Morphology, Dynamics and Hazard Management of the New River Lagoon, Westland, New Zealand

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Abstract

Coastal lagoon systems are complex and dynamic environments that respond rapidly to the changes of fluvial, marine, climatic and anthropogenic influences. The purpose of this research was to investigate the morphology and dynamics of the New River Lagoon before and after the implementation of engineering outlet management using a methodological framework to analyse active process environments. This information was then used to determine the functional effectiveness of engineering management at reducing the risk of flooding and erosion to the local community and imposing minimal impacts on the environmental integrity of the lagoon system.

This investigation used a multidisciplinary approach to investigate the morphology and dynamics of the New River Lagoon in relation to active process environments. Outlet dynamics, lagoon channel structure and adjacent shoreline stability were assessed over a decadal timescale prior to engineering management by analysing temporal aerial photographs. Following engineering management, the hydrology of the lagoon was investigated, along with the relationship between morphological changes to the artificial lagoon outlet and changes in lagoon hydrology, local wave climate and local precipitation levels. Water depth, conductivity and temperature records were used to explain lagoon hydrology and Global Navigation Satellite Surveying (GNSS) and weekly oblique photographs were used to explain and document changes in outlet morphology. Wave and rainfall data were used to explain the balances between marine and fluvial environments and their affects on outlet dynamics.

Significant changes in lagoon morphology and dynamics were observed at the New River Lagoon between pre- and post-management periods, with the former considered more stable in terms of outlet migration patterns and hydrodynamics. The lagoon outlet prior to engineering management showed morphological characteristics similar to hapua-type systems, migrating along the coastline and forming shore-parallel outlet channels in response to the dominance of a strong longshore drift of sediment. Current outlet dynamics are restricted by artificial outlet management and typically cycle intermittently between open/closed phases in response to variable levels of rainfall and marine sediment supply; characteristics similar to Intermittently Open/Closed Lagoons (ICOLs) found in areas of Australia and South Africa. Hydrologically, the lagoon is considered to be located on a continuum between hapua and estuaries during pre- and post-management periods due to intermittent tidal influences. However, artificial outlet management has significantly increased the frequency and duration of tidal exchange, which now classifies the New River lagoon closer to an estuarine environment.

The artificial lagoon outlet and associated breakwater were effective at flushing high flows of water during the study period. However, the outlet was prone to blockage and migration; two morphological states capable of causing flooding. Currently, the greatest risks to flooding at the lagoon are flash floods, following dry periods where marine sediment has established a solid barrier across the outlet, during which water levels are already elevated.

Increases in tidal influences, lower lagoon water levels and an increase in lagoon salinity are a direct result of engineering management intervention. An increase in freshwater flushing through the lagoon outlet and deepened of the outlet channel to below sea level, allows for pronounced tidal influences during outlet opening. Restriction of the lagoon outlet from forming a natural migration outlet channel in the direction of littoral drift has meant the outlet is most often oriented perpendicular to the sea, as appose to at an angle away from the direction of incoming waves and currents, further increasing tidal influences.

In order to make sustainable management decisions, future management of the lagoon system must weight-up the effects of a high energy coastline to the integrity of the engineering structure, the impact of the structure on the lagoons environmental integrity and the outlets ability to become unstable and cause a flood risk.

The findings of this research have improved the understanding of the New River Lagoon system, and its response to engineering management intervention, while adding to the understanding of river-mouth lagoon systems both nationally and internationally.

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Chapter 1 : Introduction

1.1 Thesis statement

Coastal river-mouth lagoons are highly dynamic environments that respond rapidly to changes in climate, sediment supply and anthropogenic influences (Barnes, 1980; Kjerfve, 1994). This is particularly common of such systems located on the West Coast of the South Island, New Zealand, where high-energy waves, variable climatic conditions and sediment-laden rivers attribute to rapid changes in the coastal environment (Neale *et al.*, 2007). Informed management decisions for the benefit of the sustainable wellbeing of a lagoon must be based on an in-depth understanding of the lagoon system. There has been very little previous research conducted on the processes and management of coastal environments on the West Coast (Hesp *et al.*, 1999; Kench *et al.*, 2008). Consequently, historical records are minimal, which makes it difficult for local authorities to make informed management decisions.

This study focuses on the New River Lagoon, located at Gladstone, about 10 km south of Greymouth on the West Coast of the South Island, New Zealand (Figure 1.1). The New River Lagoon is a small, but complex river-mouth lagoon fed by two waterways: the New River and Saltwater Creek. There is very little in-depth understanding of the processes and dynamics of the New River Lagoon, yet recently local council have implemented engineering management work in an attempt to stabilise the lagoon outlet to reduce the risk of flooding and erosion caused by the dynamic nature of the outlet structure and position. The aim of this thesis research is to explore the morphology and dynamics of the New River Lagoon in order to determine the functional effectiveness of current hazard management intervention. In addition, the information about New River Lagoon adds to the understanding of West Coast lagoons and provides a link between them and similar national and international systems.

This study will make use of a variety of monitoring and analysis techniques to assess the past and present structure and processes that characterise the New River lagoon. Historical aerial photographs, in combination with „hindcast" wave data and a West Coast Flood Database, are used to investigate past changes in the lagoon"s geomorphology. Global Navigational Satellite Surveying (GNSS) and periodic oblique photographs, in combination with water level monitoring, local rainfall data and „nowcast" virtual wave data, are used to investigate the lagoons current geomorphological and hydrological dynamics.

This chapter introduces the regional and international context of this research using national and international literature, following which the local context is discussed with regard to lagoon hazards and hazard management intervention at the lagoon. Gaps in existing research are highlighted, from which research objectives are derived.

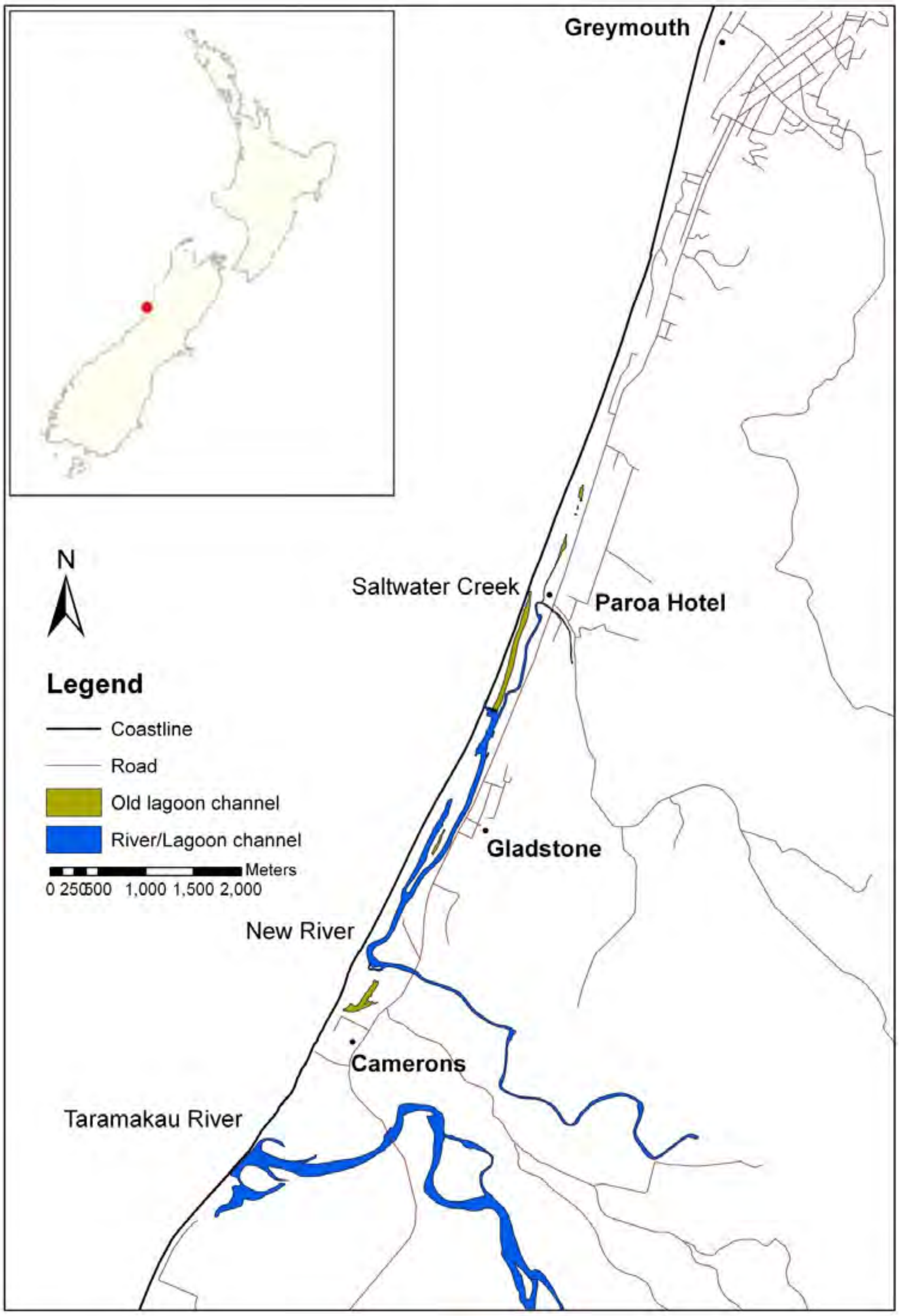

Figure 1.1. Site map showing the location of the New River Lagoon in relation to New Zealand and other local features digitised from a georeferenced 2010 aerial photograph

1.2 Regional and international context

The following section firstly provides an overview of research into the processes and dynamics of coastal lagoons in New Zealand. Particular reference is made to New Zealand hapua-type lagoons, while it is recognised that lagoons on the West Coast of the South Island, New Zealand are significant to this knowledge base, as well as forming links with similar international lagoon systems. Lastly, the management of coastal lagoons on the West Coast is discussed and comparisons are made with international trends.

Coastal lagoons are diverse waterbodies located all over the world. Hapua is a type of river-mouth lagoon found predominantly on the East Coast of the South Island, New Zealand. The term „hapua‟ traditionally means pool or lagoon and originates from *tangata whenua* (local Maori) who have long recognised these coastal lagoon environments as an ample source of *mahinga kai* (traditional Maori food and resources) (Kirk, 1991; Kirk and Lauder, 2000). It distinguishes these river-mouth lagoon environments, which are predominately fresh water and out flowing, from the more common river-mouth lagoons with tidal inflows (Hart, 2009a). Hapua are shore-parallel water bodies separated from the ocean by a coarse grained, steep sloping barrier beach, which forms as a result of the longshore drift of sediment (Hart, 1999; Kirk and Lauder, 2000; Hart, 2009a). They lack a tidal prism, although can experience „backwater effects‟ caused by the interaction of high marine water levels and out-flowing river water, leading to a reduction in out-flows and short periods of high fresh water lagoon water levels on high tides (Hart, 1999, 2007). Hapua typically form on high energy coastlines in New Zealand where there is a supply of coarse sediment, and there is little international literature describing these systems or making links between them (Hart, 2007). See Chapter 3, Section 3.3 for a more in depth discussion on hapua.

