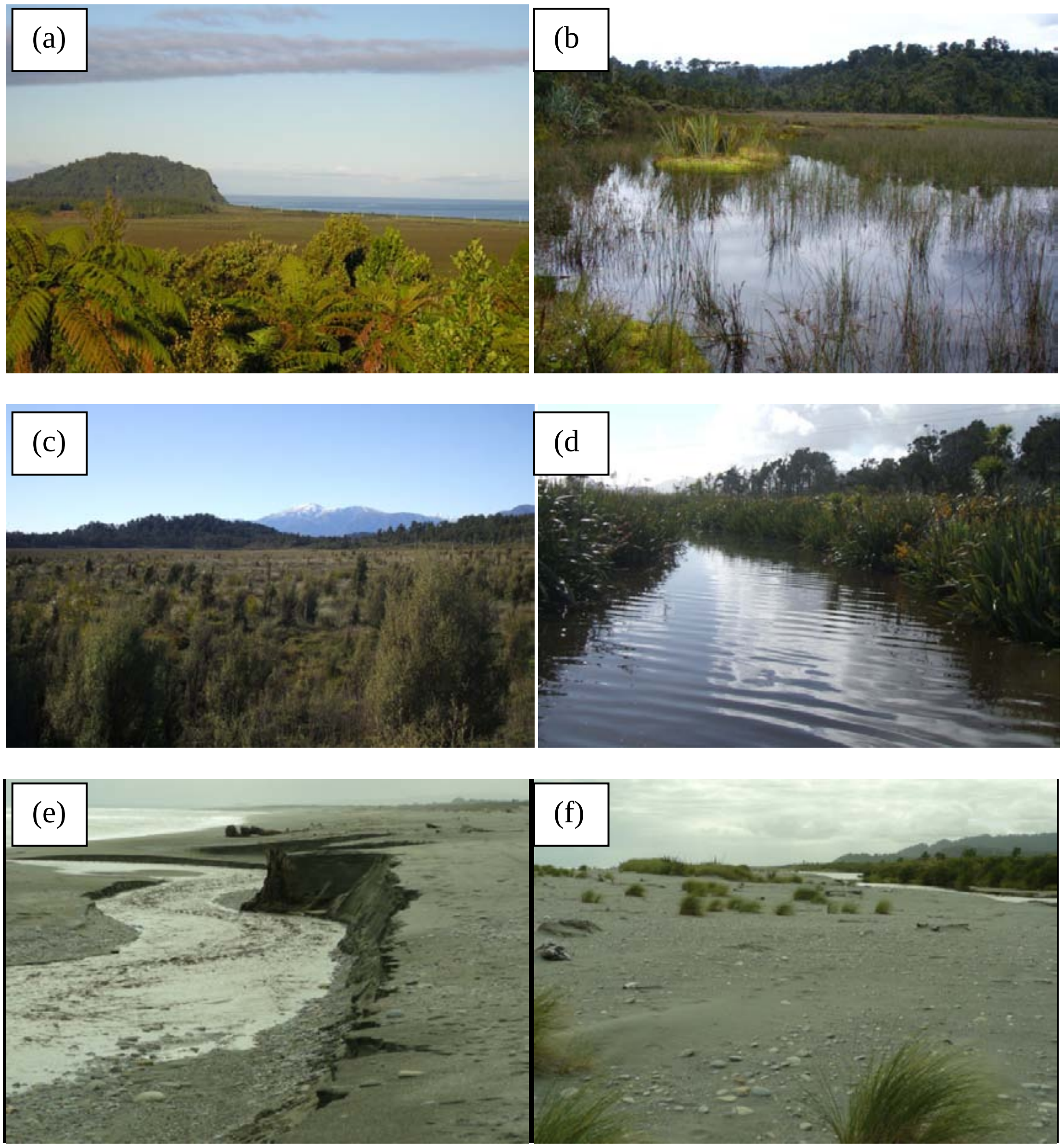


Figure 2.10. (a) Looking south across Shearer Swamp from a nearby hill. Bold Head can clearly be seen in the left of the picture. March 2009. (b) The northern end of Shearer Swamp, which is covered mostly by water and reeds. December 2008. (c) The eastern margin of Shearer Swamp. The ground is harder and scrubby vegetation has developed. May 2008. (d) Waikoriri Creek, which officially marks the southern border of Shearer Swamp. The flax of the inner swamp can be seen along the creek margins. When the water level in this creek drops, the banks are vertical and composed of mud. September 2008. (e) The outlet of Waikoriri Lagoon cutting through the beach. It cut diagonally through the beach and created similar scarps at each location at which it was observed. March 2009. (f) The barrier at Waikoriri Lagoon, with the lagoon waterbody in the background. The barrier is very low and sparsely vegetated. Photograph: Jim Hansom, March 2009.

2.10 Summary

This chapter detailed the environment of the study sites to provide a context for this study in terms of morphology, hydrology and climatic factors. The West Coast region is a very high energy environment, experiencing heavy rainfall, frequent westerly storms and a high energy wave environment, all of which interact to affect the coastal environment. Climate is generally mild on the West Coast, experiencing neither extreme hot nor cold temperatures. The two systems under investigation share the same coastal plain, which is composed mainly of paraglacial deposits related to the Otiran glaciation. The catchments of these systems extend up into the Southern Alps, and bring down large amounts of granite and schist to the coast. The marine circulation is driven by the subtropical convergence, which occurs at approximately this latitude. The predominant current affecting these systems is the northerly flowing Westland Current, and the net direction of littoral drift is northwards as a result.

Totara Lagoon is a much larger system than Waikoriri, and is fed predominantly by the Totara River from the south. It is well flushed in the south and bounded by low, rounded dunes, becoming narrower and choked in the north with dunes becoming progressively steeper and more vegetated. Anthropogenic influence on the system has occurred through mining operations, dredging and spoils dumping over historical time, and drainage of adjacent wetland for farming. The construction of a railway to service the mining industry has impacted drainage between the lagoon and adjacent swampland.

Shearer Swamp is a large, freshwater wetland that occupies 135 ha, and is bounded by two small streams: Granite Creek and Waikoriri Creek on the southern and western sides, and by a well-developed area of native bush to the north. It is heavily vegetated with flaxes, and consists of muds and peat. Waikoriri Lagoon is part of the same system, forming the outlet to the sea that drains the wetland. It is a smaller, much more dynamic system than Totara Lagoon. The lagoon occupies a swale behind the beach and foredune, and is separated from Shearer Swamp by a series of low-lying, farmed dune ridges. Sediment supply and hydrology of the system has been heavily affected by swamp drainage for farming, and changes in sediment supply related to stop banking, in addition to artificial outlet breaching of the lagoon barrier. This study will seek to understand and explain the similarities and differences between these two systems in terms of processes and morphology.

CHAPTER THREE

Methodology

3.1 Introduction

Due to their dynamism and multiple facets, coastal features and environments are difficult to investigate, often requiring a combination of techniques to capture a comprehensive set of data. Recent advances in technology have made the study of coastal environments much more accessible, allowing data collection on far greater spatial and temporal scales. This chapter discusses the individual techniques used in this study and details the way in which they are applied. Firstly, the methodology employed to document the current and recent geomorphology is presented in Section 3.2, followed by techniques pertaining to the development of the study sites over recent centuries in Section 3.3. Each of these two major sections begins with a review of the principles and techniques involved in the methodology, followed by details of the method as applied in this study.

Fieldwork was undertaken over two main periods. Ground surveying and short-term water level recording was performed during the period December 1st – 16th 2008. This is important to note, as these coastal systems are very dynamic and can change substantially in response to seasonal weather trends and random storm events. During this period, a single storm occurred on December 6th. Sediment cores were taken on a second visit during the period March 2nd – 7th 2009. Fieldwork included visual observations and photographs of the field sites, including outlet position, form, and any other features of interest. A third site visit took place over March 20th – 22nd. No quantitative measures were taken during this time, but observations about the lagoons and outlet position and form were made.

3.2 Recent Geomorphology

3.2.1 Topographic Survey Principles and Practices

Ground surveys of the topography of a given area and its features remains one of the fundamental tools for understanding its geomorphology and processes, and for monitoring changes in coastal landforms over time. In the past, surveys were performed with a total station, which although potentially very accurate, can be a time consuming task that is spatially restrictive and labour intensive. With the advent of GPS and GNSS systems, and subsequent GIS analysis packages, surveying has become applicable on a larger spatial scale and in greater detail. Data collection by ground survey techniques remains more labour intensive than remote methods such as aerial or satellite imagery analyses (e.g. LIDAR), which are superior for analysing large areas of coastline, but these may require validation and calibration by associated ground surveys (Pranzini, 2007).

Data collected from GPS ground surveys can be used to create a topographic map of the survey area, or a digital elevation model (DEM), a three dimensional digital representation of the topography and landforms. The method employed to achieve this is critical to the accuracy and applicability of the resulting model. Survey data is in the form of ‘points’, that is; individual points taken along a transect or surrounding a feature, which must be converted into a continuous surface by the process of interpolation (Andrews *et al.*, 2002). Interpolation uses the characteristics of the points collected to fill in the areas between the points, which can be achieved in several different ways. Commonly used methods of gridding are kriging, inverse distance weighted, nearest neighbour and spline (Andrews *et al.*, 2002). There is no set formula for determining which method will yield the most accurate DEM, and often several methods of interpolation, grid size, and sampling density need to be explored and compared.

Another method of producing a three dimensional model is by use of a triangulated irregular network (TIN), which triangulates adjacent points to create a continuous surface. This method works particularly well when survey data is irregular rather than collected along a grid, and when a relatively good density of points is achieved (Lo and Yeung, 2006). A TIN is not based on a grid and as it merely involves forming planes between data points, no interpolation is required (Andrews *et al.*, 2002; Kumler, 1994).

Consequently, the resulting model is not considered a DEM in the strictest definition of the word (Andrews *et al.*, 2002); however, for the purposes of this study they can be considered the same and the three dimensional models presented in Chapter 5 will be referred to as DEMs.

Data Collection

Ground surveys of representative sections of each site using a *Trimble R8* GNSS system were undertaken over a 2 week period in early December 2008. The scale and nature of the field sites and access constraints did not allow surveying of the entirety of the systems. Four representative areas along the length of Totara Lagoon were surveyed in detail: the river mouth extremity, the northern extremity, and two sections along the central reaches of the lagoon channel. These sections were chosen to provide approximately evenly spaced snapshots of the topography of Totara Lagoon along its 10 km length, from which trends of change in terms of distance from the outlet could be inferred. The river mouth end was particularly important, as this is currently where the lagoon discharges. The entire dry channel of Waikoriri Lagoon, as far as the recently abandoned opening, was surveyed, and the adjacent area between the lagoon and the western edge of Shearer Swamp was also surveyed. Sample elevation points surrounding Shearer Swamp were also taken (Figure 3.1). Details of surveyed areas are presented in Table 3.1.

Surveying was undertaken using a *Trimble R8* GNSS. Several geodetic markers maintained by Land Information New Zealand (LINZ) exist in the area and were initially considered as locations for the GNSS base station. However, no consistent signal was achieved between the base and the rovers at any of these locations. The base station was set up on a high point at Ross Cemetery, which overlooked the entire coastal plain of interest and from which a consistent signal could be achieved at both study sites via a repeater (Figure 3.1) (Appendix 1). Surveys were undertaken using the NZGD 2000 Hokitika Circuit map grid. Surveying was performed on foot, with rovers attached to researchers' backpacks, recording their position and elevation at 5 second intervals using the 'continuous topo' function. A strong signal was achieved over most of the study area, and this was surveyed using Real Time Kinematics (RTK), which yields very accurate positions that are calculated in the field rather than requiring extensive post-survey correction. This option works well where there are few obstructions between the base or repeater signal and the rovers, such as vegetation, hills or scarps. The middle and northern reaches of Totara Lagoon were unable to be surveyed using RTK. In the northern reaches, no signal was received and so the PPK (Post-Processed Kinematic) survey option was used, whereby the rovers record positions autonomously in the field and data obtained requires extensive post-processing in a GPS software programme. Where the signal was intermittent the ‘RTK and infill’ option was used, which uses RTK when a signal can be received, but reverts to PPK when it is lost. In addition to a general survey of the area, features of interest were mapped in detail. These included the lagoon waterline and seaward shoreline (when appropriate), heights and profiles of adjacent dunes, cusps, scarps, and depth of the lagoon channel when possible. Where possible, transects spanning the seaward dunes, lagoon channel and adjacent landward morphology were surveyed. Channel depth was not measured at the middle and northern sites of Totara Lagoon, due to the conditions of the channel bed. In the central and northern reaches, the channel bed was covered by a very thick layer of mud and organic sludge (measured at over 1.5 m at Totara Central North) which made surveying too dangerous to attempt.

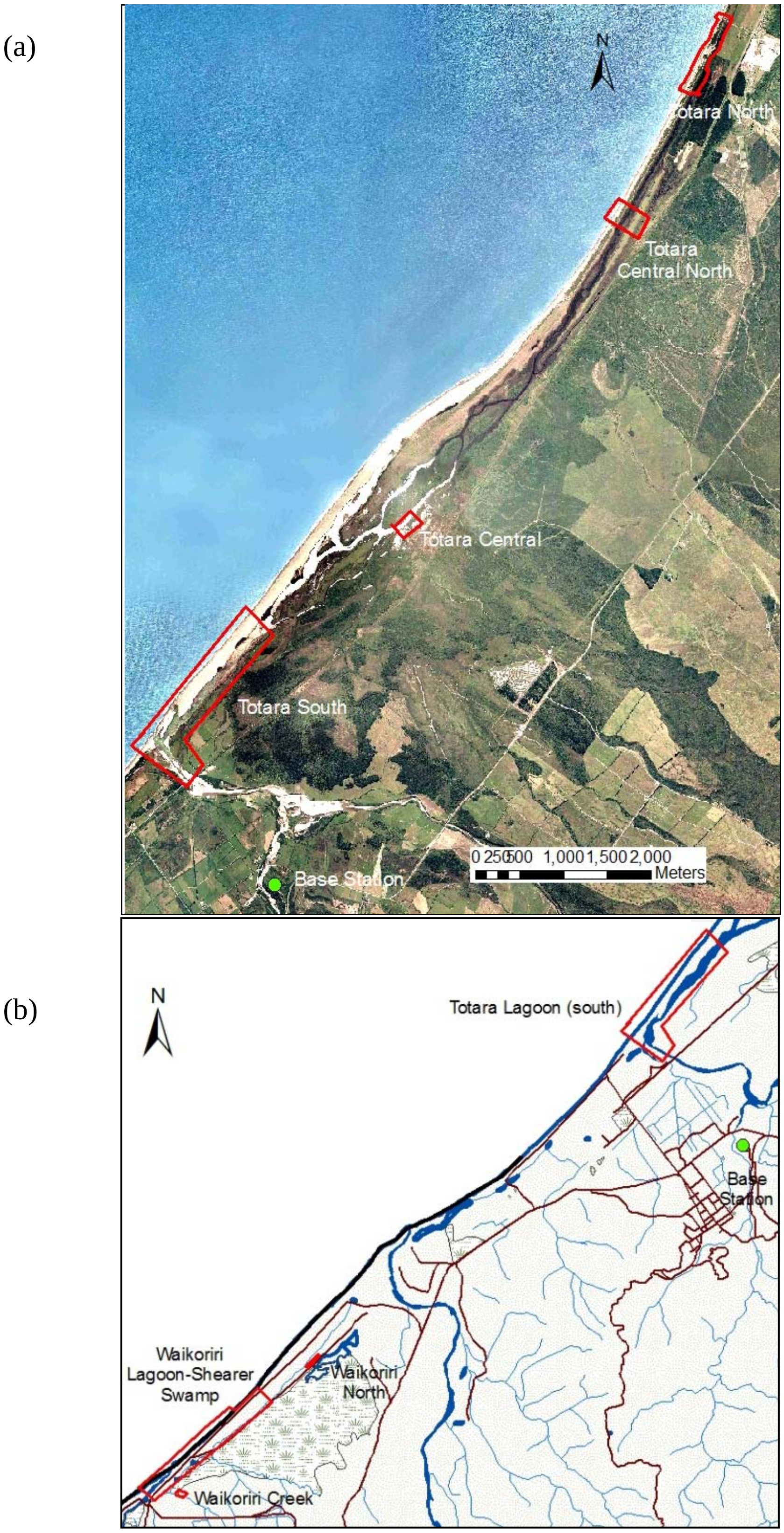


Figure 3.1. Location maps showing the surveyed areas in (a) Totara Lagoon and (b) The Shearer Swamp-Waikoriri Lagoon complex. The base station location did not change between the two study areas.

Figure 3.2. Left: Base station receiver set up at Ross Cemetery. Right: Surveying the river mouth end of Totara Lagoon.

Table 3.1. Details of GNSS surveys across both field sites.

Location	**Number of Points**	**Spatial Extent (m^2)**	**Survey method**
Totara South	7693	367 231	RTK
Totara Central	1513	12 920	RTK and infill
Totara Central North	1988	63 459	RTK and infill
Totara North	7276	188 456	PPK
Waikoriri Lagoon/ western margin of Shearer Swamp	11 529	552 044	RTK
Southern margin of Shearer Swamp	556	1 857	RTK and infill

Data Processing

Data collected in the field was transferred from the GNSS hand units to a laptop and converted to ASCII format using the *Trimble Geomatics Office* programme. An initial three dimensional model of the data was produced in *Terramodel 10.4*, which allowed erroneous data points and other anomalies to be identified. These were located and removed in the associated *Microsoft excel* file. Due to the position of the base station on an unknown point (i.e. not a LINZ geodetic marker), the base position required correction before data in the field could be corrected. This was achieved by constructing a baseline between the base station location and the location of the LINZ base station in Hokitika, following which the data collected in the field was then adjusted based on the corrected base station position. The ASCII files were later transformed for *ArcGIS* analysis into shapefiles (.shp), database files (.dbf), and *ArcView* database index files (.shx).

GIS Analysis

Following correction and file conversion, the data was imported into *ArcGIS* as a single large dataset covering both field sites. Firstly, the entire dataset required correction for field surveyor heights, which had created systematic errors in elevation. Due to the general thoroughness of surveying and density of points in each survey section, the TIN method produced the most representative DEM of the study site. Kriging and Inverse-distance-weighted interpolation methods were also trialled, but these resulted in inaccurate representations and smoothing of features such as scarps and steep dunes. Following the DEM construction, a number of erroneous points of negative elevation were identified and removed in *ArcGIS* and the model redrawn. Because the TIN method creates triangular planes between adjacent points, there was potential for areas of incorrect interpolation where point density was low and when points across large distances between survey sites were triangulated. To remedy this problem and reduce error, polygons were constructed around each survey area to eliminate outlying points and create individual DEMs of Waikoriri Lagoon and the adjacent dune ridges, Totara South, Totara Central, Totara Central North, and Totara North.

The DEMs were then compared to photographs of the morphology to assess the degree to which the areas were accurately represented by the models. Due to the complexity of the dunes in the northern reaches of Totara Lagoon, a degree of inaccuracy was accepted and noted. The DEMs were then visually assessed in conjunction with field notes and photographs taken while surveying, and features of interest identified. From this DEM, several profiles were graphed across the seaward dune ridges adjacent to Totara and Waikoriri Lagoons and across the relic dune ridges between Waikoriri Lagoon and Shearer Swamp. These are two dimensional cross-sections oriented parallel to the dune crest, which allow differences in dune heights steepness and morphology between different profile locations to be quantified.

Limitations and errors

The extent and accuracy of the point network covering the survey area is constrained by accessibility. Where researchers were unable to thoroughly cover a feature, the DEM of that feature is inaccurate due to the triangulation of insufficient points. This applies specifically to the lagoon channel in the middle and northern reaches of Totara Lagoon, and to some areas of the dunes surrounding both Totara Lagoon and Waikoriri Lagoon. The muddy nature of the lagoon channel bed and swampy margins in some places was a safety issue, and thus surveys extend only as far as the water edge, meaning the surface in the centre of the Totara Lagoon central and northern DEMs signifies the elevation of the water surface, rather than the channel morphology. This was not an issue in Waikoriri Lagoon, where the channel was dry during surveying, or in Totara South, where the channel could be waded. Heights of well established dune ridges were underestimated in places, due to large amounts of vegetation preventing accurate surveying of the crest. This occurred in the landward dunes of Waikoriri Lagoon, and in the northern reaches of Totara Lagoon on both sides. Areas that have been affected by these access issues are highlighted in the following chapter. This does not affect profile constructions or volumetric analyses, as these are based on surveyed transects of actual point data, rather than relying on the interpolation of the DEM.

One limitation of surveys in this area is the lack of accessible and accurate geodetic markers. Not only did this provide a problem in choosing a location for the base station, but it made post-processing of the data more difficult. To tie the vertical dimensions of the DEM to local mean sea level, at least 4 of these known points were required, which was not possible to obtain in the area. Consequently, the initial survey results were in terms of height above a global ellipsoid, meaning elevation data could be used in a relative form but not in terms of absolute elevation above mean sea level. As a solution to this problem, an approximation of sea level elevation in the area was calculated from the geodetic marker information provided by LINZ, which gives elevation above mean sea level for each marker. The sea level elevations at each marker location were averaged to provide a linear approximation of mean sea level elevation over the entire survey area, then the difference was applied to the entire *ArcGIS* dataset. This is not ideal, as it does not account for the elliptical nature of the Earth's surface; however, due to the close proximity of the survey areas this has a minimal effect on results.

3.2.2 Aerial photograph Analysis: Principles and practices

The use of aerial photography to assess coastal change over time has been practiced and refined for over fifty years. Early photographs were simple black and white images of low resolution, which then moved to higher resolution black and white pictures and the introduction of stereographic pairs. Colour photographs became accessible from the 1980s (Lewis and McConchie, 1994). Stereo pairs of images can be used to look at the topography of the area in the photograph and construct topographic contours, and are useful in cartography, management and planning, vegetation and species distribution mapping, and to detect large scale geological features that are difficult to map from the ground (Lewis and McConchie, 1994; Andrews *et al.*, 2002). Aerial photographs can be taken either vertically or obliquely, of which vertical photographs are the most useful for scientific mapping purposes.

The use of aerial photographs for mapping shoreline change and changes in vegetation cover in coastal areas is a well established method that has been applied and refined over the past 70 years by coastal planners, engineers and scientists (Boak and Turner, 2005). More recently, satellite imagery has started to replace aerial photography as the primary method of collecting this type of data where budgets and coverage allow. However, aerial photographs remain a relatively cheap and simple-to-analyse record of historical change in coastal zones.

Significant distortions exist in aerial photographs, which must be corrected prior to their use for mapping purposes. This correction process is known as orthorectification. This distortion includes radial distortion (which increases with distance from the photographic centre); relief distortion from topographic variation; tilt and pitch changes of the aircraft; lens distortion in older photographs; and scale variations resulting from altitude changes along the flight line (Gorman *et al.*, 1998; Boak and Turner, 2005; Al-Tahir and Ali, 2004). Because coastal areas are generally flat, relief distortion is negligible and can usually be ignored (Al-Tahir and Ali, 2004).

Data collection and orthorectification

This study utilises a collection of aerial photographs taken between 1948 and the present day, with the aim of documenting changes in outlet migration and visual changes in the systems over this period. Photographs sourced were taken on an approximately decadal time scale and covered the following years: 1948, 1963, 1972, 1976, 1981, 1986, 2002, 2005 and 2006. Images from 1988 onwards are high resolution colour photographs. Further details of the images used are presented in Appendix 2. The pre-2005 photographs were obtained in hard copy and subsequently scanned at a resolution of 700 dpi and saved as digital (.jpg) files for GIS analysis. Due to the large spatial extent of the study sites, several photographs were required to cover the whole area.

The photographs obtained in hard copy were unorthorectified, and for the Totara Lagoon site this was performed in ENVI by georeferencing each photograph to 2 orthorectified digital images produced by LINZ (2002) (Area J33 – Kaniere, LINZ, 2009b). Georeferencing involved matching several visible and stable points (referred to as control points) on the orthorectified images to those same points in the other images, then warping the distorted image to fit the orthorectified reference images. These orthorectified images obtained from LINZ covered the Totara Lagoon area, and were high resolution colour photographs taken in 2002. For the Shearer Swamp-Waikoriri Lagoon complex no orthorectified images were available, but the 2002 image (the clearest and highest resolution image available of the area) was georeferenced to a GIS shapefile of roads in the area (NZ 1:50 000 topographic survey). From this, images taken in earlier years were georeferenced and warped to control points located on the 2002 image using ENVI, by the same process as used for Totara Lagoon images. Due to the dynamic nature of the coastal zone and the lack of visible engineered structures in the study areas, control points were usually road intersections, bridges, or lone buildings. At least 4 control points were located on each image, a sufficient number to provide a satisfactory orthorectification, and these were distributed as evenly as possible across the entire image. As a part of this process, the images were spatially referenced to the New Zealand Map Grid (NZMG) datum, allowing results to be quantified spatially in terms of location and distance in metres.

No further preparation was necessary for the Waikoriri Lagoon images prior to the following analysis, as only a single image from each survey period was required to cover the entire lagoon area. Totara Lagoon required between 2 and 5 images from each survey to cover the entire lagoon. In order to create a single georeferenced image of the lagoon for each survey, the mosaicking tool in ENVI was used to stitch the individual images together while maintaining their position in coordinate space. For this to be effective, and to minimise error, the images needed to overlap approximately 30% with adjacent images.

Analysis of lagoon change

The final images of each site were compared visually and qualitative changes in outlet position and channel structure across the study period were noted. A digital representation of the lagoon area and shoreline position for each survey year were created in ENVI using the ‘Region of Interest’ tool, then the resulting polygon/line files were exported into *ArcGIS* as shapefiles for further spatial analysis. The outlet offset was measured in metres from the Totara River mouth for Totara Lagoon, and from the Waikoriri-Granite Creek confluence in the case of Waikoriri Lagoon. The surface area of Waikoriri Lagoon at each survey was calculated in *ArcGIS* from the individual digitisation polygons. This was not performed for Totara Lagoon, due to the size of the lagoon and the large errors that would be introduced as a consequence.

Limitations and errors

This process was fraught with challenges in the orthorectification/georeferencing process, due to the nature of the study sites and poor quality of some photographs. In common practice, photographs are orthorectified and georeferenced in separate processes, using a combination of digital techniques and collection of control points in the field. This was not possible for either Totara Lagoon or Waikoriri Lagoon, due to access constraints in the field and lack of features such as buildings, roads and prominent rocky areas that could act as GCPs. The roads in the area also underwent several realignments and upgrade works over the period covered by the surveys, meaning even road intersection positions were sometimes not accurate enough for this purpose. The dynamic coastal nature of these sites also meant that features in the immediate vicinity of the lagoon were very changeable and thus not suitable as GCPs.

For Totara Lagoon, GCPs were clustered landward of the lagoon in most cases. Some stable patches of vegetation were able to be used in later photographs, but these were not visible at a suitable resolution in earlier images. To obtain the most accurate result from this process, GCPs should be distributed across the entire image, particularly the area of interest. This was not possible in the beach area or where ocean covered a large part of the photograph. This was of particular concern in the 1976 images, where the scale was so small that individual photographs covered only the lagoon area. A large portion of the potential error in the georeferencing process for Totara Lagoon arose from human interpretation of features and accuracy (related to photograph resolution). This was more problematic for the earlier images. Parameters such as pixel size, tone, texture, shade, shape and position are important considerations for the researcher performing the analysis (Boak and Turner, 2005; Dahdouh-Guebas *et al.*, 2006).

The georeferencing process for Waikoriri Lagoon was further complicated by the absence of an existing orthorectified, georeferenced image from which to reference other raw images. The GIS road file that was used to reference the 2002 image was sourced from the NZ Topographic survey 1:50 000 data, which is accurate to ±22 m horizontally and ±5 m vertically (LINZ, 2008). This introduced a large source of potential error, which was then compounded by the same error sources as occurred in the Totara Lagoon images.

Once again, human interpretation and manual errors could have arisen during the digitisation of the lagoon process from the orthorectified images. In order to minimise these errors in the quantitative results, measurements of outlet position were made directly from the photographs rather than from the digitisations. In addition, the exact dimensions of the lagoon and outlet position fluctuate in response to tidal and weather factors, so quantitative data relating to outlet position and lagoon surface area were rounded to approximate values (nearest 50 m).

A common error noted in aerial photograph analysis is the issue of vertical displacement (Gorman *et al.*, 1998; Dahdouh-Guebas *et al.*, 2006); however, this was not a concern for either of these study sites as all terrain was low relief. Although the error sources discussed here appear significant, the magnitude of the changes in outlet position and lagoon structure means that they are relatively inconsequential.

3.2.3 Hydrological Principles and Practices

The hydrology of a coastal waterbody is a very important aspect of its overall dynamics. The hydrological regime of a coastal lagoon is a function of system morphology, fluvial input, marine conditions and other factors such as ecology and land-use in the surrounding area (Kirk, 1991). Data on water pressure (which is then converted to water depth), conductivity and water temperature are three commonly measured variables, which provide valuable information on the hydrological dynamics of the system.

As technology has advanced, these variables can be measured increasingly easily and at a greater spatial and temporal resolution. Often, conductivity and temperature are measured both horizontally and vertically within a waterbody to assess stratification and apply complex numerical models. For the purposes of this study, the aim was to assess broad trends rather than gain high resolution data for modelling, so data was not collected to this level of detail.

Conductivity is the degree to which a substance is able to conduct electricity which, in the case of water, is a function of the concentration of dissolved ions (salts such as chlorides, sulphates, carbonates, sodium, magnesium, potassium). As such, conductivity can be used as a proxy for determining the salinity of the water body (e.g. Fernandes *et al.*, 2004, Lucas *et al.*, 2006). In waterways, electrical conductivity can be affected by soil composition, land-use characteristics and runoff, flow rate of the water, groundwater inflows, temperature, and evaporation/dilution (Lucas *et al.*, 2006). The salinity of a coastal lagoon is an important parameter, as it provides information about the degree of water exchange between the ocean and the lagoon, or the balance between fluvial inputs and marine influence (Kirk, 1991). It is important to note, however, that conductivity is not necessarily a direct measure of marine influence in all cases, as some of the measured conductivity may be due to one of the above factors. In these studies, the patterns and degree of change above the baseline conductivity for each site were the factors assessed. It is possible to calculate the absolute salinity from conductivity and temperature data, but this was not deemed necessary for the purposes of this study. Electrical conductivity ranges of common water systems are presented in Table 3.2.

Water temperature is heavily influenced by the degree of solar insolation (Smith, 1981) and local hydrodynamics (Vaz *et al.*, 2005; Lucas *et al.*, 2006). In terms of water quality, temperature affects the density and conductivity of a waterbody, and influences the oxygenation level of the water column (Vaz *et al.*, 2005; Lucas *et al.*, 2006). Water temperature can change dramatically in response to changes in fluvial or marine inflow into a coastal lagoon.

Table 3.2. Electrical conductivity ranges of different water types. *Sourced from Suttar, 1990.*

Water Type	**Electrical Conductivity Range (mS cm^{-1})**
Deionised Water	0.0005 – 0.003
Pure rainwater	< 0.015
Freshwater rivers	0 – 0.8
Marginal river water	0.8 – 1.6
Brackish water	1.6 – 4.8
Saline water	> 4.8
Seawater (average)	51.5

Data Collection

Two sets of water level, temperature and conductivity data were taken at each field site, a long term record spanning September 2008 to March 2009, and a short term record at two sites within each field area spanning a week in early December 2008. The locations of these recorders are illustrated in Figure 3.4, with GPS coordinates given in Appendix 3. The long term water level recorders were situated at Totara North and Waikoriri Bridge. The locations of the short term recorders in Totara Lagoon were selected to allow comparisons of data between the river mouth end, middle and northern end of the lagoon over the sampling week (November 29th to December 7th 2008). Short term records were taken in Waikoriri Creek between December 8th and December 14th 2008, and recorders were situated in the stretch of creek that drains the western edge of Shearer Swamp.

Short term records were taken using two *XR-620-CTDm* water level recorders, manufactured by Richard Brankner Research Ltd (RBR, 2009)., which recorded water pressure (deciBars), temperature (° C) and conductivity (mS cm^{-1}) at ten minute intervals for the entire sampling period. These were mounted on a metal support which rested on the bed of the channel at the deepest point (Figure 3.3). The distance between the channel bed and the recording equipment was 200 mm.

Long term records were taken using two *CT2X* water level recorders (INW, 2009), which also recorded water pressure (psi), temperature (° C) and conductivity (µS cm^{-1}) at ten minute intervals over the sampling period. These were mounted vertically, attached to a warratah (Figure 3.3) which was driven into the soft mud of the channel bed in the case of Totara North. The Waikoriri Bridge recorder was initially mounted on the south-west corner of the bridge buttress, but in early November the creek drained suddenly through a breach in the Waikoriri Lagoon barrier approximately 100 m downstream, leaving the recorder out of the water and above the high water mark. This was rectified in early December, when the recorder was moved approximately 10 m downstream and mounted on the pole of a retaining wall on the northern bank of the stream.

No official weather monitoring station was available in close proximity to these study sites to provide measurements of barometric pressure from which to correct water level pressure results. This was achieved by using *PT2X-BV* barometric pressure sensor, which was mounted on a nearby building on Bold Head Rd. This data was used to correct both short and long term water pressure data from both sites.

Figure 3.3. Water level recorders set up at the field sites. Left: short term *XR-620-CTDm* water level recorder in Totara Lagoon. Right: Long term *CT2X* water level recorder affixed to Waikoriri Bridge via a warratah.

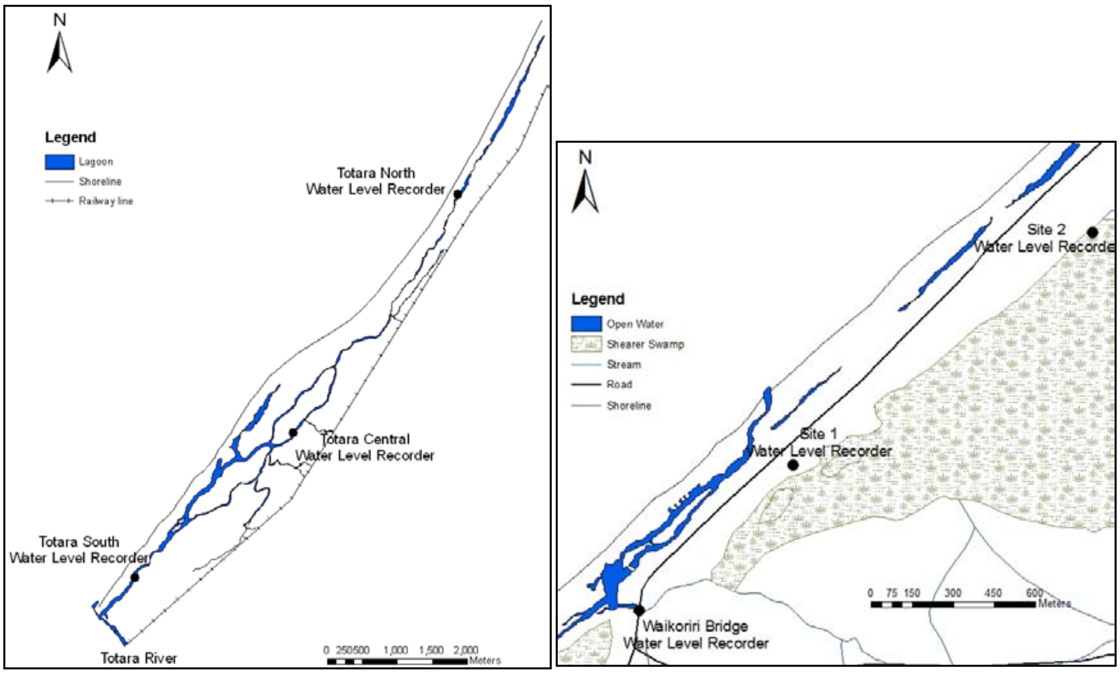


Figure 3.4. Locations of the water monitoring sites in Left Totara Lagoon and Right: The Waikoriri Lagoon-Shearer Swamp complex.

Analysis of Data

Data for pressure, temperature and conductivity obtained from the recorders was first downloaded and opened using *RBR* software for the *XR-620-CTDm* loggers and *Aquasoft* for the *CT2X* loggers. Barometric pressure corrections were performed for the long term pressure records by the *Aquasoft* software. All records were then exported into Microsoft Excel for further analysis.

Units of measurement were standardised across all records, with pressure measurements converted into Bars and conductivity measurements converted to mS cm $^{-1}$. Short term pressure records were then manually corrected for air pressure by subtracting the recorded barometric pressure from the water pressure measurement. All water pressure data was then converted to mmH_2O and the measured distance from the channel bed to the recording equipment was added to all data entries, thus giving the absolute water depth. All data that was recorded while the equipment was out of the water (both before and after the sampling period and when it was removed briefly for maintenance during the sampling period) was removed prior to analysing the corrected data. These periods were identified by water level measurements in the vicinity of 0.0 mmH_2O. In the case of the Waikoriri Bridge long term recorder, this included removing the data for most of November and early December.

Data was then graphed over time to assess trends in these parameters and to compare measurements across sites within each field area. Data from the long term records matching the time period of the short term records from each field site was extracted for these comparisons, in addition to assessing the complete long term records. Maximum, minimum and mean values were calculated for each parameter from each recording site. In the case of Waikoriri Bridge, the record was split into two time periods: September to November, and December to March. Data from these two time periods could not be directly connected because the recorder location changed following the draining of Waikoriri Creek.

Limitations and Errors

The dataset taken from Waikoriri Bridge is subject to the greatest degree of systematic error. As well as removing the data from when the water level recorder was out of the water, the water depth from the bed to the surface cannot be calculated. This is because the distance between the channel bed and the recorder was not measured as it was in all other sites. This is not of major consequence, as the most important aspect of this data is the degree of *relative* change, rather than records of absolute values. Unfortunately, this distance was not measured at either location at the bridge, meaning that the September to November and December to March records could not be connected to each other.

In terms of data analysis, it was decided not to perform any statistical transformations on the data prior to interpretation. This was not an issue for the short term records, but the long term data could have benefited from extra analyses using a set of moving averages over hours and/or days. This could potentially have made medium to long term trends more clear, as often they were obscured by shorter term variations and noise in the data.

3.3 Methods of assessing development over historical time

3.3.1 Sediment cores

The collection of sediment cores is a relatively efficient method of gathering samples of undisturbed subsurface sediment, and can be performed on a variety of scales and with equipment varying largely in size and complexity. The collection of short cores of friable sediment in a terrestrial setting can be undertaken with simple and inexpensive equipment such as that used in this study.

Sediment cores collect material that was deposited some time during the past, and a large number of analyses can be performed on samples of this sediment to assess the conditions at the time it was deposited. These analyses can be related to sediment character, ecological and microfossil content, geochemical composition, and varying dating techniques to determine the ages of different layers within the cores. This study employs sediment texture and organic percent analyses, each of which will be discussed individually in the following sections. Firstly, the collection process of the cores will be detailed.

Method

A total of three sites were chosen for coring, based on accessibility and the likelihood of sediment character being conducive to core recovery. One site was chosen at Shearer Swamp; on the western margin of Waikoriri Creek, which marks the official edge of

Shearer Swamp. Due to the muddy nature of Waikoriri Creek and equipment constraints, access to the more central reaches of the swamp was not possible. Two sites were sampled on the eastern, landward edges of Totara Lagoon; at the northern and southern ends respectively. Locations were documented using a handheld GPS unit (Figure 3.5) (Appendix 4). Due to the gravelly nature of sediments at the confluence of the lagoon and the Totara River, the southern core was taken approximately 2 km up the channel from this point.

Cores were collected with a hammer corer, which is a form of gravity corer comprised of a 1.5 m metal tube which is driven into the sediment by the manual operation of a heavy piston on the top (Figure 3.6). Several cores were taken from each site at intervals of 2 to 5 m to ensure the consistent character and lateral continuity of the observed sedimentary units. Surface sediments were infiltrated by roots in the top several centimetres, which were discarded prior to sampling. The depth of cores was constrained by the presence of coarse sand layers at all three sites, which prevented the hammer corer from penetrating further. Core compaction was estimated by measuring the difference between hole depth and core length. Once recovered from the ground, cores were ejected from the core tube into plastic half-round tubes and shrink wrapped for ease of transport and to prevent contamination (Figure 3.6). In the laboratory, cores were split lengthwise using copper wire and stored in a refrigerator. Cores were photographed and stratigraphy was examined and logged prior to sub-sampling for the analyses in the following sections. A single, representative core from each of the three sites was used for stratigraphic logs and analyses.

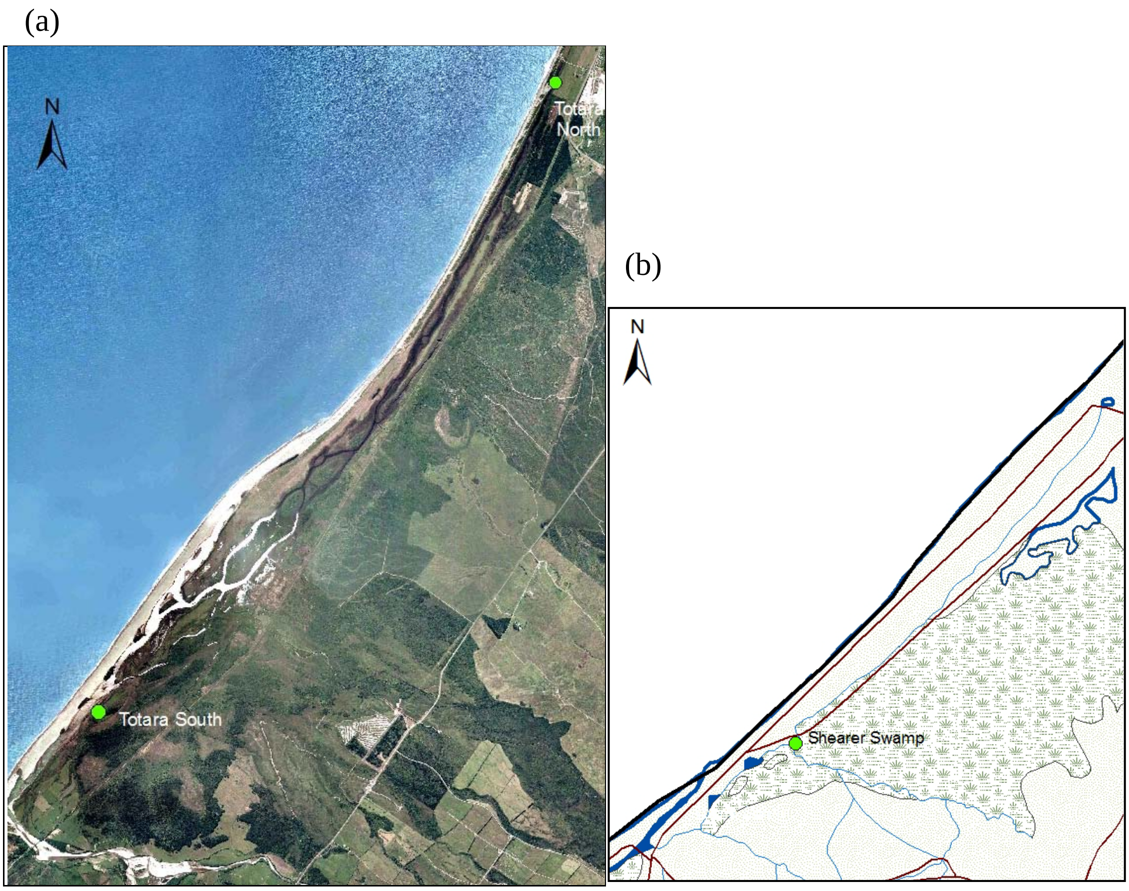


Figure 3.5. Locations of sediment cores taken from (a) Totara Lagoon and (b) Shearer Swamp.

Figure 3.6. Left: Photograph showing the process of taking a sediment core from Shearer Swamp with a hammer corer. Right: Ejecting the core into a plastic tube following collection.

Limitations and errors

The primary limitation in the collection of cores for this project was the inability to collect longer cores from a larger number of locations, due to equipment and time constraints. The diverse nature of sediment types in these environments made selection of equipment difficult, as each type of corer performs best in a relatively specific type of sediment. Initially a vibracorer was to be used, as this would work well in wetland and more sandy areas; however practical constraints meant that it could not be transported into the field sites. The hammer corer was simpler to use and was suited to the peat and mud layers of Shearer Swamp and lower Totara Lagoon. However, the presence of sand layers below depths of 0.5 m in all cores precluded the collection of longer cores. In addition to this issue, the very soft surface sediments of Shearer Swamp and northern Totara Lagoon were unable to be sampled, as the corer relies on resistance from the sediment to push the piston up inside the tube, and so the sediment was pushed to the side rather than forming part of the core sample. This limitation could not be quantified, but does not affect the integrity of the core as a whole. A similar source of error is that of core compaction, which was calculated for each core as the difference between core length and hole depth. This difference results not entirely from the compaction of unconsolidated or poorly consolidated sediments in the sample, but also from the possible loss of downcore material in a similar manner to that of the soft surface sediments.

3.3.2 Sediment texture analysis

Sediment texture is a broad term that describes the character of sediment, and includes parameters such as grain size distribution, shape, sphericity, roundness and rollability (Lewis and McConchie, 1994). These attributes are a function of the distribution of energy in the depositional environment, the type of transport processes and the timeframe within which they operate on the sediment, and character of the source rocks. Thus results of sediment texture analysis can be used to infer the type of depositional environment (Lewis and McConchie, 1994).

Each of the above attributes can be measured individually via separate techniques, but sediment analysis is often restricted to size determination. The standard descriptive grain size scale is the Udden-Wentworth scale, which is presented in Figure 3.7 with associated phi and millimetre conversions. Particle size is difficult to define in absolute terms, due to the three dimensional nature of sediment particles. There are several different techniques for size determination and all involve indirect measures, which are influenced by particle shape and in some cases by density as well. Consequently, results from differing techniques cannot be compared with accuracy and no method provides 'true' results, rather different properties of the same sediment are being measured (Konert and Vandenberghe, 1997; Lewis and McConchie, 1994; McCave *et al.*, 2006). Methods of grain size measurement include laser particle sizing, pipette analysis, sieve analysis and settling velocity. The most appropriate method to use depends on the shape and mineralogy of the sediment to be measured, its size range, equipment availability, time, funding and accuracy constraints.

The laser particle sizer method was chosen for this study, as the sediments in these samples range in shape, mineralogy and size, with the vast majority of sediment below the 1 mm maximum measureable size. The large percentage of organics, clays, and low density particles such as micas meant settling velocity was not an appropriate method, although a combination of sieve and pipette analysis would have been an acceptable alternative method. Laser diffraction grain size analysis works on the relationship between particle size and the angle by which light is diffracted when that particle obscures a laser beam (Singer et al, 1988). A laser beam is passed through a suspension of sediment in water, and the distribution of diffracted light is measured by a receiver. This diffracted light is focused at the receiver by the use of a lens, the focal length of which determines the size range that can be accurately measured (Singer *et al.*, 1988).

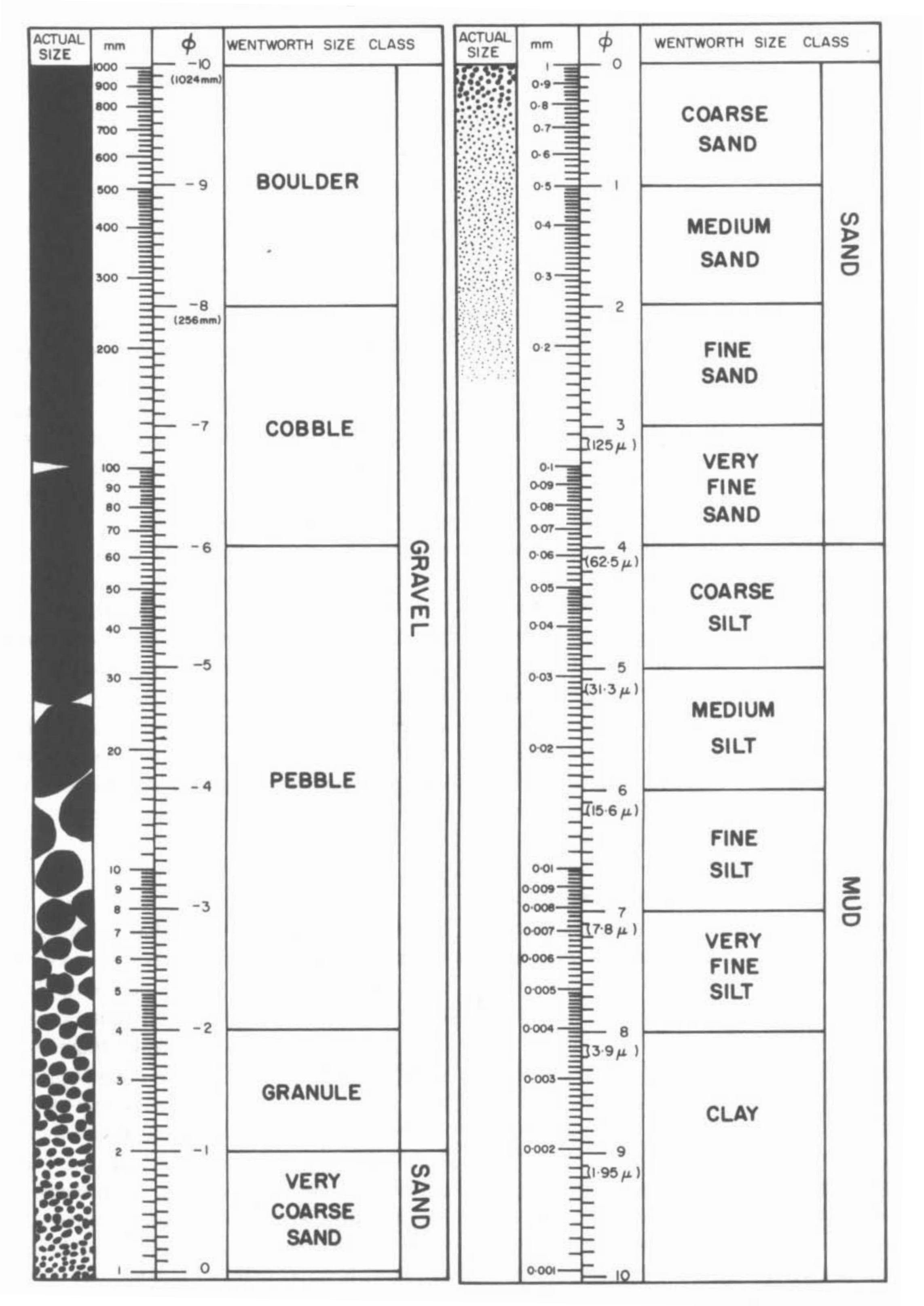


Figure 3.7. The Udden-Wentworth scale for grain sizes, with phi (φ) and millimetre (mm) conversion chart. *Sourced from Lewis and McConchie (1994, p.* 129)

Method

A total of three cores were taken from each site, and one representative core was chosen for analysis from each. Cores were consistent within sites in terms of observed stratigraphy. A total of 12 samples, 4 from each core, were taken for grain size analysis. These were sampled from depths of 30, 150, 300, and 450 mm. Samples were oven dried at 50 °C overnight, then dry sieved through a 1 mm sieve to remove material too coarse to be analysed by the laser sizer unit. No further pre-treatment of samples was performed. A *Micromeritics Saturn Digisizer 5200* was used in the grain size analysis, capable of measuring particles from 0.0001 to 1.0 mm in equivalent spherical diameter (Micromeritics, 2009a). Samples of approximately 1 cm^3 were fed slowly into the machine until a beam obscuration of between 13 and 20% was reached. The volume of sediment this required increased with coarser samples. The machine then passed a laser beam through the suspended sample at 10 different angles and measured the diffraction pattern obtained. Each sample was run through the machine three times, and the results averaged to provide the final distribution. The distributions are calculated automatically from the diffraction patterns using Mie Theory, which states that the intensity of the light reaching the receptor is a function of particle size, focal length of the lens, angle and wavelength (Micromeritics, 2009b).

Statistical analyses on these results were performed to obtain the maximum, minimum and mean grain size (µm), standard deviation, mode of the sample distributions. The standard deviation provides a measure of the degree of sorting of the sample (Folk, 1974). For coarse, sandy samples (Samples, 8, 10, and 12), the second and third runs were disregarded. This was necessary because the data obtained was clearly erroneous, giving distributions clustered around the very low end of the scale (0.0001 mm). This is likely due to the weight of the particles causing them to sink more easily, thus not being read by the machine after the first run. The grain size figures of each sample were correlated to the Udden-Wentworth grain size chart.

Table 3.3. Sorting classes. *Sourced from Folk (1974, p. 46)*

Standard Deviation σ	**Sorting**
< 0.35	Very well sorted
0.35 - 0.5	Well sorted
0.5 - 0.71	Moderately well sorted
0.71 - 1.0	Moderately sorted
1.0 - 2.0	Poorly sorted
2.0 - 4.0	Very poorly sorted
> 4.0	Extremely poorly sorted

Limitations and errors

The high organic percentage of some sediments in this study, combined with the diverse range of sediment types present between samples, creates potential error sources in laser sizer results. Although the laser particle sizer is capable of measuring larger, lower density particles such as micas or biogenic particles (Singer *et al.*, 1988), the tendency of this matter to float on the surface of the water possibly affected results. In addition, some organic particles measured were very elongated in shape and larger than 1 mm lengthwise, due to the fact that sieving (as was performed in pre-treatment removal of coarse matter) sorts particles on the basis of the intermediate axis, which meant these elongated particles slipped through the mesh. Consequently, the upper end of the size range of affected samples is potentially inaccurate. A similar problem with larger particles occurred in particularly coarse, sandy samples, which had a tendency to sink rather than remain in suspension, thus rendering the second and third runs of these samples incorrect and they were discarded.

3.3.3 Percent organics principles and practices

The amount of organic matter present in a sediment sample is important in many depositional settings, and reflects the degree to which in-situ biomass is responsible for sediment deposition at that site and can also indicate sedimentation rate (Lewis and McConchie, 1994; Sutherland, 1998). This is very much dependent on transport processes and energy in the depositional environment, thus provides insights into the environment at the time of deposition. This is important for this study because wetland

and lagoon environments are often areas of high biomass production so that comparisons in sediment organic percent in different locations and stratigraphic horizons can yield important results.

The percentage of organic matter was calculated using the Loss on Ignition (LOI) technique, as detailed by (Lewis and McConchie, 1994). This is done by calculating the mass lost from a sample following firing, with the resultant difference in weight being principally due to the combustion and loss of organic matter in the sample.

This measure is subject to considerable error, as the loss of mass is due not only to combustion of organics but also to the loss of water of crystallisation from clay minerals, loss of carbon dioxide from any carbonates present, or loss of sulphur (Sutherland, 1998; Lewis and McConchie, 1994). However, as a rough estimate of quantifying the amount of organic matter (and thus organic carbon) it is a generally accepted technique. Ideally, sedimentation rates should be measured independently at the site before interpreting percent organic results, but this is rarely performed in practice and leads to a degree of uncertainty (Doyle and Garrels, 1985). The LOI technique involves burning samples at a high temperature to oxidise (thus removing the mass component) of organic matter in the sample. The optimum temperature to use for this process is considered to be 450 °C. This is a trade-off because total removal of organic matter can require temperatures of up to 1000 °C, but beyond 500 °C any clays and carbonates present in the sample become significantly modified, affecting results and interpretation (Sutherland, 1998).

Method

Twelve samples were processed for LOI analysis and were taken from the sediment cores. Four subsamples of approximately 1 cm^3 were taken from each core, at the same depths sampled for diatom analyses (30, 150, 300 and 450 mm below the surface). Samples were oven dried for 24 hours at a temperature of 105 °C. This removes moisture from the sample prior to initial weighing. The mass of each dried sample (weighed in a crucible of known mass) was determined to an accuracy of 0.01 g, and then samples were placed in a muffle furnace at 450 °C for 18 hours. Potential for cross contamination is acknowledged, as when sizeable portions of organic matter are present and thus oxidised, ash particles can float between containers in the furnace and affect mass changes. Following removal from the furnace, the crucibles were left to cool to room temperature before weighing again. The difference in mass of each sample between initial weight and weight following ignition was then converted into a percentage of total sample weight.

3.4 Summary

This chapter detailed the methodology employed in this study, first detailing the principles and theory of each technique, followed by the processes followed in this particular project. A summary flowchart illustrating the timeframes to which each method pertains, and the results gained by each type of analysis is presented below (Figure 3.8).

Techniques employed to assess the present geomorphology includes GNSS surveys of representative sections of Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex. Digital Elevation Models of the surveyed areas were constructed using *ArcGIS*, which were then analysed for trends in topography and dune shape, height and steepness. The hydrology of the two systems was investigated over a week-long period, during which measurements of conductivity, water temperature and water level were made at ten minute intervals at three sites within Totara Lagoon and three sites within Waikoriri Creek.

Decadal-scale dynamics of Totara Lagoon and Waikoriri Lagoon were investigated through analysis of aerial photographs, covering the period from 1948 to 2006. Photographs were orthorectified and georeferenced to the New Zealand Map Grid

(NZMG) datum, and digitisations of the lagoon channel configuration and outlet position were created using *ENVI* and *ArcGIS* software programmes. From these, measurements of outlet offset and rates of outlet migration were calculated and trends in outlet migration inferred.

Sediment cores and associated analyses were used to investigate the development of selected areas of each system over a longer time period, covering up to 150 years. Cores were taken from two sites in Totara Lagoon (north and south) and one site from Shearer Swamp. Core stratigraphy was logged, and sediment texture analyses were conducted using a *Micromeritics Saturn Digisizer 5200* for selected core depths. Organic percentage of samples was also measured using the Loss on Ignition technique.

The results gained from these techniques and analyses are presented in the following three chapters.

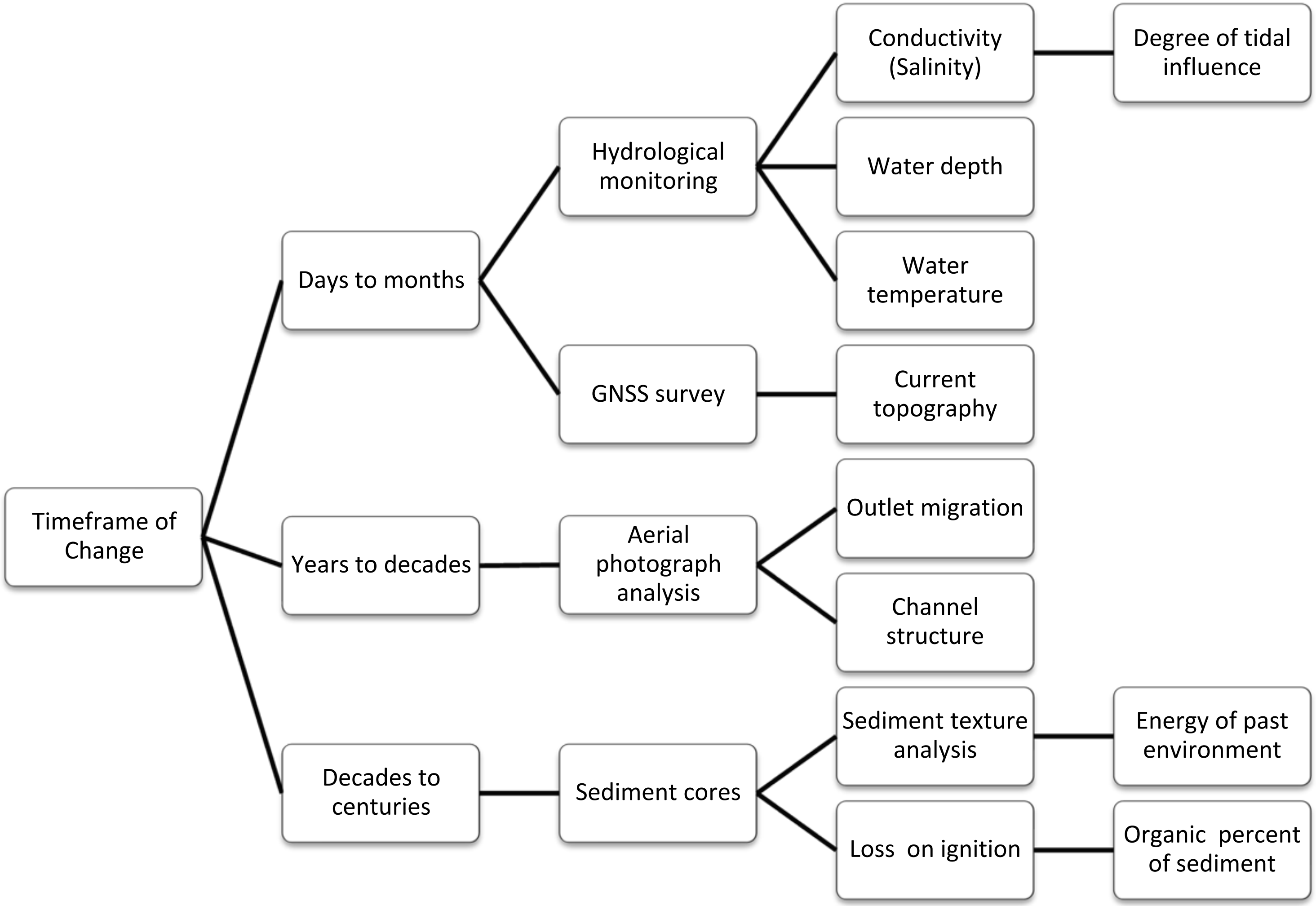


Figure 3.8. Summary flowchart of the methods employed in this project, the timeframes to which they apply, and the information provided by each technique.

CHAPTER THREE

Methodology

3.1 Introduction

Due to their dynamism and multiple facets, coastal features and environments are difficult to investigate, often requiring a combination of techniques to capture a comprehensive set of data. Recent advances in technology have made the study of coastal environments much more accessible, allowing data collection on far greater spatial and temporal scales. This chapter discusses the individual techniques used in this study and details the way in which they are applied. Firstly, the methodology employed to document the current and recent geomorphology is presented in Section 3.2, followed by techniques pertaining to the development of the study sites over recent centuries in Section 3.3. Each of these two major sections begins with a review of the principles and techniques involved in the methodology, followed by details of the method as applied in this study.

Fieldwork was undertaken over two main periods. Ground surveying and short-term water level recording was performed during the period December 1st – 16th 2008. This is important to note, as these coastal systems are very dynamic and can change substantially in response to seasonal weather trends and random storm events. During this period, a single storm occurred on December 6th. Sediment cores were taken on a second visit during the period March 2nd – 7th 2009. Fieldwork included visual observations and photographs of the field sites, including outlet position, form, and any other features of interest. A third site visit took place over March 20th – 22nd. No quantitative measures were taken during this time, but observations about the lagoons and outlet position and form were made.

3.2 Recent geomorphology

3.2.1 Topographic survey principles and practices

Ground surveys of the topography of a given area and its features remains one of the fundamental tools for understanding its geomorphology and processes, and for monitoring changes in coastal landforms over time. In the past, surveys were performed with a total station, which although potentially very accurate, can be a time consuming task that is spatially restrictive and labour intensive. With the advent of GPS and GNSS systems, and subsequent GIS analysis packages, surveying has become applicable on a larger spatial scale and in greater detail. Data collection by ground survey techniques remains more labour intensive than remote methods such as aerial or satellite imagery analyses (e.g. LIDAR), which are superior for analysing large areas of coastline, but these may require validation and calibration by associated ground surveys (Pranzini, 2007).

Data collected from GPS ground surveys can be used to create a topographic map of the survey area, or a digital elevation model (DEM), a three dimensional digital representation of the topography and landforms. The method employed to achieve this is critical to the accuracy and applicability of the resulting model. Survey data is in the form of ‘points’, that is; individual points taken along a transect or surrounding a feature, which must be converted into a continuous surface by the process of interpolation (Andrews *et al.*, 2002). Interpolation uses the characteristics of the points collected to fill in the areas between the points, which can be achieved in several different ways. Commonly used methods of gridding are kriging, inverse distance weighted, nearest neighbour and spline (Andrews *et al.*, 2002). There is no set formula for determining which method will yield the most accurate DEM, and often several methods of interpolation, grid size, and sampling density need to be explored and compared.

Another method of producing a three dimensional model is by use of a triangulated irregular network (TIN), which triangulates adjacent points to create a continuous surface. This method works particularly well when survey data is irregular rather than collected along a grid, and when a relatively good density of points is achieved (Lo and Yeung, 2006). A TIN is not based on a grid and as it merely involves forming planes between data points, no interpolation is required (Andrews *et al.*, 2002; Kumler, 1994).

Consequently, the resulting model is not considered a DEM in the strictest definition of the word (Andrews *et al.*, 2002); however, for the purposes of this study they can be considered the same and the three dimensional models presented in Chapter 5 will be referred to as DEMs.

Data collection

Ground surveys of representative sections of each site using a *Trimble R8* GNSS system were undertaken over a 2 week period in early December 2008. The scale and nature of the field sites and access constraints did not allow surveying of the entirety of the systems. Four representative areas along the length of Totara Lagoon were surveyed in detail: the river mouth extremity, the northern extremity, and two sections along the central reaches of the lagoon channel. These sections were chosen to provide approximately evenly spaced snapshots of the topography of Totara Lagoon along its 10 km length, from which trends of change in terms of distance from the outlet could be inferred. The river mouth end was particularly important, as this is currently where the lagoon discharges. The entire dry channel of Waikoriri Lagoon, as far as the recently abandoned opening, was surveyed, and the adjacent area between the lagoon and the western edge of Shearer Swamp was also surveyed. Sample elevation points surrounding Shearer Swamp were also taken (Figure 3.1). Details of surveyed areas are presented in Table 3.1.

Surveying was undertaken using a *Trimble R8* GNSS. Several geodetic markers maintained by Land Information New Zealand (LINZ) exist in the area and were initially considered as locations for the GNSS base station. However, no consistent signal was achieved between the base and the rovers at any of these locations. The base station was set up on a high point at Ross Cemetery, which overlooked the entire coastal plain of interest and from which a consistent signal could be achieved at both study sites via a repeater (Figure 3.1) (Appendix 1). Surveys were undertaken using the NZGD 2000 Hokitika Circuit map grid. Surveying was performed on foot, with rovers attached to researchers' backpacks, recording their position and elevation at 5 second intervals using the 'continuous topo' function. A strong signal was achieved over most of the study area, and this was surveyed using Real Time Kinematics (RTK), which yields very accurate positions that are calculated in the field rather than requiring extensive post-survey correction. This option works well where there are few obstructions between the base or repeater signal and the rovers, such as vegetation, hills or scarps. The middle and northern reaches of Totara Lagoon were unable to be surveyed using RTK. In the northern reaches, no signal was received and so the PPK (Post-Processed Kinematic) survey option was used, whereby the rovers record positions autonomously in the field and data obtained requires extensive post-processing in a GPS software programme. Where the signal was intermittent the ‘RTK and infill’ option was used, which uses RTK when a signal can be received, but reverts to PPK when it is lost. In addition to a general survey of the area, features of interest were mapped in detail. These included the lagoon waterline and seaward shoreline (when appropriate), heights and profiles of adjacent dunes, cusps, scarps, and depth of the lagoon channel when possible. Where possible, transects spanning the seaward dunes, lagoon channel and adjacent landward morphology were surveyed. Channel depth was not measured at the middle and northern sites of Totara Lagoon, due to the conditions of the channel bed. In the central and northern reaches, the channel bed was covered by a very thick layer of mud and organic sludge (measured at over 1.5 m at Totara Central North) which made surveying too dangerous to attempt.

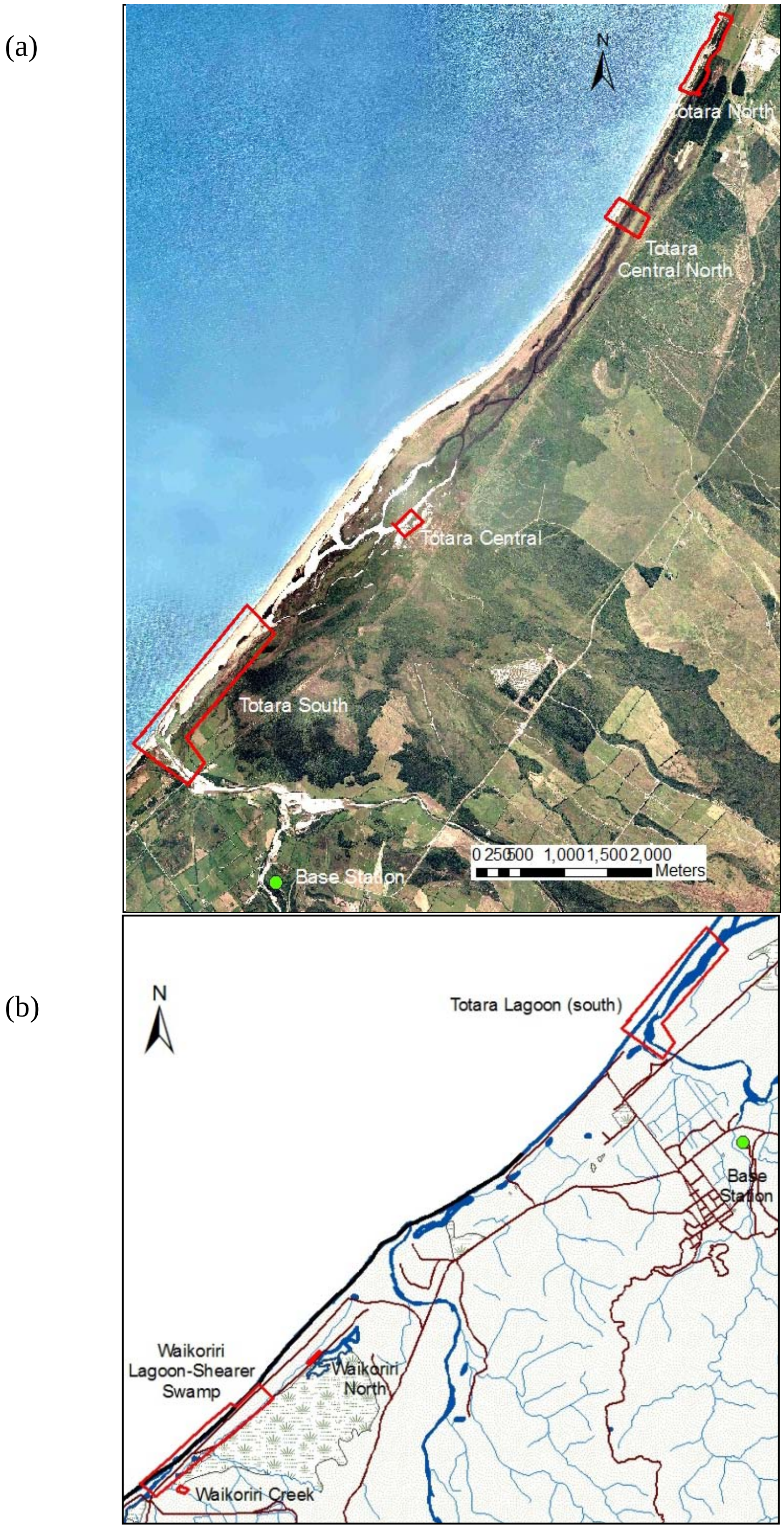


Figure 3.1. Location maps showing the surveyed areas in (a) Totara Lagoon and (b) The Shearer Swamp-Waikoriri Lagoon complex. The base station location did not change between the two study areas.

Figure 3.2. Left: Base station receiver set up at Ross Cemetery. Right: Surveying the river mouth end of Totara Lagoon.

Table 3.1. Details of GNSS surveys across both field sites.

Location	**Number of Points**	**Spatial Extent (m^2)**	**Survey method**
Totara South	7693	367 231	RTK
Totara Central	1513	12 920	RTK and infill
Totara Central North	1988	63 459	RTK and infill
Totara North	7276	188 456	PPK
Waikoriri Lagoon/ western margin of Shearer Swamp	11 529	552 044	RTK
Southern margin of Shearer Swamp	556	1 857	RTK and infill

Data processing

Data collected in the field was transferred from the GNSS hand units to a laptop and converted to ASCII format using the *Trimble Geomatics Office* programme. An initial three dimensional model of the data was produced in *Terramodel 10.4*, which allowed erroneous data points and other anomalies to be identified. These were located and removed in the associated *Microsoft excel* file. Due to the position of the base station on an unknown point (i.e. not a LINZ geodetic marker), the base position required correction before data in the field could be corrected. This was achieved by constructing a baseline between the base station location and the location of the LINZ base station in Hokitika, following which the data collected in the field was then adjusted based on the corrected base station position. The ASCII files were later transformed for *ArcGIS* analysis into shapefiles (.shp), database files (.dbf), and *ArcView* database index files (.shx).

GIS analysis

Following correction and file conversion, the data was imported into *ArcGIS* as a single large dataset covering both field sites. Firstly, the entire dataset required correction for field surveyor heights, which had created systematic errors in elevation. Due to the general thoroughness of surveying and density of points in each survey section, the TIN method produced the most representative DEM of the study site. Kriging and Inverse-distance-weighted interpolation methods were also trialled, but these resulted in inaccurate representations and smoothing of features such as scarps and steep dunes. Following the DEM construction, a number of erroneous points of negative elevation were identified and removed in *ArcGIS* and the model redrawn. Because the TIN method creates triangular planes between adjacent points, there was potential for areas of incorrect interpolation where point density was low and when points across large distances between survey sites were triangulated. To remedy this problem and reduce error, polygons were constructed around each survey area to eliminate outlying points and create individual DEMs of Waikoriri Lagoon and the adjacent dune ridges, Totara South, Totara Central, Totara Central North, and Totara North.

The DEMs were then compared to photographs of the morphology to assess the degree to which the areas were accurately represented by the models. Due to the complexity of the dunes in the northern reaches of Totara Lagoon, a degree of inaccuracy was accepted and noted. The DEMs were then visually assessed in conjunction with field notes and photographs taken while surveying, and features of interest identified. From this DEM, several profiles were graphed across the seaward dune ridges adjacent to Totara and Waikoriri Lagoons and across the relic dune ridges between Waikoriri Lagoon and Shearer Swamp. These are two dimensional cross-sections oriented parallel to the dune crest, which allow differences in dune heights steepness and morphology between different profile locations to be quantified.

Limitations and errors

The extent and accuracy of the point network covering the survey area is constrained by accessibility. Where researchers were unable to thoroughly cover a feature, the DEM of that feature is inaccurate due to the triangulation of insufficient points. This applies specifically to the lagoon channel in the middle and northern reaches of Totara Lagoon, and to some areas of the dunes surrounding both Totara Lagoon and Waikoriri Lagoon. The muddy nature of the lagoon channel bed and swampy margins in some places was a safety issue, and thus surveys extend only as far as the water edge, meaning the surface in the centre of the Totara Lagoon central and northern DEMs signifies the elevation of the water surface, rather than the channel morphology. This was not an issue in Waikoriri Lagoon, where the channel was dry during surveying, or in Totara South, where the channel could be waded. Heights of well established dune ridges were underestimated in places, due to large amounts of vegetation preventing accurate surveying of the crest. This occurred in the landward dunes of Waikoriri Lagoon, and in the northern reaches of Totara Lagoon on both sides. Areas that have been affected by these access issues are highlighted in the following chapter. This does not affect profile constructions or volumetric analyses, as these are based on surveyed transects of actual point data, rather than relying on the interpolation of the DEM.

One limitation of surveys in this area is the lack of accessible and accurate geodetic markers. Not only did this provide a problem in choosing a location for the base station, but it made post-processing of the data more difficult. To tie the vertical dimensions of the DEM to local mean sea level, at least 4 of these known points were required, which was not possible to obtain in the area. Consequently, the initial survey results were in terms of height above a global ellipsoid, meaning elevation data could be used in a relative form but not in terms of absolute elevation above mean sea level. As a solution to this problem, an approximation of sea level elevation in the area was calculated from the geodetic marker information provided by LINZ, which gives elevation above mean sea level for each marker. The sea level elevations at each marker location were averaged to provide a linear approximation of mean sea level elevation over the entire survey area, then the difference was applied to the entire *ArcGIS* dataset. This is not ideal, as it does not account for the elliptical nature of the Earth's surface; however, due to the close proximity of the survey areas this has a minimal effect on results.

3.2.2 Aerial photograph analysis: principles and practices

The use of aerial photography to assess coastal change over time has been practiced and refined for over fifty years. Early photographs were simple black and white images of low resolution, which then moved to higher resolution black and white pictures and the introduction of stereographic pairs. Colour photographs became accessible from the 1980s (Lewis and McConchie, 1994). Stereo pairs of images can be used to look at the topography of the area in the photograph and construct topographic contours, and are useful in cartography, management and planning, vegetation and species distribution mapping, and to detect large scale geological features that are difficult to map from the ground (Lewis and McConchie, 1994; Andrews *et al.*, 2002). Aerial photographs can be taken either vertically or obliquely, of which vertical photographs are the most useful for scientific mapping purposes.

The use of aerial photographs for mapping shoreline change and changes in vegetation cover in coastal areas is a well established method that has been applied and refined over the past 70 years by coastal planners, engineers and scientists (Boak and Turner, 2005). More recently, satellite imagery has started to replace aerial photography as the primary method of collecting this type of data where budgets and coverage allow. However, aerial photographs remain a relatively cheap and simple-to-analyse record of historical change in coastal zones.

Significant distortions exist in aerial photographs, which must be corrected prior to their use for mapping purposes. This correction process is known as orthorectification. This distortion includes radial distortion (which increases with distance from the photographic centre); relief distortion from topographic variation; tilt and pitch changes of the aircraft; lens distortion in older photographs; and scale variations resulting from altitude changes along the flight line (Gorman *et al.*, 1998; Boak and Turner, 2005; Al-Tahir and Ali, 2004). Because coastal areas are generally flat, relief distortion is negligible and can usually be ignored (Al-Tahir and Ali, 2004).

Data collection and orthorectification

This study utilises a collection of aerial photographs taken between 1948 and the present day, with the aim of documenting changes in outlet migration and visual changes in the systems over this period. Photographs sourced were taken on an approximately decadal time scale and covered the following years: 1948, 1963, 1972, 1976, 1981, 1986, 2002, 2005 and 2006. Images from 1988 onwards are high resolution colour photographs. Further details of the images used are presented in Appendix 2. The pre-2005 photographs were obtained in hard copy and subsequently scanned at a resolution of 700 dpi and saved as digital (.jpg) files for GIS analysis. Due to the large spatial extent of the study sites, several photographs were required to cover the whole area.

The photographs obtained in hard copy were unorthorectified, and for the Totara Lagoon site this was performed in ENVI by georeferencing each photograph to 2 orthorectified digital images produced by LINZ (2002) (Area J33 – Kaniere, LINZ, 2009b). Georeferencing involved matching several visible and stable points (referred to as control points) on the orthorectified images to those same points in the other images, then warping the distorted image to fit the orthorectified reference images. These orthorectified images obtained from LINZ covered the Totara Lagoon area, and were high resolution colour photographs taken in 2002. For the Shearer Swamp-Waikoriri Lagoon complex no orthorectified images were available, but the 2002 image (the clearest and highest resolution image available of the area) was georeferenced to a GIS shapefile of roads in the area (NZ 1:50 000 topographic survey). From this, images taken in earlier years were georeferenced and warped to control points located on the 2002 image using ENVI, by the same process as used for Totara Lagoon images. Due to the dynamic nature of the coastal zone and the lack of visible engineered structures in the study areas, control points were usually road intersections, bridges, or lone buildings. At least 4 control points were located on each image, a sufficient number to provide a satisfactory orthorectification, and these were distributed as evenly as possible across the entire image. As a part of this process, the images were spatially referenced to the New Zealand Map Grid (NZMG) datum, allowing results to be quantified spatially in terms of location and distance in metres.

No further preparation was necessary for the Waikoriri Lagoon images prior to the following analysis, as only a single image from each survey period was required to cover the entire lagoon area. Totara Lagoon required between 2 and 5 images from each survey to cover the entire lagoon. In order to create a single georeferenced image of the lagoon for each survey, the mosaicking tool in ENVI was used to stitch the individual images together while maintaining their position in coordinate space. For this to be effective, and to minimise error, the images needed to overlap approximately 30% with adjacent images.

Analysis of lagoon change

The final images of each site were compared visually and qualitative changes in outlet position and channel structure across the study period were noted. A digital representation of the lagoon area and shoreline position for each survey year were created in ENVI using the ‘Region of Interest’ tool, then the resulting polygon/line files were exported into *ArcGIS* as shapefiles for further spatial analysis. The outlet offset was measured in metres from the Totara River mouth for Totara Lagoon, and from the Waikoriri-Granite Creek confluence in the case of Waikoriri Lagoon. The surface area of Waikoriri Lagoon at each survey was calculated in *ArcGIS* from the individual digitisation polygons. This was not performed for Totara Lagoon, due to the size of the lagoon and the large errors that would be introduced as a consequence.

Limitations and errors

This process was fraught with challenges in the orthorectification/georeferencing process, due to the nature of the study sites and poor quality of some photographs. In common practice, photographs are orthorectified and georeferenced in separate processes, using a combination of digital techniques and collection of control points in the field. This was not possible for either Totara Lagoon or Waikoriri Lagoon, due to access constraints in the field and lack of features such as buildings, roads and prominent rocky areas that could act as GCPs. The roads in the area also underwent several realignments and upgrade works over the period covered by the surveys, meaning even road intersection positions were sometimes not accurate enough for this purpose. The dynamic coastal nature of these sites also meant that features in the immediate vicinity of the lagoon were very changeable and thus not suitable as GCPs.

For Totara Lagoon, GCPs were clustered landward of the lagoon in most cases. Some stable patches of vegetation were able to be used in later photographs, but these were not visible at a suitable resolution in earlier images. To obtain the most accurate result from this process, GCPs should be distributed across the entire image, particularly the area of interest. This was not possible in the beach area or where ocean covered a large part of the photograph. This was of particular concern in the 1976 images, where the scale was so small that individual photographs covered only the lagoon area. A large portion of the potential error in the georeferencing process for Totara Lagoon arose from human interpretation of features and accuracy (related to photograph resolution). This was more problematic for the earlier images. Parameters such as pixel size, tone, texture, shade, shape and position are important considerations for the researcher performing the analysis (Boak and Turner, 2005; Dahdouh-Guebas *et al.*, 2006).

The georeferencing process for Waikoriri Lagoon was further complicated by the absence of an existing orthorectified, georeferenced image from which to reference other raw images. The GIS road file that was used to reference the 2002 image was sourced from the NZ Topographic survey 1:50 000 data, which is accurate to ±22 m horizontally and ±5 m vertically (LINZ, 2008). This introduced a large source of potential error, which was then compounded by the same error sources as occurred in the Totara Lagoon images.

Once again, human interpretation and manual errors could have arisen during the digitisation of the lagoon process from the orthorectified images. In order to minimise these errors in the quantitative results, measurements of outlet position were made directly from the photographs rather than from the digitisations. In addition, the exact dimensions of the lagoon and outlet position fluctuate in response to tidal and weather factors, so quantitative data relating to outlet position and lagoon surface area were rounded to approximate values (nearest 50 m).

A common error noted in aerial photograph analysis is the issue of vertical displacement (Gorman *et al.*, 1998; Dahdouh-Guebas *et al.*, 2006); however, this was not a concern for either of these study sites as all terrain was low relief. Although the error sources discussed here appear significant, the magnitude of the changes in outlet position and lagoon structure means that they are relatively inconsequential.

3.2.3 Hydrological principles and practices

The hydrology of a coastal waterbody is a very important aspect of its overall dynamics. The hydrological regime of a coastal lagoon is a function of system morphology, fluvial input, marine conditions and other factors such as ecology and land-use in the surrounding area (Kirk, 1991). Data on water pressure (which is then converted to water depth), conductivity and water temperature are three commonly measured variables, which provide valuable information on the hydrological dynamics of the system.

As technology has advanced, these variables can be measured increasingly easily and at a greater spatial and temporal resolution. Often, conductivity and temperature are measured both horizontally and vertically within a waterbody to assess stratification and apply complex numerical models. For the purposes of this study, the aim was to assess broad trends rather than gain high resolution data for modelling, so data was not collected to this level of detail.

Conductivity is the degree to which a substance is able to conduct electricity which, in the case of water, is a function of the concentration of dissolved ions (salts such as chlorides, sulphates, carbonates, sodium, magnesium, potassium). As such, conductivity can be used as a proxy for determining the salinity of the water body (e.g. Fernandes *et al.*, 2004, Lucas *et al.*, 2006). In waterways, electrical conductivity can be affected by soil composition, land-use characteristics and runoff, flow rate of the water, groundwater inflows, temperature, and evaporation/dilution (Lucas *et al.*, 2006). The salinity of a coastal lagoon is an important parameter, as it provides information about the degree of water exchange between the ocean and the lagoon, or the balance between fluvial inputs and marine influence (Kirk, 1991). It is important to note, however, that conductivity is not necessarily a direct measure of marine influence in all cases, as some of the measured conductivity may be due to one of the above factors. In these studies, the patterns and degree of change above the baseline conductivity for each site were the factors assessed. It is possible to calculate the absolute salinity from conductivity and temperature data, but this was not deemed necessary for the purposes of this study. Electrical conductivity ranges of common water systems are presented in Table 3.2.

Water temperature is heavily influenced by the degree of solar insolation (Smith, 1981) and local hydrodynamics (Vaz *et al.*, 2005; Lucas *et al.*, 2006). In terms of water quality, temperature affects the density and conductivity of a waterbody, and influences the oxygenation level of the water column (Vaz *et al.*, 2005; Lucas *et al.*, 2006). Water temperature can change dramatically in response to changes in fluvial or marine inflow into a coastal lagoon.

Table 3.2. Electrical conductivity ranges of different water types. *Sourced from Suttar, 1990.*

Water Type	**Electrical Conductivity Range (mS cm^{-1})**
Deionised Water	0.0005 – 0.003
Pure rainwater	< 0.015
Freshwater rivers	0 – 0.8
Marginal river water	0.8 – 1.6
Brackish water	1.6 – 4.8
Saline water	> 4.8
Seawater (average)	51.5

Data collection

Two sets of water level, temperature and conductivity data were taken at each field site, a long term record spanning September 2008 to March 2009, and a short term record at two sites within each field area spanning a week in early December 2008. The locations of these recorders are illustrated in Figure 3.4, with GPS coordinates given in Appendix 3. The long term water level recorders were situated at Totara North and Waikoriri Bridge. The locations of the short term recorders in Totara Lagoon were selected to allow comparisons of data between the river mouth end, middle and northern end of the lagoon over the sampling week (November 29th to December 7th 2008). Short term records were taken in Waikoriri Creek between December 8th and December 14th 2008, and recorders were situated in the stretch of creek that drains the western edge of Shearer Swamp.

Short term records were taken using two *XR-620-CTDm* water level recorders, manufactured by Richard Brankner Research Ltd (RBR, 2009)., which recorded water pressure (deciBars), temperature (° C) and conductivity (mS cm^{-1}) at ten minute intervals for the entire sampling period. These were mounted on a metal support which rested on the bed of the channel at the deepest point (Figure 3.3). The distance between the channel bed and the recording equipment was 200 mm.