The most defining factor between hapua and other coastal waterbodies is the level of water exchanged with the open ocean. By definition, hapua can be considered at the opposite end of a hydrological continuum to estuaries, which are defined by Cameron and Pritchard (1963 pg. 309) as "*semi-enclosed body of water having a free connection with the open sea and within which the sea-water is measurably diluted with fresh water derived from land drainage*". Some coastal lagoons such as Intermittently Closed/Open Lagoon‟s (ICOLs) and in this case the New River Lagoon, are located between these two hydrological extremes, with some closer to the definition of hapua and others estuary.

In recent times there has been a considerable amount of research carried out on hapua-type lagoons on the East Coast of the South Island. These include broad studies by Kirk and Lauder

(2000) and Hart (2009a) and location specific studies on the Hurunui by Smith (1995); the Rakaia by Kirk (1991); the Ashburton and Hurunui by Hart (1999) and Hart (2007); the Ashley by Little (1991) and the Opihi by Todd (1983). In contrast, there has been very little geomorphic research into lagoons on the West Coast of the South Island; the most recent being that of Kain (2009). Evidently there is scope to broaden the knowledge of West Coast lagoons to a) better understand the process and dynamics of these systems that are exposed to different process environments, and b) sustainably manage these systems.

The New River Lagoon has been identified as having similar morphological characteristics to a traditional hapua-type lagoon, by Neale (2006a) and Neale *et al.* (2007). However, it has also been known to experiences tidal influences and is located on a predominantly composite gravel beach; two features uncharacteristic of hapua, but more common in estuary systems (explained in more detail in Chapter 2, Section 2.3). Similar features were found at the Totara and Waikoriri lagoon by Kain (2009) and she suggests that hapua be placed on a continuum alongside estuaries as a result (explained in more detail in Chapter 3, Section 3.2). Similar types of lagoons such as ICOLs are also found internationally on the south eastern coastline of Australia and in parts of South Africa (explained in more detail in Chapter 3, Section 3.4). Research into the morphology and dynamics of the New River Lagoon provides better understanding of the lagoon as a separate entity, but also broadens the understanding of different hapua and lagoon environments in New Zealand, whilst providing a link between them and similar international examples.

Despite the minimal in-depth knowledge of coastal environments on the West Coast, extensive management of such systems is still undertaken. This is often associated with a lack of funding for professional research into the diverse range of coastal systems. A report put together by Benn and Neale (1992) outlines coastal hazards and general coastal management issues on the West Coast of the South Island, New Zealand. In the past, a variety of coastal protection methods have been employed on the West Coast to prevent flooding and erosion hazards. Management methods implemented are generally site specific and little regard is given to the effects that works might have on adjacent coastal shorelines or the long term stability of the beach. „Hard‟ engineering options have been a favoured form of protection, with groynes, seawalls and river-mouth stability works being built at several locations. Many of these have failed to control natural coastal dynamics and often cannot withstand the high energy wave climate (Benn and Neale, 1992). Recently, „soft‟ engineering methods have become a more common form of management, as they are perceived as less expensive to design, build and maintain.

Figure 1.2 shows that management initiatives on the West Coast tend to be contrary to the recent trends in international coastal management that have seen „soft" beach nourishment and restoration dominate „hard" engineering management decisions since at least the 1970s.

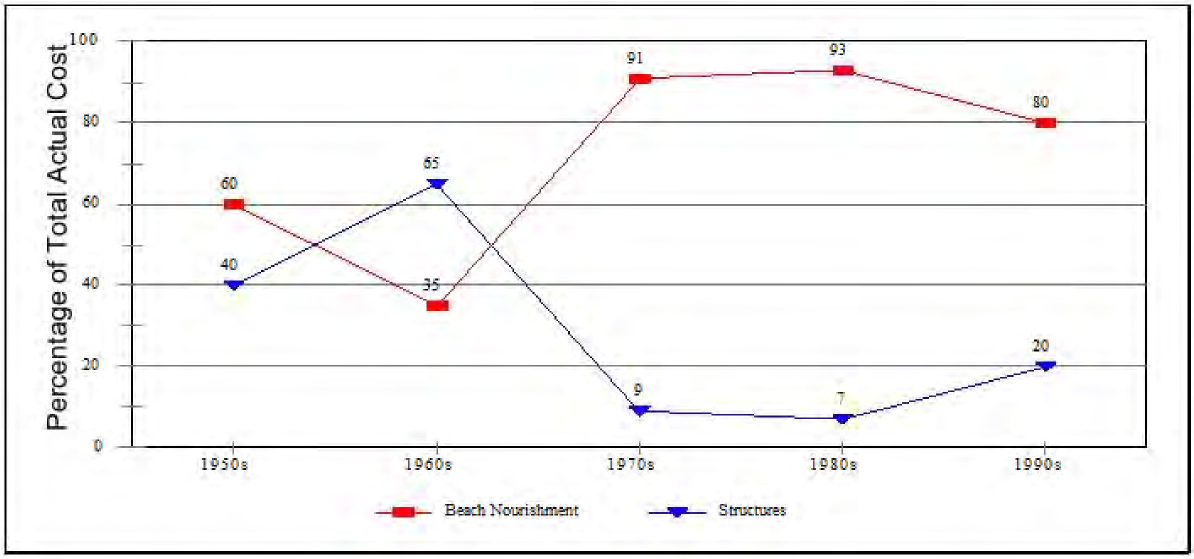

Figure 1.2. International trends in coastal management (Source: Hillyer, 1996 pg. 23)

Artificial outlet management is one of the primary anthropogenic influences and management concerns in lagoon systems on the West Coast, which has recently become a permitted activity under the West Coast Regional Coastal Plan (WCRCP). The 2010 plan change now permits the opening of river and creek outlets as a form of hazard management. The purpose of this plan change was to allow for the opening of outlets that have become closed and where closure has created a flood risk. The council"s motive for the plan change was to improve the controlled opening of river outlets, which were often opened illegally for hazard, land extension and fishing reasons (Neale *et al.,* 2007). By permitting the activity, the council felt that locals would be more inclined to notify their plans to open river outlets they felt were causing such problems. The implementation of such a rule has implications for many lagoon and estuarine environments on the West Coast. The artificial opening of a lagoon outlet has the potential to change the natural characteristics of a lagoon system, particularly if opening is carried out with no prior knowledge of lagoon dynamics (Vila-Concejo *et al.,* 2004).

Not a lot is known about the environmental effects of artificial outlet opening and relocation in hapua systems, least the impact of stabilising a hapua outlet using engineering structures. Yet recent management of the New River Lagoon has seen the artificial relocation and opening of the lagoon outlet and implementation of a rubble-mound breakwater to stabilise the lagoon outlet (explained in more detail in Chapter 1, Section 1.3.2). In order to determine the overall effectiveness of such management techniques on the natural integrity of the environment, physical (i.e. lagoon morphology and hydrological dynamics), ecological (i.e. plant biodiversity and lagoon ecology) and legislative dimensions (i.e. the New Zealand Resource Management Act 1991 (RMA), New Zealand Coastal Policy Statement (NZCPS) and West Coast Regional Coastal Plan (WCRCP)) must be considered (Figure 1.3). It is important to note that this study focuses only on the physical effects of engineering management on the lagoon system, while ecological effects and legislative parameters are considered beyond the scope of this research.

The implementation of such engineering management techniques can have implications for the physical dynamics of coastal lagoons, such as deepening of the outlet channel (Seabergh, 1974; Komar and Terich, 1976; Kieslich, 1981) and increase in tidal prism, which can lead to increased sedimentation (Fortunato and Oliveira, 2007) and greater fluctuations in lagoon water levels and salinity (Goodwin, 1996; Roy *et al.*, 2001; Gunaratne *et al.*, 2011).

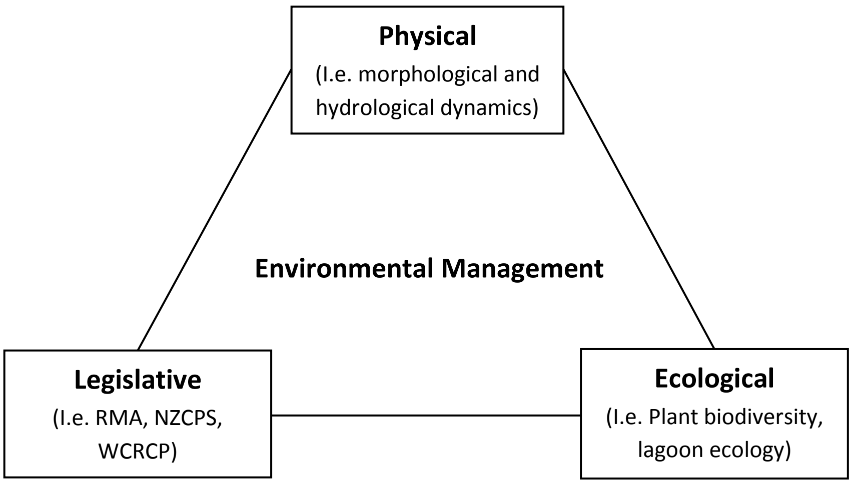

Figure 1.3. Physical, ecological and legislative dimensions to be considered when determining the effectiveness of environmental management on coastal lagoons in New Zealand

1.3 Research context

Coastal lagoons are dynamic systems that are extremely sensitive to a changing environment and can cause problems for coastal management and planning. At the New River Lagoon there are several processes associated with the dynamic nature of its outlet that have created hazards for the local community in the past. Consequently, local authorities have implemented engineering management techniques in an attempt to minimize the risk of these hazards. In order to make valuable management decisions, it is essential to have an in-depth understanding of the different processes associated with an individual lagoon system. Unfortunately, there was little in-depth knowledge of the New River Lagoon before management decisions were made. Therefore, the context of this research is largely based around understanding the morphology and dynamics of the New River Lagoon, before and after anthropogenic modifications, in order to determine the suitability and functionality of current management techniques. This section outlines what is know about the processes at the New River Lagoon and the hazards involved, followed by the past and present management regimes.