Long term records were taken using two *CT2X* water level recorders (INW, 2009), which also recorded water pressure (psi), temperature (° C) and conductivity (µS cm^{-1}) at ten minute intervals over the sampling period. These were mounted vertically, attached to a warratah (Figure 3.3) which was driven into the soft mud of the channel bed in the case of Totara North. The Waikoriri Bridge recorder was initially mounted on the south-west corner of the bridge buttress, but in early November the creek drained suddenly through a breach in the Waikoriri Lagoon barrier approximately 100 m downstream, leaving the recorder out of the water and above the high water mark. This was rectified in early December, when the recorder was moved approximately 10 m downstream and mounted on the pole of a retaining wall on the northern bank of the stream.

No official weather monitoring station was available in close proximity to these study sites to provide measurements of barometric pressure from which to correct water level pressure results. This was achieved by using *PT2X-BV* barometric pressure sensor, which was mounted on a nearby building on Bold Head Rd. This data was used to correct both short and long term water pressure data from both sites.

Figure 3.3. Water level recorders set up at the field sites. Left: short term *XR-620-CTDm* water level recorder in Totara Lagoon. Right: Long term *CT2X* water level recorder affixed to Waikoriri Bridge via a warratah.

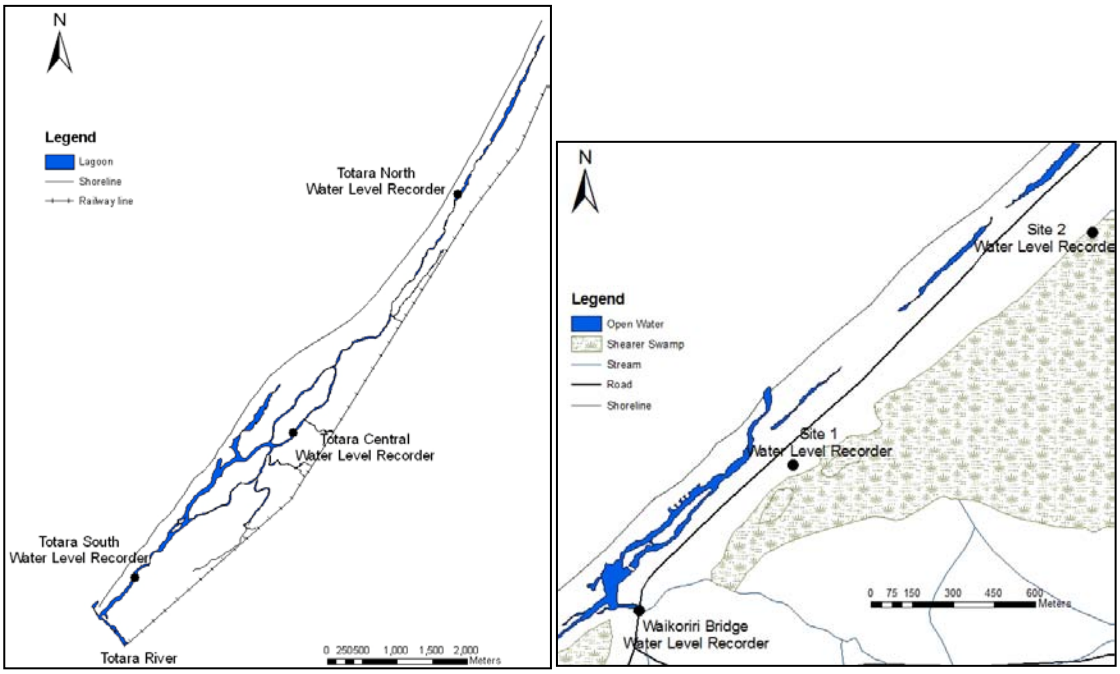


Figure 3.4. Locations of the water monitoring sites in Left Totara Lagoon and Right: The Waikoriri Lagoon-Shearer Swamp complex.

Analysis of data

Data for pressure, temperature and conductivity obtained from the recorders was first downloaded and opened using *RBR* software for the *XR-620-CTDm* loggers and *Aquasoft* for the *CT2X* loggers. Barometric pressure corrections were performed for the long term pressure records by the *Aquasoft* software. All records were then exported into Microsoft Excel for further analysis.

Units of measurement were standardised across all records, with pressure measurements converted into Bars and conductivity measurements converted to mS cm $^{-1}$. Short term pressure records were then manually corrected for air pressure by subtracting the recorded barometric pressure from the water pressure measurement. All water pressure data was then converted to mmH_2O and the measured distance from the channel bed to the recording equipment was added to all data entries, thus giving the absolute water depth. All data that was recorded while the equipment was out of the water (both before and after the sampling period and when it was removed briefly for maintenance during the sampling period) was removed prior to analysing the corrected data. These periods were identified by water level measurements in the vicinity of 0.0 mmH_2O. In the case of the Waikoriri Bridge long term recorder, this included removing the data for most of November and early December.

Data was then graphed over time to assess trends in these parameters and to compare measurements across sites within each field area. Data from the long term records matching the time period of the short term records from each field site was extracted for these comparisons, in addition to assessing the complete long term records. Maximum, minimum and mean values were calculated for each parameter from each recording site. In the case of Waikoriri Bridge, the record was split into two time periods: September to November, and December to March. Data from these two time periods could not be directly connected because the recorder location changed following the draining of Waikoriri Creek.

Limitations and errors

The dataset taken from Waikoriri Bridge is subject to the greatest degree of systematic error. As well as removing the data from when the water level recorder was out of the water, the water depth from the bed to the surface cannot be calculated. This is because the distance between the channel bed and the recorder was not measured as it was in all other sites. This is not of major consequence, as the most important aspect of this data is the degree of *relative* change, rather than records of absolute values. Unfortunately, this distance was not measured at either location at the bridge, meaning that the September to November and December to March records could not be connected to each other.

In terms of data analysis, it was decided not to perform any statistical transformations on the data prior to interpretation. This was not an issue for the short term records, but the long term data could have benefited from extra analyses using a set of moving averages over hours and/or days. This could potentially have made medium to long term trends more clear, as often they were obscured by shorter term variations and noise in the data.

3.3 Methods of assessing development over historical time

3.3.1 Sediment cores

The collection of sediment cores is a relatively efficient method of gathering samples of undisturbed subsurface sediment, and can be performed on a variety of scales and with equipment varying largely in size and complexity. The collection of short cores of friable sediment in a terrestrial setting can be undertaken with simple and inexpensive equipment such as that used in this study.

Sediment cores collect material that was deposited some time during the past, and a large number of analyses can be performed on samples of this sediment to assess the conditions at the time it was deposited. These analyses can be related to sediment character, ecological and microfossil content, geochemical composition, and varying dating techniques to determine the ages of different layers within the cores. This study employs sediment texture and organic percent analyses, each of which will be discussed individually in the following sections. Firstly, the collection process of the cores will be detailed.

Method

A total of three sites were chosen for coring, based on accessibility and the likelihood of sediment character being conducive to core recovery. One site was chosen at Shearer Swamp; on the western margin of Waikoriri Creek, which marks the official edge of

Shearer Swamp. Due to the muddy nature of Waikoriri Creek and equipment constraints, access to the more central reaches of the swamp was not possible. Two sites were sampled on the eastern, landward edges of Totara Lagoon; at the northern and southern ends respectively. Locations were documented using a handheld GPS unit (Figure 3.5) (Appendix 4). Due to the gravelly nature of sediments at the confluence of the lagoon and the Totara River, the southern core was taken approximately 2 km up the channel from this point.

Cores were collected with a hammer corer, which is a form of gravity corer comprised of a 1.5 m metal tube which is driven into the sediment by the manual operation of a heavy piston on the top (Figure 3.6). Several cores were taken from each site at intervals of 2 to 5 m to ensure the consistent character and lateral continuity of the observed sedimentary units. Surface sediments were infiltrated by roots in the top several centimetres, which were discarded prior to sampling. The depth of cores was constrained by the presence of coarse sand layers at all three sites, which prevented the hammer corer from penetrating further. Core compaction was estimated by measuring the difference between hole depth and core length. Once recovered from the ground, cores were ejected from the core tube into plastic half-round tubes and shrink wrapped for ease of transport and to prevent contamination (Figure 3.6). In the laboratory, cores were split lengthwise using copper wire and stored in a refrigerator. Cores were photographed and stratigraphy was examined and logged prior to sub-sampling for the analyses in the following sections. A single, representative core from each of the three sites was used for stratigraphic logs and analyses.

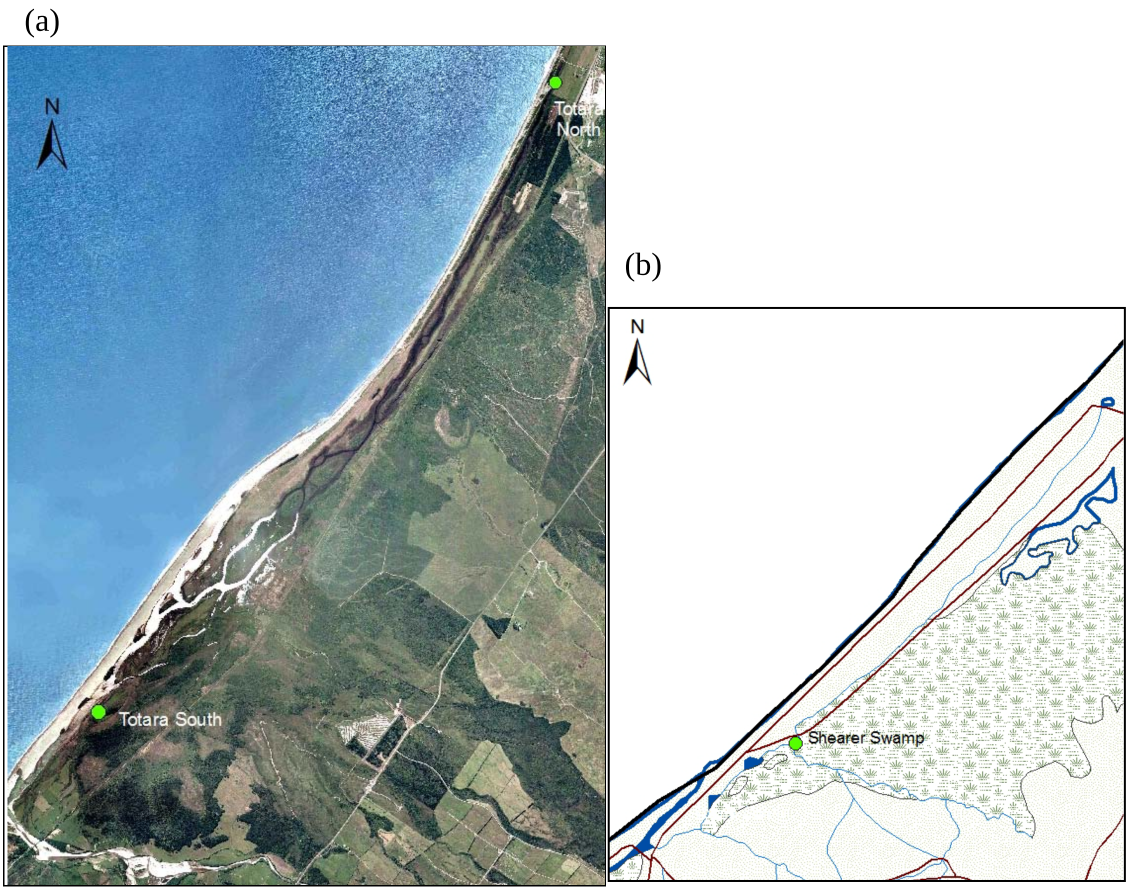


Figure 3.5. Locations of sediment cores taken from (a) Totara Lagoon and (b) Shearer Swamp.

Figure 3.6. Left: Photograph showing the process of taking a sediment core from Shearer Swamp with a hammer corer. Right: Ejecting the core into a plastic tube following collection.

Limitations and errors

The primary limitation in the collection of cores for this project was the inability to collect longer cores from a larger number of locations, due to equipment and time constraints. The diverse nature of sediment types in these environments made selection of equipment difficult, as each type of corer performs best in a relatively specific type of sediment. Initially a vibracorer was to be used, as this would work well in wetland and more sandy areas; however practical constraints meant that it could not be transported into the field sites. The hammer corer was simpler to use and was suited to the peat and mud layers of Shearer Swamp and lower Totara Lagoon. However, the presence of sand layers below depths of 0.5 m in all cores precluded the collection of longer cores. In addition to this issue, the very soft surface sediments of Shearer Swamp and northern Totara Lagoon were unable to be sampled, as the corer relies on resistance from the sediment to push the piston up inside the tube, and so the sediment was pushed to the side rather than forming part of the core sample. This limitation could not be quantified, but does not affect the integrity of the core as a whole. A similar source of error is that of core compaction, which was calculated for each core as the difference between core length and hole depth. This difference results not entirely from the compaction of unconsolidated or poorly consolidated sediments in the sample, but also from the possible loss of downcore material in a similar manner to that of the soft surface sediments.

3.3.2 Sediment texture analysis

Sediment texture is a broad term that describes the character of sediment, and includes parameters such as grain size distribution, shape, sphericity, roundness and rollability (Lewis and McConchie, 1994). These attributes are a function of the distribution of energy in the depositional environment, the type of transport processes and the timeframe within which they operate on the sediment, and character of the source rocks. Thus results of sediment texture analysis can be used to infer the type of depositional environment (Lewis and McConchie, 1994).

Each of the above attributes can be measured individually via separate techniques, but sediment analysis is often restricted to size determination. The standard descriptive grain size scale is the Udden-Wentworth scale, which is presented in Figure 3.7 with associated phi and millimetre conversions. Particle size is difficult to define in absolute terms, due to the three dimensional nature of sediment particles. There are several different techniques for size determination and all involve indirect measures, which are influenced by particle shape and in some cases by density as well. Consequently, results from differing techniques cannot be compared with accuracy and no method provides ‘true’ results, rather different properties of the same sediment are being measured (Konert and Vandenberghe, 1997; Lewis and McConchie, 1994; McCave *et al.*, 2006). Methods of grain size measurement include laser particle sizing, pipette analysis, sieve analysis and settling velocity. The most appropriate method to use depends on the shape and mineralogy of the sediment to be measured, its size range, equipment availability, time, funding and accuracy constraints.

The laser particle sizer method was chosen for this study, as the sediments in these samples range in shape, mineralogy and size, with the vast majority of sediment below the 1 mm maximum measureable size. The large percentage of organics, clays, and low density particles such as micas meant settling velocity was not an appropriate method, although a combination of sieve and pipette analysis would have been an acceptable alternative method. Laser diffraction grain size analysis works on the relationship between particle size and the angle by which light is diffracted when that particle obscures a laser beam (Singer et al, 1988). A laser beam is passed through a suspension of sediment in water, and the distribution of diffracted light is measured by a receiver. This diffracted light is focused at the receiver by the use of a lens, the focal length of which determines the size range that can be accurately measured (Singer *et al.*, 1988).

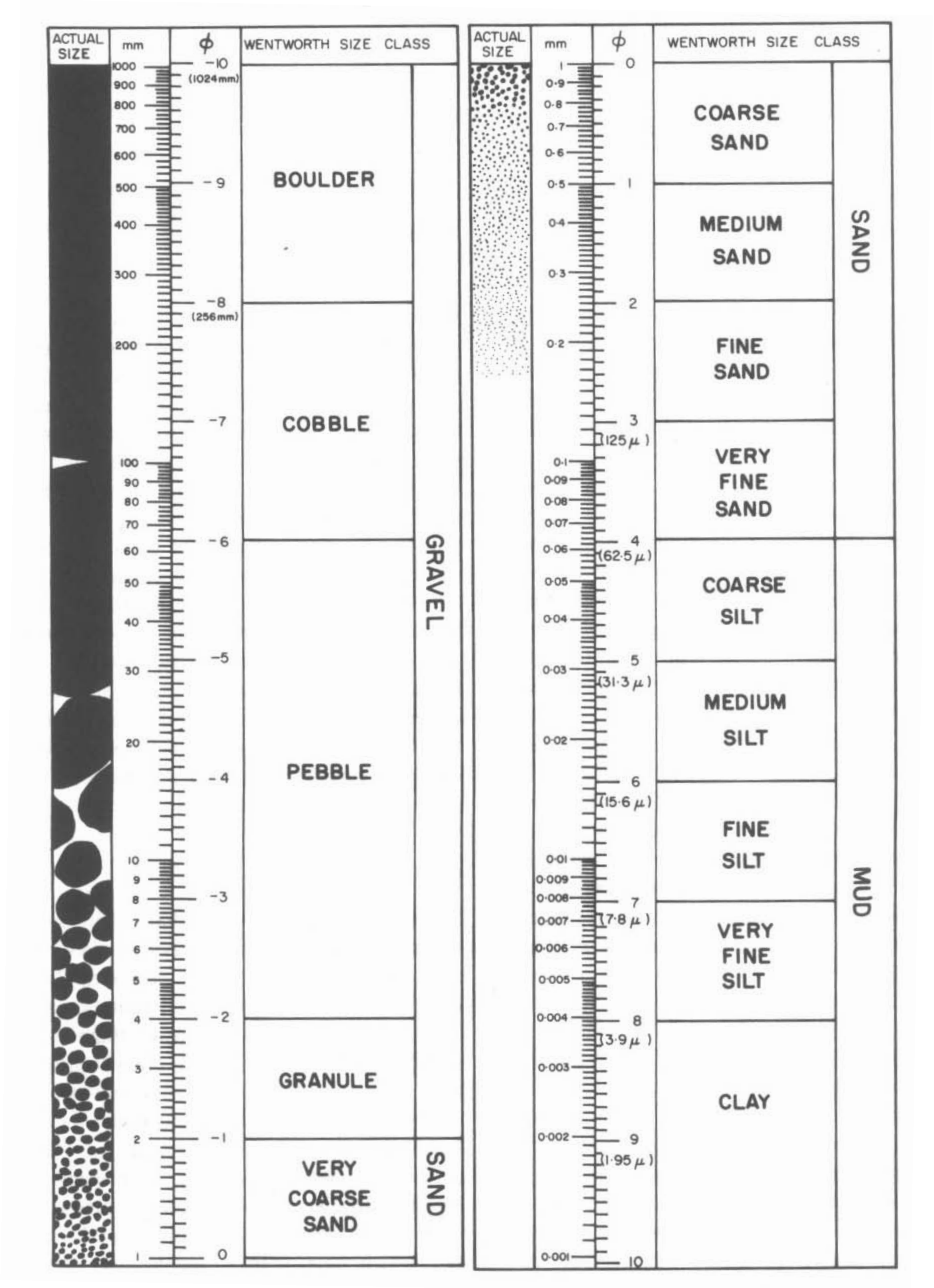


Figure 3.7. The Udden-Wentworth scale for grain sizes, with phi (φ) and millimetre (mm) conversion chart. *Sourced from Lewis and McConchie (1994, p.* 129)

Method

A total of three cores were taken from each site, and one representative core was chosen for analysis from each. Cores were consistent within sites in terms of observed stratigraphy. A total of 12 samples, 4 from each core, were taken for grain size analysis. These were sampled from depths of 30, 150, 300, and 450 mm. Samples were oven dried at 50 °C overnight, then dry sieved through a 1 mm sieve to remove material too coarse to be analysed by the laser sizer unit. No further pre-treatment of samples was performed. A *Micromeritics Saturn Digisizer 5200* was used in the grain size analysis, capable of measuring particles from 0.0001 to 1.0 mm in equivalent spherical diameter (Micromeritics, 2009a). Samples of approximately 1 cm^3 were fed slowly into the machine until a beam obscuration of between 13 and 20% was reached. The volume of sediment this required increased with coarser samples. The machine then passed a laser beam through the suspended sample at 10 different angles and measured the diffraction pattern obtained. Each sample was run through the machine three times, and the results averaged to provide the final distribution. The distributions are calculated automatically from the diffraction patterns using Mie Theory, which states that the intensity of the light reaching the receptor is a function of particle size, focal length of the lens, angle and wavelength (Micromeritics, 2009b).

Statistical analyses on these results were performed to obtain the maximum, minimum and mean grain size (µm), standard deviation, mode of the sample distributions. The standard deviation provides a measure of the degree of sorting of the sample (Folk, 1974). For coarse, sandy samples (Samples, 8, 10, and 12), the second and third runs were disregarded. This was necessary because the data obtained was clearly erroneous, giving distributions clustered around the very low end of the scale (0.0001 mm). This is likely due to the weight of the particles causing them to sink more easily, thus not being read by the machine after the first run. The grain size figures of each sample were correlated to the Udden-Wentworth grain size chart.

Table 3.3. Sorting classes. *Sourced from Folk (1974, p. 46)*

Standard Deviation σ	**Sorting**
< 0.35	Very well sorted
0.35 - 0.5	Well sorted
0.5 - 0.71	Moderately well sorted
0.71 - 1.0	Moderately sorted
1.0 - 2.0	Poorly sorted
2.0 - 4.0	Very poorly sorted
> 4.0	Extremely poorly sorted

Limitations and errors

The high organic percentage of some sediments in this study, combined with the diverse range of sediment types present between samples, creates potential error sources in laser sizer results. Although the laser particle sizer is capable of measuring larger, lower density particles such as micas or biogenic particles (Singer *et al.*, 1988), the tendency of this matter to float on the surface of the water possibly affected results. In addition, some organic particles measured were very elongated in shape and larger than 1 mm lengthwise, due to the fact that sieving (as was performed in pre-treatment removal of coarse matter) sorts particles on the basis of the intermediate axis, which meant these elongated particles slipped through the mesh. Consequently, the upper end of the size range of affected samples is potentially inaccurate. A similar problem with larger particles occurred in particularly coarse, sandy samples, which had a tendency to sink rather than remain in suspension, thus rendering the second and third runs of these samples incorrect and they were discarded.

3.3.3 Percent organics principles and practices

The amount of organic matter present in a sediment sample is important in many depositional settings, and reflects the degree to which in-situ biomass is responsible for sediment deposition at that site and can also indicate sedimentation rate (Lewis and McConchie, 1994; Sutherland, 1998). This is very much dependent on transport processes and energy in the depositional environment, thus provides insights into the environment at the time of deposition. This is important for this study because wetland

and lagoon environments are often areas of high biomass production so that comparisons in sediment organic percent in different locations and stratigraphic horizons can yield important results.

The percentage of organic matter was calculated using the Loss on Ignition (LOI) technique, as detailed by (Lewis and McConchie, 1994). This is done by calculating the mass lost from a sample following firing, with the resultant difference in weight being principally due to the combustion and loss of organic matter in the sample.

This measure is subject to considerable error, as the loss of mass is due not only to combustion of organics but also to the loss of water of crystallisation from clay minerals, loss of carbon dioxide from any carbonates present, or loss of sulphur (Sutherland, 1998; Lewis and McConchie, 1994). However, as a rough estimate of quantifying the amount of organic matter (and thus organic carbon) it is a generally accepted technique. Ideally, sedimentation rates should be measured independently at the site before interpreting percent organic results, but this is rarely performed in practice and leads to a degree of uncertainty (Doyle and Garrels, 1985). The LOI technique involves burning samples at a high temperature to oxidise (thus removing the mass component) of organic matter in the sample. The optimum temperature to use for this process is considered to be 450 °C. This is a trade-off because total removal of organic matter can require temperatures of up to 1000 °C, but beyond 500 °C any clays and carbonates present in the sample become significantly modified, affecting results and interpretation (Sutherland, 1998).

Method

Twelve samples were processed for LOI analysis and were taken from the sediment cores. Four subsamples of approximately 1 cm^3 were taken from each core, at the same depths sampled for diatom analyses (30, 150, 300 and 450 mm below the surface). Samples were oven dried for 24 hours at a temperature of 105 °C. This removes moisture from the sample prior to initial weighing. The mass of each dried sample (weighed in a crucible of known mass) was determined to an accuracy of 0.01 g, and then samples were placed in a muffle furnace at 450 °C for 18 hours. Potential for cross contamination is acknowledged, as when sizeable portions of organic matter are present and thus oxidised, ash particles can float between containers in the furnace and affect mass changes. Following removal from the furnace, the crucibles were left to cool to room temperature before weighing again. The difference in mass of each sample between initial weight and weight following ignition was then converted into a percentage of total sample weight.

3.4 Summary

This chapter detailed the methodology employed in this study, first detailing the principles and theory of each technique, followed by the processes followed in this particular project. A summary flowchart illustrating the timeframes to which each method pertains, and the results gained by each type of analysis is presented below (Figure 3.8).

Techniques employed to assess the present geomorphology includes GNSS surveys of representative sections of Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex. Digital Elevation Models of the surveyed areas were constructed using *ArcGIS*, which were then analysed for trends in topography and dune shape, height and steepness. The hydrology of the two systems was investigated over a week-long period, during which measurements of conductivity, water temperature and water level were made at ten minute intervals at three sites within Totara Lagoon and three sites within Waikoriri Creek.

Decadal-scale dynamics of Totara Lagoon and Waikoriri Lagoon were investigated through analysis of aerial photographs, covering the period from 1948 to 2006. Photographs were orthorectified and georeferenced to the New Zealand Map Grid

(NZMG) datum, and digitisations of the lagoon channel configuration and outlet position were created using *ENVI* and *ArcGIS* software programmes. From these, measurements of outlet offset and rates of outlet migration were calculated and trends in outlet migration inferred.

Sediment cores and associated analyses were used to investigate the development of selected areas of each system over a longer time period, covering up to 150 years. Cores were taken from two sites in Totara Lagoon (north and south) and one site from Shearer Swamp. Core stratigraphy was logged, and sediment texture analyses were conducted using a *Micromeritics Saturn Digisizer 5200* for selected core depths. Organic percentage of samples was also measured using the Loss on Ignition technique.

The results gained from these techniques and analyses are presented in the following three chapters.

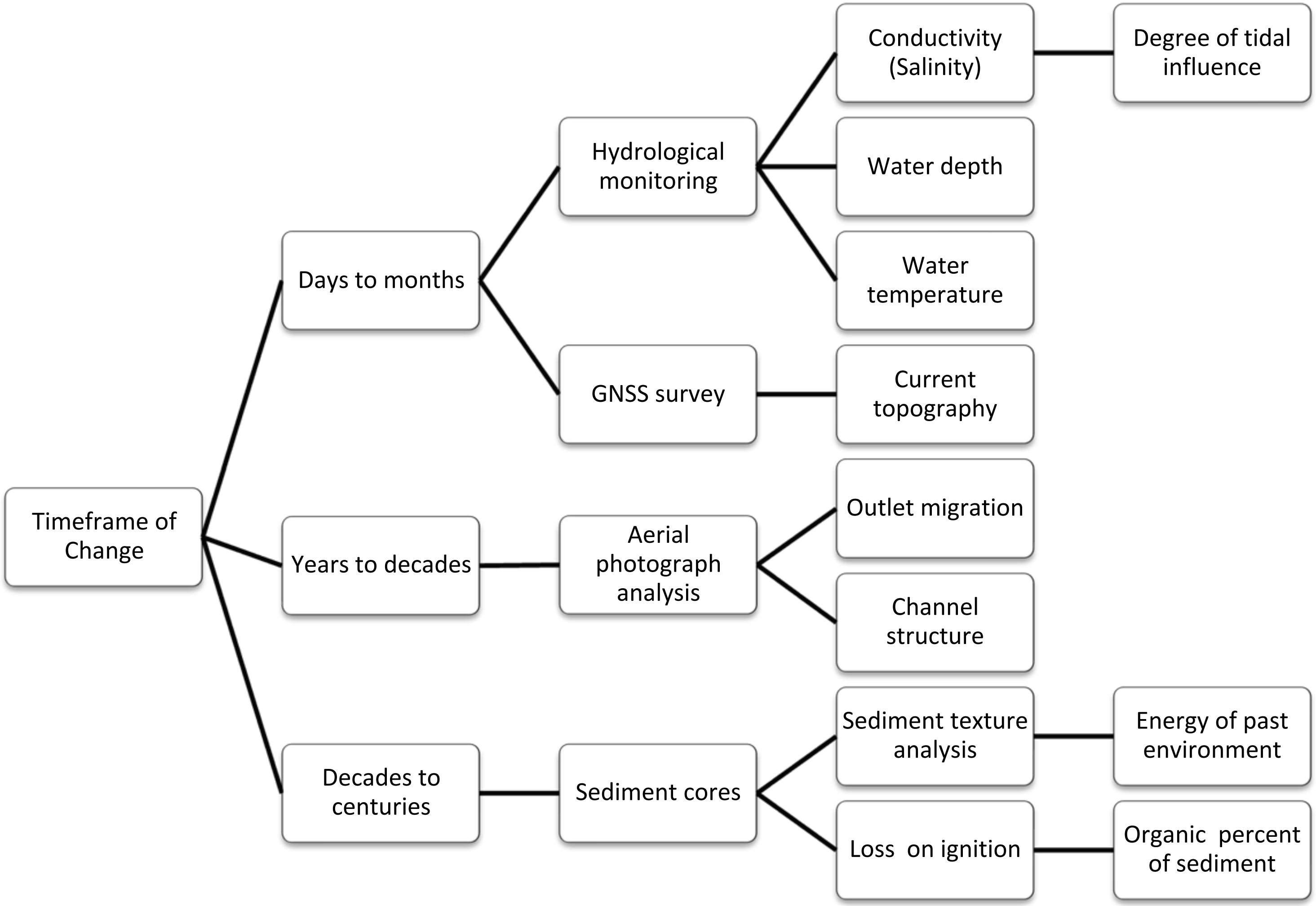


Figure 3.8. Summary flowchart of the methods employed in this project, the timeframes to which they apply, and the information provided by each technique.

CHAPTER FOUR

Existing Geomorphology and Hydrology

4.1 Introduction

The results of this investigation are separated into three chapters, according to the time period to which each set of results relates. Results pertaining to the present day geomorphology and hydrology of the study sites are presented in this chapter. This includes: digital elevation models (DEMs) of representative sections of each lagoon's topography, profiles across the lagoon channels and adjacent dune ridges, and measurements of water level, temperature and conductivity. Most data presented in this chapter was collected over a two week period in early December 2008, thus represents a snapshot of conditions at the time of surveying. The exception to this is the long term records of water character, which were taken over a six month period from September 2008.

Results from Totara Lagoon are presented in Section 4.2, and those of the Shearer Swamp-Waikoriri Lagoon complex in section 4.3. A discussion and interpretation of the results for each site is presented in section 4.4, including a comparison of the two sites in terms of geomorphology and hydrology. An integrated discussion of results for the two sites is reserved for Chapter 7, following the presentation of results from aerial photograph analysis in Chapter 5 and results of sediment cores and associated analyses in Chapter 6.

The following research objectives are addressed by this chapter:

- To document the current topography and structure of representative sections of each study site through GPS surveys and DEM creation,

- To investigate the hydrology of Totara Lagoon and Shearer Swamp in terms of water level, temperature and conductivity measurements over both short and longer timescales,

- To examine the causal processes of the observed results and discussion of linkages between processes and geomorphology in these systems.

4.2 Totara Lagoon

4.2.1 Topography from GNSS survey

Four representative sections of Totara Lagoon were surveyed over the period December 1st – 8th 2008. The locations of these areas were shown in Chapter 3, Figure 3.1 and the DEMs and cross sectional profiles created from each survey are presented in Figures 4.2 – 4.8. The spatial extent of each survey varies, and the number of points and areal extent of each survey were displayed in Table 3.1. The DEMs are illustrated using different scales, which was necessary due to the large differences in spatial extent between individual surveys. However, all cross section profiles taken from these DEMs are plotted against the same scale to allow comparisons to be made. All figures and tables for section 4.2.1 are displayed together on pages 4 to 8, following the associated text.

The geomorphology and topography of Totara Lagoon varies substantially between the northern and southern ends of this system. Dune profiles exhibit crest heights in the north of between 10 and 13 m ASL while those to the south peak at only 6 to 7.5 m ASL. Dunes become steeper and more heavily vegetated northwards. Channel width and character also changes throughout the lagoon, the channel is relatively shallow, wide and well-flushed in the south, becoming narrower, deeper and muddier in the north.

The DEM of Totara South (the river mouth end of the lagoon system, near the Ross township) extends 1.7 km northeast up the lagoon channel (Figure 4.1). The lines labelled A to H correspond to the profile graphs in Figure 4.2, showing a cross section of the river (A-B) and the seaward dunes and across the lagoon channel (C-H). This was the largest survey undertaken in the Totara Lagoon region, both spatially and in terms of number of GPS points taken (Table 3.1). Areas of grey cross-hatching indicate zones of insufficient point density, thus rendering the interpolation inaccurate. In reality, the dunes on the seaward side of the lagoon extend the entire length of the DEM, including through the cross-hatched zone to the south. The southern arm of this DEM represents the lower 650 m of Totara River, where it currently discharges to the sea and forms the entrance to Totara Lagoon. At this point the lagoon channel is deep and narrow, with a width of 38 m and a channel bed elevation of 2.0 m ASL at profile C. The channel then becomes wider and shallower as it meanders northwards, with widths of 42 and 35 m at profiles D and E respectively. The channel narrows and bifurcates at profile F, with the main channel at 25 m wide. It then rejoins and shallows again towards G and H, with a width of 58 m at profile G, and a total of 75 m at H, at which point the channel widens and splits into two main channels around a large, well vegetated island. Dunes on the seaward side of the lagoon channel remain relatively low and rounded throughout the entire area shown here, gradually decreasing from a maximum height of 8 m ASL at profile H to 7 m ASL at profile C (Figure 4.2). The channel bed slopes downwards towards the southern end of the lagoon, elevation ranging from 3.4 m ASL at profile H to 2.4 m ASL at profile D.

The central reaches of Totara Lagoon bifurcate, with islands of established vegetation separating two main channels. A small area of the most landward channel was surveyed, which was located approximately 4 km from the river mouth and extended 150 m in a north east direction (Figure 4.3). The area surveyed was very flat, extending into a swamp on the eastern margin, with well-developed vegetation on the western, island margin. No dune ridges were present on either side of this channel. The highest point surveyed was at an elevation of 5.4 m ASL, with the majority of the land adjacent to the channel reaching between 4 to 5 m ASL. The channel is a consistent width of 27 to 28 m across all profiles (I-L)(Figure 4.4). Channel depth was unable to be measured at this site due to the dangerous muddy nature of the channel bed, hence the purple area of the DEM shows the elevation of the water surface at 3.8 m ASL, rather than the channel bed elevation as is depicted in the Totara South DEM.

The northern third of the lagoon was choked by rushes growing across the channel at several points, limiting water and sediment exchanges below the surface of the water column such that this end appears relatively stagnant at depths greater than 1 m. Another small survey was undertaken approximately 8 km from the river mouth, extending 220 m north east along the channel (Figure 4.5). Steep, well vegetated dune ridges are present on both sides of the channel at this site, reaching a maximum height of 12.3 m ASL on the seaward side (south of profile M) and 8.3 m ASL on the landward side at profile M (Figure 4.6). Channel width varies between a minimum of 27 m at profile M, where a large sand deposit lies, and a maximum of 48 m at profile N. Most of the channel is between 38 and 42 m wide. Once again, the channel bed was unable to be surveyed due to the muddy nature of sediments, and the middle of the survey area reflects the elevation of the water surface at 4.0 m ASL in the south and 4.3 m ASL in the north.

The northernmost extremity of Totara Lagoon was very similar to conditions at Totara Central North. A comprehensive survey was performed over this section of the lagoon, approximately 10 km from the river mouth, and extending 1 km along the lagoon (Figure 4.7). Dunes were steep and well vegetated, reaching a maximum height of 13.1 m on the seaward side (Figure 4.8). Dunes on the landward side of the channel were unable to be surveyed, due to impenetrable vegetation cover. Channel width varied substantially along the channel within the survey area, ranging between 54 m south of profile O, to 16 m at profile Q. Width was 20 m at profiles P and R.

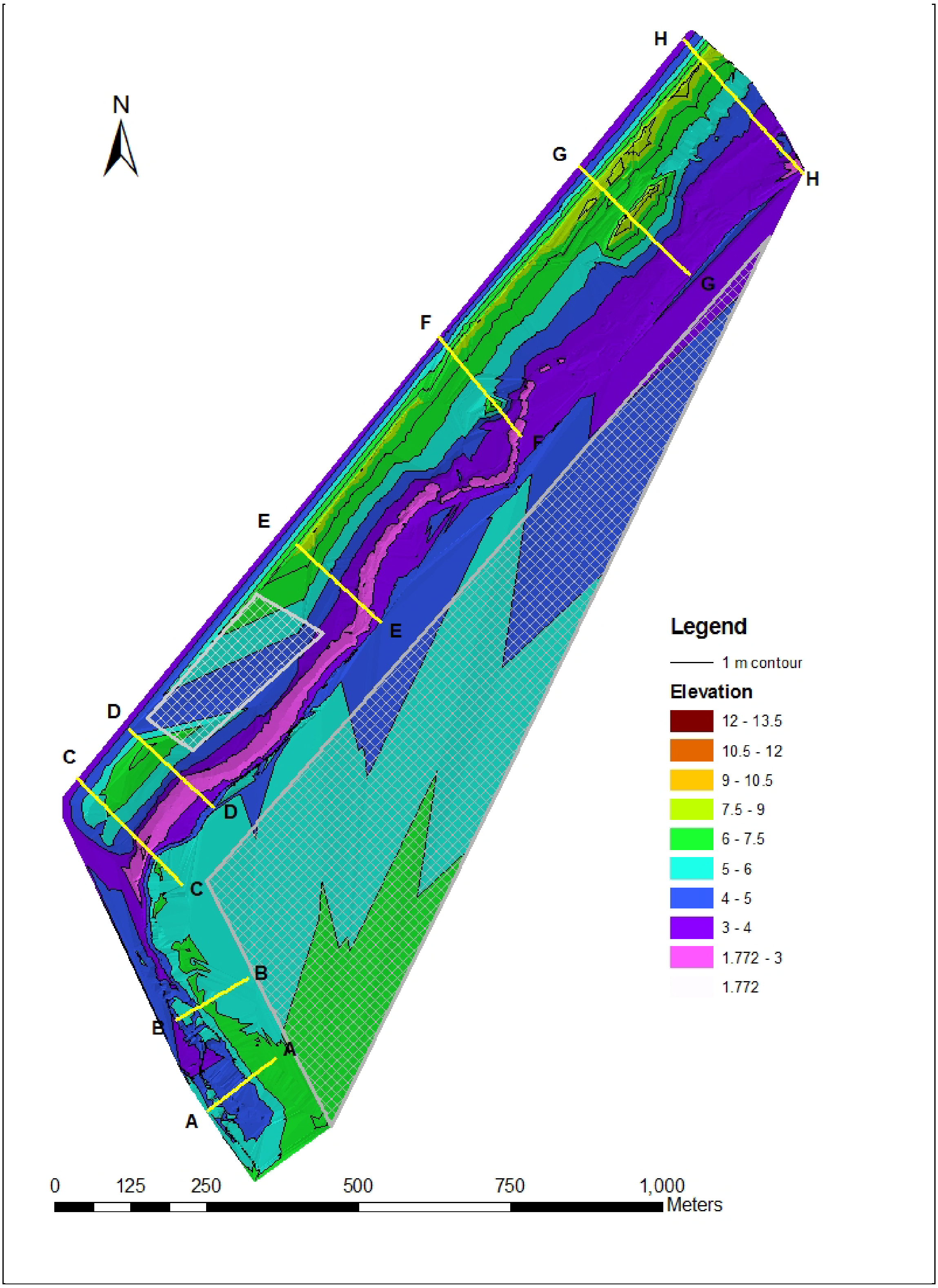


Figure 4.1. DEM of Totara South. Surveyed December 1st – 8th 2008.

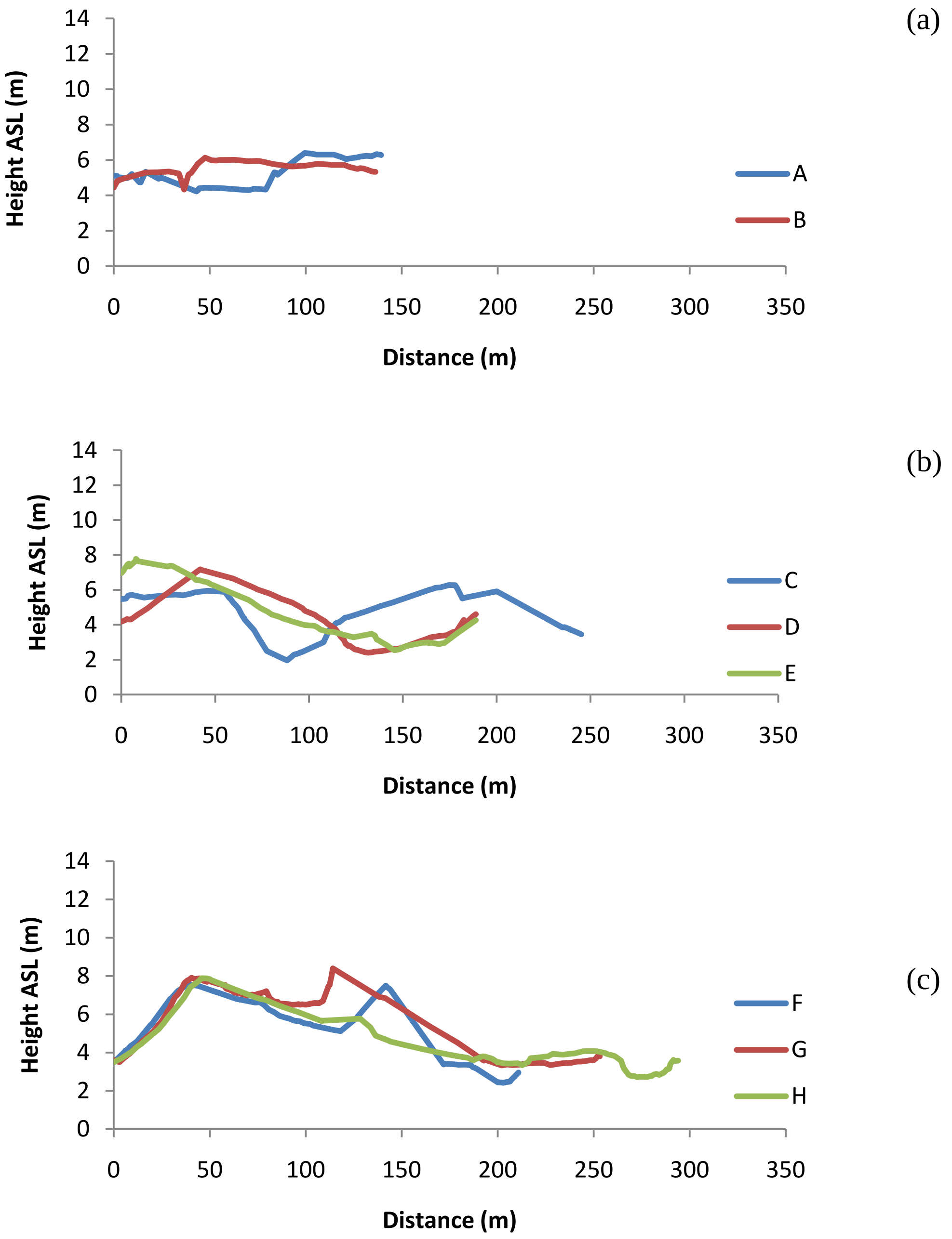


Figure 4.2. Cross sectional profiles of the Totara Lagoon/Totara River channel, taken from positions A-H as marked in Figure 4.1.