1.3.1 Hazards at the New River Lagoon

The New River Lagoon is an extremely dynamic environment that is sensitive to the balance between marine and fluvial processes. The lagoon is comprised of two intersecting waterways: Saltwater Creek flowing from the north and the more dominant New River flowing from the south (Figure 1.1). Two outlet states can create hazards at New River Lagoon: blockage of the lagoon outlet causing flooding, and migration of the lagoon outlet causing erosion of the seaward side of the State Highway.

Lagoon outlet blockage at the New River Lagoon is caused by the deposition of beach sediment forming a barrier that restricts the exchange of water between fluvial and marine environments. Blockage occurs during times of low river flow when there is insufficient discharge of water to flush sediment through the outlet (Benn, 2004; Smart, 2010). If there is insufficient drainage though the lagoon outlet, the convergence of flood water from Salt Water Creek and the New River at the same point can cause Salt Water Creek (the smaller of the two waterways) to back up and flood the surrounding low lying land. There have been various flooding events over the last 50 years at the New River Lagoon. On the 11 and 12 February 1997, extensive backwater flooding of the Paroa Primary School occurred as a result of heavy rainfall following blockage of the New River Lagoon outlet. Other documented examples include, extensive flooding of the Paroa Hotel during heavy rainfall in 1978 (Figure 1.4), and the most recent flooding of the Paroa Primary School on the 28 December 2010.

Figure 1.4. 1978 flooding of Saltwater Creek causing inundation of Paroa Hotel (Source: Smart, 2010 pg. 2)

Lagoon outlet migration is caused by the longshore transport of sediment, predominantly deflecting West Coast lagoon outlet‟s to the north, or river flooding, which can breach established outlets and create new ones (Benn, 2004). The New River Lagoon outlet has been recorded to have migrated from north of Paroa to Cameron‟s in historical times, a distance of over 7 km (Figure 1.1). Until recent management intervention, northward movement of the river outlet had been consistent, caused by the longshore migration of beach gravel from the south. The northerly drift of gravel would deposit as a bar on the southern bank of the river outlet (Figure 1.5). To compensate and maintain flow, the river would erode the northern bank of the river outlet, which resulted in a northward movement (Smart, 2010). As the lagoon outlet migrated further north, so did the flow of water from the New River Lagoon. The New River Lagoon eventually travelled parallel to the southward flow of Salt Water Creek, separated only by a thin, vegetated dune system. Erosion of the outside banks of the lagoon channel often occurred during periods of high river levels, which increased the migration rate of a northward deflecting river outlet and increased the risk of dune breach and subsequent disruption of the southerly flowing Salt Water Creek. If a breach were to occur, there would have been major flooding implications for infrastructure on the seaward side of the highway, caused by the interaction of two opposite flowing waterways. It is also notable to mention that scouring of the outside banks of the outlet as it migrated north, was slowly eroding land north of the outlet that was being preserved and protected for the nesting of blue penguins. Further analysis of past lagoon outlet and channel dynamics are provided in Chapter 4.

Figure 1.5. Formation of a gravel bar as the lagoon outlet migrates north, creating a barrier between the lagoon channel and the sea and forcing the river to erode its outside banks (Source: Smart, 2010 pg. 5)

1.3.2 Hazard management of the New River Lagoon

As human activities exert more pressure on the coastline and catchments worldwide, understanding the dynamic nature of lagoon and estuarine environments is becoming more important for coastal management. Until recently, the only form of management at the New River Lagoon had been a „monitor-and-do-nothing" approach with emphasis on preserving and maintaining the natural environment that is home to a diverse range of wildlife and used for various recreational activities, such as kayaking and whitebait fishing. Consequently, the morphology of the lagoon evolved considerably, due to processes of longshore drift and stream bank erosion. As mentioned above, the interaction of these processes led to hazards for the local infrastructure and conflict between the community and the council, especially in times of pronounced flooding and erosion.

On the 9 December 2010, the Guardians of the Paroa-Taramakau Coastal Area Trust (PTCAT) applied to the West Coast Regional Council for a coastal permit to conduct a trial into opening the New River Lagoon. The trial would consist of a digger to excavate sand and gravel from the beach to form a new lagoon outlet at the point the confluence of the two rivers used to enter the sea, before longshore sediment transport shifted the river outlet to a northerly location. The community group was concerned that the northerly migration of the lagoon outlet was preventing public access to the beach and could exacerbate flooding of the hotel, school and private property that occupy past lagoon channels on the seaward side of the highway at Paroa.

On the 28 December 2010 a heavy rainfall event caused flooding of the Paroa Primary School and surrounding low lying areas. This flooding preceded finalisation of the consent process, which necessitated the Grey District Council to carry out emergency engineering works (under the Emergency Works Provisions of the Resource Management Act 1991) at the New River Lagoon.

On the 30 December 2010 an artificial opening was excavated using a digger where the Saltwater Creek and New River currently converge (Figure 1.1). The channel bed of the artificial outlet appears to sit at an elevation considerably lower than the adjacent barrier beach to allow a constant flow of water through the outlet. The downdrift bank of the artificial outlet has been supported by a rubble-mound breakwater that lies across the previous lagoon channel, protruding close to the nearshore breaker zone (Figures 1.6, 1.7). Essentially, the breakwater has been put in place to divert water from the New River Lagoon through the artificial outlet, preventing the dominant flow of the New River from travelling northward along its natural migration channel. It is also in place to restrict the artificial outlet from migrating northwards. The engineering intervention is aimed at: 1) eliminating the erosion caused by northward migration of the lagoon outlet, by reducing the effects of longshore drift, and 2) maintaining an open outlet to drain high flows of water during flood events.

Further to the emergency engineering works at the lagoon and the initial consent application by the PTCAT, the Grey District Council applied for a coastal permit for on-going works at the lagoon. Consent was granted on the 21 March 2011. It is uncertain as to whether the reinstated outlet will stay in place for any length of time; therefore, consent was granted on a medium term basis for five years. Consent allows the applicant to maintain/re-excavate no more than five times during the term of the consent. The exceptions to this are in times where the backup of water is likely to reach the trigger level (height at which flooding becomes a hazard) and/or the outlet moves north of the location identified as the beach opposite the northern exit to SH6 off Sumner Road, when excavations above and beyond the consented five occasions may be undertaken.

Figure 1.6. Artificial lagoon outlet and rubble-mound breakwater at the confluence of New River and Saltwater Creek (photo courtesy of Laurie Anderson, 23/05/2011)

Figure 1.7. Artificial lagoon outlet and rubble-mound breakwater looking north (above) and rubble-mound breakwater and updrift beach looking south (below) (23/05/2011)

1.4 Research Gap and Objectives

The West Coast region represents a large gap in New Zealand coastal research with very little documentation and understanding of its dynamic coastal environments. Having in-depth understanding of coastal systems is important for the sustainable management and development of coastal areas. The majority of existing research on the West Coast has been undertaken by government organisations, private companies or individuals, often as a part of consent applications. Kench *et al.* (2008) recognises the West Coast of the South Island as one of the most neglected areas of university coastal research in New Zealand. This lack of knowledge provides a large scope for more in-depth study into different coastal environments; information that can then be used by local government to better manage the region‟s resources.

Hapua are unique lagoon environments to New Zealand with little international literature describing these systems or making links between them and other similar overseas examples. Research surrounding hapua-type lagoons has largely been confined to the East Coast of the South Island, New Zealand. As such, there is a necessity to broaden the understanding of lagoon systems on the West Coast of New Zealand, which are inherently different to East Coast hapua, as first shown by Kain (2009). West Coast lagoons are exposed to different environmental processes such as sediment supply, tidal regimes and local climate, differentiating their natural characteristics from those of East Coast hapua. These differences mean West Coast lagoons also share similar characteristics to international lagoon systems.

Despite the inherent differences between East and West Coast lagoons, many share similarities in their ability to cause flooding and erosion hazards, due to the dynamic nature of their outlets. Few different management techniques have been trialled to control such problems and subsequently few studies have assessed the effects of engineering management techniques on such environments. The New River Lagoon provides an opportunity to further the understanding of West Coast lagoons and make links between them and similar international systems, while determining the functionality of alternative outlet management.

The aim of this thesis research is to explore the geomorphology and dynamics of the New River Lagoon and evaluate the functional effectiveness of current hazard management intervention.

The objectives of this research are:

- to document morphological and positional changes to the New River Lagoon prior to engineering management intervention, including lagoon outlet and channel migration, and changes to shoreline position,

- explain the processes driving morphological change,
- investigate current lagoon hydrology and explain the relationship between morphological changes to the artificial lagoon outlet and changes in lagoon hydrology, local wave climate and local precipitation levels,
- make comparisons between lagoon characteristics pre- and post-engineering management and draw links between these and similar national and international lagoon systems,
- assess the functionality of the current artificial lagoon outlet at managing lagoon outlet migration and flood hazard control and imposing minimal physical effects on the surrounding environment, and
- recommend future management options at the New River Lagoon where they are needed,

1.5 Thesis structure

The purpose and objectives of this research have been presented in this chapter, along with the regional context to which the New River Lagoon is placed, and the context to which this research is based around.

Chapter 2 provides an in-depth overview of the study area using available literature and past local research. This overview covers the geology and geomorphology, climate, ocean currents and marine environment, waves and sediment sources that have contributed to the development of the New River Lagoon over time. In addition, a more specific site description of the New River Lagoon and its associated beach environment are explained.

Chapter 3 provides a detailed analysis of national and international literature surrounding the issues associated with defining and classifying coastal waterbodies; the processes environments driving the dynamics of coastal lagoons and hapua; and the effects that management can have on natural lagoon dynamics.

Chapters 4 and 5 present the methodology and results of an investigation into lagoon morphology and dynamics. Chapter 4 presents the results of aerial photographs analysis and describes the morphology and dynamics of the New River Lagoon prior to engineering management intervention. Wave „hindcast" data and a West Coast Flood Database are used to support the changes in channel structure, lagoon outlet position and beach stability evident in the series of photographs.

Chapter 5 investigates the morphology and dynamics of the New River Lagoon over a 7 month period following engineering management. Lagoon hydrological dynamics are determined and used in combination with local MetOcea „nowcast" wave data, local NIWA rainfall data, and oblique photographs, to explain the relationship between outlet dynamics and lagoon hydrology.

Chapter 6 provides a discussion and interpretation of the combined results found in chapters 4 and 5. Changes to lagoon morphology and dynamics are first compared between periods of pre- and post-engineering management. Lagoon characteristics are then related to similar national and international lagoon classification schemes and the classification of the New River lagoon is determined. The effectiveness of engineering management intervention at stabilising the lagoon outlet is analysed, along with the suitability of management works for differing lagoon systems. Furthermore, suggestions for future management options are discussed.

Chapter 8 discusses the main findings of this research, the limitations to the application of results from this study and future research opportunities are identified.

Chapter 2 : Study Area

2.1 Introduction

The West Coast comprises an extremely dynamic shoreline that runs for 600 km between Kahurangi Point and Awarua Point in the South Island, New Zealand (Neale *et al.,* 2007). The shoreline is broadly orientated SW-NE; an orientation which is dictated by uplift along the axis of the Southern Alps. The West Coast has a diverse variety of environments ranging from low-lying dunes, estuary and river beds composed of unconsolidated sands and gravels, to solid, steep bedrock cliffs (Benn and Neale, 1992). The dynamic coastline is largely influenced by the high energy coastal marine environment, plentiful sediment supply from many rivers and extreme climatic conditions. Wave action can be considered the primary factor of coastal change and is a dominant force controlled largely by New Zealand‟s orientation across a belt of strong westerly winds and their associated wave systems. The West Coast is situated on the windward side of the South Island, so it is generally considered to be exposed to a rougher wave climate than the eastern coastline. Studies have shown that high energy wave events (waves greater than 1.5 m) can occur up to 36% of the time and approach the shoreline twice as often from the south than from the north (Benn and Neale, 1992; Neale *et al.*, 2007). Heavy orographic precipitation is caused by the interaction of a prevailing western flow and the Southern Alps, which means the West Coast is one of the wettest regions in New Zealand (Garnier, 1958; Salinger, 1980). Consequently the coastline is supplied with an abundance of sediment from the West Coast‟s many rivers.

This study focuses on the New River Lagoon, located between Camerons Township in the south and the Paroa Hotel in the north (Figure 1.1). The New River Lagoon is formed by the interaction between the New River flowing from the south and Salt Water Creek flowing from the north, both of which flow out to sea via the one outlet. The New River is the dominant channel within the lagoon; therefore the lagoon is referred to in this study as the New River Lagoon.

This chapter utilises available literature to provide an overview of the different environments that directly influence the dynamics of coastal systems on the West Coast. This is followed by a more in-depth site description of the New River Lagoon and its associated beach environment in Section 2.3, using the limited information available from past studies and observations made in the field over the study period.

2.2 Regional setting

2.2.1 Geology and geomorphology

The West Coast region is an area of high tectonic activity due to its close proximity to the Alpine Fault; a major active fault that forms the plate boundary between the Pacific Plate (located to the southeast) and the Australian Plate (located to the southwest). The plate boundary formed during the Cenozoic period and eventually gave rise to the Southern Alps during the early Quaternary due to uplift caused by the Australian Plate being subducted beneath the Pacific Plate (Suggate *et al.*, 1978; Nathan *et al.*, 2002). Faulting and folding continues to the present day, creating further deformation of the landscape. The Southern Alps largely consist of highly erodible schist‟s, which are formed by compression and shear along the Alpine Fault (Suggate *et al.*, 1978).

The New River Lagoon is fed by two waterways: the New River and Saltwater Creek. The New River catchment is 117 km^2 in area and Saltwater Creek catchment is 27 km^2 (Smart, 2010). They are both situated between the Grey and Taramakau Rivers (Figure 2.1). The New River is the dominant waterway within the catchment and is fed by several tributaries. Saltwater Creek is a much smaller waterway situated further north of the catchment, connecting with the New River at the coastline to form the New River Lagoon. The catchment is covered in late Quaternary glacial and glacifluvial sedimentary deposits. These deposits are underlain by finer grained Stillwater Mudstone, with the exception of a small area of Cobden Limestone situated northwards in the headwaters of Saltwater Creek (Soons, 2001). Over years, the interactions between tectonics, glaciations, and processes of fluvial development have added to the evolution of the New River catchment, which has had affects on the geomorphology of the coastline and the formation of the New River Lagoon.

Glacial advances during the late Quaternary have been important in shaping the regional landscape. The Taramakau Glacier was the most influential glacier. It made its way down the valley during several glaciations, constructing moraines and spreading outwash gravel to the coastline (Soons, 2001) (Figure 2.2). The earliest glaciation to have significant effects on catchments geomorphology was the Waimaunga: 248,000-300,000 Y.B.P (Soons, 2001). Patches of Tansey sediments along the crests of ridges either side of Rutherglen Road indicate the extent of ground level following this glaciation to have been well above modern landscape (Figure 2.2). This sloping outwash surface suggests the coastline was situated somewhat west of its present location (Soons, 2001).

The Brunner Anticline and Grey Valley Syncline cross through the centre of the catchment, roughly parallel to the coastline (Figure 2.2). The tectonic activity associated with these folds has caused deformation of the regional landscape. Continuous warping occurred during the late Quaternary causing regional uplift, which has raised shore platforms, cliffs and beaches (Soons, 2001; Nathan *et al.*, 2002). The New River Lagoon now dominates much of these immediate surfaces; whilst housing and development are built on the higher terraces. The current beach fronting the New River Lagoon has formed since the last glaciation (10-14,000 Y.B.P) when sea level started to rise and is the lowest in the series of inter-glacial beach surfaces (Benn, 2004).

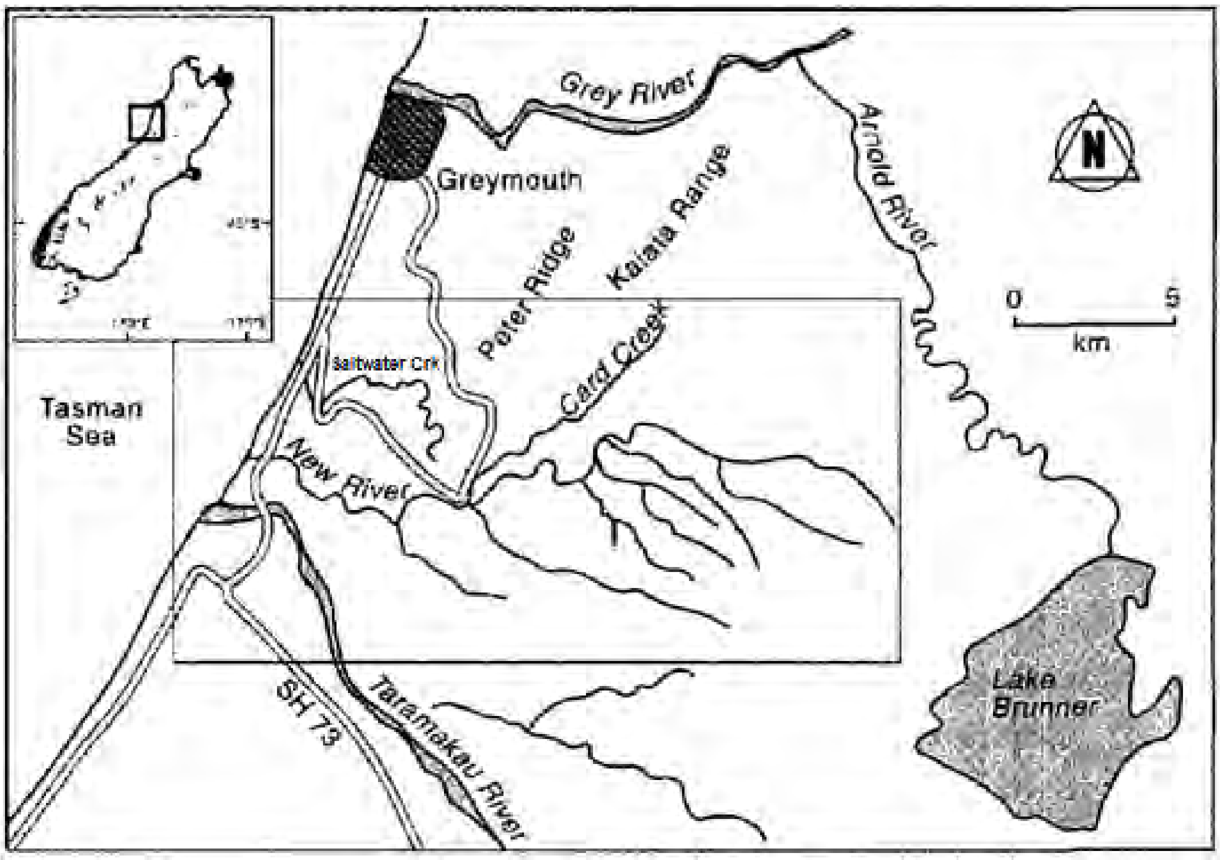

Figure 2.1. Location of the New River catchment in relation to the Grey River and the Taramakau River (Source: modified from Soons, 2001 pg. 137)

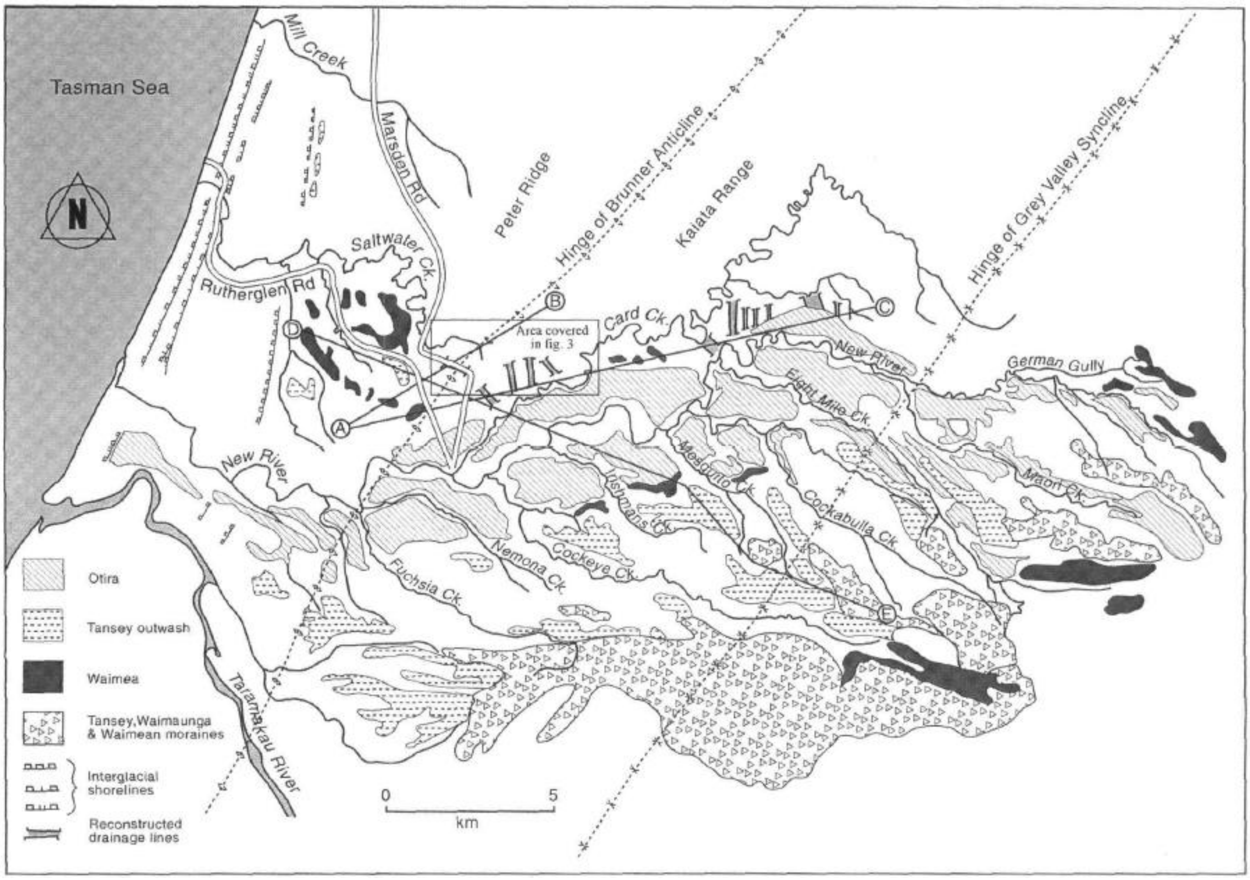

Figure 2.2. The general drainage pattern of the New River catchment, including late quaternary shorelines, moraines, fault lines and glacial outwash deposits (Source: Soons, 2001 pg. 138).