(a) Totara River channel

(b) Southern extremity of Totara Lagoon channel

(c) Northern section of Totara South survey area

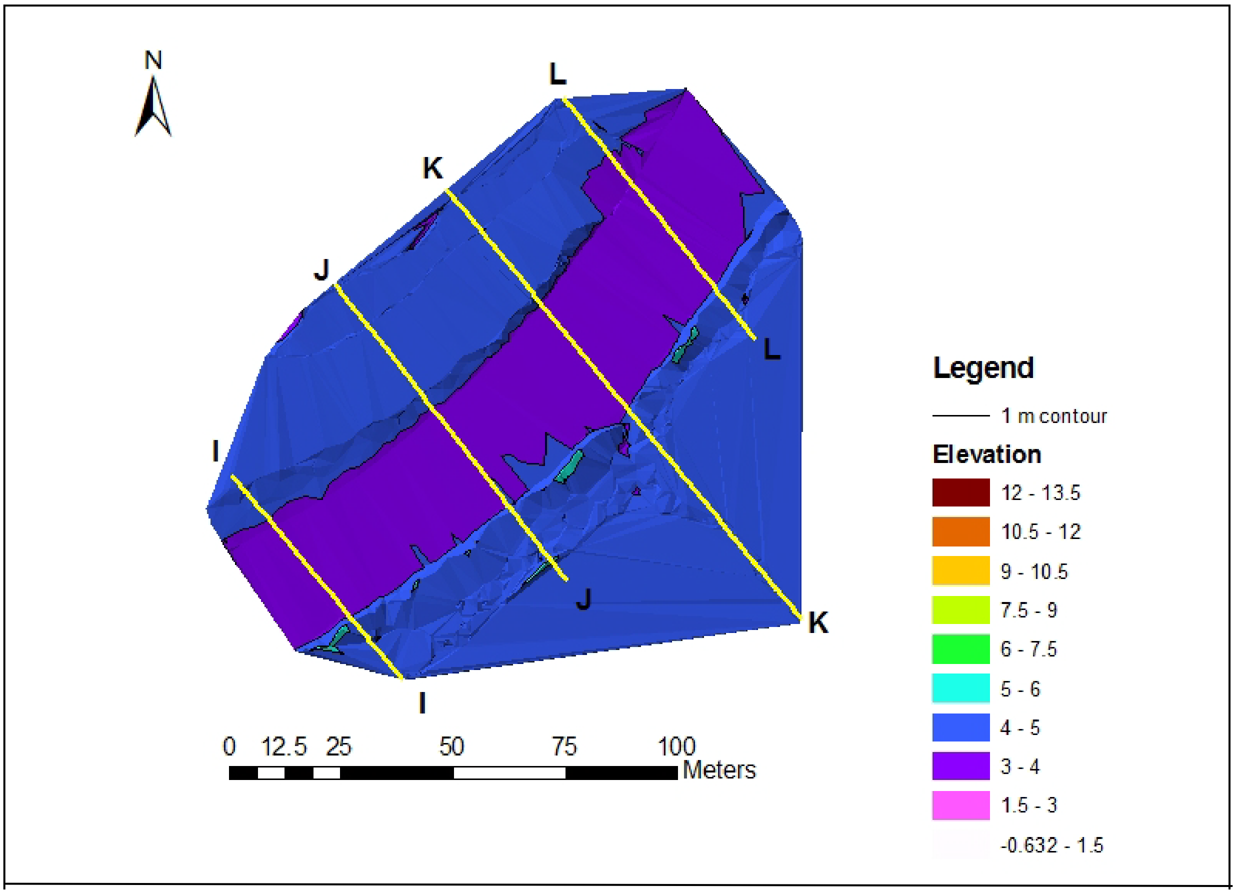


Figure 4.3. DEM of Totara Central survey area. Surveyed December 5th 2008.

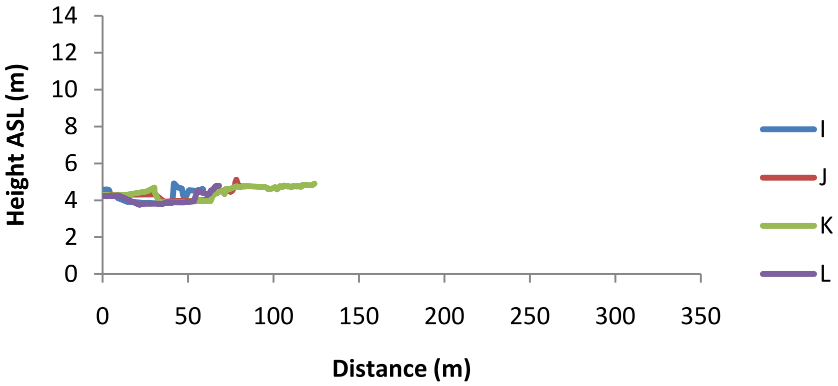


Figure 4.4. Totara Central dune profiles, taken at the locations marked I to L in Figure 4.3.

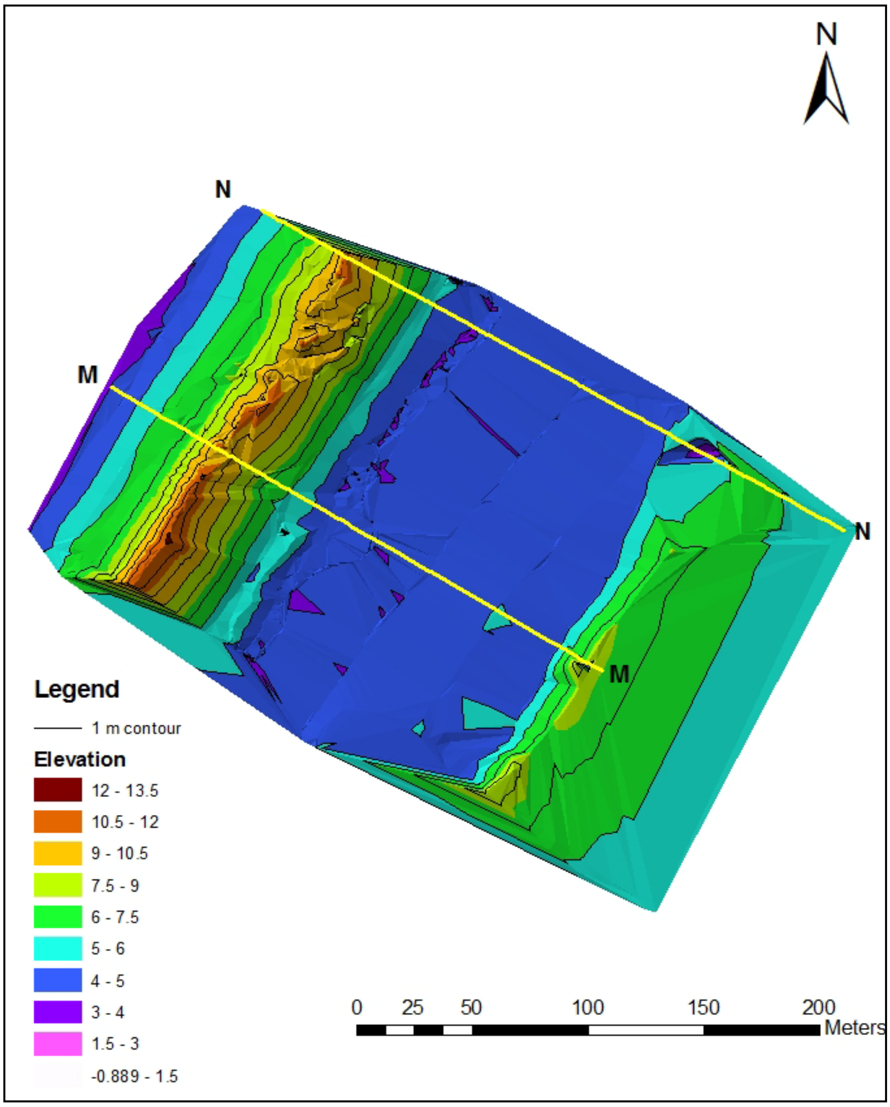


Figure 4.5. DEM of the Totara Central North survey area, surveyed December 6th 2008.

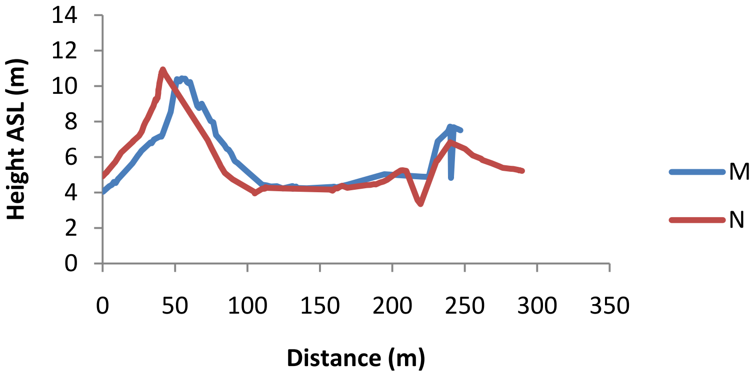


Figure 4.6. Profiles across the dunes (and channel surface) at Totara Central North, locations are marked M and N in Figure 4.5.

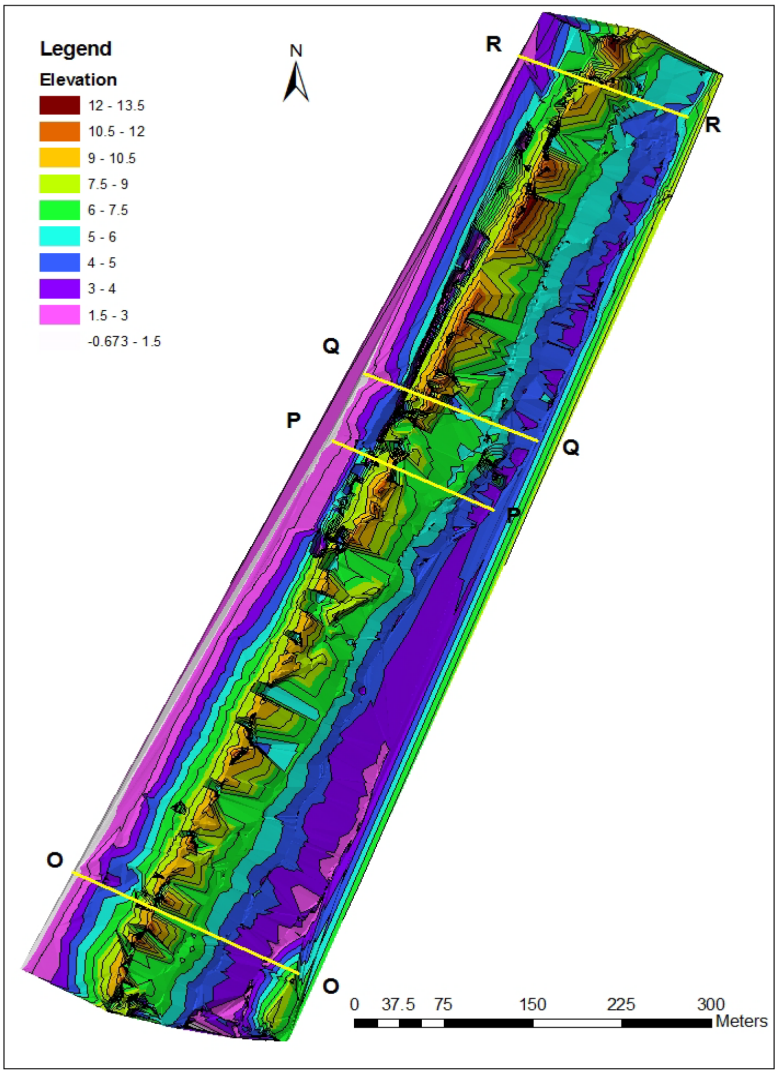


Figure 4.7. DEM of the Totara North survey area, surveyed December 7th and 8th 2008.

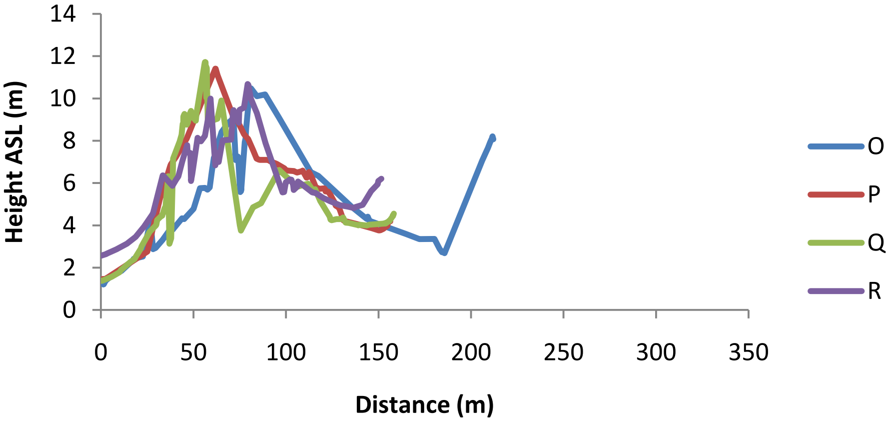


Figure 4.8. Profiles across the dunes and channel surface at Totara North. Profile locations are marked O to R in Figure 4.7.

4.2.2 Water level and character records

Water level, temperature and conductivity measurements were taken at two sites in Totara Lagoon over the period of December 1st – 7th 2008. A longer term record was taken at the northern end, spanning a 6 month period from September 2008 - March 2009. Locations of these water level recorders were displayed in Chapter 3, Figure 3.4, and the sites will be referred to as Totara South, Totara Central and Totara North. In addition to the complete long term record at Totara North, data for the period December 1st to 7th 2008 was extracted from this record and presented with the data for Totara Central and South, to provide a comparison of water characteristics between different areas of the lagoon.

Water level

Water level variation at both Totara South and Totara Central follows the tidal cycle (Figure 4.9). There is both a temporal lag and dampening of the effect of tidal cycle variation on water level from south to north along the lagoon. The maximum water level at Totara Central is reached approximately 90 minutes after that at Totara South. There is also an evident tidal current asymmetry, whereby the water level increases much faster on the incoming tide than it decreases on the outgoing tide. This is most distinct at Totara Central. The tidal influence is more pronounced at Totara South, with the variation between peak and lowest levels much more extreme than at Totara Central. Maximum and minimum recorded water level values at Totara South were 1942 and 391.6 mm, with a mean of 945.9 mm. Totara Central recorded a maximum and minimum of 1565 and 714.9 mm, with a mean of 916.6 mm. Water level at Totara North over this period was much more stable than at the other two sites, with only extremely slight peaks marking the high tides over the first five days: the variation between maximum and minimum recorded values was small, from 1929 to 1387 mm, with a mean water level of 1485 mm. The maximum water level was reached on December 5th at all three sites in response to a large storm event and consequent river flood.

The long term record from Totara North showed a much greater degree of variation, ranging from a maximum of 2830 mm to a minimum recorded value of 563.9 mm, with a mean water level of 1485 mm (Figure 4.10). The mean over the 6 month period was

1527 mm. The water level varied significantly on timescales of days to weeks, with two particularly high water level events occurring in late October and late February.

Water temperature

Temperature in the lagoon varied significantly between the locations and temporally within each individual record (Figure 4.9). The record at Totara South showed the greatest variation in temperature, ranging from a maximum of 21.5 °C to a minimum of 12.5 °C. The mean temperature over the study period was 15.6 °C. There is a loose diurnal trend. Water temperature at Totara Central follows the same pattern as that of Totara South, but is subject to less extreme values; ranging between 19.3 and 12.8 °C with a mean of 16.1 °C. The northern end of Totara Lagoon was generally 2 – 3 °C warmer than Totara Central and Totara South, the exceptions being a during the late afternoon of December 3rd and again December 6th. The mean water temperature at the northern site over the short term study period was 17.5 °C, with maximum and minimum recorded temperatures of 20.6 and 14.5 °C respectively.

The long term record at Totara North shows a clear seasonal trend, with temperatures increasing over the summer months of December, January and early February and decreasing again in late February and early March (Figure 4.10). Temperatures ranged between a maximum of 26.5 °C, which was achieved in mid-January, and a minimum of 10.0 °C in early September. The mean water temperature over this six month period was 18.3 °C.

Conductivity

Conductivity in Totara Lagoon decreased significantly in terms of variability and absolute values with distance from the lagoon entrance (Figure 4.9). At Totara South conductivity varied largely with tidal cycle, from a maximum of 33.9 mS cm^{-1} to a minimum of 0.181 mS cm^{-1}. The mean value over the study period was 6.97 mS cm^{-1}. This pattern was repeated at Totara Central, although the maxima reached were much reduced and shorter in duration, and there was a time lag of approximately one hour between Totara South and Totara Central. Conductivity at Totara Central ranged between 16.0 and 0.414 mS cm^{-1} with a mean of 1.35 mS cm^{-1}. Both these sites experienced a period of consistently very low conductivity over the period December 5th to 7th. Totara North exhibited consistently low conductivity throughout the December study period, with a maximum and minimum of 1.05 and 0.111 mS cm $^{-1}$ respectively, and a mean of 0.712 mS cm $^{-1}$. This changed little over the longer monitoring period (Figure 4.10), with only 2 occasions on which the conductivity rose above 2.5 mS cm $^{-1}$, reaching a maximum of 2.83 mS cm $^{-1}$ in late February. Minimum and mean values for this period were 0.564 and 1.55 mS cm $^{-1}$.

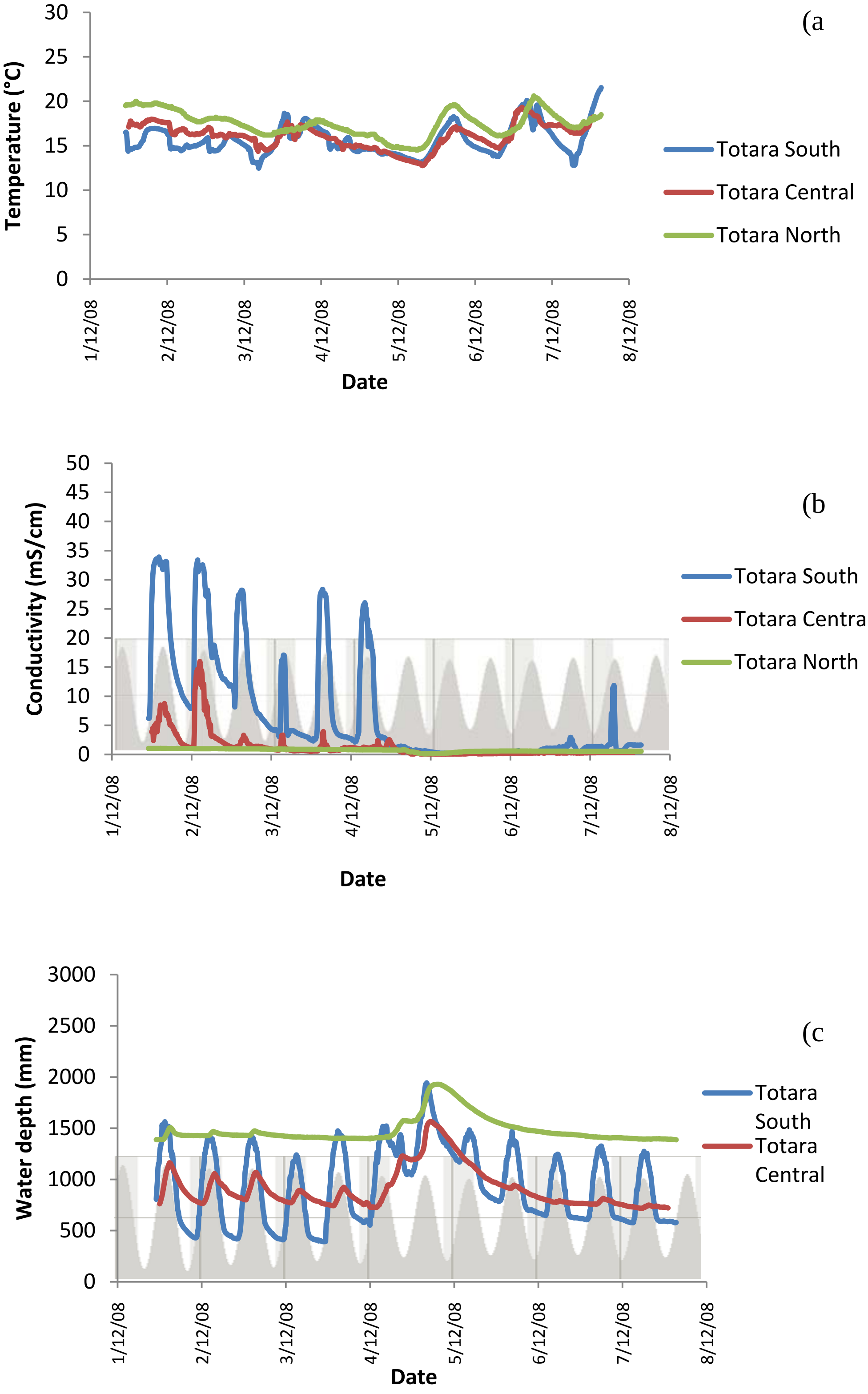


Figure 4.9. Short term water records taken between November 29th and December 8th 2008 across three sites in Totara Lagoon. The tidal cycle (1 m height) for the survey week is superimposed on the conductivity and water level graphs.

(a) Water temperature (b) Conductivity (c) Water depth

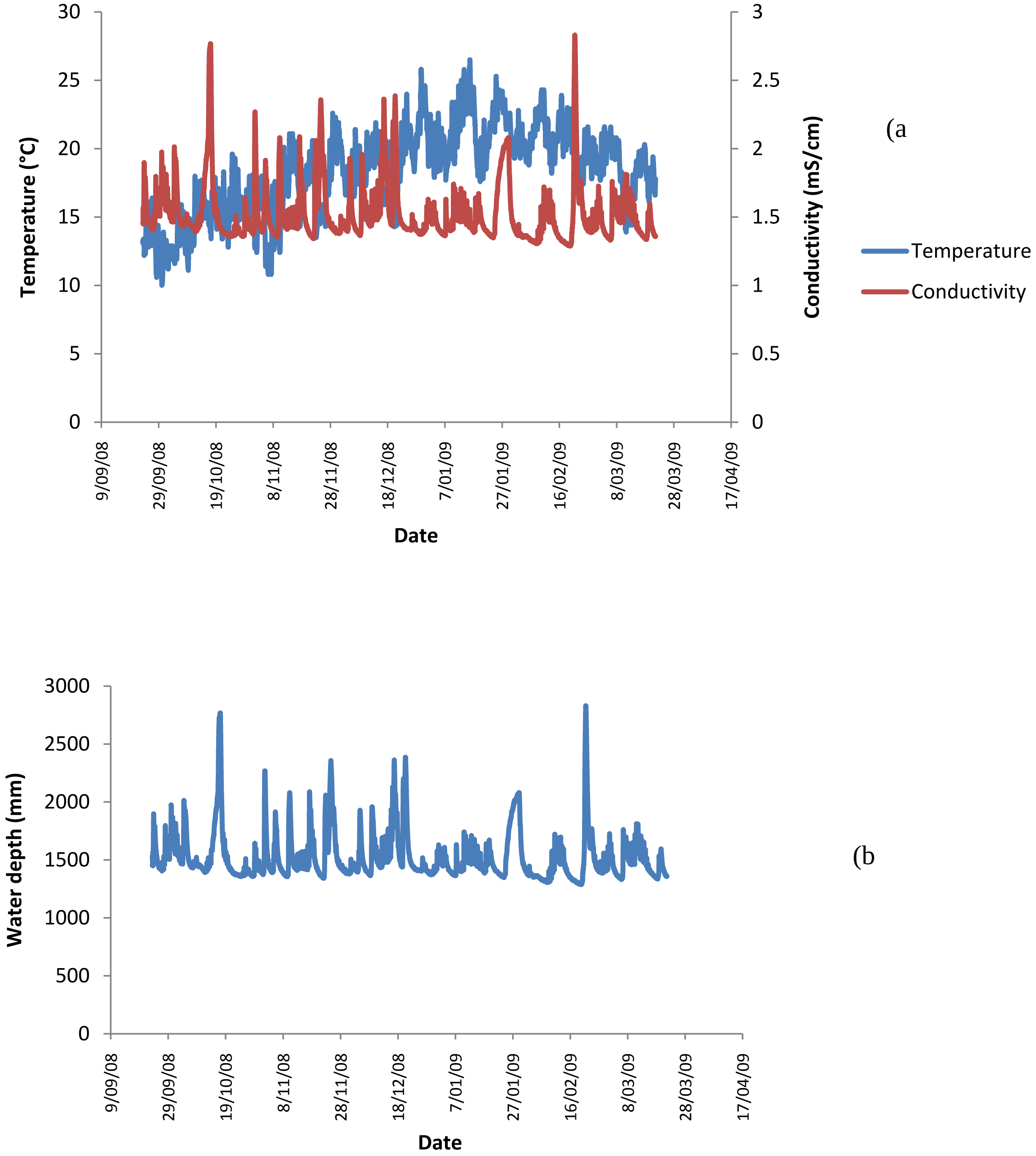


Figure 4.10. Long term water records taken at Totara Central North between September 2008 and March 2009. (a) Water temperature and conductivity (b) Water depth.

4.3 Shearer Swamp-Waikoriri Lagoon Complex

4.3.1 Topography from GNSS survey

Two surveys of representative areas of the Waikoriri Lagoon-Shearer Swamp complex were undertaken over the period December 9th – 15th 2008. The locations of these areas were shown in Chapter 3, Figure 3.1 and the DEMs and cross sectional profiles created from each survey are presented in Figures 4.14. The largest survey includes the Waikoriri Lagoon channel and dunes either side, and the relic dune ridges between Waikoriri Lagoon and the western margin of Shearer Swamp. The number of points and areal extent of each survey was displayed in Table 3.2. Once again, all figures and tables for section 4.3.1 are displayed together, following the associated text.

The main survey of the Waikoriri Lagoon/Shearer Swamp complex begins at the southern end of the complex where Waikoriri Creek currently discharges to the sea and extends 2.3 km northwards (Figure 4.11). The survey encompasses 1.8 km of the then dry Waikoriri Lagoon channel and the surrounding dunes, then extends a further 0.5 km northeast on the landward side of the channel down to the edge of Shearer Swamp. The lagoon channel is clearly visible as the area of blue near the western edge of the DEM. The northern limit of this blue illustrates the position of the outlet prior to the breach of November 2008. Profiles S to V show cross sections of the Waikoriri Lagoon channel and adjacent dunes on either side (Figure 4.12). Profiles W and X cross the relic dune ridges between Shearer Swamp and Bold Head Road (to the east of the lagoon and its landward dune ridge) (Figure 4.13).

The Waikoriri Lagoon channel varies in width and splits into two at the southern end, the second channel turning back upon itself to form a blind channel parallel to the main channel, which extends 400 m from the southernmost extremity and lies landward of the main channel. At profile S, the width of the main channel is 21 m and the second, blind channel is 31 m wide. The bed elevation is 5.2 m ASL in both channels. At profile T the channel becomes deeper and narrower, with a width of 18 m and a bed elevation of 4.8 m ASL. The channel remains narrow at profile U, with a width of 20 m and deepens slightly to a bed elevation of 4.4 m ASL. At profile V the channel narrows considerably to a width of 10 m, with a bed elevation of 4.3 m ASL. This profile is located approximately 500 m from the recent lagoon opening and there is a steep scarp seaward of the channel which reaches 6.4 m ASL in height.

The dune ridge seaward of Waikoriri Lagoon is rounded and low, with crest heights ranging between 6.9 m ASL at profiles U and V to 7 and 7.5 m ASL at profiles S and T respectively (Figure 4.12). In contrast, the landward dune ridge adjacent to the lagoon channel becomes steeper and more heavily vegetated northwards along the channel. The crest reaches an elevation of 7.3 m ASL at profile S, increasing to 8.0 and 8.9 m ASL at profiles U and V respectively. No data was obtained for the height of the landward dune ridge at profile T.

Shearer Swamp lies to the west of profiles S to V and extends to the northern limit of the DEM. The western margin of the DEM depicts the water line of the swamp. Adjacent to profile T, the elevation of the water surface lies at 5.3 m ASL, which increases to 5.5 and 6.1 m adjacent to profiles U and V. The farmland to the west of the swamp margin is a series of old dune ridges, which extend the length of Shearer Swamp on the western side. Profiles W and X show cross sections of these relic dune ridges, which reach a maximum elevation of 9.5 m ASL and extend as far as the current active landward dune ridge, a distance of up to 175 m (Figure 4.13).

A small section (100 m in length) of the eastern margin of Shearer Swamp and Waikoriri Creek was surveyed and the resultant DEM is presented in Figure 4.14. The elevation of the swamp surface at this site ranges between 5.4 and 5.7 m ASL. The banks of Waikoriri Creek are near vertical at this location and are approximately 1 m in height above the water surface.

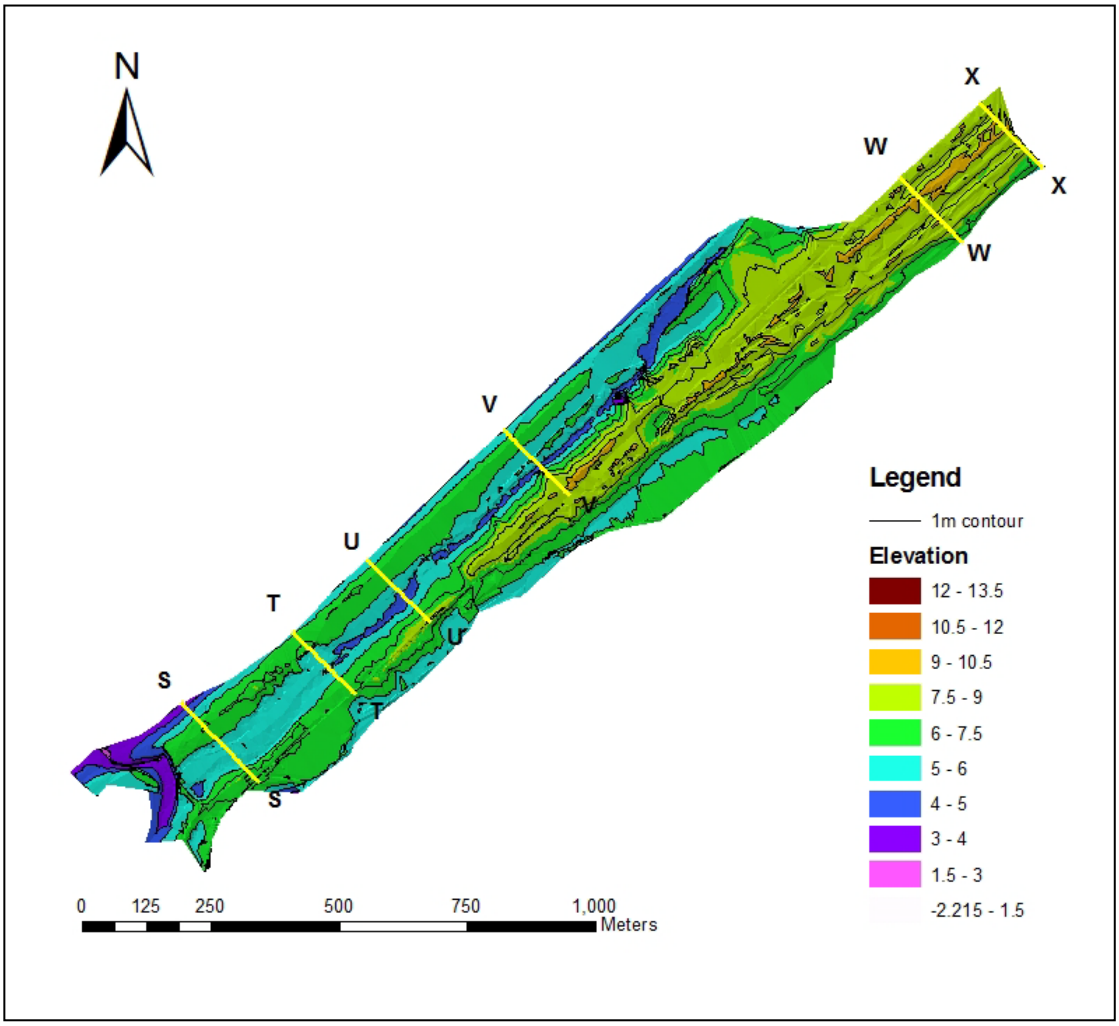


Figure 4.11. DEM showing the topography of Waikoriri Lagoon and the western margin of Shearer Swamp. Surveyed December 9th to 14th 2008.

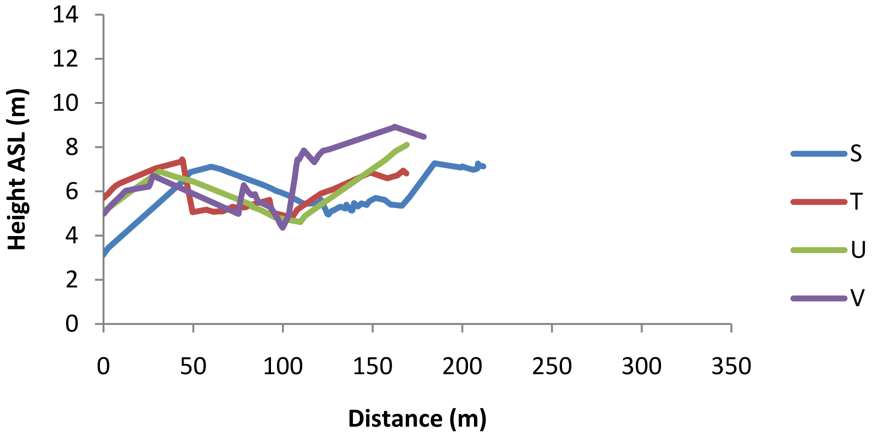


Figure 4.12. Cross sectional profiles of the Waikoriri Lagoon channel, marked S to V in Figure 4.11.

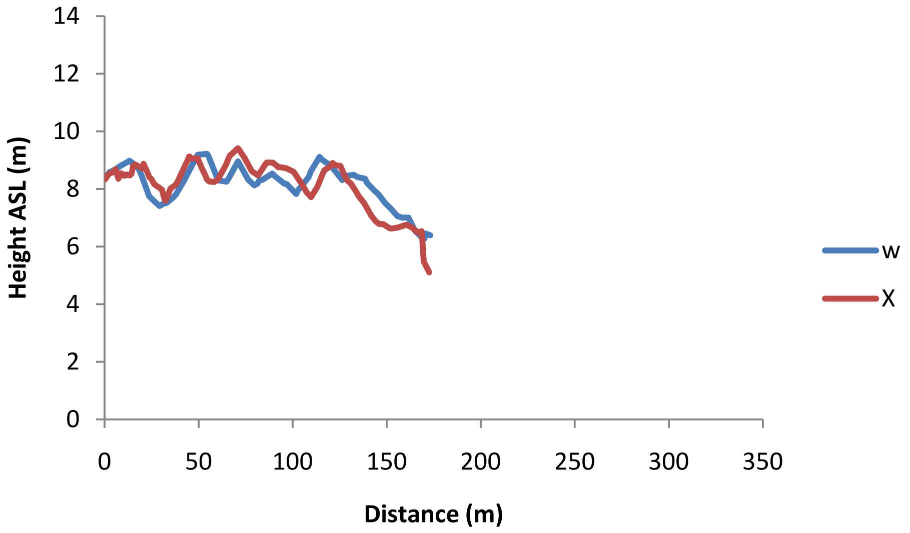


Figure 4.13. Cross sectional profiles of the relic dune ridges along the western margin of Shearer Swamp. Locations are marked W and X in Figure 4.11.

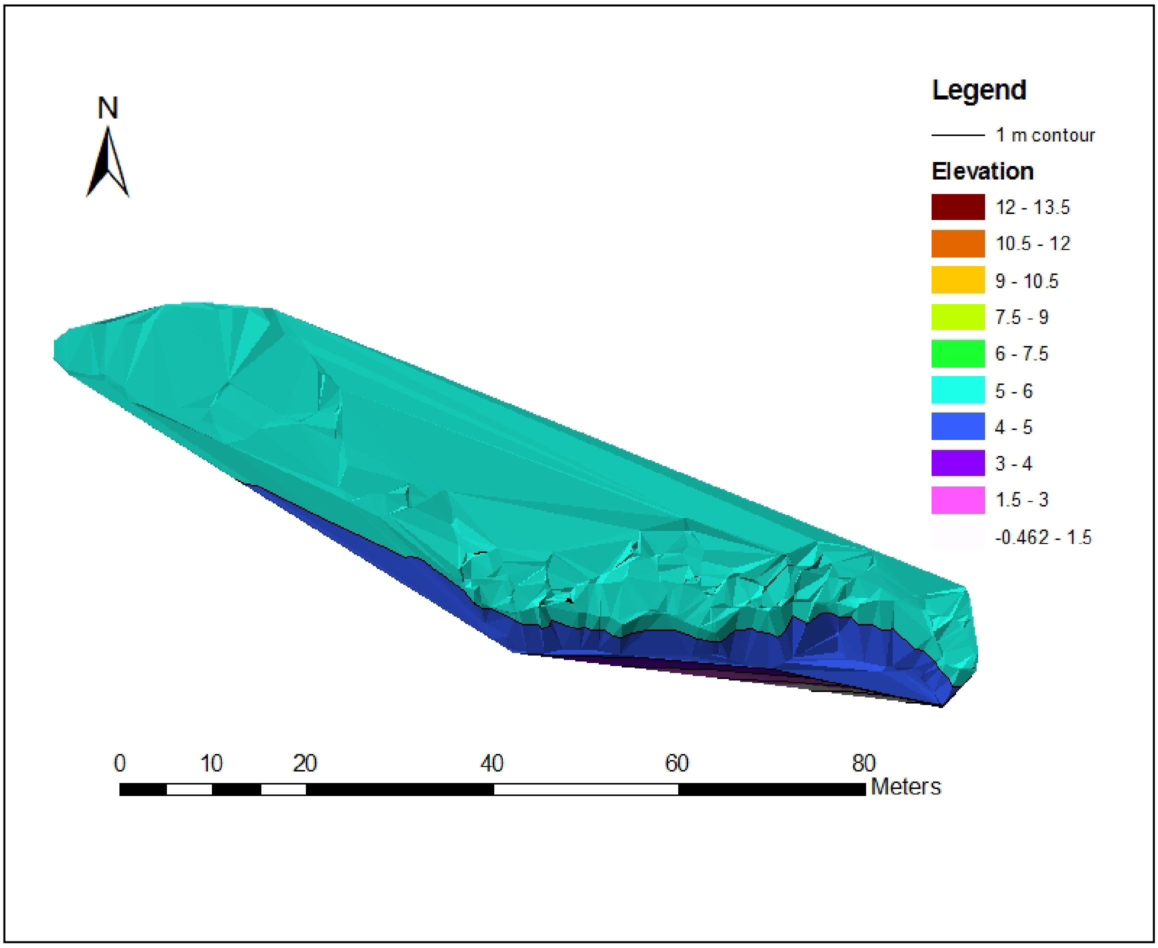


Figure 4.14. DEM of a small section of the south-eastern margin of Shearer Swamp, along Waikoriri Creek. Surveyed December 13th 2008.

4.3.2 Water level and character records

Water level, temperature and conductivity measurements were taken at two sites in Waikoriri Creek on the western edge of Shearer Swamp over the period of December 8th – 15th 2008. Like Totara Lagoon, a longer term record was taken in Waikoriri Creek under the Bold Head Road bridge at the southwest corner of Shearer Swamp. This record spans a 6 month period from September 2008 - March 2009. Locations of these water level recorders were displayed in Chapter 3, Figure 3.4, and the sites will be referred to as Site 1, Site 2 and Waikoriri Bridge. Once again, data from the long term record for the period December 8th-15th was extracted and plotted with the short term records to provide a comparison of water character at different locations within Waikoriri Creek.

Water level

Absolute water level varied significantly between locations within Waikoriri Creek, but the same general trend of a rapid rise water level at the beginning of the study period followed by a gradual decline was common to all three sites (Figure 4.16). Following the stabilisation of water level after this decrease, Waikoriri Bridge and Site 1 showed a tidal influence in water level changes. This was very prominent at Waikoriri Bridge, where the water level changed by up to 1000 mm between low and high tide. Maximum and minimum recorded values were 1179 and 281.9 mm respectively, with a mean of 406.6 mm. The tidal signal was dampened at Site 1, with water level varying by a maximum of 550 mm over a tidal cycle. Water depth at Site 1 ranged between 1891 and 1113 mm, with a mean value of 1325 mm. Water level at Site 2 was subject to less variation and was not influenced by tidal cycles at all, and ranged from a maximum of 902.8 mm to a minimum of 649.6 mm, with a mean level of 745.4 mm.

Results from the long term record at Waikoriri Bridge are divided into two time periods; September to November 2008 and December 2008 to March 2009, as the recorder was out of the water from early November until early December. When it was returned to the water in early December 2008 the location was slightly downstream from the bridge, thus the results from these two separate records cannot be directly connected. Between September and November 2008 the water level showed several spikes on a weekly timescale, decreasing over October before spiking again prior to drainage of the creek in early November (Figure 4.17). No water level variation in response to the tidal cycle was observed (Figure 4.15). The maximum recorded water level over this period was 1465 mm with a mean of 937 mm. The minimum recorded value was 7 mm, which was recorded as the creek drained and the recorder became exposed. Water level showed a much greater level of variation between December and March, increasing and decreasing up to 700 mm on scales of days to weeks. A comparatively long period of stable high water level (approximately 1450 mm) occurred in January, before spiking to the maximum recorded level of 1780 mm and promptly dropping back to base level. The mean water level over this period was 804 mm.

Water temperature

Water temperature showed a very clear pattern of diurnal change in all three sites (Figure 4.16). The temperature at Site 1 and Waikoriri Bridge remained consistently the same throughout the entire period. Temperatures at these two sites ranged between a maximum of 17.9 °C and a minimum of 13.0 °C, with a mean of 15.4 °C. The record from Site 2 followed the same temporal trend, but remained between 1 and 3 °C warmer than Site 1 and Waikoriri Bridge at all times during the study period. Water at Site 2 ranged between 20.4 and 14.9 °C, with a mean of 18.1 °C.

The long term record at Waikoriri Bridge showed a seasonal trend, reaching warmest temperatures over the summer months of December and January (Figure 4.17). The maximum temperature recorded was 20.3 °C, which occurred several times in late January, with a minimum of 9.4 °C recorded overnight in late September. The mean temperature over the study period was 15.2 °C. Temperatures were much cooler over the September to November period (maximum of 16.7 °C and mean of 12.4 °C) than over December to March (minimum of 12.2 °C and mean of 16.5 °C). There was a diurnal trend in temperature, overlain by a longer, synoptic trend. A period of consistently warm temperatures and less variation coincided with the recorded period of high water level in February.

Conductivity

Conductivity was extremely low at all three sites for the majority of the study period, remaining close to zero at Sites 1 and 2 for the entire duration (Figure 4.16). Values ranged between 0.01 and 0.06 mS cm^{-1} at Site 1 and between 0.02 and 0.04 mS cm^{-1} at Site 2. The mean value for both sites was 0.03 mS cm^{-1}. Waikoriri Bridge experienced similarly low levels of conductivity until the last two days of the study period, during which time three large spikes in conductivity occurred, reaching peaks of 31.7, 21.3 and 49.1 mS cm^{-1}. Between these peaks the conductivity returned to normal levels approaching zero. The maximum recorded value over the study period was 49.1 mS cm^{-1}, with a minimum of 0.002 and a mean of 1.24 mS cm^{-1}.

The long term record at Waikoriri Bridge showed these large conductivity spikes continued to occur regularly and became longer in duration until the record ended in late March 2009 (Figure 4.17). No such spikes occurred in the record prior to December 14th 2008. Intervals between these occurrences ranged from hours to weeks and they increased in frequency towards the end of the record. The maximum recorded value of this six month period was the December 14th occurrence at 49.1 mS cm^{-1}. There is a distinct difference in conductivity trends between the September to November period and the December to March period. Conductivity levels remained extremely low over the entire period from September to November, with maximum and minimum recorded values of 0.068 and 0.003 mS cm^{-1} respectively, and a mean of 0.042 mS cm $^{-1}$. The minimum and mean values of the December to March period were 0.021 and 6.826 mS cm^{-1}.

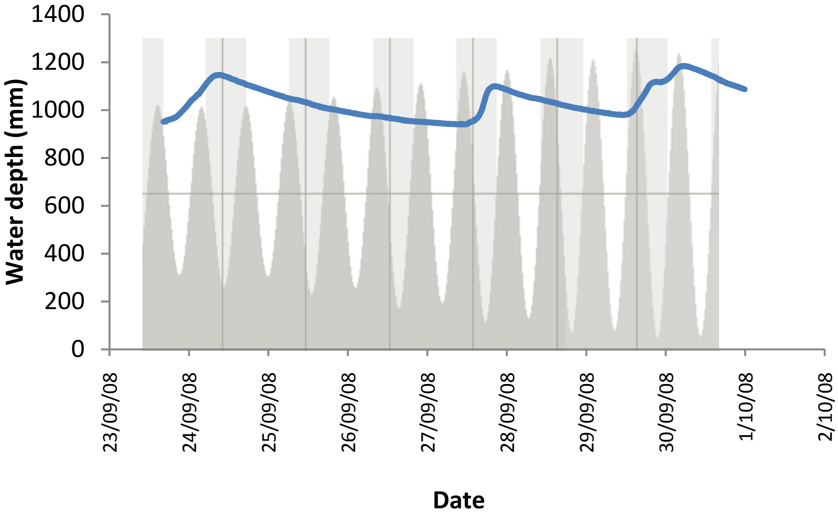


Figure 4.15. An excerpt from the long term water depth record of Waikoriri Bridge, taken September 23rd to 30th 2008. Water level variations during this period were not tidally influenced.

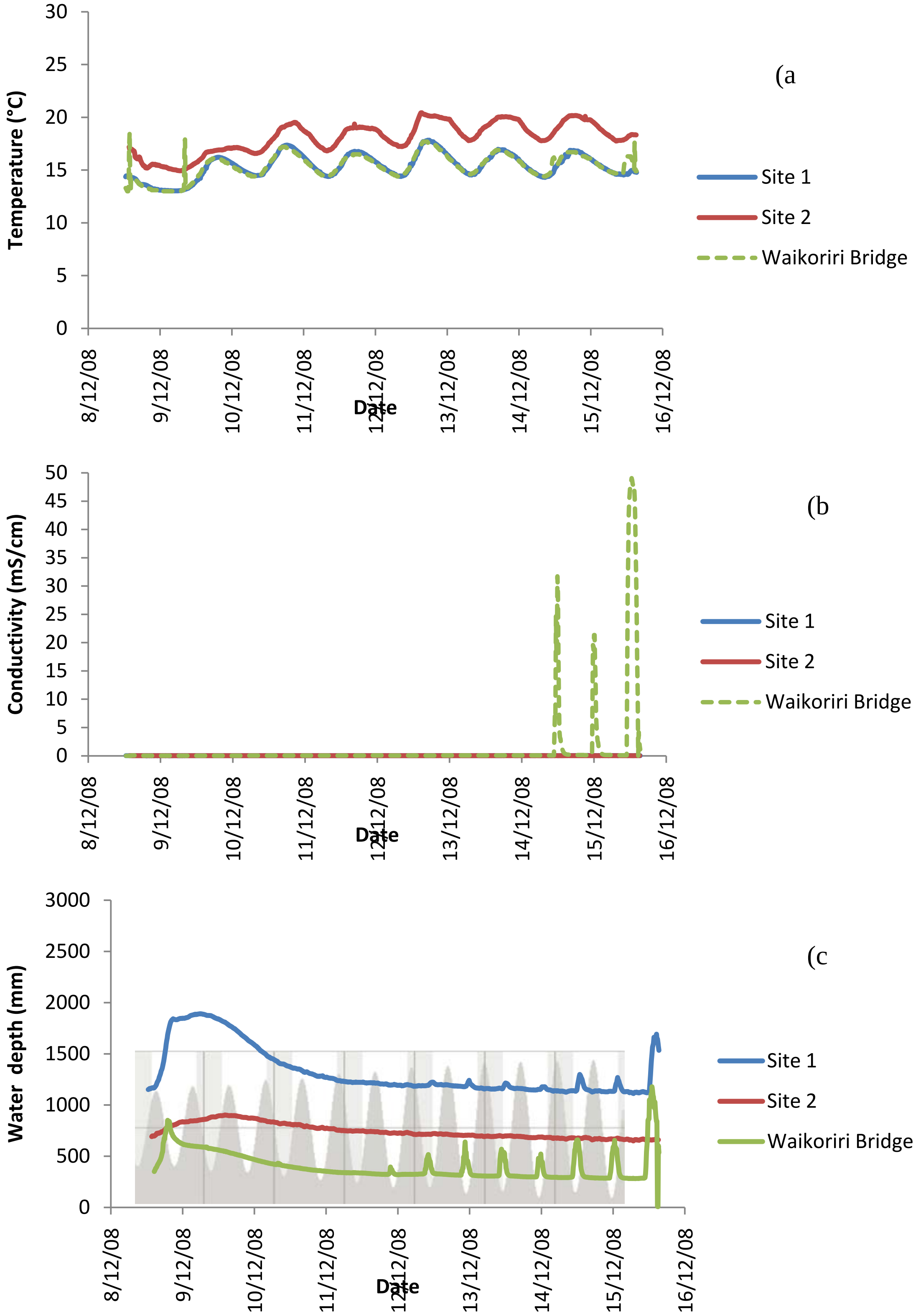


Figure 4.16. Short term water records taken over three sites in Waikoriri Creek and the western margin of Shearer Swamp, December 8th – 15th 2008.

(a) Water temperature (b) Conductivity (c) Water depth

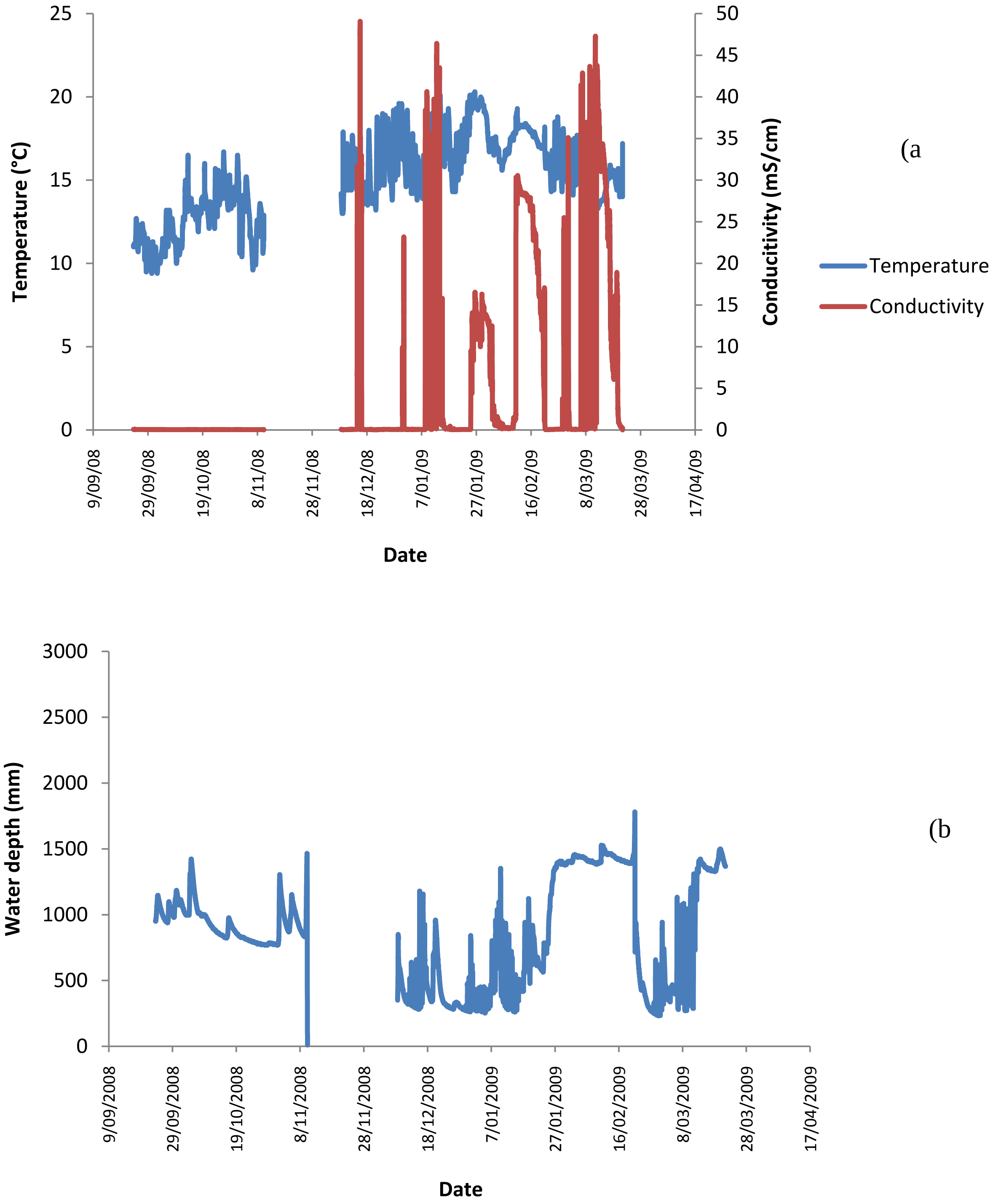


Figure 4.17. Long term water records taken at Waikoriri Bridge between September 2008 and March 2009. Data from November and early December 2008 has been removed. (a) Water temperature and conductivity. (b) Water depth

4.4 Interpretation and qualitative results

The purpose of this section is to offer an interpretation of the results presented above, and to provide an overview of the current dynamics of each system. These results were collected over a short time frame, thus providing a mere snapshot of conditions, but qualitative changes observed in this and subsequent site visits are also discussed here. Some aspects of these systems changed dramatically between visits, and these observations are extremely valuable despite the lack of data to quantify these changes. The relationship between the results reported for these systems and hapua dynamics in general is reserved for Chapter 7, following the presentation of all results.

4.4.1 Totara Lagoon

The physical environment of Totara Lagoon remained relatively constant in the short term survey period. There are definite spatial trends in dune stability and energy level of the lagoon environment along the channel, evident from both topographic surveys and field observations. The field site was described in Chapter 3. To understand the results presented in section 5.2 and contextualise them in terms of lagoon dynamics, it is important to consider the position of the lagoon outlet, which has been situated at the southern extremity of the system for several years.

Totara Lagoon is a very large system, which exhibits a progression of decreasing dynamism and energy from south to north along the channel. The southernmost two kilometres of the lagoon represent the most active part of the system currently. The low, rounded dunes on the seaward side are not well vegetated, indicating that they are much more susceptible to modification from sea storms and floods than the steeper, higher, heavily vegetated dunes of the northern reaches. Vegetation cover along the lagoon margins increases northwards in a similar fashion to that of the dunes. The northward trend of decreasing energy in the channel is also evident in the nature of the channel bed, which progresses from sand (interspersed with muddy areas) in the south, to deep, thick mud and organics in the north. The northern end did not change visibly between site visits, providing further evidence of its medium to long term stability.

The elevation of the channel bed decreases towards the south, which is a function of the position of the outlet. At the time of surveying, the channel was narrow and deep at the entrance itself, likely a result of scour from strong fluvial currents and wave action. The outlet was very open to wave action in December, but by March, a large sediment wedge had accreted across the opening. This narrowed the channel, and water was pooling behind the barrier, creating a large expanse of water and lessening the energy occurring at the lagoon entrance. It would have been interesting to reassess the salinity at the southern and central points, to determine to what degree the tidal influence was lessened by the constraint of the opening.

The observed changes in morphology at the river mouth between December 2008 and March 2009 demonstrate the short timeframes within which hapua can change dramatically (Figure 2.18). In terms of driving forces of this event, the growth of the barrier across the river mouth would have occurred in response to an increase in relative sediment supply (resulting from either an actual volumetric increase deposited by littoral drift, or from a decrease in fluvial or wave action removing sediment from the barrier).

The hydrological measurements identified clear temporal and spatial patterns of water level and conductivity in Totara Lagoon. There was a significant tidal influence in Totara Lagoon, the lateral extent of which was not discovered. There is both a temporal lag and dampening of the effect of tidally induced variation northwards along the lagoon. As expected, water level and conductivity variations were significantly greater close to the river mouth and outlet, but were still clear at Totara Central. Slight increases in response to high tide were observed at Totara North prior to December 5th; however, no associated increases in conductivity occurred. Consequently, it can be concluded that these water level increases were a result of a tidal backwater effect, rather than direct tidal intrusion.

The effect of a significant storm event on the hydrology of Totara Lagoon was recorded on December 5th and 6th. Overnight on December 4th a large storm occurred, causing the Totara River to flood. In response, lagoon water levels rose significantly over the following two days, before returning to normal on December 7th. During this period of high water level, fluctuations continued to occur in response to the tidal cycle at Totara South. In contrast, conductivity levels over this flood period did not fluctuate with the tidal cycle at either site, suggesting these tidally induced water level oscillations were a result of a backwater effect at this time. As a result of high river volume and flow velocity, the tide would have been unable to penetrate at the river mouth and/or unable to propagate up the lagoon channel. Water level and conductivity patterns at Totara Central were disturbed by this flood event for a longer period than at Totara South, which was likely due to a continued increase in freshwater input as overflow from adjacent swamps drained. Similarly, water level at Totara North took longer again to stabilise, and pre-storm patterns had yet to resume at the end of the short term study period.

The degree of tidal influence observed in Totara Lagoon was somewhat surprising, as this does not occur in hapua studied on the East Coast (e.g. Kirk, 1991; Todd, 1992; Hart, 1999; Kirk and Lauder, 2000). Indeed, in the strictest definition of a hapua, *no* degree of tidal propagation and salinity fluctuation is acceptable. Tidally induced oscillations in water level can occur in hapua in response to a tidal backwater effect (as was observed at Totara North), but the recording of concurrent spikes in conductivity confirmed that this process was not responsible for the water level oscillations at Totara South and Totara Central. The issue of hapua definition and dynamics with respect to tidal influence will be discussed further in Chapter 7, section 7.3.

Water temperature responded primarily to diurnal variations in air temperature. The maximum water temperature was generally reached in the middle of the afternoon, which is consistent with previous studies of lagoon energy exchange dynamics (Smith, 1981). A spatial trend of increasing temperature and decreasing variation was evident in a northward (upstream) direction. As distance from the outlet increases, the lagoon becomes less well flushed and can potentially become stratified, allowing temperatures to remain higher at the bottom of the water column, where the measurements were taken.

Figure 4.18. Changes in the configuration of the Totara Lagoon outlet between December 2008 and March 2009. In photos (a) and (b) the lagoon entrance is at the right edge of the photograph. Photos (c) and (d) were taken from the true left bank of Totara River, showing the outlet. (a) December 2008 – river mouth was open to wave action. (b) March 2009 – a sediment wedge had been deposited across the open mouth. The outlet can be seen traversing the barrier at the very right of the photograph. (c) December 2008 – close up view of the open river mouth. (d) March 2009 – The narrow, winding outlet caused water to pool behind the newly emplaced barrier, covering the sandbar that is visible in the December 2008 photograph.

4.4.2 Shearer Swamp-Waikoriri Lagoon Complex

The greater part of Shearer Swamp is essentially a stable wetland in the context of short term dynamics, and this study focuses on the more dynamic western margin along with Waikoriri Lagoon. In contrast to the Shearer Swamp basin, Waikoriri Lagoon is an extremely dynamic system that can change visibly on even an hourly to daily scale. Once again, a description of the study site during fieldwork was presented in Chapter 3.

The topography of the dune ridges west of Shearer Swamp is constant and did not change between site visits, and this set of ridges acts as a natural boundary for the swamp. The topography of Shearer Swamp itself and these dune ridges are not of particular relevance to the short term dynamics of the system, except to note that the position of Waikoriri Creek, at the margin of Shearer Swamp, is constrained by the most landward dune ridge. These ridges are significantly higher than the basin behind and are oriented parallel to the coast. This, combined with their height above present sea level, suggests they developed as the coast prograded during the marine recession following the Holocene sea level highstand. A developmental history of the Shearer Swamp-Waikoriri Lagoon Complex inferred from this study is presented in Chapter 7, following the remaining results.

In contrast, Waikoriri Lagoon can exhibit dramatic changes in morphology over short timeframes. The landward ridge constraining the lagoon channel is well vegetated, indicating medium to long-term stability, but the seaward barrier is significantly lower and bare of vegetation in most places. The nature of this barrier allows the outlet of the lagoon to migrate easily along the beach. Further evidence of the less permanent nature of the waterbody is the nature of the channel bed, which is sandy with small areas of mud, debris and cobble sized material. The larger material in the channel is likely to be deposited by wave overtopping during storms, which is apparent in the amount of debris lining the beach following a sea storm event.

As alluded to earlier in this thesis, Waikoriri Lagoon experienced a major (artificially assisted) barrier breach at the river mouth extremity in November 2008. The effect of this breach was to drain the lagoon channel, so that Waikoriri Creek discharged directly to the ocean, bypassing Waikoriri Lagoon (Figure 2.19). This had a profound impact on the beach morphology at either end of the lagoon, with the abandoned opening closing up by sediment deposition from littoral drift due to insufficient flow from the draining channel to maintain it at this position. New scarps were rapidly eroded into the beach face at the new opening, which is testament to the pace at which these changes can occur. The elevation of the water surface at this discharge point was approximately a metre less than the bed elevation of the Waikoriri Lagoon channel at the point where it joined the creek.

By March 2009, a sediment wedge had begun to accrete across the mouth of Waikoriri Creek, offsetting the outlet and causing it to narrow. The erosional scarps were still present, but water level behind the outlet had risen significantly, to the point where once again some water was flowing into the abandoned lagoon channel. If natural processes continue according to the model of hapua behaviour presented by Todd (1992), the mouth will continue to be offset by sediment accretion, and the channel will fill until a new breach occurs further north along the beach, or a previously abandoned channel is reoccupied.

Hydrological measurements taken in Waikoriri Creek before and after this breach provided a valuable insight into the change in dynamics that occurred as a result of the change in outlet position. Prior to the breach, water levels were very high in Waikoriri Creek and into Shearer Swamp, due to a backwater effect caused by the length of Waikoriri Lagoon. During this period, there were no tidally induced oscillations in water level, either through direct tidal influence or a tidal backwater effect. The changes in water level that did occur were very asymmetric; water level rose very quickly, but dropped slowly over the following days. These patterns can be attributed to precipitation events, with water level rising rapidly in response to water influx, but draining slowly via Waikoriri Lagoon in the following days.

The high resolution, short term water level records taken in early December show that following this breach, these patterns changed substantially. In addition to the dramatic water level decrease in response to the breach (which left the water level recorder at Waikoriri Bridge out of the water, requiring it to be moved), the proximity of the new outlet caused water levels in the creek to respond to tidal fluctuations. This was not apparent for the first half of the short term record, which showed a sudden increase in water level (due to a precipitation event), followed by a gradual decline to normal patterns mid-week, when flow velocities and volumes decreased sufficiently for the tidal influence to reassert itself. The absence of concurrent spikes in conductivity suggests that these tidally induced fluctuations are occurring through a tidal backwater effect, rather than actual tidal penetration. The effect of this breach on the hydrology of Granite Creek (which joins Waikoriri Creek downstream from the bridge) was not investigated, but would have likely experienced a similar change in dynamics. A dampening of this effect was observed in an upstream direction, consistent with models of hydrodynamics within lagoon systems (Blanton *et al.*,2002; Fernandes *et al.*, 2004).

The large conductivity spikes occurring throughout the Waikoriri Bridge record are erratic and do not appear to be related to regular, direct tidal propogation up the creek channel. They do, however, coincide with times of high tide, suggesting that they are related indirectly to the tidal cycle. In this case, they have been interpreted as saltwater influx in response to wave overtopping, which would occur more readily at the higher water levels associated with high tide.

Water temperature trends in Waikoriri Creek were very similar to those of Totara Lagoon, responding primarily to diurnal variations in air temperature, and following a seasonal trend. Once again, an upstream gradient of increasing water temperature was evident in these records. In this case, it is most likely due to the depth of water in which the recorders were located. The recorder at Site 2 was located in a relatively shallow, open expanse of water to the side of the main creek channel, which would absorb more energy than the main, flowing channel.

Figure 4.19. Photographs showing the changes in Waikoriri Lagoon following the breach in November 2008. (a) and (b) show Waikoriri Creek before and after the breach, with water levels much lower in the latter. (c) The empty Waikoriri Lagoon channel. (d) The Waikoriri Lagoon outlet in March 2009, when sediment had started to stabilise the opening again.

4.4.3 Comparison of Totara Lagoon and Waikoriri Lagoon

Both Totara and Waikoriri Lagoons have been classified as hapua-type systems (DOC, 2005), yet they are extremely different in terms of spatial scale, dynamics and geomorphology. The most important difference between the two systems is spatial scale; Totara Lagoon is at least five times the size of Waikoriri Lagoon, meaning that the response time of Totara Lagoon as a whole is greater than that of Waikoriri. Totara River is substantially larger in volume than Waikoriri Creek, therefore creating a larger lagoon. In addition, Totara Lagoon is also fed by several large tributary creeks upstream from the river mouth, whereas Waikoriri Lagoon is fed solely by the creek at its southern end.

The level of stability of the two systems differs largely, and this is apparent in the morphology of the channels and the barriers, as well as field observations of vegetation and other indicators. The length and volume of Totara Lagoon allows it to absorb the effects of things like flood events more readily than a smaller system like Waikoriri Lagoon. Moreover, Totara Lagoon is able to survive despite a sustained river mouth outlet position, whereas Waikoriri Lagoon drains in response to such an outlet position. The changes in conditions along the channel also vary between systems. Totara Lagoon exhibits a substantial gradient of decreasing energy and increasing vegetation from south to north, but Waikoriri Lagoon retains similar characteristics along its entire length, suggesting a more dynamic and less developed regime.

Hydrologically, although these systems are both described as hapua, only Waikoriri Lagoon currently fits that definition exactly. In contrast to Totara Lagoon, Waikoriri Creek experienced no direct tidal intrusion at any stage of the study period. Another significant difference existed between the water temperature trends of the two systems. Waikoriri Creek responded almost exclusively to even, diurnal variations in air temperature in the short term record, while the record of Totara Lagoon was overprinted by some other factor driving variation. The diurnal trend was present, as was the spatial trend of increasing temperature upstream, but a lot more noise was apparent in the data. Part of this discrepancy in the earlier part of the Totara Lagoon record can be explained by the influence of the December 4th storm, which would have disrupted normal flow and temperature patterns in the lagoon. However, despite these apparently large differences, both systems generally exhibited similar spatial trends hydraulically, as would be expected in a comparison of two hapua, regardless of their size.

4.5 Summary

This chapter described the current geomorphology and hydrological regime of Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex, and presented the results of GNSS surveys and water records of the two sites. DEMs of representative sections of each site illustrated the topography, and water depth, conductivity and water temperature records were used to explain the hydrology.

Totara Lagoon varied significantly in terms of both morphology and structure along its 10 km length. The system was much more dynamic and active at the river mouth (current outlet) end, constrained by low rounded dunes and subject to a significant degree of tidal intrusion. The central sections were flat and swampy, but the channel still experienced direct saltwater intrusion related to the tidal cycle. Further north, dunes became steep and heavily vegetated, indicating a relatively high level of system stability at this end. Water level was generally unaffected by tidal influence at this position; however at times a backwater effect was observed.

Waikoriri Lagoon was much more dynamic than Totara Lagoon, which is a result of its much smaller size and lesser degree of development and stability. Shearer Swamp and the inactive dune ridges to the west are very stable in the short term, and act merely to constrain the position of Waikoriri Creek. The hydrology of Waikoriri Creek upstream from the lagoon is determined by the position of the lagoon outlet. When the outlet was offset by 1.5 km, the water level in the creek was high, and no tidal influence was detected. A breach at the creek mouth subsequently drained the lagoon, and water levels dropped dramatically in the creek behind also. In addition, water levels in the creek began responding to tidal oscillations via a backwater effect, which became progressively dampened in an upstream direction.

Differences in dynamics and stability between the two lagoons will be further examined over decadal timescales in Chapter 5, which examines outlet migration patterns over a 59 year period.

CHAPTER FIVE

Outlet and Channel Migration

1948 – 2006

5.1 Introduction

A detailed record of outlet migration and changes in lagoon channel structure is fundamental to understanding the dynamics of any given hapua system. This chapter presents the results of aerial photograph analyses for both Totara Lagoon and Waikoriri Lagoon, undertaken using photographs from eight different survey years spanning a time period of 59 years, and aims to document changes in these systems on approximately a decadal scale. In some cases, photographs spanning a lesser time gap were available, allowing a comparison over less than decadal timescales. Two different approaches were taken to these analyses. Firstly, a visual comparison of lagoon structure, area and outlet position was made between photographs and the changes described. Secondly, quantitative measures of change in outlet position and lagoon length were made in *ArcGis* and, where a clear progression could be seen, net rates of change in outlet position were calculated. It is important to note that aerial photographs represent snapshots of change, from which net changes can be inferred. Other changes between survey years may have occurred that are unrecorded.

This chapter is divided into two main sections; with results pertaining to Totara Lagoon presented in Section 5.2 and those of Waikoriri Lagoon in Section 5.3. A discussion and interpretation of findings is presented in section 5.4. This chapter addresses the following research objectives:

- To compare aerial photographs taken over a 59 year period and examine temporal changes in outlet position, lagoon structure and other features of interest in each system,

- To provide quantitative measures of outlet change and quantify approximate rates of change where possible,
- To identify and explain trends in outlet migration and channel utilisation,
- To determine the driving forces of observed changes and system dynamics.

5.2 Totara Lagoon

Eight separate surveys were available covering the Totara Lagoon area, covering a 57 year period between 1948 and 2005. Details of the survey runs, years and photographs utilised are displayed in Appendix 1. Several photographs from each survey were required to cover the entire lagoon area, and mosaics of each survey set are displayed in Figure 5.1. Digitisations of the lagoon structure during each survey period are presented in Figure 5.2 and outlet positions are marked. These have been divided into five sections, A to E, for the purposes of presenting results and descriptions of change.

5.2.1 Changes in outlet and channel position

Outlet position

The position of the lagoon outlet varied significantly over the entire survey period, and fluctuated between 0 and 5800 m from the river mouth (Table 5.1, Figure 5.2). It remained within sections A and B in every year surveyed except 1988, when it migrated as far as section C. It was common for the lagoon to discharge at the point where the Totara River meets the coast, as was the case in 1972, 2002 and 2005. In 1948 the outlet position was only a short distance upstream from this point. There has been a degree of anthropogenic control on the position of the outlet in recent years, which may be responsible for the lack of outlet migration between 2002 and 2005. The outlet reached its maximum recorded offset of 5800 m in 1988, when it was situated towards the upper end of section C. Following this, no data was available until 2002, when the discharge point had returned to the Totara River mouth and the outlet was artificially managed, meaning no inferences can be made about Totara Lagoon’s natural dynamics beyond 1988.

Migration of the outlet appears to follow a general northward (upstream) progression along the lagoon channel between 1972 and 1988, when the photographs are available at approximately five year intervals (Figure 5.2, 5.4). This temporal resolution of photographs allowed approximate net annual rates of outlet change to be calculated. The location of the outlet moves relatively evenly northwards from the river mouth in 1972 to its northernmost point in 1988, approximately half way up the length of the lagoon channel. Between 1972 and 1976 the mouth migrated northwards a total of 2300 m, which equates to a net rate of 575 m yr^{-1} (Table 5.1) It moved a further 1675 m northwards between 1976 and 1981, a net rate of 335 m yr^{-1}. This decreased to a net rate of 280 m yr^{-1} between 1981 and 1988, during which time the mouth migrated 1950 m in total. Outside of this timeframe, rates of change were not calculated, because photographs were not available at a suitable temporal scale to make calculations relevant.

Where the outlet was upstream from the river mouth, the discharge channel tended to be oriented in a northwards direction, with the length of this channel (i.e. the distance between the main channel and the outlet) varying significantly and increasing with distance upstream from the river mouth. The position of the lagoon's northern extremity did not change on a visible scale throughout the period photographed (Figure 5.1).

Table 5.1. Offset of the Totara Lagoon outlet, measured north from the point at which the Totara River meets the coast.

Survey Date	Outlet offset (m)	Net Difference (m)	Net Rate (m yr^{-1})
April 1948	560	-	-
February 1963	2590	+ 2030	-
February 1972	-125	-2710	+ 575
October 1976	2175	+2300	
October 1981	3850	+1675	+335
January 1988	5800	+1950	+280
February 2002	0	-5800	-
August 2005	0	0	0

Channel utilisation

In addition to substantial outlet change, the distribution of water throughout the channels changed dramatically (Figure 5.2). It is important to note that these changes were not the result of the lagoon forging new channels, but merely abandoning or reoccupying the existing series of channels that were present in all photographs. The total volume of water in the lagoon also appeared to vary, although this is somewhat less pronounced and could be a result of temporary external factors such as storm events. The position of the main river channel and the entrance to the lagoon changed little between surveys, but there was substantial variation in the number, size and placement of sand bars at the river mouth, and in the width and orientation of the discharge channel in the years where the lagoon discharged at this point (Figure 5.1).

Within section A, a single channel was present in the majority of the survey years (Figure 5.2). There are several small areas of well vegetated dunes on the seaward side of the main channel, which have become islands between two channels at times in the lagoon’s history. This was evident in photographs from 1948, 1963 and 1976, where a smaller channel has formed to the seaward side of these dunes (but remaining landward of the main active dune ridge) and then rejoined the main channel (Figure 5.1). This was particularly well developed in the 1963 photograph, where this secondary channel was longer and linked directly to the nearby outlet channel upstream.

Basic channel structure in section B remained relatively constant over all survey periods; however, the volume of water within different channels varied markedly depending on outlet position (Figure 5.2). In this section of the lagoon the channel bifurcates around a large, well vegetated island, then rejoins and subsequently splits again around another island of similar size. The primary lagoon channel flows to the seaward side of this island, with the smaller channel to landward. This smaller channel is present in all photographs and is maintained by two major streams which flow into this channel. The lagoon outlet was present in section B during 1963, 1976, and 1981, causing the volume of water flowing through the primary channel to decrease due to the diversion of water to a third channel – the outlet channel. Conversely, in 1948, 1972, 2002 and 2005 (when the outlet was situated at the river mouth), a large volume of water remains in the blocked outlet channels of this section. This is particularly evident in the 2002 image.

Section C was the most variable part of the lagoon in terms of channel utilisation, despite the fact that the outlet only reached as far as this in 1988. Within this section, the channel splits around an island, rejoins, and splits again for the final time. Channels on both sides of the two islands contained water in the following years: 1948, 1972, 1988, and 2005 (Figure 5.1). In 1976 and 1981 there is only a single water-carrying channel within this entire section, and in both 1963 and 2005 the lagoon exhibits only a single channel following the first island. Periods of high water content and full channel occupation tend to coincide with a river mouth outlet position (Figure 5.2).

Channel occupation and area of the water surface appear relatively constant throughout all images in sections D and E. The lagoon is reduced to a single, choked channel throughout the length of these sections, and there is no change in the position of this channel over the study period (Figure 5.2). This could be due in part to the presence of a major stream which flows from an adjoining area of swampland and feeds the upper lagoon at the boundary of sections C and D. No data is available for section E from the 1948 photographs. Total surface area of the lagoon appears to be greatest in 2002, followed by 1972 and 1948. 1981 and 1976 exhibit the smallest total surface areas.

Vegetation and features of interest

The distribution of vegetation in the immediate lagoon area changed little over the study period, although scrub cover on the islands in section C and D was much more developed in the 2005 photograph than in the 1948 image. There are several smaller empty channels running across these islands and other flatter, non-vegetated areas that appear to be flood washover areas. Larger channels abandoned prior to the 1948 photograph are clearly visible as areas bare of vegetation in sections A and B, which become progressively more grassed over in each successive photograph (Figure 5.3).

The old railway line that runs along the landward side of the lagoon is a distinct landmark visible in all photographs and was used as a baseline for aerial photograph analysis (Figure 5.1, 5.2). This feature consists of an artificially constructed raised bank upon which the railway line sits. This is likely to obstruct natural drainage flow and limit adjustment between the lagoon and the swampy areas landward of the railway line. Drainage through this boundary is directed through several large streams, which are constrained artificially by culverts and bridges as they pass through the bank. Consequently, their position does not change over this 58 year period.

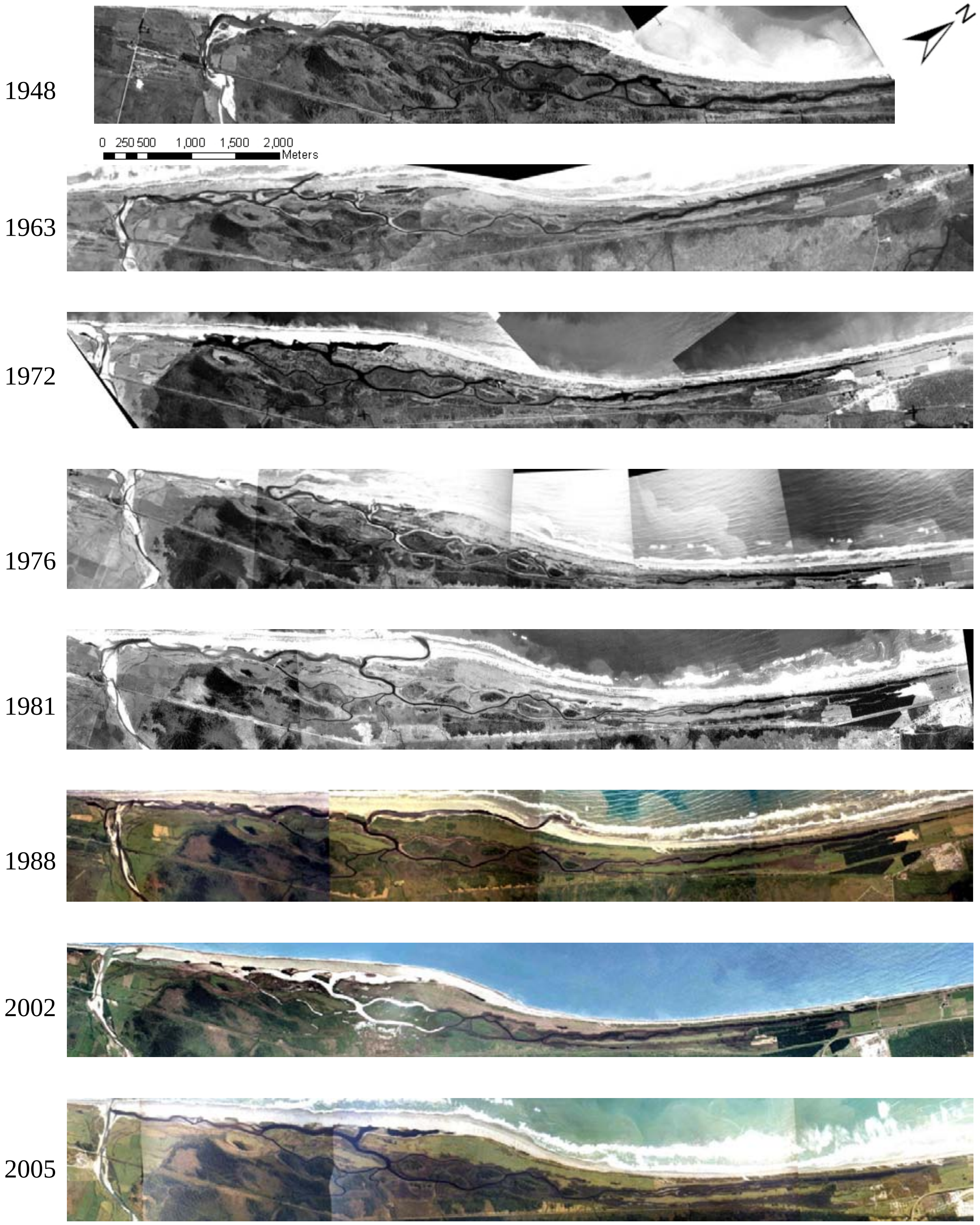


Figure 5.1 Totara Lagoon aerial images 1948-2005, areas outside of the lagoon have been cropped.

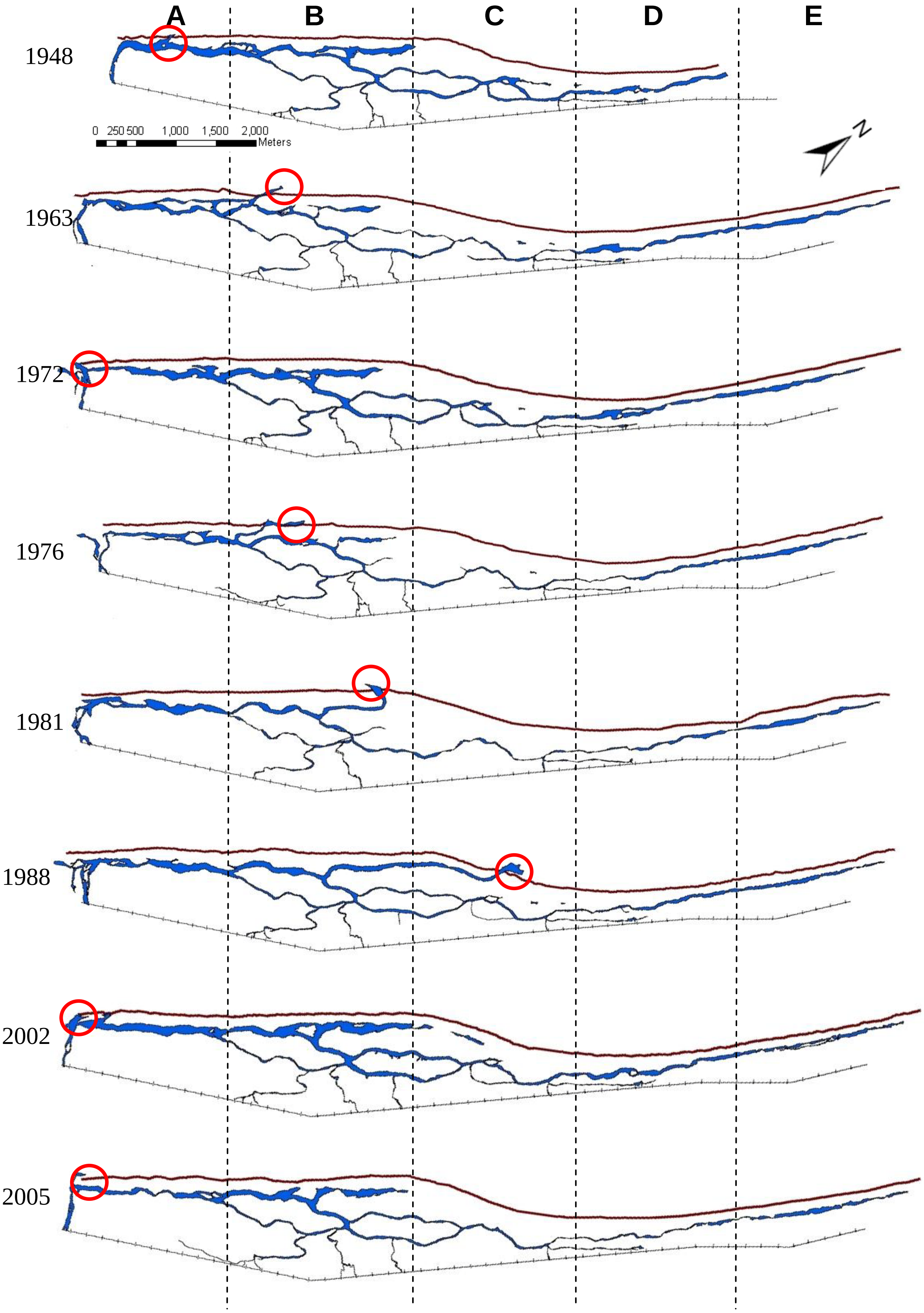


Figure 5.2 Digitisations of Totara Lagoon over time from aerial photographs. Outlet position is circled in red.

Figure 5.3 Disused channels of Totara Lagoon. Those in the left half of the picture were abandoned some time prior to the 1948 aerial photograph.

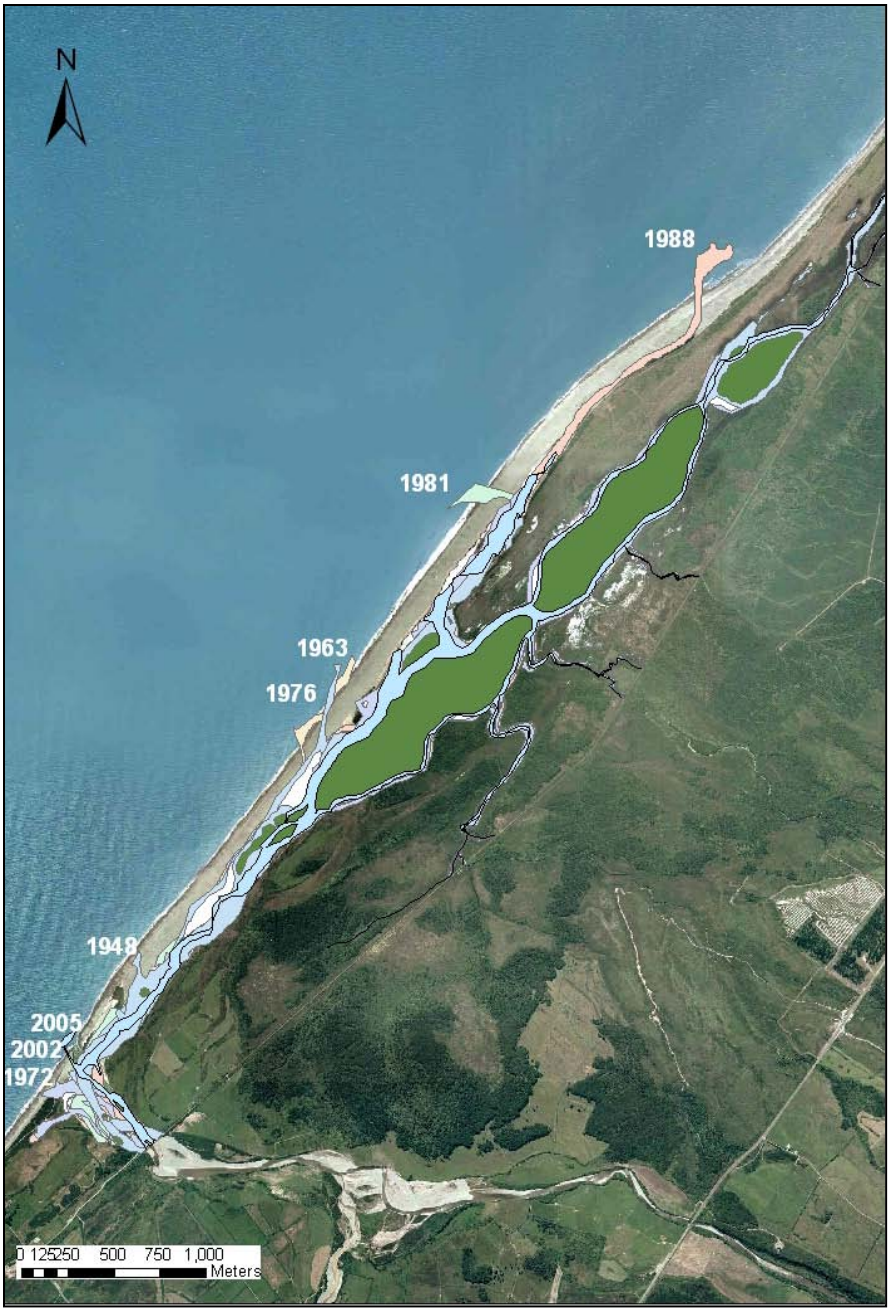


Figure 5.4 Summary of outlet positions of Totara Lagoon 1948 to 2005.