2.2.2 West Coast climate

The climate experienced on the West Coast, New Zealand is largely influenced by the prevailing westerly weather system, also known as the „roaring forties‟; a characteristic of New Zealand‟s mid-latitude location (Salinger, 1980). The interaction between the Southern Alps and the prevailing westerly wind flow creates a highly variable climate for the West Coast region.

The Southern Alps are oriented southwest-northeast extending above 1000 m elevation for a distance along the South Island of approximately 750 km (Salinger, 1980). They provide a barrier that deflects the westerly air flow, forcing it to ascend, causing prolonged periods of heavy rainfall (Hessel, 1982). Consequently, the West Coast is known to be one of the wettest regions in New Zealand with an annual rainfall in excess of 2500 mm and annual highs reaching over 12000 mm in some mountainous areas (Salinger, 1980). According to Hessel (1982), nearly all West Coast rainstorms occur when winds have a northerly component and when temperatures during rainfall are mild. Rainfall can vary considerably due to the West Coast‟s rugged topography, but tends to dominate between spring and autumn as opposed to the winter months (Garnier, 1958; Hessel, 1982). Hessell (1982) explains this trend as a consequence of a higher frequency of local wind prevailing from an N-NW direction between spring and autumn. Further analysis of the meteorology and climate over the study period is provided in Chapter 5.

2.2.3 Ocean currents and coastal marine environment

There are numerous oceanic currents that move and interact with one-another around the South Island of New Zealand and have a large effect on the West Coast‟s marine and coastal environment. The major oceanic flow paths are shown in Figure 2.3. The southern boundary of the West Coast lies at the subtropical convergence zone that separates warmer northern subtropical oceanic mass from the cooler southern sub-Antarctic waters (Stanton, 1976; Bradford, 1983; Neale *et al.*, 2007). The warmer Tasman Current, derived from the East-Australian Current, has the most effect on the West Coast, whilst the cooler sub-Antarctic waters, derived from the strong westerly winds of the „Roaring Forties‟ tend to move around the bottom of the South Island and do not directly influence the West Coast (Neale *et al.,* 2007).

The New Zealand continental shelf, situated less than 20 km offshore in some places, acts as a barrier, forcing the warm Tasman oceanic currents to flow around the landmass as surface currents, controlled predominantly by local winds that prevail from the south-west (Stanton, 1976; Bradford, 1983; Neale *et al.*, 2007). These surface currents flow northward forming the Westland Current; the West Coast‟s most dominant nearshore current. On some occasions a less dominant southward flowing current called the Southland Current, derived from southward flowing „coastal trapped waves‟, can cause the West Coast‟s coastal surface currents to slow down or change direction (Neale *et al.,* 2007).

The coastal marine area seaward of the study site is characterised by a steady sloping continental shelf that extends to the Challenger Plateau (Heath, 1982; Neale *et al.*, 2007). Further south of the study site, the continental shelf becomes narrow, dissected by a series of submarine canyons that protrude into the coastal marine area. These canyons act as sediment sinks, intercepting sediment carried by northerly longshore drift. In this southern half of the West Coast the seabed drops off quickly into deep water, which means the coastline is more susceptible to wave processes in comparison to the northern end where the seabed is steady sloping (Heath, 1982; Neale *et al.*, 2007).

The level of tidal exchange in a system is dependent on the width, thus the depth of the continental shelf (tidal range is less in deep water than in shallow water) (Kirk, 2001). The West Coast tidal cycle occurs twice daily every 12.4 hours (Neale *et al.,* 2007) and the tidal range at

Greymouth (approximately 7.5 km north of Paroa) is meso-tidal. Tidal elevations are shown in Table 2.1.

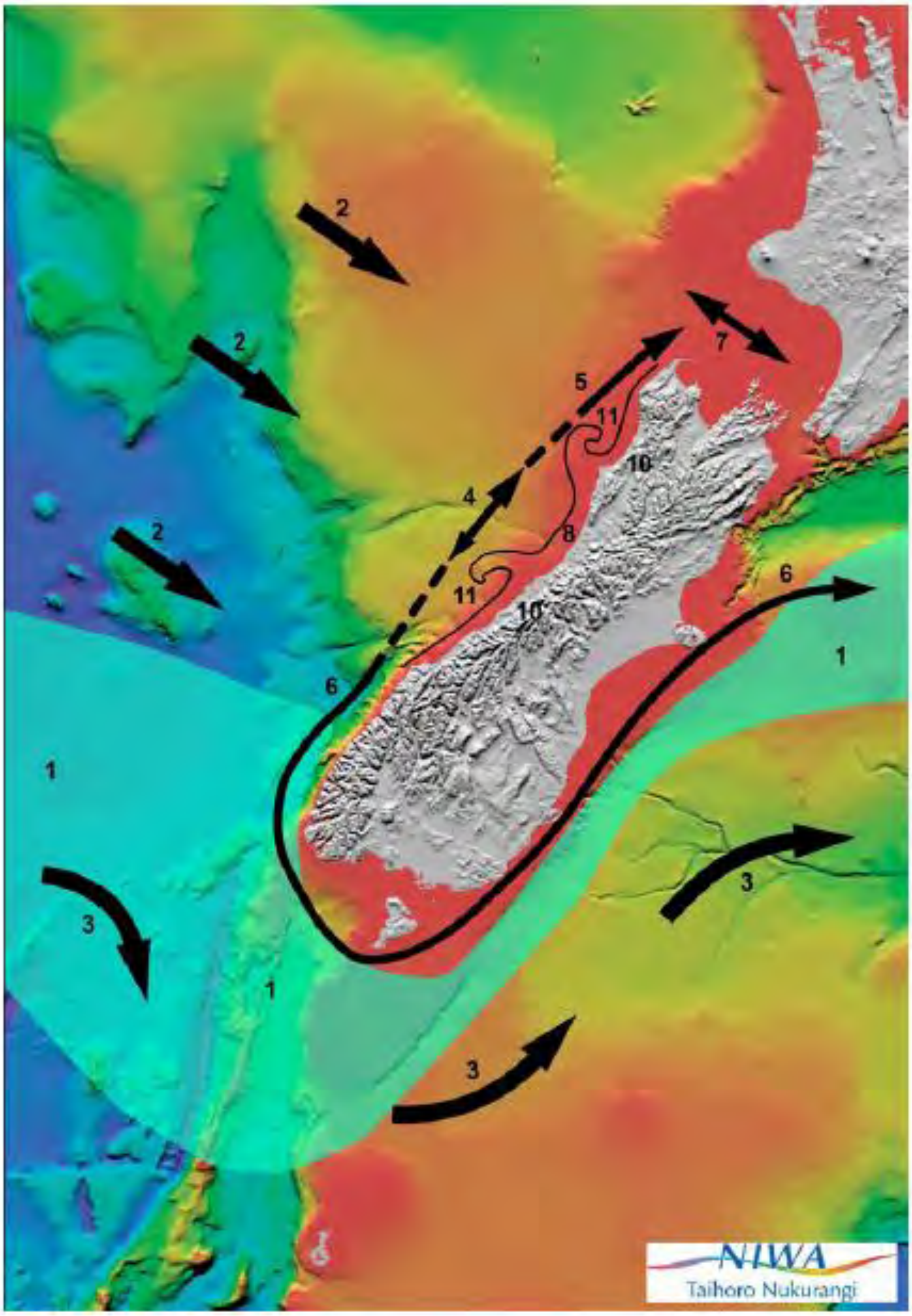

Figure 2.3. Oceanic currents of the West Coast Region. The numbered arrows correspond to features mentioned within the text, as follows: 1 = Subtropical Convergence, 2 = Tasman Current, 3 = Antarctic Circumpolar Current, 4 = West Coast shelf surface currents, 4 = Westland Current, 6 = Southland Current, 7 = Wind-generated oscillation in Cook Strait, 8 = West Coast inshore zone, 9 = Upwelling (not depicted), 10 = Freshwater inflows, 11 = "Squirts" (Source: Neale *et al.,* 2007 pg. 15).

Table 2.1. Tidal elevations at Greymouth (Source: Land Information New Zealand, 2011)

Tidal Stage	Corrected Elevations (m)	Tidal Range (m)
Mean Sea Level	0.0	0.0
Mean High Water Spring	+1.4	
Mean Low Water Spring	-1.4	2.8
Mean High Water Neap	+0.6	
Mean Low Water Neap	-0.7	1.3

2.2.4 West Coast wave environment

Wave processes are an important source of coastal change and have a dominant role in shaping the dynamics of different coastal environments. Waves are generated by wind blowing across the sea surface, thus the size of waves is reflected in the strength of the prevailing wind. Since New Zealand lies across the belt of dominant westerly winds, the West Coast is a windward shore, so typically experiences a rougher wave climate than the eastern coasts (Neale *et al.,* 2007). Pickrill and Mitchell (1979) describe wave climate on the Western Zone of New Zealand as having the second highest wave energy after the Southern New Zealand Zone.