5.3 Shearer Swamp-Waikoriri Lagoon Complex

Photographs spanning a 58 year period from 1948 to 2006 were analysed to explore temporal and spatial changes in extent and structure of Waikoriri Lagoon. Images from nine separate surveys during this time period were available, from which digitisations of the lagoon were made for each individual survey year in *ArcGIS*. Snapshots from photographs are displayed in Figure 5.5 along with individual digitisations of the lagoon area for each survey year in Figure 5.6.

5.3.1 Changes in Waikoriri Lagoon and surrounding area

Waikoriri Lagoon is a small, very dynamic hapua which shows a pattern of outlet migration northwards along the beach, interspersed with periods where the outlet returns to the point at which the combined Waikoriri and Granite Creeks intersect and reach the coast (Figure 5.6). The outlet was situated at this location (or marginally northwards of it) in the following surveys: 1948, 1972, 1976, 1981 and 1988. Between 1948 and 1976 the outlet offset fluctuated between 120 and 560 m, before increasing five times in length in the five years between 1976 and 1981 (Table 5.2). The lagoon was at least 900 m long in the remainder of the photographs, except for a single recorded return to 150 m in length in 1988. The lagoon outlet reached its maximum offset of 2500 m in the 2002 photograph, before retreating 1600 m to a distance of 900 m up the coast by the 2006 survey, halving the lagoon length since 2002 (Table 5.2).

Evidence for the shift of the outlet in a north – south direction was apparent in the photographs from 1972 and 2006, where there was still remnant water present in the abandoned channel to the north of the outlet (Figure 5.5). In both these cases, the photograph from four years previously clearly shows the outlet position at the point to which the remnant water reaches. In 1972, the outlet was situated a mere 120 m north of the confluence, but water was present in the channel up to 610 m north of this discharge point. At the time of the 2006 photograph, the channel north of the outlet contained water for a distance of 1520 m. At times water has also backed up at the Granite Creek-Waikoriri Creek confluence, causing a wide channel to form along Granite Creek to the south of the lagoon entrance. This is particularly evident in 1948, 1972, 1981 and 2006.

The outlet position in 1981 and 1986 is approximately the same as in 2006, suggesting a tendency for the lagoon to discharge at this point. The lagoon appears to have remained relatively stable over the period 1981 – 1986, as the outlet is in the same position during both these images. Due to the tendency for Waikoriri Lagoon outlet to migrate over short timescales (i.e. timescales shorter than those covered by these aerial photographs), no calculations were made of the rate of change of the outlet between survey years.

The surface area of water and shape of the lagoon varied significantly across the study period (Table 5.2). In most cases the area of the water surface correlates with the length of the lagoon. The greatest surface area measured was 56 500 m^2, which occurred in the 2002 photograph; also the period of greatest length. This trend was also apparent in 2006 and 1981, the next largest years in terms of both length and surface area. 1972 presents as a distinct anomaly, possessing a surface area of 30 500 m^2 but with a mouth offset of only 120 m. The lagoon was at its smallest during 1976 and 1988. It is important to note however, that water surface area can be affected by factors such as rainfall and tides, and thus is only a rough estimate of lagoon size and is not necessarily indicative of the average conditions around the time the photograph was taken. No data was available for the 1948 or 1986 aerial photographs, as the resolution did not allow the channel to be mapped with sufficient accuracy.

In the two latest photographs the lagoon splits into two channels at the southern end, separated by a low, sparsely vegetated sand bar (Figure 5.5, 5.6). Rather than this being a case of two inlet channels, the landward channel is filled by water flowing out of the main channel then back in the opposite direction parallel to the main channel. This is a blind channel which is terminated at the point where it is crossed by a raised walkway alongside Waikoriri Creek. In earlier photographs this channel forms part of the outward-flowing main channel, which is wider along this section in 1948, 1963, 1972 and 1981.

Beach width also appears to vary spatially and temporally across the different photographs. The wet-dry line was used as a proxy for the shoreline position when creating the digitisations from the images. Beach width opposite the Waikoriri Creek-Granite Creek confluence appeared greatest between 1963 and 1988, decreasing significantly in width in the later images (2002 and 2005). A wedge of sediment accreting around the outlet is clearly visible as a ‘bulge’ in the position of the wet-dry line in many of the photographs.

Shearer Swamp appears to have changed little over this 58 year period, and streams which drained the swamp remained in the same position throughout the photographs. The swamp area itself was largely constrained by Bold Head Road and the defunct tramway to the west, and by areas of forest to the east and north, none of which changed significantly over the survey period. The southern edge of the swamp however, was subject to ongoing drainage works and clearing of land for farming, which affected the hydrology and structure of that section of the swamp. This did not have a direct effect on the structure of Waikoriri Lagoon itself, as no related artificial modification of the channel of Waikoriri Creek, Granite Creek or Waikoriri Lagoon was made below this area.

An artificial drainage channel that connected Shearer Swamp and Waikoriri Lagoon (known locally as ‘The Causeway’) is clear in all photographs, situated approximately 100 m north of the Waikoriri Creek Bridge. Another similar, smaller feature is observed just south of The Causeway (Figure 5.5). These features are no longer actively used, but a channel leading across Bold Head Road through the dune ridge is apparent in earlier photographs. This provided a method of draining water directly from Shearer Swamp via upper Waikoriri Creek when water levels in the swamp rose and threatened nearby land.

Table 5.2. Outlet offset and change in lagoon surface area between surveys.

Survey Date	Outlet offset (m)	Difference (m)	Surface Area (m^2)	Change (%)
April 1948	325	-	-	
February 1963	560	+235	21500	-
February 1972	120	-440	30500	+42
October 1976	205	+85	8500	-72
October 1981	1050	+845	33500	+294
January 1986	1250	+200	-	-
January 1988	150	-1100	9500	-72
February 2002	2500	+2350	56500	+495
August 2006	900	-1600	36500	-35

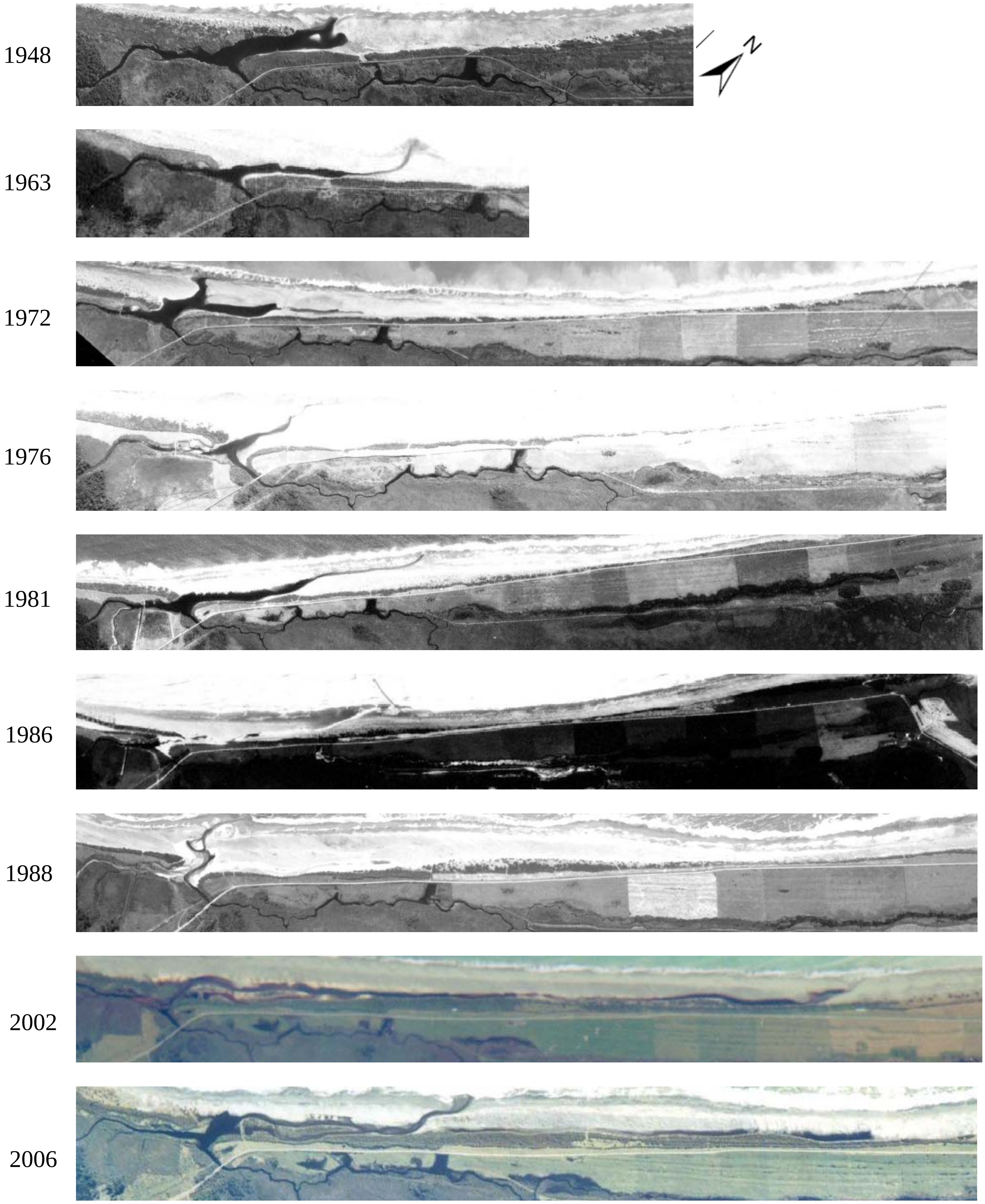


Figure 5.5 Aerial photographs of Waikoriri Lagoon, showing Bold Head Road to the landward side of the lagoon and the ‘Causeway’ next to the road.

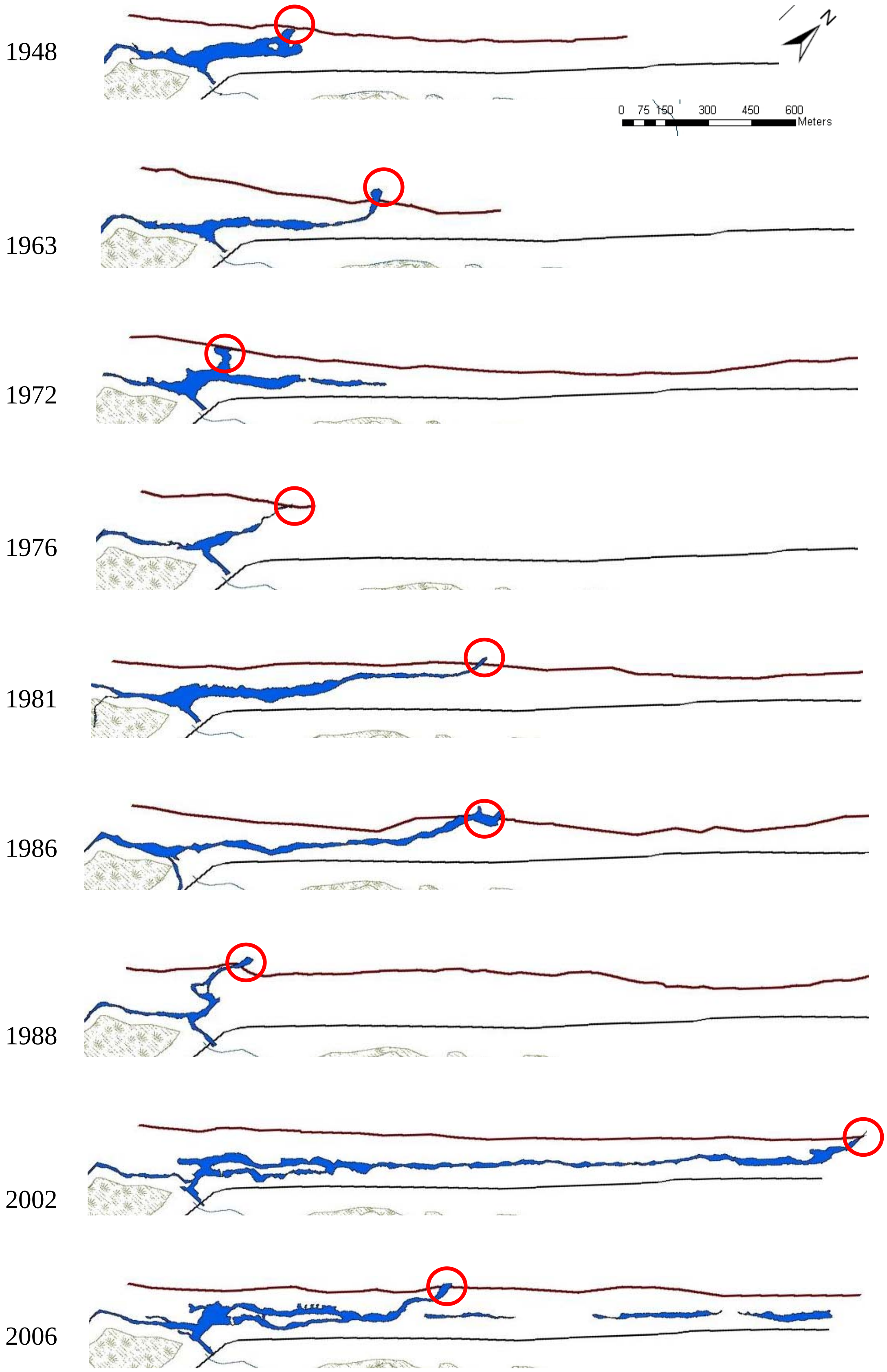

1948
N
0 75 150 300 450 600
Meters
1963
1972
1976
1981
1986
1988
2002
2006

Figure 5.6 Digitisations of Waikoriri Lagoon from aerial photographs, 1948 – 2006. Outlet position is circled in red.

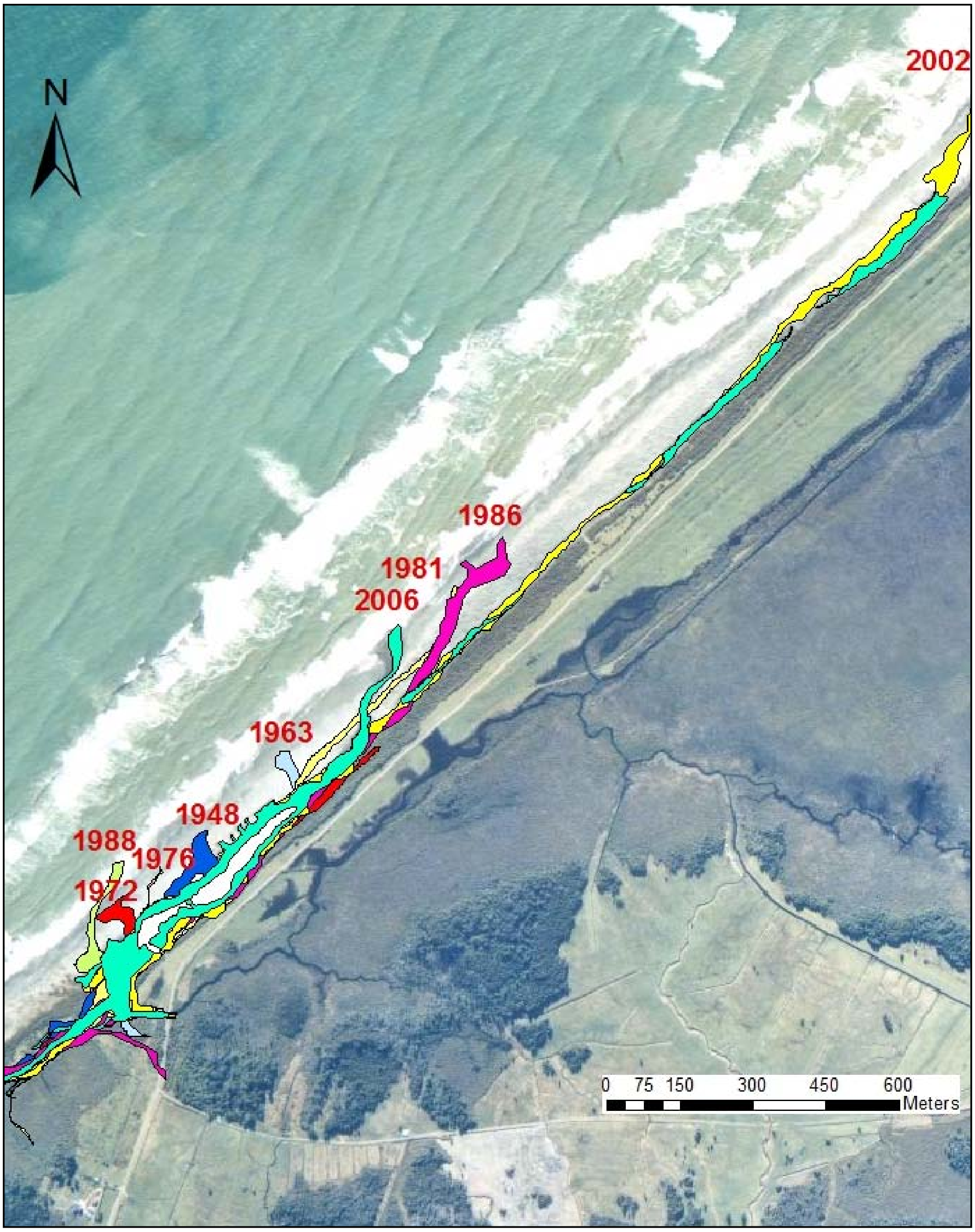


Figure 5.7 Summary of outlet positions in Waikoriri Lagoon, 1948 to 2006.

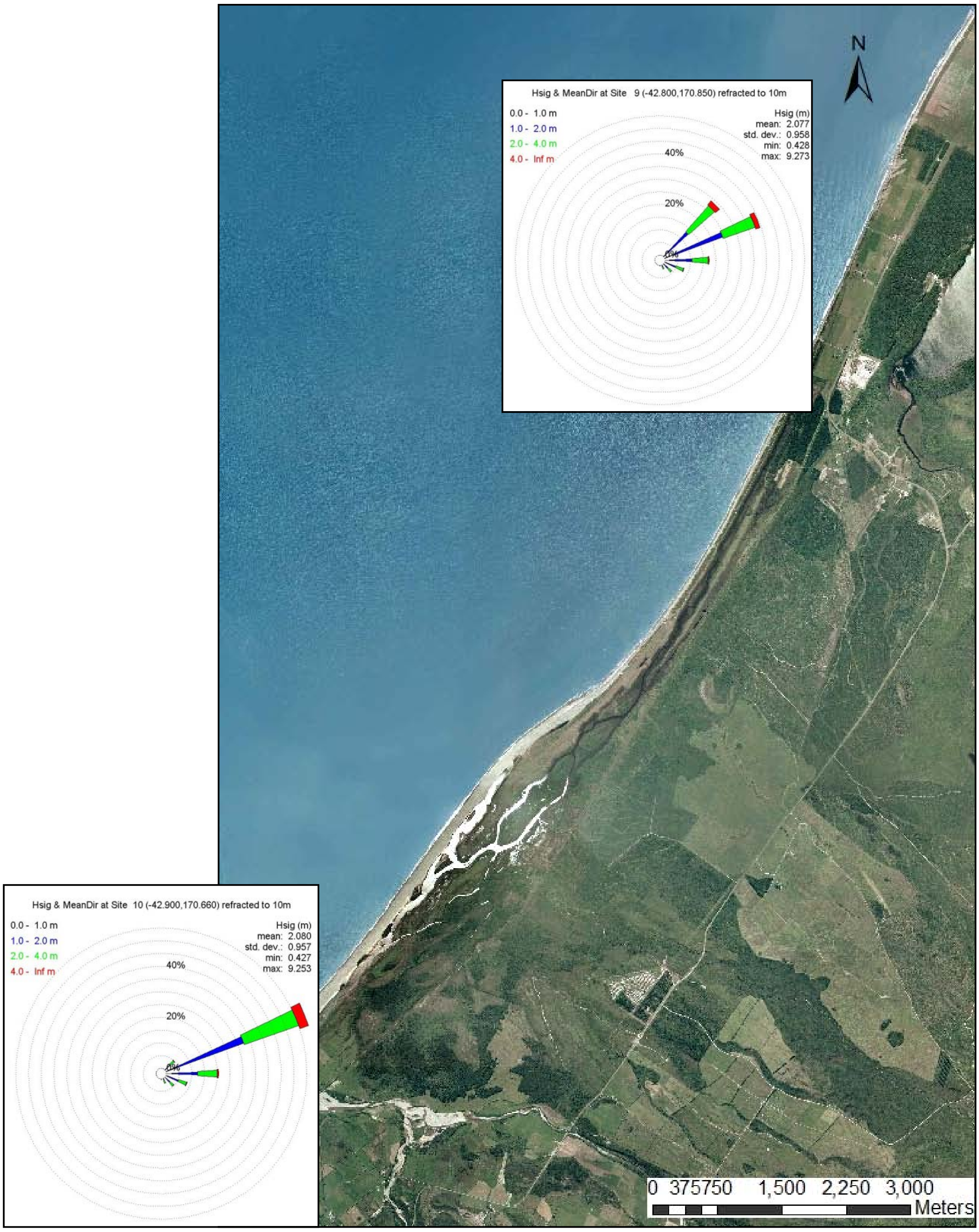


Figure 5.8. Wave climate at each end of Totara Lagoon. The waves arrive sub-parallel to the coast, which enhances the deposition of sediment which builds the barrier across the outlet from the south. *Wave data sourced from NIWA, WAM 20 year hindcast data.*

5.4 Interpretation and discussion of outlet dynamics

This section aims to provide an interpretation of the results presented here, and to discuss the dynamics of Totara Lagoon and Waikoriri Lagoon with respect to outlet migration. A comparison of the two lagoons is presented here in terms of outlet dynamics, but a discussion of these systems with detailed reference to existing models of hapua dynamics is reserved for Chapter 7. This allows all results to be presented and integrated into a single discussion of dynamics and development within these and similar systems over all timeframes studied within this project.

5.4.1 Totara Lagoon

Throughout most of the study period (1948 – 1988), the outlet of Totara Lagoon was not artificially managed, allowing a natural pattern of outlet migration to occur. The results from 1972 to 1988 are particularly important here, as they are of a suitable temporal resolution to show this pattern clearly and accurately. The outlet was exhibited a net displacement progressively northwards across this timeframe, which is consistent with the model of hapua dynamics presented by Todd (1992). On the West Coast the predominant direction of littoral drift is northwards, which has caused this pattern of northerly offset, and also caused the outlet channel to be orientated diagonally through the barrier in a northwards direction, which is evident in most photographs and digitisations. This is enhanced by the north-easterly direction of wave approach, which means waves approach sub-parallel to the coast along the length of the system (Figure 5.8). The exception to this discharge channel orientation is that of 1988, where the channel curves back upon itself to discharge facing south. It is unclear whether this was the average condition of the outlet during that period, or whether it was a temporary situation at the time of photography.

The outlet appears to migrate steadily and consistently northwards until 1988, but it is unclear whether this was a gradual, steady process or whether the outlet ‘jumped’ between positions. This could be caused by the existence of low passages through the seaward dune ridge, such as areas of dune blowouts or old abandoned outlet channels.

Outlet position appears to have a significant effect on lagoon channel structure and water volume, particularly in the central reaches. At times where the outlet was situated at the river mouth there was a greater volume of water present in the lagoon, and thus greater channel utilisation. This is due to a fluvial backwater effect (Hart, 2007), whereby water is flowing into the lagoon at the southern end via Totara River, but as this is also the only discharge point for the lagoon, water level increases along its length in response. Several of the central channels remained throughout every photograph, which is a consequence of the position of several primary creeks which discharge into them. The position of these creeks is constrained by the railway embankment landward of the lagoon, which forms a very inflexible and well vegetated barrier between the swampland and lagoon. The abandonment of the channel network visible at the southern end of the lagoon (Figure 5.3) could potentially be related to the construction of this barrier and drainage of swampland for faming in historical times. Prior to these events, there would have been a margin of adjustment between the lagoon and swampland behind it, and drainage would have occurred through a larger network of creeks than those which are now artificially amalgamated and directed through this barrier at arbitrarily constructed points. Conversely, it could potentially be related to migration of the entire lagoon system in response to coastal progradation or fluvial change prior to these events, but the former scenario is more probable due to the lack of vegetation present in these old channels compared with that of the islands in the central reaches.

The total length of Totara Lagoon did not change over the study period, which is due to the sheer size of the lagoon and the large capacity to absorb changes in water supply and distribution through its many channels, by increasing the water volume in active channels or by reoccupying disused channels. The central reaches of the lagoon acted as a buffer zone in this process, with little change occurring in lagoon structure at the southern and northern ends. The stability and vegetation cover of the dunes, as discussed in the previous chapter, helps prevent the barrier from breaching at multiple or new positions. This is a positive feedback loop, as the lack of breaching allows the vegetation to develop, and the vegetation stabilises the barrier and reduces the likelihood of further breaching. Despite the fact that no change in length occurred over this 58 year period, there is clear evidence that the lagoon has continued further north at some time prior to 1948, as a dry, grassed-over channel exists between the two dune ridges extending a further 200 m.

It is unclear to what degree the structure of Totara Lagoon is constrained by the presence of the railway line to the east of the lagoon, and how the lagoon has been affected by the drainage and farming of adjacent swampland to the east of the railway. The clearing of this area can be followed through the photographs from 1948 onwards, but no consequent structural changes were evident over this timeframe.

5.4.2 Waikoriri Lagoon

Data and digitisations of Waikoriri Lagoon show that it has changed dramatically in terms of length and structure over the period surveyed. Due to the dynamism of this small hapua, it is likely that significant unrecorded change in outlet position and water volume occurred between these photographs as well, meaning that calculations of rates of outlet migration, such as were made for Totara Lagoon, would be false representations of change.

There is a history of artificial breaches in the Waikoriri Lagoon barrier at the point where Waikoriri Creek reaches the coast, some of which are responsible for the observed migration of the Waikoriri Lagoon mouth in some photographs. A managed breach was initiated prior to the 1988 photograph (when the outlet is situated at the south) and again in 2004 in response to a flood event threatening nearby land and infrastructure. This accounts for the movement in outlet position from the northern extremity in the 2002 photograph, to the more southerly position in 2006. As noted by Hart and Single (2004), the lagoon has been artificially opened at the southern extremity many times since the late 1800s, and the mouth is shown at the southern position in maps of the area from 1897 and 1981. Although there is an extensive history of artificial outlet change in the southerly direction, the natural migration of Waikoriri Lagoon’s outlet position northward follows the pattern depicted by Kirk (1992), whereby littoral drift (northward in this case) causes a sediment wedge to build over the mouth which causes it to migrate along the beach in this direction.

Although there was no direct effect on Waikoriri Lagoon itself during the clearing and drainage of swampland upstream from the lagoon over recent decades, the hydrology and sediment supply to the lagoon via Waikoriri and Granite Creeks has been influenced indirectly. The channels of these creeks have been realigned by local farmers in some areas, and stop-banks of unconsolidated material from nearby slips have been constructed along the margins of Granite Creek. This sediment tends to become remobilised during flood events and is carried downstream to be deposited at the coast.

This sediment build-up alters the drainage patterns of the network of creeks that ultimately drain Shearer Swamp and form the lagoon.

5.4.3 Comparison of Totara Lagoon and Waikoriri Lagoon

As discussed in Chapter 4, the spatial scales of Totara Lagoon and Waikoriri Lagoon are very different, and consequently, so are the spatial and temporal scales of outlet migration. Aerial photograph analysis of outlet change works well with Totara Lagoon, as it most likely captures a relatively complete record of change in the outlet position. In the case of Waikoriri Lagoon, the record is much less complete, as the outlet has been observed to migrate on much smaller scales than those recorded by the aerial photograph surveys. As a consequence, any calculation of rate of outlet migration would be very artificial, so was not attempted.

The level of stability of the barrier is very important in terms of outlet dynamics. The barrier at Waikoriri Lagoon is much less stable than that of Totara Lagoon, which is more heavily vegetated with higher dunes. As a result, there is much more scope for the position of the Waikoriri Lagoon outlet to migrate, as it is less constrained by vegetation and topography.

The permanence of the lagoon bodies is very different. In the case of Totara Lagoon, the waterbody remains consistently present and approximately the same size throughout the entire study period. It remains a complete, connected water body while the outlet migrates. Waikoriri Lagoon fluctuates hugely in size in response to the offset of the outlet, essentially draining completely when the outlet position is at the southern extremity. Unlike Totara Lagoon, water is very rarely present north of the outlet position, and if it is present, is not connected to the rest of the lagoon body. Rather than being a part of the lagoon, it is merely pools of water trapped behind the barrier that have yet to evaporate. Once again, it is important to note that Waikoriri Lagoon has no tributary streams north of the mother creek to feed the lagoon channel, unlike Totara Lagoon, which is fed in the north by several large streams.

The physical configuration of the lagoons varies enormously in more than spatial scale. The photographic record shows Totara Lagoon has retained a multi-channel configuration for the past 60 years, whereas Waikoriri Lagoon is usually restricted to a single, shallow channel. Combined with the sheer size difference of the lagoons, this has implications in terms of their differing abilities to absorb changes in water volume in response to storm events, thus contributing to the difference in temporal dynamics.

Ultimately, the differences in outlet position and dynamic regime between these two systems are a function of many interacting variables, which will be discussed further in later chapters.

5.4.4 Limitations and errors

Significant limitations exist in the use of these aerial photographs, particularly in terms of the numeric calculations of outlet position. The main methodological concerns and errors introduced in the orthorectification and georeferencing processes were detailed in Chapter 4; however the ways in which these have affected the specific results are discussed here.

The primary limitation in this context is that aerial photographs record only the conditions at the exact moment the image was taken. This is only of minor concern when mapping lagoon water surface and outlet position, but means the calculations of offset and surface area are net and approximate only. No calculations of changes in beach width could be made, as the margins of error created by tidal and weather-related water level variations were too great. Larger absolute errors exist in the Totara Lagoon photographs, due to the need for mosaicking of several images to cover the entire area.

The exact magnitude of error present varies between years and lagoon area, depending on the quality of orthorectification of each individual photograph and the mosaicking process. In terms of outlet position, measurements were rounded and can be considered accurate to within 50 m (± 25 m).

5.5 Summary

This chapter presented the results of outlet migration and channel structure in Totara Lagoon and Waikoriri Lagoon, gained from analysis of aerial photographs taken between 1948 and 2006. The net change in outlet position between survey periods was measured, and visual observations of change noted.

Both systems exhibited northward offsets of the outlet position, reaching a maximum of 5800 m from the river mouth in Totara Lagoon, and 2500 m in Waikoriri Lagoon. Rates of outlet migration were calculated to be between 0 and 575 m yr^{-1} for Totara Lagoon, but were not calculated for Waikoriri Lagoon due to its tendency to migrate on timescales shorter than those captured by these aerial photographs.

Variations in channel structure were small in Totara Lagoon, but significant changes did occur in the auxiliary channels of the central reaches. Lagoon surface area appeared to correlate negatively with outlet offset (i.e. the surface area of water in the channels is greatest when the outlet is situated at the river mouth). In contrast to Totara Lagoon, Waikoriri Lagoon drained completely when a breach occurred at the river mouth, and the channel was restricted to a single conduit along its entire length in all photographs.

The differences in outlet dynamics between these two systems were related to differences in spatial scale and level of development of the seaward barrier. This, combined with hydrological factors and channel morphology, means Totara Lagoon is inherently more stable and subject to less variation than Waikoriri Lagoon.

CHAPTER SIX

Development over Decades to Centuries

6.1 Introduction

This focus of this chapter is the results of the sediment coring and associated analyses, providing a detailed record of the nature of the subsurface sediment at three locations: one in Shearer Swamp and one each at the southern and northern ends of Totara Lagoon respectively. Stratigraphic logs of each core are displayed, followed by the results of sediment texture and percent organics analyses of individual sediment facies from within each core. Once again, results pertaining to Totara Lagoon are presented in section 6.2, followed by those of the Shearer Swamp-Waikoriri Lagoon Complex in section 6.3. Results from each technique are presented individually within each site section. An interpretation of the changes in depositional environment within each core is presented in Section 6.4.

This chapter addresses the following research objectives:

- To determine how the depositional environments of specific sites within Totara Lagoon and Shearer Swamp have developed over historical time and relate this to the current state and dynamics of each system,

- To understand the processes driving these changes in depositional environment.

6.2 Stratigraphy and sediment texture

6.2.1 Totara Lagoon

Sediment size was measured using a *Micromeritics Saturn Digisizer 5200* laser particle sizer capable of measuring grains up to 1000 µm in diameter, and the percentage by weight of each sample above this cut-off value is displayed in Table 6.1. The degree of sorting of each sample was calculated from its grain size distribution and interpreted according to categories presented in Chapter 3, Table 3.3. Individual sediment distribution graphs are presented in Appendix 5.

The substrate at the northern end of Totara Lagoon was relatively sandy (Figures 6.1, 6.3). Sediments between the surface and 0.3 m depth consisted of organic-rich dark-brown mud. Underneath this layer was a unit of dark-brown, muddy, medium-grained sand with occasional wood fragments. A gradational contact occurred between this unit and a grey, medium- to coarse-grained quartz sand layer between 0.26 and 0.33 m below the surface. This unit was underlain by a sharply contacting brown-grey fine-grained sand layer at a depth of 0.45 m below the surface. All units had high moisture content.

At a depth of 0.03 m the mean grain size of sediment was 124 µm and it was extremely poorly sorted, with a standard deviation (σ) of 71.3 (Figure 6.5). Organic content at this depth was very high, at 41% (Figure 6.7). At 0.15 m the mean grain size increased to 281 µm and σ = 1.1, corresponding to a poorly sorted, medium grained sand, with an organic level of 5%. Mean grain size continued to increase down-core, and was 294 µm at 0.3 m below the surface. Sediment was once again poorly sorted at this depth, σ = 2.0, and organic content was 0%. The mean grain size at 0.5 m was 434 µm with a very low organic content of 0.7%. This sample was very poorly sorted, σ = 2.3.

Relative to the cores from Totara north, the southern end of Totara Lagoon presented a comparatively simple stratigraphy (Figures 6.2, 6.4). Surface sediments were organic-rich medium-brown mud, with a gradational contact at a depth of 0.08 m below the surface between the top layer and a similar unit of brown mud beneath. The latter contained occasional wood fragments and was underlain at a depth of 0.43 m below the surface by a medium-brown, very poorly-sorted, coarse-grained sand and fine gravel layer. The thickness of this layer is unknown as it continued beneath the maximum core depth. Once again, all units had high moisture content.

Sediment was fine grained and extremely poorly sorted at a depth of 0.03 m below the surface, with a mean grain size of 45 µm and σ = 4.5 (Figure 6.6). Organic content at this depth was 10% (Figure 6.7). Samples were analysed from depths of 0.15 and 0.3 m, both of which were part of the same brown mud unit. Mean grain size at these depths was 27 and 29 µm respectively, and the sorting of this layer decreased from σ = 2.8 (very poorly sorted) at 0.15 m depth to σ = 1.7 (poorly sorted) at 0.3 m depth. Measures of organic content varied markedly between these sampling depths, from 7.0% at 0.15 m to 3.8% at 0.3 m below the surface. There was a large change in sediment character between this unit and the following coarse sand layer, which had a mean grain size of 719 µm and was very poorly sorted, σ = 2.8. Percentage of organic matter was 0.7% at a depth of 0.5 m.

Table 6.1. The percentage of each sediment sample greater than 1000 µm, which was removed prior to laser sizer grain size analysis.

	Percentage by weight > 1000 µm diameter	
Depth (mm)	**Totara North**	**Totara South**
30	3.88	12.8
150	2.15	2.25
300	6.11	1.95
450	7.45	12.4

Figure 6.1. Sediment core taken from Totara North. *Photograph: Marney Brosnan*

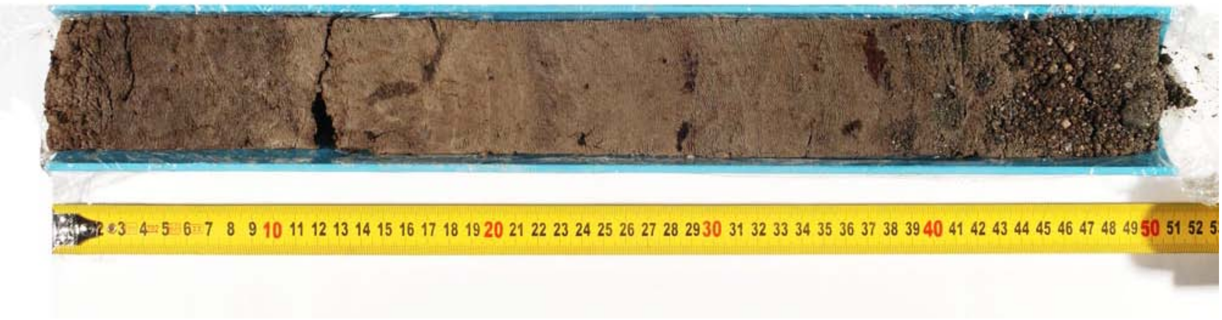


Figure 6.2. Sediment core taken from Totara South. *Photograph: Marney Brosnan*

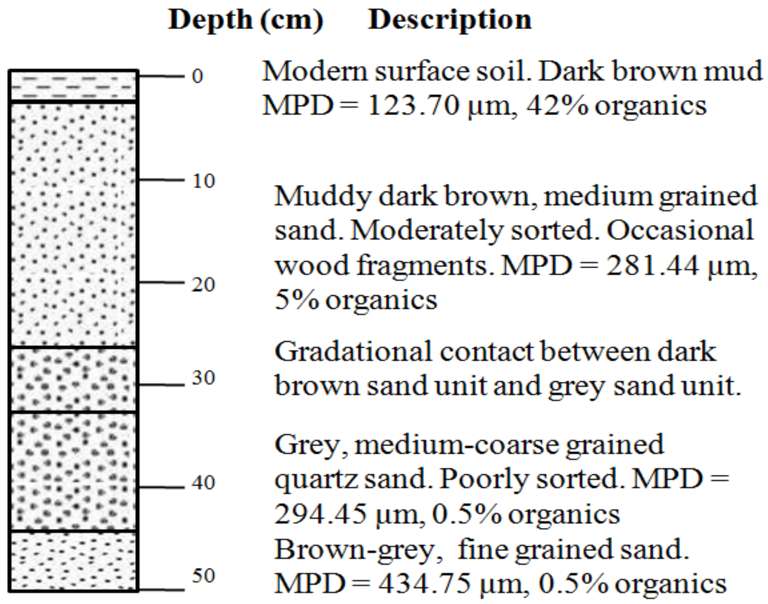


Figure 6.3. Graphic log of the stratigraphy and sediment character from the Totara North sediment core. MPD = mean particle diameter.

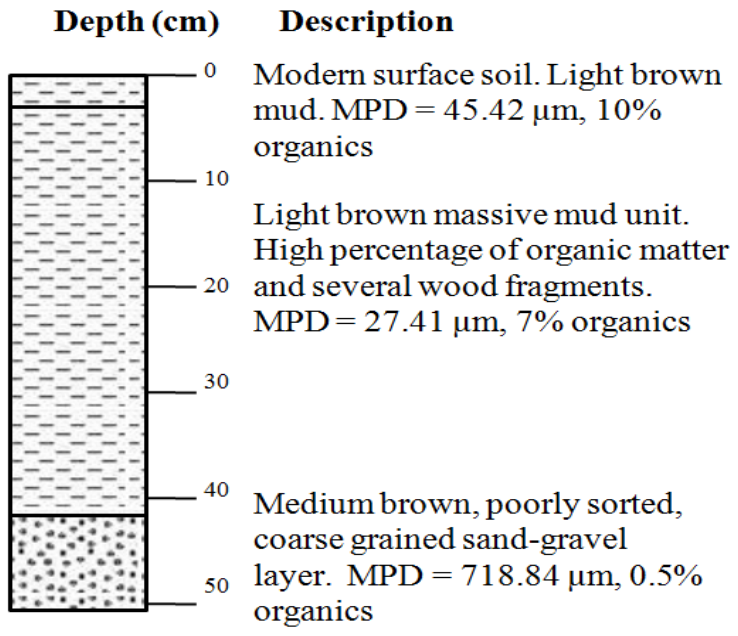


Figure 6.4. Graphic log of the stratigraphy and sediment character from the Totara South sediment core. MPD = mean particle diameter.

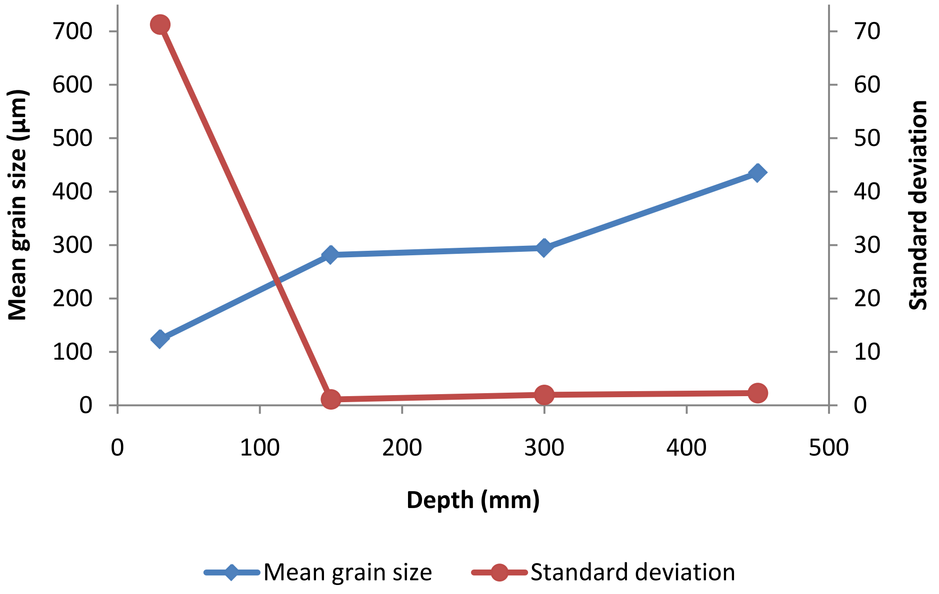


Figure 6.5. Results of grain size analysis for Totara North, showing mean grain size and degree of sorting for each sample depth. Individual sediment distribution graphs are displayed in Appendix 5.

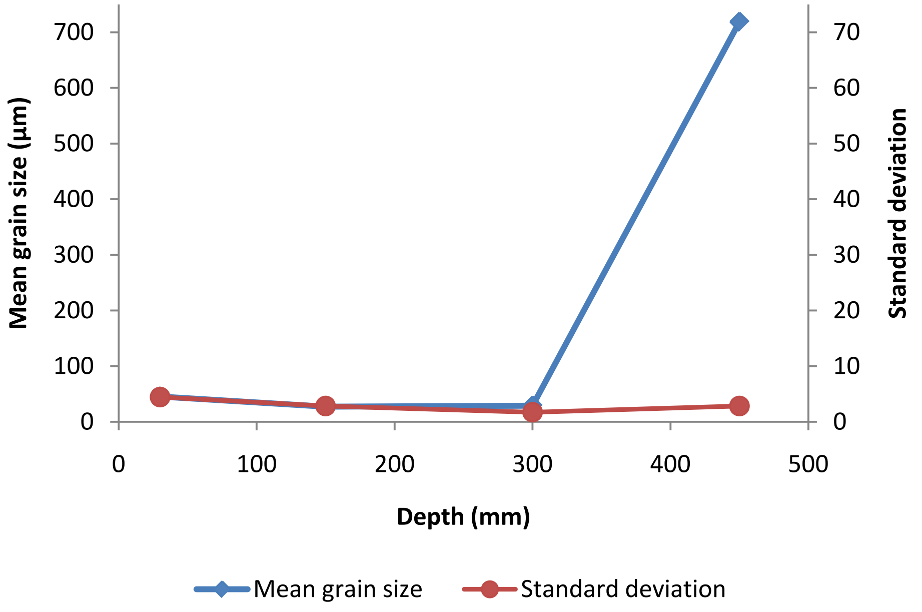


Figure 6.6. Results of grain size analysis for Totara South, showing mean grain size and degree of sorting for each sample depth.