Several authors have described the wave climate of the West Coast using a variety of monitoring methods. In general, the coastal environment of the West Coast can be described as having 1.0 to 3.0 m high waves, moving in a NE direction. High energy wave events propagate from the south on average twice as often than from the north (Pickrill and Mitchell, 1979; Benn and Neale, 1992; Jones, 1992; Neale *et al.*, 2007).

The most relative set of wave climate data to this study is that of Pfahlert (1984) who investigated coastal processes occurring between Karoro and Point Elisabeth, immediately north of the study area. The author found significant wave heights on this stretch of coastline to be between 1.5 and 2.4 m, with a mean wave period of 10.1 s. Pfahlert (1984) also found that longshore transport currents were mirrored by wave direction, with waves directed to the north 67% of the time and to the south 33% of the time.

A study by Gorman *et al.* (2003a) uses wave hindcasting to predict past wave climates for sites around the full extent of New Zealand. The study compared wave hindcast data from the West Coast with data obtained from a nearshore wave buoy located in Hokitika. The authors found that predominant wave direction was oriented in an E/NE direction, indicating strong influences from generation in the Southern Ocean, rather than the Tasman Sea, to which the West Coast is also fully exposed. The authors explained these findings as a function of local winds aligning parallel to the coast, caused by the parallel orientation and close proximity of the Southern Alps to the coastline. Figure 2.4 shows wave direction taken at the 20 m contour west of the New River Lagoon (Longitude -42.557^0 S, Latitude 171.065^0 E) calculated from wave hindcast data between 1979 and 1999. The wave rose shows a high frequency of waves travel towards a NE direction, with wave heights mostly between 1 to 3 m. Further analysis of the wave climate and wave conditions during the study period is provided in Chapter 5.

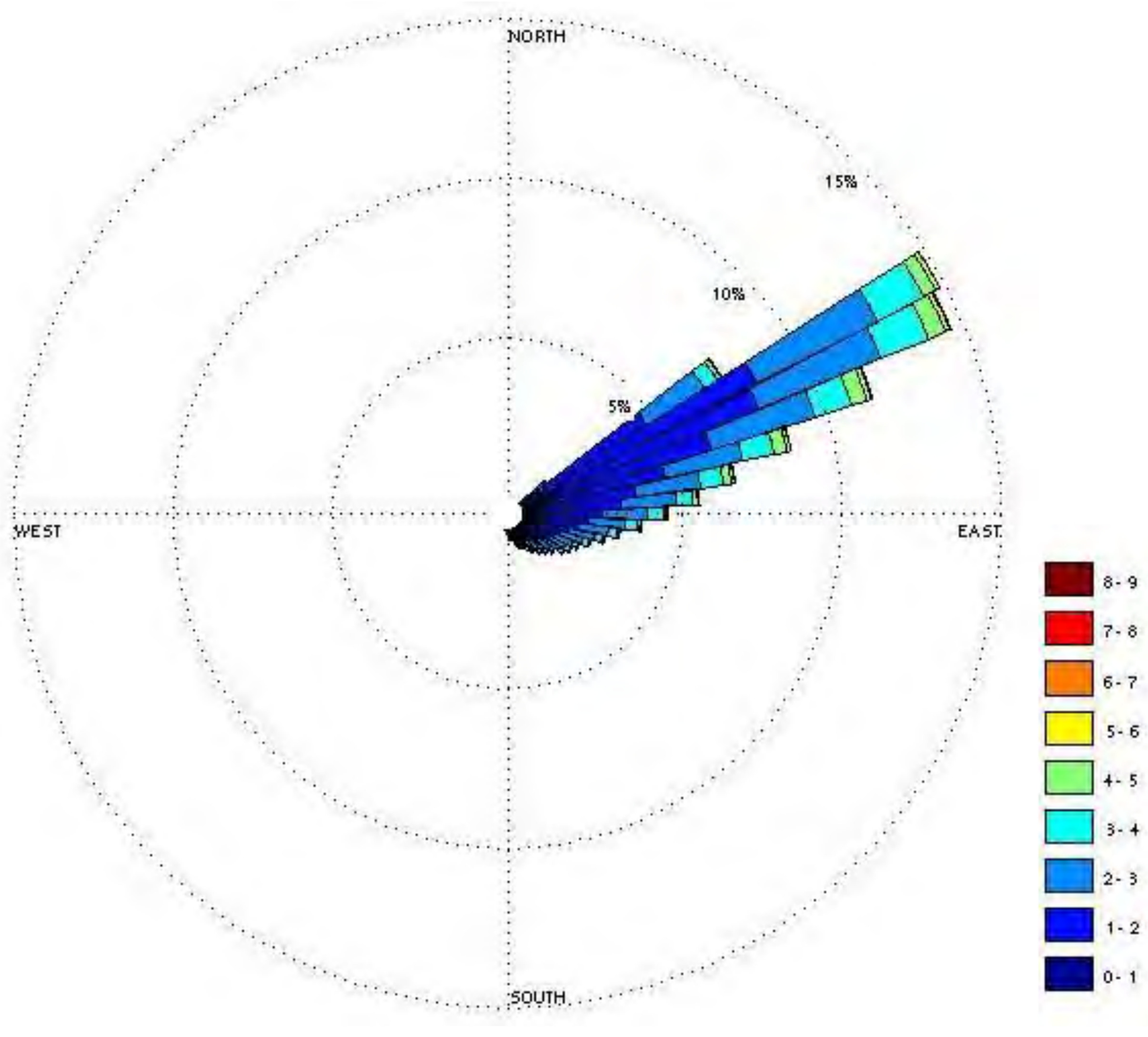

Figure 2.4. Frequency of wave height and wave direction west of the New River Lagoon, 1979-1999 (Latitude -42.557 ^{0}S, Longitude 171.065 ^{0}E)

2.2.5 West Coast sediment supply

The majority of sediment supplied to the West Coast marine area comes from major rivers and is deposited on the beaches and continental shelf. It can be lost offshore via the Hokitika and Cook Canyons or further north on the Challenger Plateau (Neale *et al.,* 2007). Sedimentation rates along the West Coast"s continental shelf are among some of the highest in New Zealand, estimated to be approximately 1.3 $mm.y^{-1}$ (Norris, 1978).

Precipitation patterns have a large influence on sediment supply to the coastline causing sediment runoff into waterways and adding to stream flow. During periods of high river flows (i.e. flooding) sediment movement is generally at its greatest, in comparison with low river flows where the movement of bedload sediment is less likely (McConchie, 2001). As mentioned in Section 2.2.2, heavy rainfall on the West Coast tends to occur during spring and autumn months. Therefore, based on precipitation levels, the period between October and March is likely to produce the highest sediment levels at the coastline. Furthermore, the combination of high precipitation and snow melt in larger catchments, such as the Taramakau, is also likely to elevate river flows and subsequent sediment volume at the coast during spring (Benn and Todd, 2005).

As mentioned in Section 2.2.4, the prevailing wave climate along the West Coast is in a NE direction, making longshore sediment transport dominant in a northerly direction. Therefore, the Taramakau River, located immediately south of the New River Lagoon (Figure 1.1, 2.1), is the most likely source of sediment to the lagoons immediate coastline. According to Benn (2004) the Taramakau River delivers approximately 122,220 m^3 of bedload sediment to the adjacent coastline every year. Benn calculated that approximately 81,500 m^3yr^{-1} of this sediment drifts northwards. Benn and Todd (2005) suggest that the majority of sediment supplied to the coastline follows periods of heavy rainfall in the Taramakau catchment and the majority of sediment supplied to the beach fronting the New River Lagoon follows periods of northerly longshore drift.

2.3 Site description

2.3.1 New River Lagoon

The New River (*Kaimata*) Lagoon is a long, narrow, river-mouth lagoon system located on the West Coast of the South Island, New Zealand (Neale, 2006a; Neale *et al.,* 2007). It actively spans approximately 4.2 km from Camerons to Paroa and is fed by two waterways: the New River, flowing from the south; and Saltwater Creek, flowing from the north (Figure 2.5). Both waterways flow parallel along the coastline and converge to form one lagoon and outlet system. At present, the lagoon discharges at the point where both waterways converge, which is controlled by an artificial outlet and breakwater, described in more detail in Chapter 1, Section

1.3.2. There has been very little research into the characteristics and behaviour of the New River Lagoon and its surrounding environment, aside from a few small reports written for consent application purposes. These include (Benn, 2004; Benn and Todd, 2005; Smart, 2010). Figure 2.6 shows several images of the New River Lagoon environment.

The New River Lagoon is classified by Neale (2006a) and Neale *et al.* (2007) as a hapua-type lagoon based on geomorphological characteristics such as its parallel movement behind a predominantly mixed sand and gravel barrier beach and its tendency to migrate in the northerly direction of longshore drift. Both these characteristic are typical of a high energy coastal environment and express the dominance of marine processes at this lagoon. However, the New River Lagoon displays some different characteristics to the traditional hapua, described in detail on the East Coast of the South Island (Hart, 1999; Kirk and Lauder, 2000). The most notable difference is that the New River Lagoon experiences tidal influences, which in the past was thought to be confined mostly to the lagoon outlet (Neale *et al.*, 2007), but at present is likely to have increased due to recent engineering work that now allows for more consistent exchange of water between the lagoon and the sea. The hydrological regime of the New River Lagoon following engineering management is provided in Chapter 5 and a discussion regarding the similarities and differences between the New River Lagoon and hapua is provided in Chapter 6.

There are several remnant lagoon channels surrounding the study site; two in particular are recent and have the potential to be reinstated. To the south, a past channel runs parallel along the coastline adjacent and in front of the current New River channel. This channel eventually runs dry, but manages to divert some water from the New River, so is constantly wetted. A second channel to the north has been cut-off by the rubble-mound breakwater in an attempt to prevent the lagoon from migrating further north. In the past, this channel meant the New River flowed parallel with Salt Water Creek. This channel is now completely cut off from the lagoon system, but could become active if Salt Water Creek breaches its barrier, or if the breakwater fails to maintain a stable lagoon outlet. A third channel, currently acting as a vegetated drain, flows north of Saltwater Creek. It is unlikely this channel will ever become re-instated, but it is low-lying and prone to flooding when Saltwater Creek water levels back-up.

The landward edge of the lagoon, lagoon islands and much of the surrounding land of both New River and Saltwater Creek channels are densely vegetated (Figure 2.6), while the barrier beach fronting the lagoon is variable in its vegetation cover, ranging from almost completely covered in vegetation to being completely exposed, which is due to processes of wave overtopping and lagoon outlet migration. Muddy depressions close to the Paroa Hotel consist of localised areas of raupo, flax and oio. Kowhai and flax are located along the riparian margins of the lagoon, while species farther from the water include kahikatea saplings, mahoe, pigeonwood, cabbage tree, and wineberry. Weeds such as gorse and blackberry are also present in abundance.

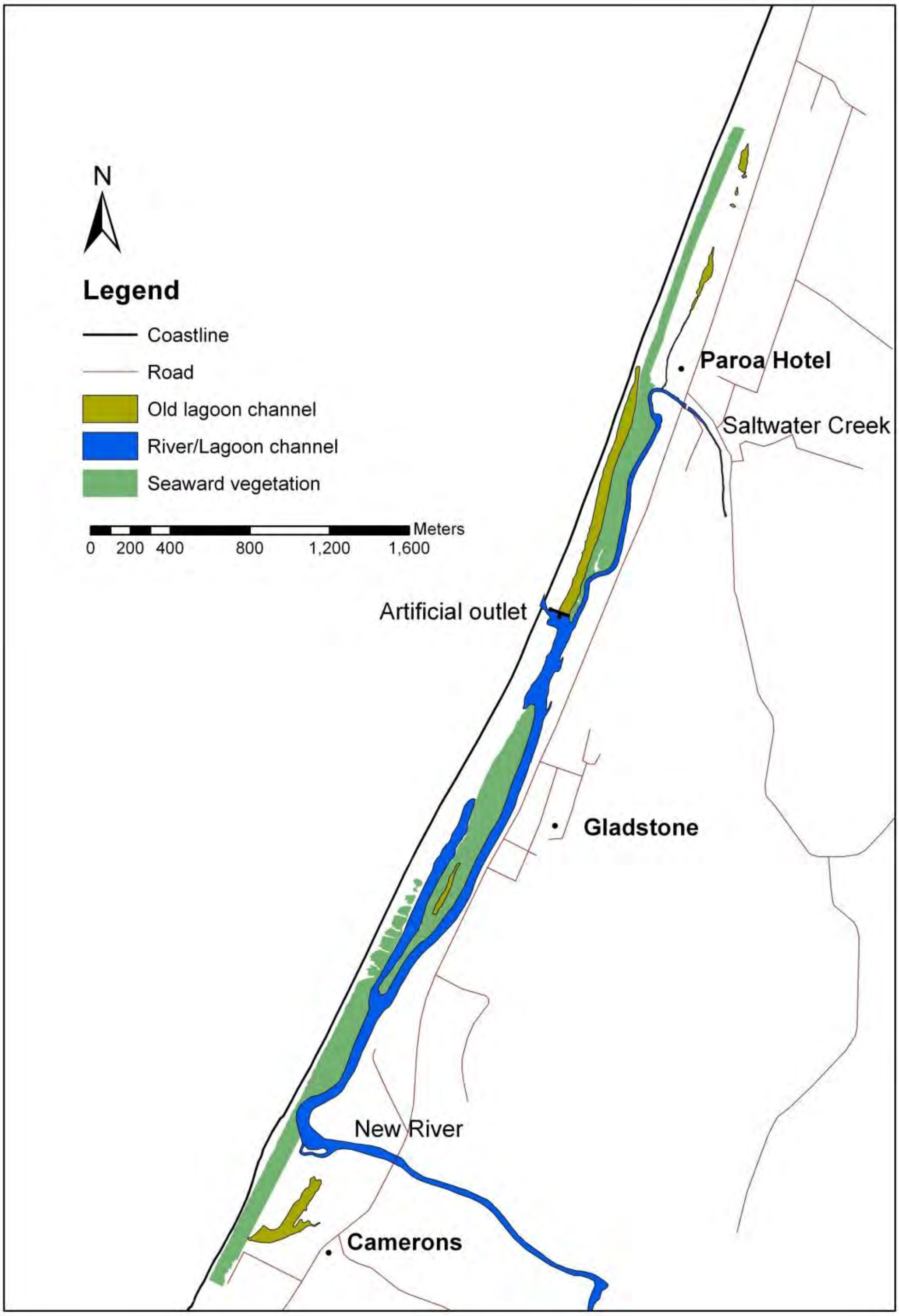

Figure 2.5. New River Lagoon site map showing past and present lagoon channels (features digitised using a georeferenced 2010 aerial photograph)

Figure 2.6. The New River Lagoon environment. A) Longitudinal view of the lagoon looking south, showing remnant lagoon channels flowing into the Saltwater Creek channel in the foreground and the New River in the background (photo courtesy of Trevor Johnson, taken in 1999). B) Longitudinal view of the lagoon looking north, showing the New River channel bending and flowing parallel with the coastline. Vegetation is dense landward of the lagoon and surrounding channels and islands, whilst the seaward extent of vegetation decreases northwards (photo courtesy of Don Neale, taken on 01/05/2006). C) Saltwater Creek channel, highly vegetated on both sides and approximately 10 m wide (03/03/2011). D) New River channel, highly vegetated on both sides and approximately 25 m wide (02/03/2012). E) Wide angle view of the artificial lagoon outlet, showing the New River channel to the right, remnant lagoon channel to the left and Saltwater Creek in the background (09/10/2011, photo courtesy of Laurie Anderson).

2.3.2 Beach environment

The present day barrier beach fronting the New River Lagoon has formed since the end of the last glaciation period (10-14,000 Y.B.P) and is the newest in a series of inter-glacial beach surfaces (Soons, 2001; Benn, 2004). It is between approximately 40 m and 140 m wide in places with the widest section of beach located between north of the New River and mid-Gladstone. There is evidence of blowouts along the barrier beach, especially at the southern end of the lagoon where the New River has changed course in the past. Figure 2.7 shows the beach environment fronting the New River Lagoon.

To date there have been no in-depth beach sediment analysis other than site observations, so it is not possible to know its exact morphological classification. Greywacke, granite and schist make up the general composition of beach sediments, eroded from the region"s bedrock (Benn, 2004). The beach material is highly variable both alongshore and across-shore, ranging from fine sand to cobble-sized sediments. The character of the beach can change rapidly depending on the regime of sediment distribution at the time. For example, beach morphology can range from a typical „mixed sand-gravel beach" (a mixture of sediment sizes, mixed across and within the extent of the beach) to a „composite sand and gravel beach" (finer sands covering a gentle sloping foreshore and boulder size sediment forming a steep upper foreshore) (Shulmeister and Rouse, 2003), to an almost completely gravel beach (Benn, 2004) (Figure 2.7). A report by Benn (2004) attributes these changes in beach type to a change in prevailing river and sea conditions.

There is an obvious change in beach character between the northern, central and southern beach sections fronting the New River Lagoon. According to Benn (2004), the barrier beach termini are fixed roughly between opposite the New River Bridge and the Paroa Hotel, which explains the decline in sediment accumulation north and south of these two points. This was particularly evident at the southern section of the beach during a site visit, where the build-up of gravel sediments was seen to steadily decline southwards, exposing the hinterland to storm surge events (Figures 2.7).

The stretch of coastline between the Taramakau River and Greymouth has been in a state of accretion, according to studies by Pfahlert (1984), Benn and Todd (2003) and Benn (2004). Although there has been very little specific research into beach characteristics along the coastline fronting the New River Lagoon, Benn (2004) drew together information from profile surveys undertaken at Pandora Ave and the Paroa Hotel, carried out during the years of 1992 and 2004. Results from these surveys show the beach to be in a state of accretion, increasing in volume by a net total of 290,875 m^3 during the 12 years between surveys. Similar results were found in a study by Pfahlert (1984) for Kororo beach, between the southern end of the aerodrome and northern end of South Beach, immediately north of the New River Lagoon. Pfahlert (1984) found the beach was accreting at an average rate of 6,165 m^3yr^{-1}. A study by Benn and Todd (2003) also found the stretch of beach between the Paroa Hotel and Blaketown to have increased in volume by a net total of 37,000 m^3 between 1992 and 2002. The stability of the beach fronting the New River Lagoon is analysed using aerial photographs in Chapter 4.

Figure 2.7. Beach environment fronting the New River Lagoon. A) Barrier beach immediately south of the New River Bridge. The berm is relatively low lying and the landward extent of vegetation cover extents close to the beach. There is evidence of scouring of the back beach due to storm surge and a lack of built-up protection (27/10/2011). B) The same stretch of beach 4 months later. Note the change in sediment composition from predominantly gravel dominated to sand dominated (02/03/2012). C) Barrier beach north of the lagoon outlet is steep and wide (04/08/2011). D) The same stretch of beach 7 months later. Sediment composition has changed from composite sand and gravel to dominant gravel (02/03/2011). Note the alongshore differences in sediment compositions between photos C and D, both taken on the same day.

2.4 Summary

This chapter has described in detail the New River Lagoon on a regional and site specific scale using available literature and observations made in the field. The West Coast region is identified as a high energy environment controlled by extreme climatic conditions, consequential of its location on the windward side of the South Island, New Zealand. The interaction between high levels of rainfall, which contribute to a large sediment yield at the coast and a high energy wave climate, shape the coastal environment. Marine circulation is controlled by the West Coasts location in close proximity to the subtropical convergence zone. The Westland Current is the dominant current affecting the West Coast, creating a distinctive northerly drift of sediment.

The New River Lagoon is fed by two rivers: the New River, flowing from the south and Saltwater Creek, flowing from the north. Both waterways drain relatively small catchments and converge to form one lagoon system that drains through a single artificial outlet. Both catchments have been exposed to processes of glacial advance, covering the catchment in Quaternary sedimentary deposits and tectonic activity causing deformation of the landscape and uplifting of shore platforms and cliffs. The New River Lagoon currently resides on the lowest of a series of inter-glacial beach surfaces. The lagoon shows several geomorphological characteristics similar of hapua, but is also strongly influenced by tides; a characteristic more common of estuary systems. Several past lagoon channels are present at the study site, attributing to the dynamic nature of the lagoon outlet in the past. The dynamic lagoon outlet, in combination with a high energy wave climate, has meant that vegetation is variable in areas seaward of the lagoon, while landward areas of the lagoon are covered in dense vegetation.

The beach fronting the lagoon is considered to be in a state of accretion and is composed of greywacke, granite and schist eroded form the regions bedrock. Its sediment composition is variable alongshore and across-shore and can cycle from mixed sand and gravel to composite sand and gravel.

Chapter 3 : Lagoon and Hapua Process Environments

3.1 Introduction

Coastal research has advanced greatly over the last 50 years with the development and availability of technology enhancing the scope and detail to which research can be undertaken. This chapter provides a comprehensive overview of available New Zealand and international literature surrounding the process environments affecting coastal lagoons, their dynamics and management. In doing so, the interaction between marine and fluvial process environments is highlighted as a key factor in determining the behaviour, morphology and hydrology of a coastal river-mouth system. As such, the New River Lagoon is exposed to a distinct processes environment that means it shows characteristics of both hapua and estuarine systems. Hence, this chapter provides an in-depth critique of the characteristics of each of these lagoon types. Similar lagoons are identified on the West Coast of New Zealand and in areas of Australia and South Africa.