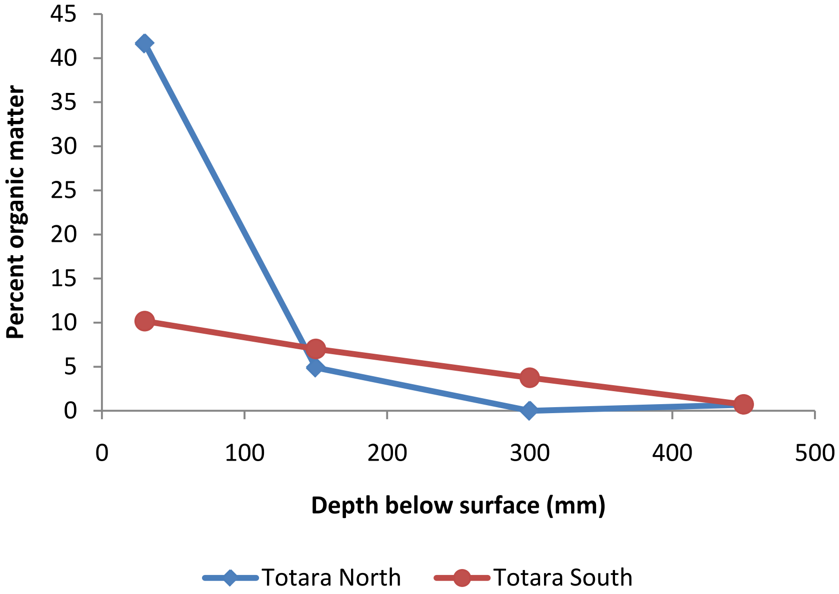


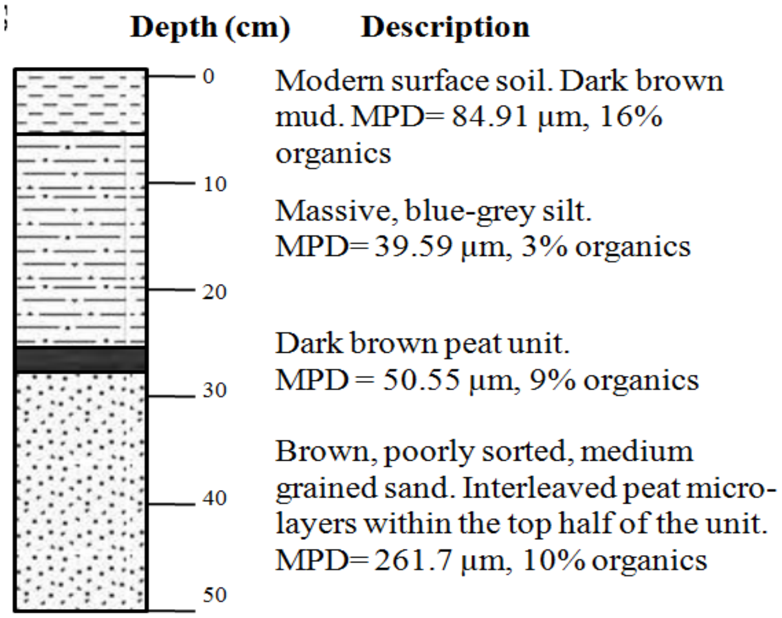
Figure 6.7. Percentage of organic matter for samples taken from Totara Lagoon cores.

6.2.2 Shearer Swamp-Waikoriri Lagoon Complex

Surface sediments in the Shearer Swamp core consisted of dark brown mud with significant living organic content, underlain by a sharply contacting unit of low-organic blue-grey silt at a depth of 0.05 m below the surface. The silt was underlain by a dark brown peat layer at a depth of 0.235 m below the surface. At 0.27 m below the surface an organic-rich, brown, poorly-sorted, medium-grained sand layer occurred. This contained micro-layers of peat in the top half of the unit, eventually giving way entirely to sand, preventing the corer from penetrating and retrieving material from further below. (Figure 6.6).

Samples were analysed from depths of 0.03, 0.15, 0.3 and 0.5 m for grain size, degree of sorting and percentage of organic matter. The percentage of material in each sample above 1000 µm in diameter is presented in Table 6.2. At 0.03 m below the surface the mean grain size was 85 µm and the sediment was extremely poorly sorted, σ = 9.2. Organic matter constituted 16% of the sample. The blue-grey silt had a mean grain size of 40 µm and was very well sorted, σ = 0.3, at a depth of 0.15 m. The amount of organic matter in this sample was low at 3%. At a depth of 0.3 m mean grain size was 51 µm and the sample was extremely poorly sorted, σ = 6.2. Organic percent increased to 9% in this layer. Mean grain size increased significantly in the sand layer at the base of the core, to 261 µm, with an organic constituent of 10%. This layer was also extremely poorly sorted, σ = 32.2. (Figures 6.7 and 6.8).

Figure 6.8. Sediment core taken from Shearer Swamp. *Photograph: Marney Brosnan*



Modern surface soil. Dark brown mud. MPD= 84.91 µm, 16% organics

Massive, blue-grey silt. MPD= 39.59 µm, 3% organics

Dark brown peat unit. MPD = 50.55 µm, 9% organics

Brown, poorly sorted, medium grained sand. Interleaved peat micro-layers within the top half of the unit. MPD= 261.7 µm, 10% organics

Figure 6.9. Graphic log of the stratigraphy and sediment character from the Shearer Swamp sediment core. MPD = mean particle diameter.

Table 6.2 Percentage of each sediment sample greater than 1000 μm in diameter, which was removed prior to laser sizer analysis.

Depth (mm)	Percent > 1000 μm
30	12.8
150	2.3
300	1.9
450	12.4

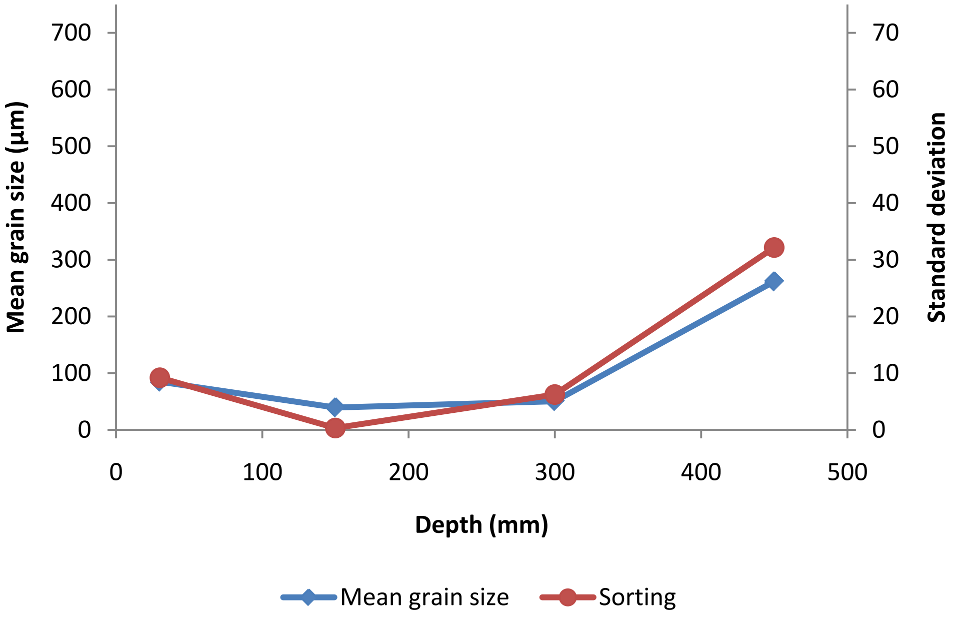


Figure 6.10. Results of grain size analysis for Shearer Swamp, showing mean grain size and degree of sorting for each sample depth. Further details are presented in Appendix 5.

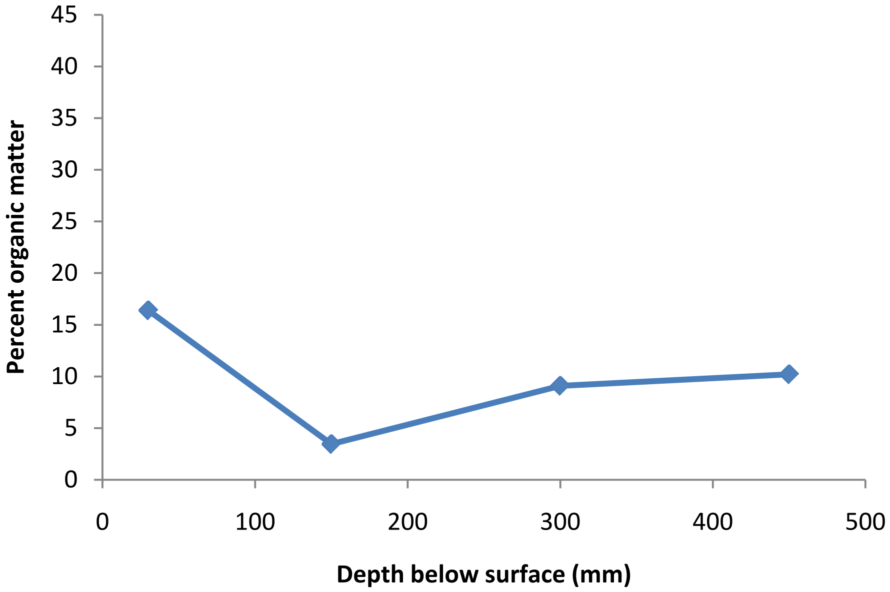


Figure 6.11. Percentage of organic matter at each sample depth for the Shearer Swamp core.

6.3 Interpretation and discussion

The purpose of this section is to provide an interpretation of the sedimentological results presented above, and to present an overview of changes occurring at these core sites over the time period covered by the cores. Comparisons are made between the two ends of Totara Lagoon, and between Totara Lagoon and Shearer Swamp.

6.3.1 Totara Lagoon

Cores were taken from two sites in Totara Lagoon, at either end of the system. Totara North was dominated by sand, whereas Totara South was predominantly comprised of mud, suggesting two very different process regimes. These cores provide a snapshot of changing conditions at these specific sites; they are not intended to be extrapolated to a complete developmental history of Totara Lagoon.

The area at the Totara South core site east of the main channel was dry and covered in tussock vegetation. The nature of the cores extracted from Totara South suggests the area has remained in a similar state for a long period. The majority of the core consists of brown mud, virtually indistinguishable from the modern surface soil. The level of organic matter decreases slightly in the bottom half of the mud unit, indicating that vegetation was not as well developed here at this time. This area is not marginal wetland, and only experiences water cover during large floods. No evidence to the contrary exists for the majority of this core.

In contrast to stable, dry environment interpreted from the deep mud layer, the poorly sorted, coarse sand and gravel layer below it signifies a much higher energy environment. From aerial photographs, the position of this core site within an old, abandoned lagoon channel is evident, a fact which is not apparent at ground level. Consequently, this layer can be interpreted as a mid-channel lagoonal deposit, consistent with the energy levels and patterns exhibited by the current major channel at this end of Totara Lagoon. The gradational nature of the contact between this layer and the mud above it is further evidence of this scenario. The larger grained gravel and coarse sand progressively gives way to medium grained sand, pockets of which are intruded into the mud layer above. This pattern can be explained by the abandonment and gradual drying out of this channel, which probably occurred relatively rapidly, followed by the establishment of vegetation and deposition of the mud layer. Flood events and aeolian transport were likely to have also been significant during this transitional phase.

The stratigraphic changes in the Totara North core are much less dramatic, but with more inherent grain size variability throughout the core. The stratigraphy of most of the core is sand-dominated, which is unsurprising as the narrow lagoon channel is constrained by well-developed dunes on both sides. The sand throughout this core is marine in origin and deposited by aeolian transport, as the mineral composition clearly matches that of the adjacent dune ridges. The changes in colour observed in these different sand units are likely to be related to changes in the chemistry of the lagoon waterbody and margins. The bottom half of the core is very low in organics and is almost exclusively sand, suggesting that this point was not underwater or a marginal lagoon zone at this time. This can be explained by two scenarios; either the lagoon did not stretch as far as it currently does, or that this area was part of a sand bar on the fringe of the lagoon (similar to those observed in the northern reaches today) and thus unvegetated.

The overlying muddy sand layer can be interpreted as a definitive increase in lagoon influence. The sand within this layer would still have been wind-blown from nearby dunes, but the mud indicates that this area was now at the margin of a low-energy water body. The increase in organic content is likely to be a result of developing marginal vegetation. This unit underlies the modern surface sediment, which is extremely organic-rich. This is a result of decaying swamp surface vegetation and the high biological productivity of the lagoon water column, as the site is currently situated at the water edge and is frequently submerged.

6.3.2 Shearer Swamp

A progressive change in energy levels and exposure is evident from the Shearer Swamp core. Results from this site are not indicative of conditions over the entire swamp, but provide a snapshot of changes occurring at the swamp margin, which is the most dynamic area of the swamp, and the point of greatest interest to this study.

The basal unit of this core, comprised of interleaved peat and sand layers, is likely a result of a wetland environment subject to significant aeolian sand deposition from nearby dunes. This suggests the wetland was already developed and the margin situated at approximately this point for the duration of the time period covered by this core. The interpretation of the sand as wind-deposited is due to the close proximity of the relic dune ridges, and the fact that there are high-organic peat layers interleaved with the sand. This suggests that there was vegetation present on the surface of the sediment at the time of deposition, and peat would not have been able to accumulate had the sand layer been a result of marine or fluvial processes. The adjacent dune ridges are currently farmed, thus covered with grass and other vegetation, but it is likely that they were less well vegetated at the time this layer was deposited.

Above the previous unit lies a layer of pure peat. This represents a low-energy wetland deposit, unaffected by aeolian sand transport or fluvial influence. This is likely a result of the stabilisation, or slight migration, of the swamp margin, combined with stabilisation of the adjacent dune ridges. The conversion of the relic dune ridges into farmland would have substantially reduced the volume of windblown sand, and this combined with the further growth of swamp vegetation would have allowed this peat deposit to form.

The massive, low-organic silt layer is indicative of an increase in energy conditions at this site, following the deposition of the peat layer below it. This silt is of fluvial origin, and the current proximity of Waikoriri Creek to the coring site suggests that the creek may have flowed over this area at the time of the silt deposition. The consistent, fine grain size implies a fluvial environment such as this creek is currently, with relatively low but constant flow velocities. The low organic content of this unit indicates a low degree of biological productivity in the water column at the time.

The preceding unit is overlain by the modern surface soil, which is an organic-rich mud. The creek had migrated eastwards of this point following the deposition of the underlying silt layer, and swamp vegetation and grasses have grown on the surface. Decay of this vegetation has led to the organic-rich nature of this layer, which is typical of swamp deposits. The mud is likely to have been emplaced during flood events, when water pools on the swamp surface and suspended sediment settles out.

6.3.3 Limitations and errors

The primary limitation of the coring investigations within this project is spatial scale. Ideally, several cores from each system would have been taken at different locations, and then they would have been correlated to show an overall picture of change for the entire system. Due to equipment and access constraints, only a snapshot of change at a few isolated sites could be investigated. The numerical errors (discussed in Chapter 3) that arose from coring technique and sediment character are negligible in terms of describing the broad changes in depositional environment evident in these cores, and have been disregarded in this chapter.

The use of the Loss on Ignition (LOI) technique to measure the amount of organic carbon in a sediment sample has been the subject of much debate, and many researchers consider it to be so fraught with error that results are unreliable (Doyle and Garrels, 1985; Sutherland, 1998). As a result, interpretations presented here from LOI results should be treated with caution and do not aim to provide absolute quantitative measures of total organic content in the sediment samples. These results have instead been used as a loose proxy for vegetation cover and/or water column productivity, in order to make comparisons between sediment units and infer the local environment at the time of deposition. The tendency for LOI to produce incomparable results between samples of differing grain size is acknowledged (Sutherland, 1998), but is likely to be of little consequence in this context of interpretation.

6.4 Summary

This chapter presented the results of sediment core stratigraphy and sediment analyses from two sites at Totara Lagoon, and one site at the western margin of Shearer Swamp. The aim of these analyses was to investigate the changes in depositional environment at these sites over historical timeframes (in isolation from one another) and examine the relationship between these changes and current system dynamics.

The Totara South site exhibited a dramatic transition from a very poorly sorted, coarse grained sand and gravel layer at the very bottom of the core, to a massive consistent mud unit for the remainder. This represented the abandonment and gradual drying out of a large channel, followed by the stabilisation and vegetation of the area.

The core recovered from Totara North was dominated by wind-blown sand, transported from the adjacent dunes. The lower half of the core consisted of medium grained sand units, shifting to a muddy sand layer and organic soil above, and increasing in organic content upcore. This represents a shift from open, unvegetated sand bar type conditions, to a greater degree of lagoon influence at this specific location.

The core site at Shearer Swamp has undergone a series of changes in depositional conditions, while maintaining a position at the swamp margin for the entirety of the time period represented by the core. A medium grained sand unit, resulting from aeolian transport of sand from nearby dunes, gives way to a unit of highly-organic peat, which represents a shift to wetland conditions. A unit of massive, low-organic silt overlies this, suggesting Waikoriri Creek ran over this site for a time, before the transition to the current muddy, well vegetated surface soil typical of wetland systems.

CHAPTER SEVEN

Integrated Discussion and Management Implications

7.1 Introduction

The previous three chapters presented the results of this research, first documenting the current geomorphology and hydrology of the study systems, followed by their development over timeframes of decades to centuries. Each of these chapters possesses an interpretation and related discussion of the chapter findings presented, and this information will not be reproduced here. The purpose of this chapter is to bring together these results; providing a complete picture of the development of the coastal plain shared by Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex, and discussing the morphology of these coastal systems in the context of national and international research. Potential response of these systems to differing future pressures is examined in a conceptual manner, and the management implications of this are discussed.

Firstly, an integrated discussion of the results of this investigation is presented in section 7.2, highlighting the similarities and differences between Totara and Waikoriri Lagoons. The definitions and classification schemes pertaining to coastal lagoons and estuaries are discussed in section 7.3, and the systems researched here are placed in this context. Existing models of hapua dynamics developed in relation to East Coast systems are evaluated in terms of applicability to the more sandy West Coast systems in Section 7.4, and the importance of considering barrier permeability is highlighted. Section 7.5 discusses the past development of these systems in the context of morphodynamic theory and seeks to predict the response of these systems over the next century under differing climatic factors and management pressures. A conceptual model depicts the response of a sandy hapua-type system to differences in forcing factors, including differing management regimes.

This chapter addresses following research objectives:

- to understand these West Coast systems in the context of existing morphodynamic classification schemes,
- to analyse the processes driving changes in geomorphology within the study systems,
- to explore factors likely to influence their development over the next 100 years,
- to develop a model to predict their response to differences in these forcing factors, and
- to apply this model in the context of management of hapua type systems.

7.2 Comparison of Totara Lagoon and Waikoriri Lagoon

The results of this investigation have been previously interpreted in detail and discussed in isolation within each chapter, and will not be repeated here. This section will discuss the implications of these results as a whole, and briefly compare Totara Lagoon and Waikoriri Lagoon over the entire time period covered by the preceding three chapters. The study of processes on varying timescales is very important from a morphodynamic perspective, due to the complex nature of feedback loops that exist between processes on a variety of spatial and temporal scales.

The primary observation of results from all timescales is the importance of spatial scale in determining system response time. From both aerial photograph results on a decadal scale and field observations on a monthly to weekly scale, the difference in temporal dynamics between the two systems is glaringly apparent. Outlet position was more variable, and a greater degree of morphological change was observed in Waikoriri Lagoon than in Totara Lagoon. The same pattern of hapua outlet dynamics occurred in both systems, but it occurred much faster in Waikoriri Lagoon.

From the combination of all results gathered, Totara Lagoon can be described as a very large, stable rivermouth lagoon system that exhibits large scale morphological change on a decadal scale, and experiences smaller, spatially restricted changes in morphology on scales of days to months. Large scale morphological changes take the form of changes in outlet position, channel structure and water cover, whereas the majority of small scale change is centred at the outlet position. The morphological structure of the lagoon is relatively constant, but hydrologically, the lagoon switches between an estuarine phase (experiencing tidal inflows) and a hapua-like, freshwater phase. This conclusion was reached from a combination of topographic surveys of dune morphology, field and aerial photograph observations of spatial trends in vegetation development, sediment core analysis, and aerial photograph analysis of outlet and channel changes. There were no conflicting conclusions from individual sets of results, rather each set of results confirmed aspects of other sets, and results built upon each other to provide a comprehensive picture of the temporal and spatial scale of lagoon dynamics. Totara Lagoon displays a strong trend of decreasing energy with distance from the river mouth, both morphologically and hydraulically.

In contrast, Waikoriri Lagoon can be described as a very small, dynamic hapua-type lagoon system that experiences large scale morphological change on scales of months to years, and experiences small scale morphological changes on scales of hours to weeks. The patterns of morphological change are similar to Totara Lagoon, but exist on a smaller scale. Hydrologically, the two systems exhibit very different dynamics, which is a consequence of their differing size, stability and boundary conditions. In the case of Waikoriri Lagoon, coring data cannot be used to infer lagoon conditions, as the core location was in Shearer Swamp. Conditions at Waikoriri Lagoon itself were not conducive to core extraction, due to the dynamic nature of the system and position right on the beach.

The issue of defining boundary conditions of these lagoon systems is a complex matter, and the balance of factors contributing to these systems is very different between Totara Lagoon and Waikoriri Lagoon. In the case of Totara Lagoon, the lagoon itself is the most prominent feature when considering the system as a whole, including the river and catchment and adjacent swamp. On the contrary, Waikoriri Lagoon is a very small feature relative to Shearer Swamp behind, and the catchment dynamics are very different as a result of the influence of Shearer Swamp.

Despite the physical differences just highlighted, the patterns of behaviour and processes in these systems are very similar to each other and to accepted models of hapua behaviour (Kirk, 1991; Todd, 1992; Hart, 2007). However, Totara Lagoon appears to be generally more stable than a typical hapua. The differences in temporal dynamics between Totara Lagoon and Waikoriri Lagoon can be explained by the disparity in size between the two systems, as system stability and response time increases proportionally with size in systems of similar morphology. Consequently, behaviour patterns in these systems can be considered consistent with hapua dynamics in general and representative of West Coast sandy-hapua systems.

7.3 Morphodynamic classification of coastal lagoons

Terminology and classification schemes of coastal systems and landforms have been well developed and discussed in literature for over 50 years, but the definition and classification of coastal lagoon systems is still somewhat uncertain. The purpose of the present research was not to disassemble or modify existing definitions or classification schemes, but to examine them in detail to provide a context within which to understand the dynamics and processes occurring in the lagoon systems under study, and compare them with similar systems elsewhere.

The systems examined here fit adequately into the general, non-specific definitions of coastal lagoons and their sub-types, discussed in Chapter 1, that are based primarily on morphology (e.g. Phleger, 1969; Kjerfve, 1986), but uncertainties arise when hydrological parameters are introduced into the definition. The issue of tidal influence and terminology with respect to these systems is of significant importance to this study and will be discussed in the following section.

In addition to the actual physical parameters involved, the terminology used to describe coastal lagoons and estuaries varies hugely across international literature, and consequently has been the subject of much debate (Tagliapietra *et al.*, 2009). For example, ‘hapua’ is a term of solely local (New Zealand) usage, and is not used globally to describe similar systems. Therefore, the exact terminology used to describe a given system in the literature is not likely to be of primary importance to the reader. More crucial is the need to describe the dynamics and dominant processes acting on a system, in order for the reader to understand the nature of the system and classify it to themselves in the context of their local terminology.

7.3.1 The hapua-estuary continuum

The classification of coastal lagoon and estuary systems has been the subject of continued debate over recent decades. As discussed in Chapter 1, the definitions of an estuary compared with a coastal lagoon are very similar, and are not always mutually exclusive. Existing classification systems are based on the hydrology and morphology of the system, which are inherently related and interconnected on a variety of timescales, and are constantly changing as a result. Consequently, there is a large number of sub-classifications within the overarching term 'estuary' or 'coastal lagoon' and in many cases the definitions and terms overlap. In the context of this argument, these terms are discussed for the case of wave-dominated coasts and barrier-enclosed systems only, as both Totara Lagoon and Waikoriri Lagoon are of this nature.

The connectivity between these definitions and the overlap at their boundaries is particularly apparent in the case of Totara Lagoon, which has been previously classified as a hapua (Neale *et al.*, 2007, DOC, 2005). In terms of barrier structure and outlet behaviour this is an accurate classification. The environment is wave dominated, with a strong northward littoral drift, and the pattern of barrier formation, mouth offset and barrier breaching presented by Todd (1992) clearly occurs in this system. The conflicting factor in this case is the significant tidal influence that currently occurs in the system. By definition, hapua possess a true outlet, experiencing no tidal inflow or saltwater prism (Kirk, 1991; Hart, 2007), although water levels in the lagoon can be affected indirectly by a tidal backwater effect. As discussed in Chapter 5, the water level and conductivity records from Totara Lagoon clearly indicate the presence of inflows and outflows in response to tides, which suggests that, hydraulically, this system should currently be defined as an estuary rather than a hapua-type lagoon. Despite this, the structure and morphological behaviour of the system remains more closely related to that of other hapua than to systems classified as wave-dominated or river-dominated estuaries. This observation raises the question of which should be the ultimate defining factor – morphology or hydrology. This research suggests that although these terms are mutually exclusive, a waterbody can switch between the two states at different times, and in this case should be referred to as a rivermouth lagoon, followed by the qualifying term of ‘estuarine phase’ (tidal ingress occurring) or ‘hapua-phase’ (no tidal prism, i.e. freshwater).

Another question arises as to the cause of this significant tidal influence during an estuarine phase. As evidenced by aerial photograph analysis and field visits, the outlet is currently (and has remained for the past few years) situated at the river mouth, in a state of ‘primary breach’ according to the model of hapua behaviour presented by Todd (1992) and Hart (1999). Field observations suggest that if this was not artificially maintained, the barrier would grow across the outlet, causing it to migrate as in the past. The Totara River is not a large river, and the mean flow is not sufficient to naturally maintain a primary breach. As a consequence of this weak fluvial output combined with the high energy marine environment, tidal flows are able to penetrate at the mouth and propagate up the channel. It is important to note, however, that the evidence of a substantial tidal prism in Totara Lagoon was collected over a single week, thus may not be representative of conditions over a longer timeframe. At the time of these observations, the mouth was very open to wave exposure, and no sediment wedge had built across it. Several months later the channel was still in essentially the same position, but it was narrower and oriented diagonally through the barrier, as a large sediment wedge had accreted across the mouth. It is likely that at this time, there would have been significantly less tidal intrusion into the main lagoon channel.

The position of the outlet at the river mouth likely contributed significantly to the ability of the tide to penetrate into the lagoon. The channel at the point where the river, lagoon and sea met was very deep and was subject to scour from current activity, meaning the channel bed elevation was not above sea level. In addition, the direction of wave approach versus the orientation of the lagoon outlet is important. At the river mouth, wave approach is predominantly southwest and at an oblique angle to the outlet, oriented almost directly into the lagoon entrance at this point, which enhances saltwater influx. Aerial photograph evidence shows the when the outlet was offset, it was almost exclusively orientated diagonally northwards, so waves did not directly approach the outlet frequently. In addition, the outlet channel would likely have been subject to less scour and thus less subject to tidal intrusion.

In reality, the concepts of hapua and wave-dominated estuaries or lagoons are closely related, and both respond to fluvial input, marine climate and sediment supply. The morphology and hydrology which is exhibited by any river mouth system is a function of the balance between these three factors, and a change in any one of them can affect this balance and cause the system to effectively change state. The observations described above support the idea that river mouth behaviour is a three dimensional continuum (Hart, 2007), and that although hapua are essentially freshwater lagoon systems in most cases, they can be subject to tidal influence in response to a change in conditions. The point at which a system should no longer be termed a hapua has not been specifically defined, and if adhering strictly to terminology used in previous research, any degree of regular tidal intrusion within such a system excludes it (Hart, 1999; Kirk and Lauder, 2000, Hart, 2007). A paradox lies in the fact that although a system like Totara Lagoon can be experiencing a significant tidal influence (potentially described as an estuarine phase), the system remains wave-dominated rather than tidally-dominated, thus fitting neither the strictest definition of a hapua nor that of a true estuary.

Not all definitions of estuary focus on tides; many focus on dilution of seawater by freshwater derived from rivers/land drainage. The various classification schemes of estuaries and lagoons from international literature were examined in Chapter 1, and one of particular relevance to this study is that of Hume and Herdendorf (1988). This is a detailed scheme pertaining to all types of coastal landforms, in which coastal lagoons are classified as part of the overarching estuary section. The systems here fit into this classification as ‘river mouth estuaries’, which are further subdivided into three types, two of which are spit-lagoons. The difference between these two types of spit lagoons is tidal influence. A Type 9 spit-lagoon occurs on sandy coasts and experiences a tidal influence, while Type 10 is a hapua-type lagoon with a coarser grained barrier and no tidal prism. The systems studied here possess characteristics of both these types, and Totara Lagoon demonstrates the transition back and forth between them, while still ultimately maintaining the title ‘spit-lagoon’, which is an accurate description of morphology and process dynamics.

Kirk (1991) disagrees with this classification of hapua as a form of estuary, with particular reference to Hume and Herdendorf (1988), as a common factor to all definitions of an estuary is the requirement for seawater to be present in the system; a factor which is clearly absent in a hapua-type lagoon. This research suggests that rather than treating hapua-type lagoons as a type of estuary, they should be placed on a continuum with estuaries, included in an overarching classification of coastal lagoons. However, it is important to note that although all hapua are coastal lagoons, not all estuaries can be classified as coastal lagoons. Within such a scheme, there is greater provision for a systems such as Totara Lagoon and the Ashley River mouth (Kirk and Lauder, 2000), which function in the transition zone between an estuary and a hapua and exhibit characteristics of both. This makes the connection between estuaries and hapua, while recognising that one system can switch between the two hydrological states while maintaining the same basic morphological structure.

The classification of rivermouth lagoons within an overarching estuarine classification scheme has also occurred internationally. The depiction of a river-dominated estuary by Cooper (2001) in South African systems, and that of a barrier lagoon by Roy et al (2001) for Australian rivermouth environments, both describe systems that are morphologically similar to hapua. In many ways, these definitions share more commonalities with the West Coast systems, as they are based on empirical evidence from a variety of barrier types, rather than being restricted to coarse barrier systems.

7.4 Conceptual models of hapua dynamics

Early models of hapua dynamics focus on river volume and flow patterns as the primary driving force of hapua behaviour (e.g. Kirk, 1991; Todd, 1992). The importance of wave energy in affecting barrier morphology and thus hapua dynamics has been well documented in subsequent research (Hart, 1999, 2007). The two hapua systems studied here represent two extremes of spatial scale, yet are by and large representative of the morphology of hapua-type systems across the West Coast. These can be considered functionally the same in terms of long term morphology and behaviour within this theoretical discussion, and will no longer be discussed as separate systems in this section but referred to in the plural.

7.4.1 Comparisons with East Coast hapua

National research surrounding hapua dynamics has centred on the East Coast of the South Island, where hapua-type systems have developed under similar conditions to those on the West Coast, but with some important differences. Both coasts experience a high energy wave environment and strong littoral drift, but East Coast hapua are restricted to beaches of mixed sand and gravel composition, and form in rivers of higher flow rates than those in Westland. One further difference between the East Coast environment compared to the West Coast is tidal regime. The tidal range on the East Coast is microtidal, with tidal ranges of between 1 and 2 m, while the West Coast experiences a mesotidal regime, with variations of between 2 and 4 m (NIWA). The region under study here experiences the lower end of the mesotidal zone, with variations of just over 2 m. The difference in tidal regime between the East and West Coasts is not dramatic, but the combination of a low river flow, exposed outlet/river mouth, and a slightly larger tidal influence could explain the significant degree of tidal influence observed in Totara Lagoon.

The findings of this research are generally in agreement with existing models of hapua behaviour patterns in response to changes in river flow, but the details of these models are often very different to the observations of West Coast systems. On the surface, the patterns of outlet migration and natural breaching observed in these systems appear to correlate well with the models of Todd (1992), Kirk (1991) and Hart (1999), as presented in Chapter 1. However, despite appearances, the set of conditions that gives rise to the accepted behaviour patterns in these sandy hapua can be very different to those predicted by these models. This is due to their basis in observations of East Coast hapua, which possess coarser, mixed sand and gravel barriers.

The importance of wave processes in hapua behaviour is a key point presented by Hart (2007), and this is also true of West Coast conditions. Field observations throughout this investigation suggest that the model presented by Hart (1999) can be applied to the sandy barriers of West Coast systems also, although the numerical values of low, moderate and high river flow are very much lower. Not all coarse-barrier systems exhibit every type of behaviour, and the same is true for sandy West Coast systems

In terms of system boundaries, there are significant differences in the land adjacent to the lagoon systems between coasts. West Coast systems are generally more complex and connected to adjacent land via wetland systems, whereas East Coast systems often currently have no connecting wetlands. These wetlands serve several functions in West Coast systems; draining into the lagoon from multiple locations, and acting as a buffer zone for water and sediment storage between the catchment and the lagoon system. Without these wetlands attached, the behaviour of East Coast systems in response to catchment dynamics is almost entirely river-dependent. It is important to note, however, that most East Coast hapua once did have connecting wetlands, but these have been progressively drained and cleared for land development.

A clear difference observed between East Coast and West Coast systems is the direction of outlet migration. In both cases, the net littoral drift is northwards, but on the East Coast the outlet position will sometimes migrate south of the river mouth (Kirk, 1991). This was not observed in West Coast systems even once during the 59 year aerial photograph record.

Flood duration in West Coast rivers is much shorter than in those on the East Coast, due to the narrow coastal plain and steep terrain behind. Periods of high river flow and sediment discharge last in the order of hours to a few days, and as a result, intense flood related pressure on lagoon outlet morphology is not sustained for long periods, and the system regains an equilibrium state in a much shorter time than on the East Coast. This difference is further increased by the disparity in feeder river sizes between typical systems on the two coasts. The actual volume of sediment delivered to a lagoon by larger, East Coast rivers during a flood can be far greater than the small, West Coast lagoon-feeding rivers.

As presented in Chapter 1, Figures 1.2 and 1.4, Kirk (1991) discussed hapua behaviour in terms of a sediment budget and variations in river flow. One important point in this paper that somewhat contrasts with West Coast observations is the assumption that nourishment of the barrier occurs largely via sediment discharge from the primary river feeding the lagoon. This is certainly true of coarse barriers, as coarse sediment cannot be transported far from the source by way of littoral drift, but is less true of sandy hapua. West Coast hapua form at the end of rivers that can be considered small, both in terms of flow volume and sediment load. Most of the material that forms the barriers of these hapua is sand that has been transported by littoral drift from larger rivers further along the coast, or reworked from the long expanse of beach sediment.

7.4.2 The issue of barrier permeability

As previously discussed, the behaviour of the West Coast systems investigated here correlates relatively well with existing East Coast models of behaviour patterns and outlet migration, but the relationship between river flow and hapua formation and outlet maintenance thresholds are very different between the two coasts. This disparity in threshold levels can be attributed to differences in barrier permeability and stability, both of which dramatically affect outlet dynamics. Barrier permeability determines the degree of percolation through the barrier and thus the ease of which lagoon water level rises sufficiently high to breach the barrier (Todd, 1992). Permeability is a function of grain size and degree of sorting; the coarser the material and the better the level of sorting, the more permeable the barrier (Todd, 1992). Consequently, the coarse and poorly sorted nature of East Coast mixed sand and gravel barriers means they are much more permeable than the sandy barriers of West Coast hapua.

As a result of the sandy and less permeable nature of the West Coast barriers, hapua are able to sustain permanent outlets at the mouths of much smaller rivers than their East Coast counterparts, and maintain a similar pattern of outlet migration and breaching despite some very small fluvial inflows. In addition, the sandy nature of West Coast barriers renders them more stable and conducive to vegetation growth than the coarser East Coast beaches, which are often bare or scantily vegetated with marram grass. As discussed in Chapters 5 and 6, vegetation cover has a further stabilising effect on outlet migration, as it is less likely for a breach to occur in a heavily vegetated section of the barrier.

Barrier permeability has been acknowledged in previous literature as a very important determinant in river mouth functioning (Kirk, 1991; Todd, 1992; Hart, 1999, 2007), but barrier composition (mixed sand and gravel versus predominantly sand) has not been investigated in the context of hapua formation and dynamics. As research has been centred on East Coast systems of similar barrier composition, mixed sand and gravel type barriers have been considered the norm for hapua type systems. One exception to this standard morphology in East Coast systems is the Hurunui river mouth, which is of intermediate grain size and permeability (i.e. between the mixed sand and gravel nature of most East Coast barriers and the sandy West Coast barriers) (Smith, 1995). Kirk (1991) also pointed out that a large volume of silt and fine sand is transported downriver, in this case the Rakaia River, which can substantially reduce the permeability of these essentially coarse grained barriers.

Another consequence of high barrier permeability is that high rates of throughflow between the lagoon and the barrier can result in a tendency to easily breach the barrier when water levels in the river and lagoon rise (Kirk, 1991). This leads to instability in the barrier and frequent outlet migration, as observed in East Coast examples (e.g. Rakaia, Opihi). In contrast, the sandy and stable nature of the West Coast barriers promotes less variable outlet migration. This supports the suggestion put forward in Chapter 6 that the outlets of West Coast hapua may skip between old abandoned outlet channels more frequently than they exhibit a steadily migrating pattern or forge new breaches.

A significant finding that emerged from this present research is that hapua-type lagoons can form in very different environments to those found on the East Coast. The very existence of these systems on the West Coast, and Waikoriri Lagoon in particular, demonstrates the wide spectrum of conditions under which hapua can form. The existence of these low-river-flow systems demonstrates that the absolute flow volume and velocity, and the type of sediment transported by the river are not of primary importance; rather it is the balance of these two factors with the nature of the barrier that is paramount. Several key parameters remain necessary for the formation of a hapua-type system over other river mouth systems such as deltas or estuaries, which are: a high energy, wave dominated environment, and strong longshore drift and sediment transport. These conditions are necessary for the formation and maintenance of a barrier behind which the lagoon waterbody can form, and are responsible for the pattern of outlet migration central to the formative mechanism and behaviour of hapua. These coastal marine conditions are common to both coasts of New Zealand’s South Island. A schematic diagram illustrating the variety of conditions under which New Zealand hapua have formed is presented in Figure 7.1.

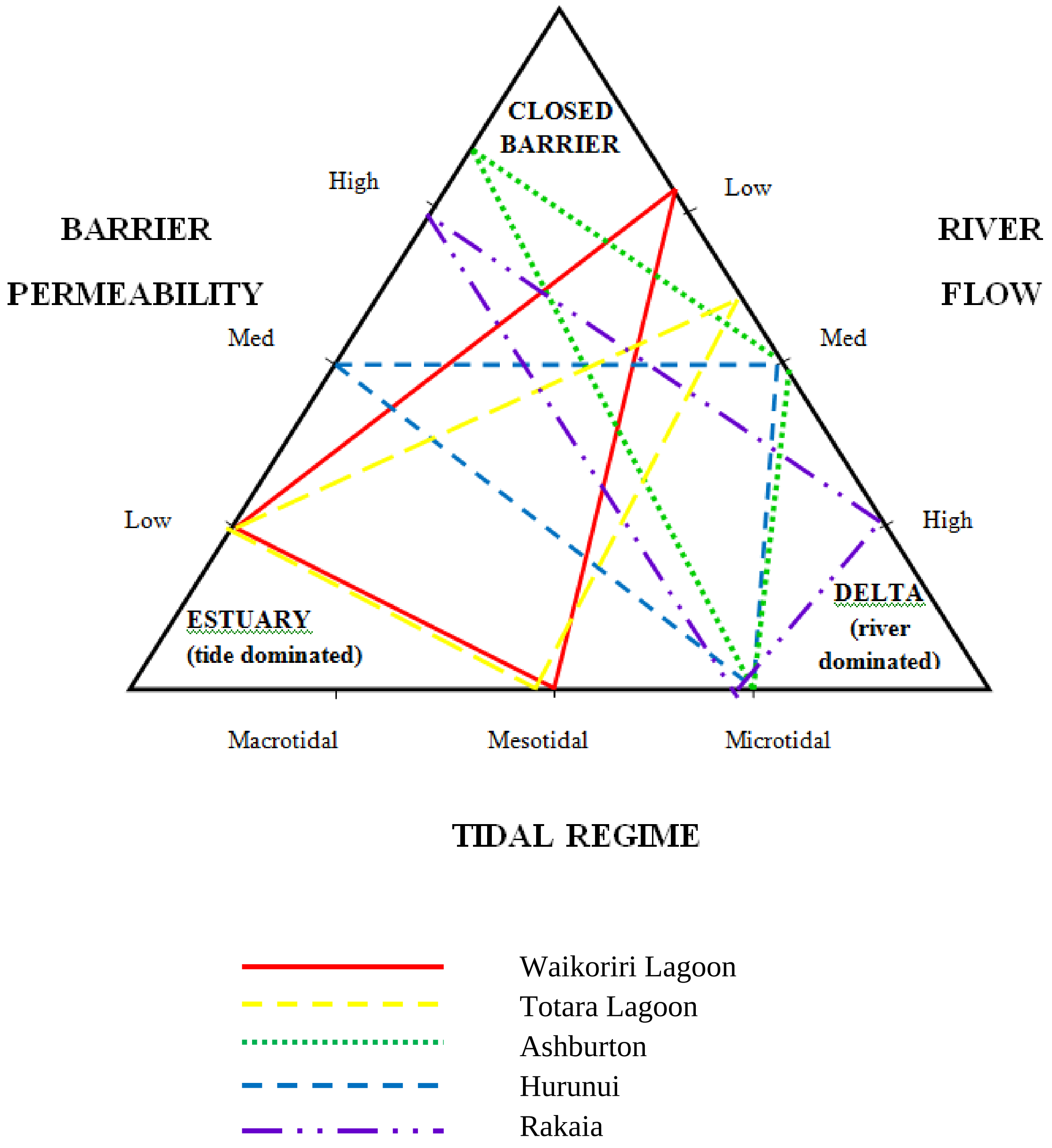


Figure 7.1. Schematic representation of the relationship between barrier permeability, mean river flow and tidal regime in selected South Island hapua. Ashburton, Hurunui and Rakaia Rivers are East Coast, mixed sand and gravel systems.

7.5 Morphodynamic development in Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex

Coastal lagoons are complex, dynamic systems that respond to a large number of driving factors which interact with each other on a variety of timescales. The multidisciplinary approach used in this study is based on the theory of morphodynamics, discussed in Chapter 1, which is defined by Wright and Thom (1977, p. 412) as *“the mutual adjustment of topography and fluid dynamics involving sediment transport”*. This is the fundamental framework behind coastal evolution, stating that the developmental path taken by a landform is a function of antecedent morphology, hydrology and sediment supply.

The nature of hapua and the way in which they develop are a function of past geomorphology and processes within an area, by the principle of Markovian Inheritance (Cowell and Thom, 1994), as discussed in Chapter 1. The focus of this research is on the short term development and changes within these two systems and in those that are similar as a whole. However, to understand the development of these systems on a decadal to centennial scale, and make confident predictions of future response to changes in driving factors, the long term coastal development of the area must be considered.

7.5.1 Long term development of the study area

Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex share the same coastal plain, which developed over the late Holocene, following the sea level highstand approximately 6000 years ago. The presence of a marine-cut cliff in the Loopline terminal moraine, extending behind Totara Lagoon and along past the Mikonui River (at the north end of the Shearer Swamp-Waikoriri Lagoon Complex), indicates that this was the position of the coastline at this highstand, with several embayments existing between cliffed areas. Therefore, the age of all surface landforms between this cliff and the current coastline can be inferred to be less than 6000 years.

At the point of highest sea level, the area that is now Shearer Swamp would have been a coastal embayment, constrained on three sides by hills. Following sea level fall (and potentially compounded by tectonic uplift), the area would have become an estuary. During this period, the large amount of sediment transported from the nearby mountains would have led to coastal progradation, which further enhanced the evolutionary process initiated by falling sea level. It is likely that at this time the system was still essentially wave-dominated, as the orientation of the coast to westerly systems was the same as present. This argument is supported by the presence of the series of relic dune ridges at the western margin of Shearer Swamp. These would have been the result of the combination of a heavy sediment load to the coast and high wave energy creating a barrier, similar to the processes occurring today. Behind the most landward of these dune ridges, it is likely that the system underwent a progression from an open estuarine system to a lagoon system, becoming increasingly closed to the ocean as relative sea level fell and the coast prograded. These relic dune ridges are composed of sand of a similar nature to the current active dune ridge, suggesting that processes very similar to the current conditions were operating. Assuming offshore circulation patterns and thus direction of littoral drift were similar to present, there is a distinct possibility that a hapua may have formed, drained or infilled, and reformed between these disused barriers several times during this period of coastal evolution. The transformation of the area into swampland was likely to be very recent in terms of geological time, as it would not have occurred until the area became completely cut off from marine influence behind the inactive dune ridges.

This progression from open coastal embayment to freshwater wetland also represents a change in energy levels within the system. Currently, no large waterways discharge into Shearer Swamp; the Mikonui River flows just northwards of the swamp boundary, and the Waitaha River flows south of Bold Head. These rivers could have avulsed substantially over the late Holocene, which could also help account for the ultimate development Shearer Swamp.

The evolutionary succession presented here is based on the developmental sequence posited by Roy *et al.* (1994) for the development of coastal lagoons and estuaries on wave-dominated coasts in response to marine regression. This succession has been confirmed for several similar systems in New Zealand (Hicks and Nichol, 2007; Horrocks *et al.*, 2000). Many questions remain surrounding the exact developmental sequence of Shearer Swamp, which would require a substantial amount of further research to clarify.

A similar developmental succession likely occurred further up the coast behind the current location of Totara Lagoon. The marine cut cliff extends most of the length of the lagoon, in front of which was swampland similar to that of Shearer Swamp, present during historical times. Once again, rows of inactive dune ridges extend approximately 100 m inland from the current coastline. These dune ridges, and those of Shearer Swamp, are generally parallel to each other and to the current coastline, indicating that this section of coastline remained relatively straight for most of the Holocene development.

An exception to this trend of parallel dune ridge development occurs at the northern extremity of Totara Lagoon and for several hundred metres beyond. Here, the dune ridges are oriented towards the current coastline, at an angle of approximately 30° from the standard direction of the dunes and the marine cut cliff. These ridges pinch out when they meet the current active dune ridge approximately 100 m north of the lagoon extremity. This change in dune orientation, and thus coastline configuration, would have resulted from changing sediment supply and wave approach dynamics along this stretch of coastline. The vast majority of sediment that reaches the system currently is injected via the Totara River and Mikonui River, and transported north via littoral drift. This pattern is unlikely to have changed in recent geological time, as the driving oceanic circulation patterns are driven by seabed topography (Stanton, 1976; Bradford, 1983), which remains essentially unchanged over this timeframe.

One potential mechanism for this change is the idea of a ‘hinge point’ around which this section of coast has rotated during progradation (Dr. Jim Hansom, University of Glasgow, 20th March 2009. *pers. comm.).* The growth of the central area of Totara Lagoon (and tendency for the lagoon to discharge here) could have acted as a sediment trap for sediment brought northwards by littoral drift. As a result, the stretch of coastline northwards of this area would have received comparatively less sediment, and wave approach direction would also be affected as a result of the coastline curvature.

7.5.2 **Potential response under changing climate and management scenarios**

As such dynamic systems controlled by a complex network of interacting factors, the response of these hapua to changes in climate conditions, catchment dynamics and management pressures is difficult to predict. Ultimately, it is the balance between these multidirectional pressures that determines the morphological and hydrological state of the system and determines what, if any, transformations will take place. The anthropogenic factors that have influenced these systems historically were discussed in Chapter 3.

A flowchart of process and response is presented in Figure 7.3, which illustrates the hierarchy and interaction between factors likely to influence these systems over the next century. Three possibilities of lagoon state are presented: lagoon loss (i.e. no lagoon present), natural lagoon, or artificially modified lagoon. It is important to note that these are very broad descriptions only, and there are many possible morphological and hydrological states within each of these categories.

Climate change and coastal lagoons

The effect of climate change on coastal systems is of particular concern internationally, operating through sea level rise and changes in weather patterns. The ultimate change in coastal morphology that results from these factors depends on how changes are managed once they occur.

Sea level rise alone leads to a long term erosional trend at the affected coastline, provided this is not counterbalanced by increased sediment supply (Pethick, 2001). This is already a chronic problem along much of the Westland coast (Neale *et al.*, 2007; Ishikawa, 2008), although a few small sections have been recently accreting. Climate change is expected to result in an increase in frequency and intensity of westerly weather systems in the Westland region (MfE, 2008a). A consequence of this increase in weather intensity is that more sediment will be transported to the coast from the upper catchment. However, this will not be distributed evenly along the coastline, further adding to spatial disparities in erosion and accretion trends.

As stated by morphodynamic theory, the actual response of the system depends on the balance and direction of feedback operating between antecedent topography, sediment supply, and fluid dynamics, including sea level and fluvial processes (Cowell and Thom, 1994). This is of primary importance in the future development of these systems, as the predicted response of climate change on the West Coast is to affect both sea level and sediment supply. The importance of investigating both these controlling factors when considering long term changes in barrier morphology is highlighted by Orford and Carter (1995) and Carter (1989).

Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex are highly likely to be affected by sea level rise and erosion of the seaward barrier over the next century. In a natural, unconstrained lagoon system, this would result in rollback of the barrier and landward migration of the entire hapua system, while maintaining essentially the same morphological form (Pethick, 2001). There is evidence of this already occurring in the southern half of Totara Lagoon, with a low, wide seaward barrier and heavily eroded farmland on the landward margin of the lagoon channel (Figure 7.2). This pattern of morphological change is currently restricted to the southern reaches of Totara Lagoon, which is unsurprising as it is the most active section of the lagoon and thus has a faster response time. As discussed in earlier chapters, the central reaches of Totara Lagoon exhibit a large degree of variation in channel utilisation, which would likely absorb any such changes occurring in this section of the lagoon and prevent large scale changes at the landward margin. In addition, the landward margin of the central reaches is wetland, which is much more able to deal with such dynamic changes than the rigid, eroding farmland in the south. The northern section of the lagoon will respond last to any large scale changes in morphology in the southern and central reaches. Both seaward and landward barriers are much more stable here, and are unlikely to change significantly over the next century. Sea level rise and increased storminess will likely be manifested in increased wave overtopping and dune blowouts along the entire system, including in the northern reaches.

Interestingly, the aerial photograph and coring results show evidence of a *seaward* migration of the southern end of Totara Lagoon in relatively recent history (sometime prior to 1948). This was interpreted as a response to land use change, but the morphological imprint of these old channels could be very important antecedent conditions for future development and migration of the southern end of the lagoon and the mouth of the Totara River.

Figure 7.2. Photograph showing the eroding landward margin of Totara Lagoon at the southern end of the system. This is representative of conditions along the first 2 km of the lagoon channel.

Hydrologically, the Totara lagoon waterbody could become increasingly influenced by marine processes. In the absence of an increase in sediment supply to counterbalance sea level rise, there will be increased incidence of wave overtopping of the barrier and marine incursion at the outlet, increasing the salinity of the lagoon waterbody. In addition, percolation of water through the barrier is a function of hydraulic head between the lagoon and the ocean (Todd, 1992), which will be lessened if sea levels rise. This would result in increased water levels within the lagoon, although this would be less pronounced in sandy West Coast systems compared with East Coast systems, which experience a much greater degree of throughflow.

This process of landward lagoon migration is not currently occurring at Waikoriri Lagoon, and changes in outlet morphology and sediment supply are currently the dominant drivers of change in this system. These factors are anthropogenic in origin, and will be discussed in the following section. The effect of climate change on Shearer Swamp in the geological short term (timescale of decades to centuries) will be relatively small. Sea level rise will not affect the swamp itself in terms of saltwater intrusion, as the western margin is situated 200 m from the coast, behind Waikoriri Lagoon and a set of old dune ridges. However, it could affect it indirectly through alteration of the level and character of the water table. Moreover, the effect of increased weather intensity would take the form of increased water storage and sedimentation rates in the swamp, thus a faster rate of infilling.

The landward margins of Totara Lagoon and Waikoriri Lagoon are not currently heavily constrained by infrastructure or engineering works. Although the land is farmed, the future development of the lagoon depends on the management regime. Natural processes could be allowed to prevail, resulting in the sequence of changes presented above. The interaction of these processes with anthropogenic forcing factors is discussed below, along with the consequences of differing management responses.

Management response

The management response to observed morphological change is central to the preservation or degradation of these lagoon systems under continuing pressure from external factors. Existing coastal management schemes are often spatially and temporally restrictive, often constrained to short term solutions (less than 50 years) and pertaining only to a narrow part of the coastal zone, rather than taking a holistic view that includes marine factors and catchment dynamics. The findings of this research support the idea of an integrated coastal and catchment management plan, an idea which is raised by Hart (2009).

Aside from the general concerns of overarching management programmes, the immediate physical response to the events discussed in the previous section is of major importance to the future of these lagoon systems. In the case of barrier rollback and lagoon migration, there are several measures that can be taken. The most natural of these is the concept of ‘managed retreat’, whereby loss of adjacent land is accepted as a consequence of coastal migration and the system is allowed to naturally migrate landwards and maintain its morphology, as the coastal energy gradient is maintained (Emmerson *et al.*, 1997; Pethick, 2001). In the case of Westland lagoons, this is the most desirable solution from the perspectives of lagoon preservation and hazard management, due to the low population density of the area, small funding base and lack of structural development along lagoon margins. The loss of adjacent land could be significant for those affected, but cheap compared to the cost of protecting that land, in terms of both dollar amount and in degradation of the lagoon environment.

Other management strategies for mitigating the effects of erosion range in extent of interference with natural processes and result in varying degrees of change in lagoon morphology. Hard structures such as rock walls and revetments have commonly been used on the West Coast to combat erosion (Kain, 2008; Ishikawa, 2008), but these are currently absent from the eroding channel in Totara Lagoon. These measures are totally impractical in this situation due to the length of affected area, financial cost and most of all because of cost to the lagoon environment. If they were to be used in such a system, the result would be eventual loss of the lagoon system, with the seaward barrier becoming eroded from both sides and unable to migrate landwards. This behaviour of morphological change and loss of the natural coastal sequence in response to hard engineering has been termed 'coastal squeeze' by Pethick (2001)(Figure 7.3). Soft measures of erosion mitigation involve the artificial redistribution of sediment (e.g. beach nourishment), but the benefit of this in such an isolated, natural and unconstrained area as Westland is not great. In addition, it is not particularly viable on the West Coast due to budgetary constraints and the large quantities of sediment and coastline involved.

Outlet management in Totara Lagoon and Waikoriri Lagoon

The artificial management of the lagoon outlet has been, and continues to be, the primary anthropogenic influence in both Totara Lagoon and Waikoriri Lagoon. The response of these systems to artificial management of the outlet position and configuration is very different, as a result of the large difference in spatial extent between the two systems. The response of the Shearer Swamp-Waikoriri Lagoon system to an artificial breach was well documented during the study period, the results of which are very useful from a management perspective.

There are varying methods and degrees of artificial outlet management, from full outlet relocation via a new breach, to management of an existing channel. The frequency and scale of any intervention is very system dependent. Evidence from the breach at Waikoriri Lagoon in November 2008 demonstrates the importance of carefully choosing the position of a new breach to accomplish the desired result with as little disruption to the hydrology and ecology of the system as possible. As previously discussed, the position of this breach at the primary breach location caused the lagoon waterbody to drain entirely, rather than merely reducing water levels in the lagoon and swamp behind to an acceptable level. This conclusion is in agreement with Vila-Concejo *et al.* (2004), who stressed the importance of impact-assessment studies prior to undertaking outlet relocation, and the need for post-relocation monitoring to determine the efficacy of the method decided upon.

From models of hapua dynamics and empirical observations, if an artificial breach becomes necessary, it should not be undertaken at the position of primary breach (i.e. directly opposite the river mouth). A breach upstream from this point and oriented on a slight diagonal through the barrier in the direction of littoral drift is likely to result in the least disturbance to the hydrological patterns and ecology of the system. The initiation of a new breach in the barrier in response to flooding or the threat of flooding of adjacent land is referred to here as ‘threshold management’ (Figure 7.3). This is usually only performed as a last resort to lower water levels, if the lagoon has failed to breach naturally, and further increases in water level are deemed to be hazardous to property and/or life. This has been the rationale behind the irregular, historical record of artificial breaches in Waikoriri Lagoon in particular.

The conditions at Totara Lagoon appear to contradict the argument against artificially maintaining a breach opposite the river mouth. As discussed in previous chapters, the outlet is currently situated at the river mouth without significant morphological effect on the system. However, the hydrological effects of this outlet position in terms of tidal dynamics have been observed. Ultimately, this further supports the idea that each system must be treated individually in terms of developing an outlet management plan.

The need for artificial management of the outlets of Totara Lagoon and Waikoriri Lagoon is likely to continue to be an issue over the next century. This research suggests that the best way to deal with this is with regular monitoring and small interventions when necessary to preserve land and infrastructure, rather than waiting for a large flood event to prompt emergency breaching measures. These ‘threshold’ breaches tend to be far more devastating for the system as a whole and for the connecting areas, as no time provision is made for system adjustment.

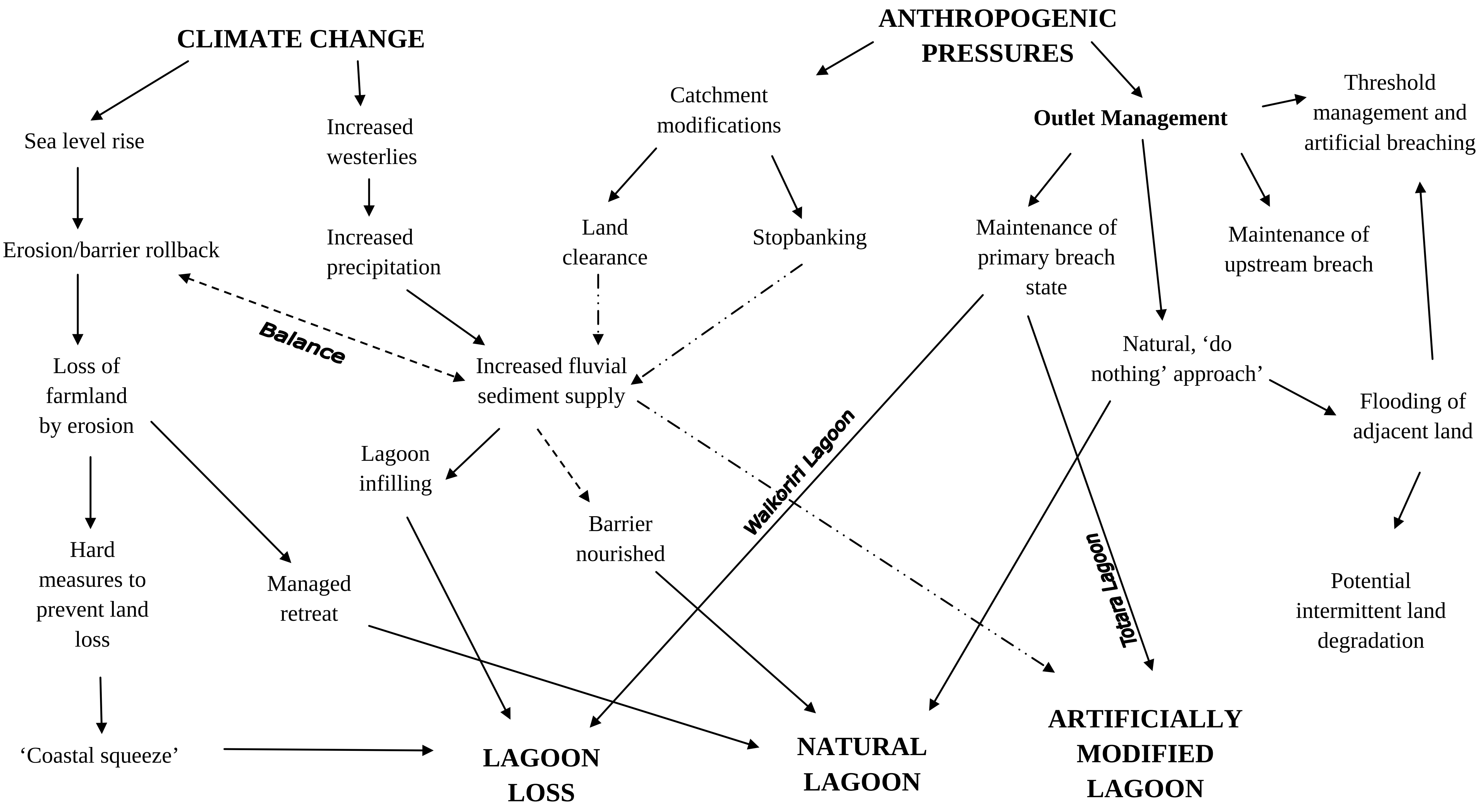


Figure 7.3. Flowchart depicting the response of a hapua to climate and anthropogenic influences.

7.6 **Summary**

The purpose of this chapter was to provide an integrated discussion of the results, presented in the previous three chapters, and to assess the characteristics of these systems relative to existing models of hapua dynamics. The development of Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex was discussed, and the future development of these lagoons in response to changes in physical factors and management pressures was examined from a morphological perspective.

In the context of system dynamics, Totara Lagoon and Waikoriri Lagoon differ greatly in terms of spatial scale and response time, yet the patterns of outlet migration and barrier dynamics they exhibit appear consistent with existing models of hapua dynamics. Hydrologically, only Waikoriri Lagoon can be classified as a hapua, as the tidal inflows observed in Totara Lagoon exclude it by definition. Instead, Totara Lagoon appears to be in an estuarine phase. This is evidence of the continuum between hapua and estuaries, with systems such as Totara Lagoon functioning in the centre of this continuum and switching between states at different times in response to changes in conditions.

The importance of barrier permeability in determining river flow thresholds for outlet maintenance was highlighted. West Coast barriers are comprised primarily of sand, in contrast to East Coast systems, which typically consist of mixed sand and gravel. Consequently, on the West Coast, hapua are able to maintain a permanent outlet at the mouths of rivers that have much smaller flow volumes than their East Coast counterparts.

Aspects likely to influence these systems over the next century include those induced by climate change, such as sea level rise and increased storminess, and anthropogenic factors such as catchment modifications and outlet management. These factors interact on a variety of temporal scales, and three broad potential responses could result depending on the direction and magnitude of these interactions: lagoon loss, natural lagoon present, or artificially modified lagoon present.

The primary pressure in terms of anthropogenic influence and management concern in these West Coast systems is the issue of artificial outlet management. Outlet management strategies include the natural, ‘do nothing’ approach, regular maintenance of the outlet, or ‘threshold’ breaching, which involves artificially breaching the barrier when water levels reach a level deemed hazardous. The choice of position for any artificial breach is paramount, and it is suggested that if it is unavoidable, a breach should be performed upstream from the river mouth and be orientated on a slight diagonal through the barrier in the direction of littoral drift. This results in the least disturbance to system hydrology and ecology. The best way to deal with the issue artificial outlet management is through regular monitoring and small interventions when necessary, rather than managing the outlet purely through emergency measures.

CHAPTER EIGHT

Conclusions

Coastal lagoon and wetland systems are complex and dynamic environments, responding rapidly to a complex network of climatic, tectonic, anthropogenic and other synergistic drivers. The purpose of this thesis was to investigate two such systems in the Westland Region; Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex, using a multidisciplinary methodological framework to investigate active processes and document changes in these systems over historical time. This information was then used to predict future developmental changes under differing climate and management pressures; information which is a valuable aid in coastal management decisions. The approach used in this research is highly transferable, and the findings and questions raised are applicable to other similar systems elsewhere in New Zealand and internationally.

The primary objectives of this thesis with respect to the two study sites were:

- To document their current topography and structure,
- To explain their current hydrology,
- To understand their development over historical time and relate this to the current state of each system,
- To analyse the processes driving these changes in geomorphology,
- To explore factors likely to influence changes in these systems over the following 100 years and determine how each system might respond to these drivers individually and collectively,
- To develop a conceptual model of process and response that can be used to predict future changes of each system and which is applicable to similar settings elsewhere.

A summary of the main findings, limitations of this study, and suggested areas for future research are presented in the following sections.

8.1 Summary of main findings

8.1.1 Description of current topography, observed geomorphology and hydrology

The two study sites, Totara Lagoon and the Shearer Swamp-Waikoriri Lagoon Complex, share a coastal plain in the Westland Region. Totara Lagoon is a large hapua type lagoon system, stretching 10 km north from the Totara River mouth. Shearer Swamp is a large freshwater wetland, and Waikoriri Lagoon is a small hapua type lagoon which drains Shearer Swamp behind. The current topography and hydrodynamics of these systems were investigated using a combination of GNSS surveys, hydrological records, and field observations.

Totara Lagoon shows significant differences in structure and morphology along its length, and exhibits a gradient of decreasing energy with increasing distance from the rivermouth. At the river mouth extremity the lagoon was very dynamic, experiencing regular variations in water level and conductivity related to tidal influence. This tidal intrusion extended as far as Totara Central, although the effect dampened with distance from the river mouth.

This is a very important finding, as it challenges the existing classification of Totara Lagoon as a hapua, as the definition of a hapua excludes systems showing any degree of tidal influence. This research supports the idea of a continuum between the definitions of ‘hapua’ and ‘estuary’ within an overarching category of ‘rivermouth lagoon’. This recognises that the pattern of tidal influence observed here may not be permanent, suggesting this system is merely experiencing an ‘estuarine phase’; a concept that is not well documented in existing literature or classification structures of estuaries and lagoons.

Dune morphology also shows evidence of this decreasing energy gradient northwards. Dunes are low and rounded in the south with scant vegetation, and becoming steeper and more heavily vegetated to the north. No direct tidal influence was observed in the north, but water level did vary in response to a tidal backwater effect at times. Evidence of dune blowouts related to wave overtopping is apparent along the entire channel, including in the northern reaches.

Waikoriri Lagoon is a much smaller lagoon than Totara Lagoon, and is much more dynamic and less stable. A series of relic dune ridges exist between Waikoriri Lagoon and the western margin of Shearer Swamp, which are evidence of the continuing progradation of the coastline following the sea level highstand and the infilling and development of Shearer Swamp. The lagoon occupies a swale behind the foredune, which is low and sparsely vegetated, showing the dynamic nature of the lagoon outlet.

The hydrology of Waikoriri Lagoon and the creek behind it is a function of the position of the outlet. Long term hydrological measurements in Waikoriri Creek showed that when the lagoon outlet was offset substantially, there was no tidal influence in the creek behind in terms of either water level or conductivity changes. In contrast, when a breach occurred at the river mouth water level began responding to the tidal cycle with regular oscillations. Conductivity records show that there was no regular tidal influx occurring, thus it can be concluded that the water level response was due to a tidal backwater effect. However, isolated conductivity spikes suggest saltwater incursions occurred sporadically in response to occasional wave overtopping at high tide.

One of the most significant findings of this research is the importance of barrier permeability in controlling the formation of hapua. The morphology of the seaward barrier of these systems is sandy, in contrast to the typically mixed sand and gravel nature of East Coast barriers. The implications of this are that on the West Coast, hapua are able to form at the mouths of rivers that have much smaller flow volumes than their East Coast counterparts. Thus, there is an approximately linear, positive relationship between river flow and barrier permeability (assuming a wave-dominated environment and suitable sediment supply and littoral drift conditions) in terms of providing conditions conducive to hapua formation. To distinguish these low-flow systems from East Coast examples of hapua, the term ‘sandy hapua’ has been introduced.

8.1.2 Outlet dynamics on a decadal scale

The behavioural changes of these systems in terms of outlet migration and lagoon structure were investigated by analysis of aerial photographs taken between 1948 and 2006. Visual assessments of lagoon change were made, and the net change in outlet position between surveys was measured.

As a consequence of the strong net northward direction of littoral drift, both systems experienced outlet offset in solely a northerly direction. Measurements from aerial photographs show Totara Lagoon reached a maximum offset of 5800 m, while Waikoriri reached a maximum of 2500 m offset. The rate of migration was calculated for Totara Lagoon to be between 0 and 575 m yr^{-1}. As a much more dynamic system that migrates on short timescales, rates of outlet migration were not calculated for Waikoriri Lagoon.

The degree of change in channel structure over time varied hugely between the two systems. Channel structure and utilisation did not vary largely over time in Totara Lagoon, except for notable changes in channel structure through the central reaches. Lagoon surface area appeared to correlate negatively with outlet offset, thus the surface area of water in the central channels was greatest when the outlet was situated at the southern (river mouth) extremity. Waikoriri Lagoon was much more variable in size and structure, tending to drain completely northward of the outlet. When the outlet was situated at the river mouth, the lagoon channel was observed to drain completely.

These differences in outlet dynamics between Totara Lagoon and Waikoriri Lagoon are interpreted to be a consequence of the vast differences in spatial scale and barrier development (and stability) between the two systems. Totara Lagoon is inherently much more stable than Waikoriri Lagoon.

This longer term record of outlet migration supports the classification of these two systems as hapua-type lagoons, as they display long-term patterns of behaviour and dynamics consistent with models of East Coast hapua. It is very unlikely that Totara Lagoon experienced tidal inflows during periods of large outlet offset, further supporting the argument that this system exists in the middle of the hapua-estuary continuum; shifting between these two hydrological states at different times.

8.1.3 Development over historical time

Snapshots of dynamics occurring at specific locations in these systems over a longer timescale was investigated using sediment cores, from one site in Shearer Swamp and two sites in Totara Lagoon. Stratigraphy, sediment texture and organic percent analyses were used to investigate changes in depositional environment at these sites over time and examine the relationship between these changes and system dynamics.

The core from Totara South showed a dramatic transition from a coarse sand and gravel layer at the bottom, to a massive mud unit for the remainder of the core. Combined with aerial photograph observations, this was interpreted as representative of the abandonment of a large channel, which then dried out and became stable and vegetated. The coarse nature of the bottom layer suggests that this was deposited mid-channel in a large channel similar to the southern section of Totara Lagoon today.

The core from Totara North exhibited a more gradual change from sand dominated to muddy sand, to organic mud, and increased in organic content up the core. This sequence has been interpreted as a shift from open, unvegetated (possibly sand bar) conditions, to a lagoon margin environment. This interpretation is very spatially restrictive, and is unlikely to be due to large-scale changes in the lagoon environment, as the northern end of the lagoon has been observed to be very stable and unchanging from field observations and aerial photograph analysis.

A series of changes in depositional conditions occurred at the Shearer Swamp core site, which was situated on the swamp margin. Peat layers in the lower half of the core suggest the site was well developed swamp for the entire duration, and the presence of a silt layer above this represents a period of migration of Waikoriri Creek. The most important observation from this core is the decreasing amount of wind-transported sand present in the core, representative of the increasing vegetation cover (related to land-use change in the form of farming) of the dune ridges adjacent to the swamp. This demonstrates the potential for changes in surrounding areas to impact dynamics within a complex coastal system, which is very important from a coastal management perspective.

8.1.4 The future of these systems

Over the next century, these systems are likely to experience pressure from a variety of factors, both climate induced and anthropogenic, which interact in a complex network of feedback loops. Climate change is likely to result in an increase in sea level, which puts pressure on the barrier and can result in landward migration of the entire system unless barrier erosion is counteracted by increased sediment supply. In addition, increased frequency and intensity of westerly weather systems could result in changes to the catchment dynamics and river flow patterns.

Three potential broad potential lagoon states could result depending on the direction and magnitude of these interactions: lagoon loss, natural lagoon present, or artificially modified lagoon present. There are many different potential management responses to these changes, but this research suggests that the preferable strategy is to maintain the system as naturally as possible, and avoiding all hard measures to prevent erosion in particular.

Artificial outlet management is likely to remain the issue of primary importance to coastal managers in the area. Outlet management strategies include the natural, ‘do nothing’ approach, regular maintenance of the outlet, or ‘threshold’ breaching, which involves artificially breaching the barrier when water levels approach a stage that threatens property or life. The choice of position for any artificial breach is of the utmost importance, and this research suggests that if it becomes necessary, a breach should be performed upstream from the river mouth and orientated on a slight diagonal in the direction of littoral drift. This minimises disturbance to system hydrology and ecology, which can be devastated by these artificial breach events. The preferable way to deal with the issue of artificial outlet management is by implementing a regular monitoring programme and staging small interventions when necessary, rather than managing the outlet purely through larger, emergency measures.

8.2 Limitations to this investigation and suggested areas for future research

The greatest limitations to this study lie in spatial and temporal scale. In many cases, results gained were a snapshot of conditions at the time of monitoring, and benefit could be gained from performing some of them over a larger scale and for a longer time period.

This is particularly true of the hydrological measurements in Totara Lagoon, which have challenged the existing classification of Totara Lagoon as a hapua, and suggested it should be positioned in the centre of a continuum between hapua and estuaries, which acknowledges its ability to change between states. Further research could address the hydrodynamics in this lagoon in greater detail and at a higher spatial resolution, and enormous benefit would be gained in long term salinity and water level measurements in the southern section of the lagoon. Combined with regular observations of outlet morphology, the relationship between outlet configuration and channel hydrology could be investigated, and the reasons behind the hydrological results in this study could be better understood. Further research is required into these ‘in-between’ systems such as Totara Lagoon and the Ashley River, which may be more common than previously realised. Previous research has focused mainly on pure hapua systems, or pure estuary systems, rather than on those that switch between the two modes.

Sediment coring showed evidence of significant changes in energy levels at the locations surveyed, but these were also spatially restrictive and limited to a small timeframe. Understanding of the long term development of this coastal plain and these systems could be enhanced by the use of geophysical techniques, such as Ground Penetrating Radar, to assess the subsurface morphology. In addition, microfossil analysis of longer sediment cores would be beneficial to determine the salinity of observed layers, and thus infer the degree of tidal influence at the time of deposition. This was initially to be performed on the sediment cores collected here, but equipment and time constraints prevailed.

In terms of coastal management of systems like Totara Lagoon and Waikoriri Lagoon, the most important tool for decision making is data gained through coastal monitoring. As well as aiding decision making, it would provide valuable ongoing data that would facilitate greater scientific understanding of this locally common, yet globally quite rare, type of coastal lagoon.

Finally, it is important to recognise the ever-evolving nature of scientific research and the need to understand the relationship between past morphology and dynamics to better understand those of the present. There is a need for long term studies of coastal environments and their dynamics to aid in the quest to understand and predict the potential effects of climate change in this sensitive, and very important, environment. This would be particularly beneficial in the Westland region, where funding is limited, yet science could benefit greatly from the study of a rich coastal environment that is relatively unconstrained by engineering and infrastructure.

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APPENDICES

Appendix 1. List of important points used in GNSS surveys.

Geodetic Marker	NZMG Northing	NZMG Easting	Orthometric Height	Vertical Order
A9WW	5811574.26	2330140.79	6.045	2V
B8FP	5815112.46	2336590.09	41.546	1V
B8G5	5809914.04	2329394.1	16.1213	1V

Base Station Location	NZMG Northing	NZMG Easting	Elevation (m)
Ross Cemetery	5810834.071	2332166.1	59.28

Appendix 2. Details of aerial photographs used.

Date	Survey Number	Scale	Run and Frame	Area covered
12/04/1948	SN 508	1:16000	1448-2 1449-2 1450-2	Totara Lagoon
			1453-4	Waikoriri Lagoon
28/02/1963	SN 1542		3688-3 3688-5 3689-3	Totara Lagoon
			3689-8	Waikoriri Lagoon
18/02/1972	SN 3509		4566-2 4567-3 4568-3	Totara Lagoon
			4570-1	Waikoriri Lagoon
4/10/1976	SN 2977		H3-2 I1-1 I2-2 I3-2 J1-2	Totara Lagoon
			K2-2	Waikoriri Lagoon
18/10/1981	SN 5940	1:25000	A-1 A-3 A-4 A-5	Totara Lagoon
			C-11	Waikoriri Lagoon
1986	SN 8585		B-2 C-1 C-2	Totara Lagoon
			D-1	Waikoriri Lagoon
15/01/1988	SN 8922c	1:15000	W-13	Waikoriri Lagoon
			X-3 X-5 X-7 X-9	Totara Lagoon
14/02/2002	SN 30003	1:50000	4-189	Waikoriri Lagoon
			LINZ j33a, j33c	Totara Lagoon
15/05/2002	SN 12755D	1:15000	A-03	Waikoriri Lagoon
28/08/2005	SN 12947	1:25000	08-07 08-08 08-09 08-10 08-11	Totara Lagoon
2/08/2006	SN 13023B	1:25000	01-01	Waikoriri Lagoon

Appendix 3. Details of water level recorder locations, elevations and recording periods.

Location	Northing	Easting	Recording period
Site 1 - Waikoriri	5806330.03	2324458.31	8/12/08 - 15/12/08
Site 2 – Waikoriri	5807216.831	2325538.89	8/12/08 - 15/12/08
Waikoriri Bridge	5805804.264	2323935.49	24/9/08 – 21/3/09
Totara South	5812865.248	2331235	29/11/08 - 3/12/08
Totara South	5812864.426	2331239.68	3/12/08 - 7/12/08
Totara Central	5814954.3	2333551.9	29/11/08 – 7/12/08
Totara North	5818368.2	2335875.5	24/9/08 – 21/3/09

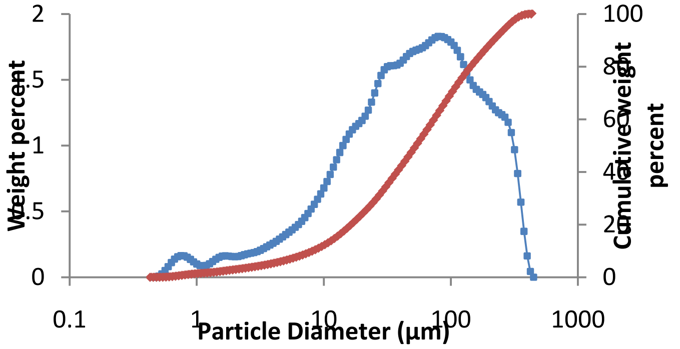
Appendix 4. Sediment core locations

Location	Northing	Easting
Totara South	5813436.8	2331867.0
Totara North	5820665.8	2337047.0
Shearer Swamp	5806527.0	2324813.4

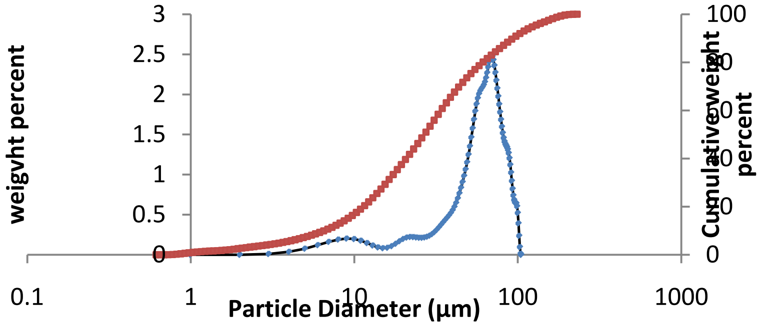
Appendix 5. Grain Size Distribution Graphs.

Shearer Swamp

30 mm



150 mm



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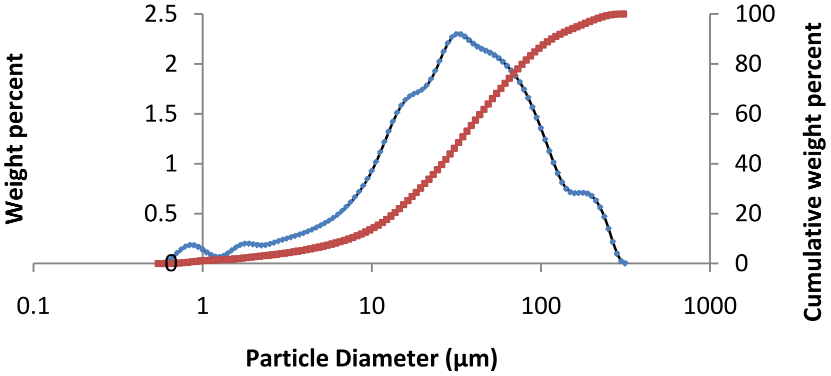

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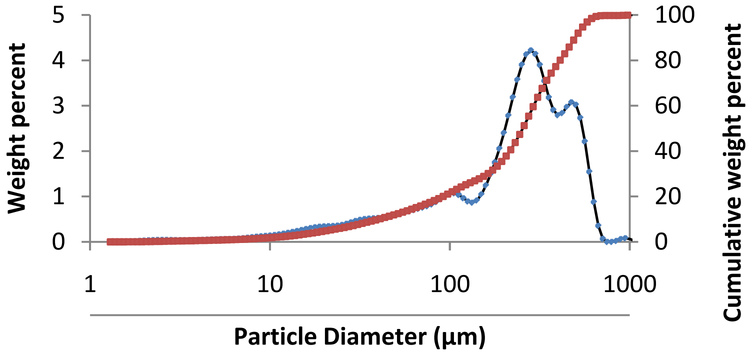

Totara South

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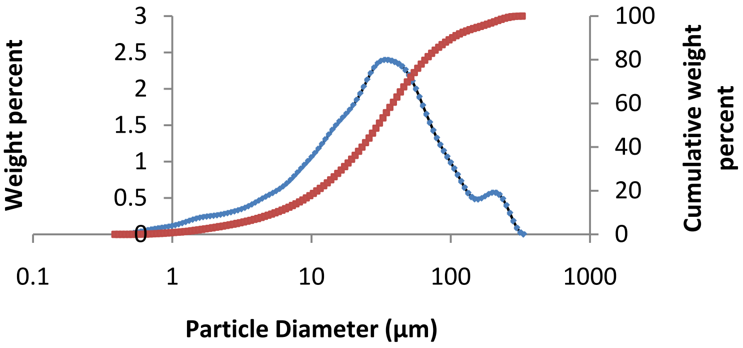

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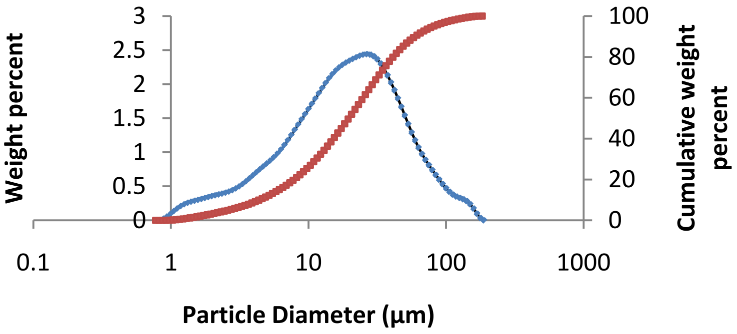

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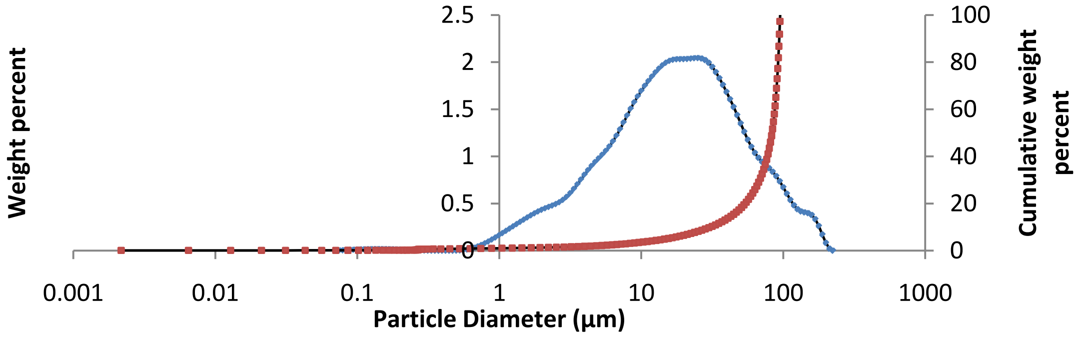

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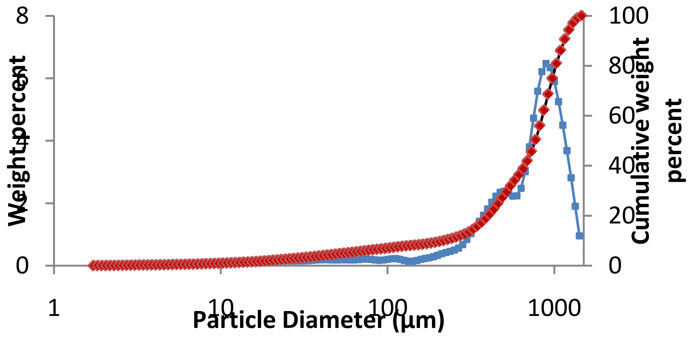
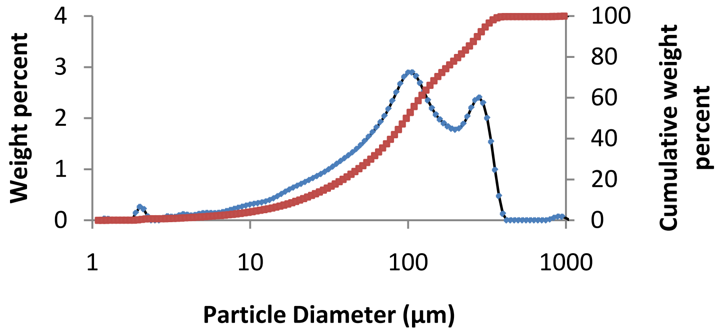


Totara North

30 mm



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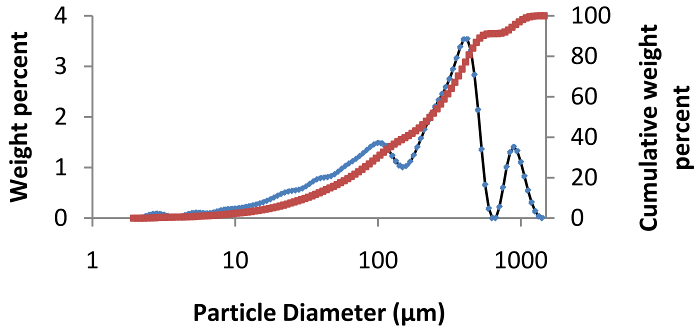

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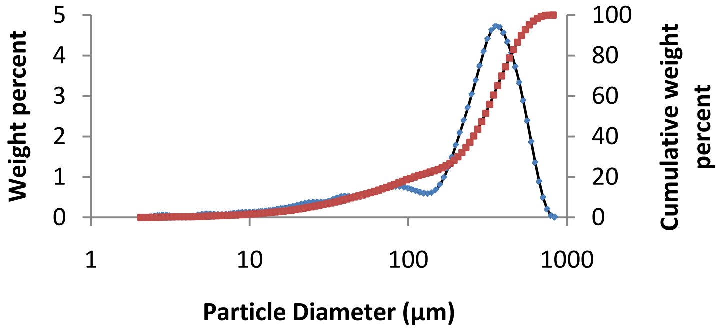

450 mm