The following chapter is divided into four sections: Section 3.2 discusses the uncertainty surrounding the definition of different coastal waterbodies, in particular the classification of coastal lagoons and estuaries. Section 3.3 looks at the process environments affecting the dynamics of hapua; Section 3.4 focuses on lagoon hydrology and morphodynamics and describes the process environments of Intermittently Open Closed Lagoons (ICOLs); a similar tidally influenced type of lagoon to the New River Lagoon, found predominantly on the East Coast of Australia and in areas of South Africa. Finally, Section 3.5 briefly discusses the effects that management intervention can have on the dynamics of coastal lagoons.

3.2 Coastal lagoons

Coastal lagoon systems occupy approximately 13% of coastal areas worldwide (Kjerfve, 1994) and are most abundant on micro-tidal coastlines (Barnes, 1980). The term „coastal lagoon" can refer to a diverse range of coastal waterbodies, each with different geomorphological and process characteristics and dynamics (Tagliapietra *et al.*, 2009). Generally, coastal lagoons can be considered as shore-parallel, shallow waters, separated from the ocean by a barrier, but connected to the ocean at least intermittently by one or more restricted outlets (Kjerfve, 1994). The variability in geomorphology of coastal lagoon systems, caused by differences in local process environments, means they exhibit salinities that range from completely freshwater coastal lakes to hypersaline lagoons. Many coastal lagoons formed during the Holocene and Pleistocene as a result of sea level rise and barrier building marine processes (Kjerfve, 1994).

Apparent similarities between coastal lagoons and estuaries have created confusion about the correct definition and classification of coastal waterbodies around the world (Tagliapietra *et al.*, 2009). Earlier definitions of estuaries by Pritchard (1952), and Cameron and Pritchard (1963) were based on the hydrology and morphology of a coastal system. Cameron and Pritchard (1963 p. 306) define an estuary as a "*semi-enclosed body of water having a free connection with the open sea and within which the sea-water is measurably diluted with freshwater derived from land drainage*". Whilst Phleger (1969) and later Kjerfve (1994 pg. 2) define lagoons 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"*. These two definitions are not only similar but they are also not mutually exclusive, meaning that a waterbody could be an estuary but also fit into the lagoons definition. The key factor distinguishing the definition of lagoons from estuaries is the level of water exchanged with the open ocean. Different process environments determine the degree to which fluvial and oceanic systems interact with one another to determine the morphology and hydrology of a coastal system. Estuaries are generally exposed to a process environment dominated by tidal influences, while the interactions between marine and fluvial environments are generally more restricted in coastal lagoons (Kjerfve, 1986). Variations in the extremity of these process environments, and thus the morphology and hydrology of coastal waterbodies, have resulted in the development of a number of sub-classifications for coastal lagoons and estuaries that overlap with one another.

The most recognised classification of different coastal lagoon systems comes from Kjerfve (1986, 1994), who characterises them into leaky, restricted or choked categories based on their degree of water exchange with the ocean (Figure 3.1). Leaky lagoons are shore-parallel water bodies that consist of many ocean entrance channels and are typically found along coastlines where tidal currents are dominant over sediment transport and wave processes. Restricted lagoons are large, wide, shore-parallel water bodies that generally consist of one or more channels and are influenced by tidal circulation. Choked lagoons are at the opposite end of the water exchange spectrum from leaky lagoons and commonly occur on high wave energy coastlines that are largely affected by processes of longshore drift. They are characterised by one or more long, narrow entrance channels and are susceptible to long durations of closure. The lagoon system that is the focus of this study is of the choked variety.

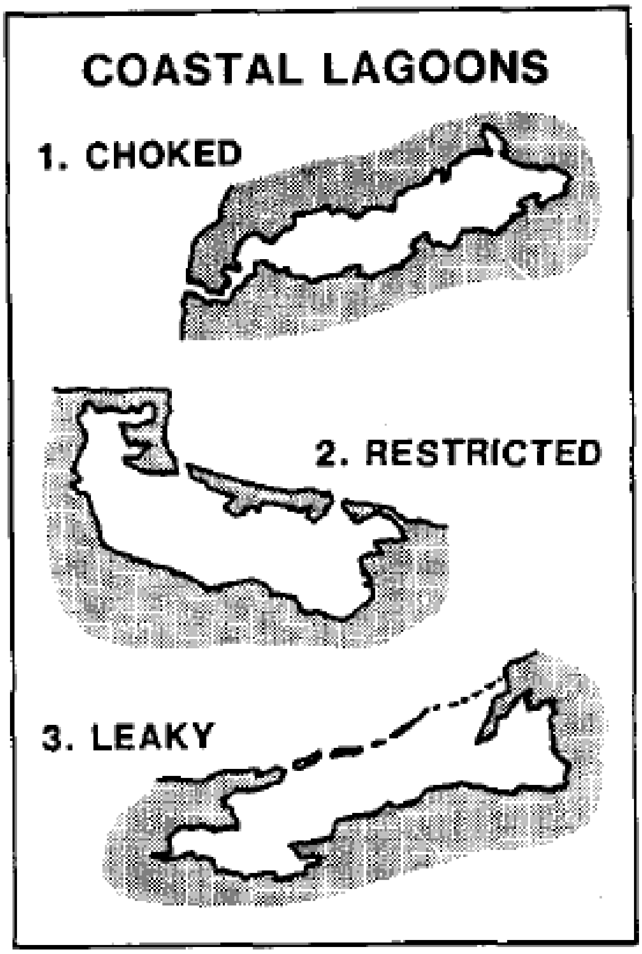

Figure 3.1. Coastal lagoons can be sub-divided into choked, restricted or leaky based on their degree of water exchange with the ocean (Source: Kjerfve, 1994 pg. 4)

Coastal lagoons in the South Island of New Zealand consist of the choked and restricted variety, whilst leaky lagoons are more common in the tropical areas of the world (Kirk and Lauder, 2000). Kirk and Lauder (2000) identify two types of chocked coastal lagoons on the eastern and southern coasts of the South Island: hapua, which can be described as „river-mouth lagoons", and waituna, which can be described as „coastal lakes". Neither type of waterbody is subject to regular tidal ingress, nor do they have a tidal prism, although back-water effects can occur due to lagoon drainage lessening at higher tidal stages. Importantly, both have outlets, not inlets (i.e. water flows out rather than being exchanged in and out). For the remainder of this chapter all lagoon entrances will be referred to as outlet, regardless of hydrological dynamics.

The scope of research on hapua-type lagoons is limited mostly to the East Coast of New Zealand. Some available literature, such as Neale (2006) and Neale *et al.* (2007) define specific coastal lagoons on the West Coast of New Zealand as hapua, despite their inherent differences to the traditional definitions. This stems mostly from lack of understanding and research into the processes and dynamics of West Coast lagoons. A study of the Totara Lagoon, located on the West Coast of New Zealand by Kain (2009), highlighted the differences between East and West Coast hapua and provided insight into the connectivity of coastal lagoons and estuaries in New Zealand. The Totara Lagoon was initially defined as a hapua-type coastal lagoon, based on its barrier structure, behaviour and coastal setting. However, during the extent of Kain‟s (2009) study, it was revealed that the lagoon was undergoing tidal exchange with the open sea, a trait strictly uncharacteristic of hapua (Kirk and Lauder, 2000; Hart, 2007), but characteristic of estuaries. On the whole, the lagoon showed more characteristics of hapua than of estuaries and although the lagoon experienced tidal ingress, it was situated on a wave-dominated coastline rather than a tidally dominated coastline, so could be defined as neither. Instead, Kain (2009) suggests that hapua should in fact be placed on a continuum at the opposite end from estuaries, with an overarching classification of river-mouth lagoons.

Similarly, Intermittently Open/Closed Lagoons (ICOLs), found in south-east Australia and South Africa (Haines, 2006; Whitfield and Bate, 2007), can also fluctuate between estuaries and non-estuarine classifications, due to intermittent levels of tidal exchange associated with periods of outlet opening and closing (Tagliapietra *et al.,* 2009). These examples reinforce the way in which hydrological and morphological features in lagoons and estuaries can vary in scale and extremity to a point where classifications schemes overlap. The gap that divides estuaries from coastal lagoons is particularly important for the New River Lagoon, as it displays various characteristics that are traditional of both coastal lagoon and estuary definitions, similar to Totara Lagoon and ICOLs.

3.3 Hapua formation and dynamics

The formation of hapua environments is reliant on a micro-tidal or near micro-tidal coastline, where tidal range is approximately or less than 2 metres, a high energy swell-wave climate and strong longshore drift of sediment. Many hapua are products of what is termed „small rivers‟ (Kirk and Lauder, 2000). Zenkovich (1967) defines „small rivers‟ as those that do not produce a sufficient supply of sediment to the marine environment to maintain a stable or accreting coastline. Therefore, many hapua reside on coastlines that are in a state of erosion due to processes of abrasion and longshore sediment transport (Kirk and Lauder, 2000). Most examples of hapua in published literature are formed at the mouth of large braided rivers (Kirk, 1991; Kirk and Lauder, 2000). However, hapua can occur on smaller braided to meandering rivers and small lowland streams (Hart, 2009a). The lagoon in this study has formed at the conjoint mouth of a meandering river (New River) and a low land stream (Saltwater Creek).

As depicted in Figure 3.2, the formation of hapua is initiated by the accumulation of sediment in the nearshore zone, which is reworked landward by cross-shore currents and simultaneously alongshore by longshore transport, forming a barrier spit across the river mouth. This process often follows a primary breach (a breach of the barrier beach directly opposite the river mouth) where a large amount of sediment is injected into the nearshore zone (Kirk, 1991; Todd, 1992; Hart, 1999). The formation of a barrier diverts the flow of the river parallel to the ocean, carving out a depression between the hinterland and back barrier beach to form the main lagoon channel (Kirk, 1991; Hart, 1999).

River discharge, wave-induced longshore transport, wave-overtopping processes and lagoon morphology are four components controlling the on-going dynamic change in hapua. These processes of morphological change have been observed to occur consistently amongst hapua, but influence on hapua behaviour can vary in frequency and scale (Hart, 2009a). The general trend for hapua is that marine wave processes are often more dominant than fluvial processes, forcing morphological changes such as lagoon outlet closure and migration (Hart, 1999, 2009a). Fluvial processes only dominate morphological change during periods of peak river flow, causing primary barrier breaches and injecting sediment into the coastal marine environment (Kirk, 1991; Todd, 1992; Hart, 1999).

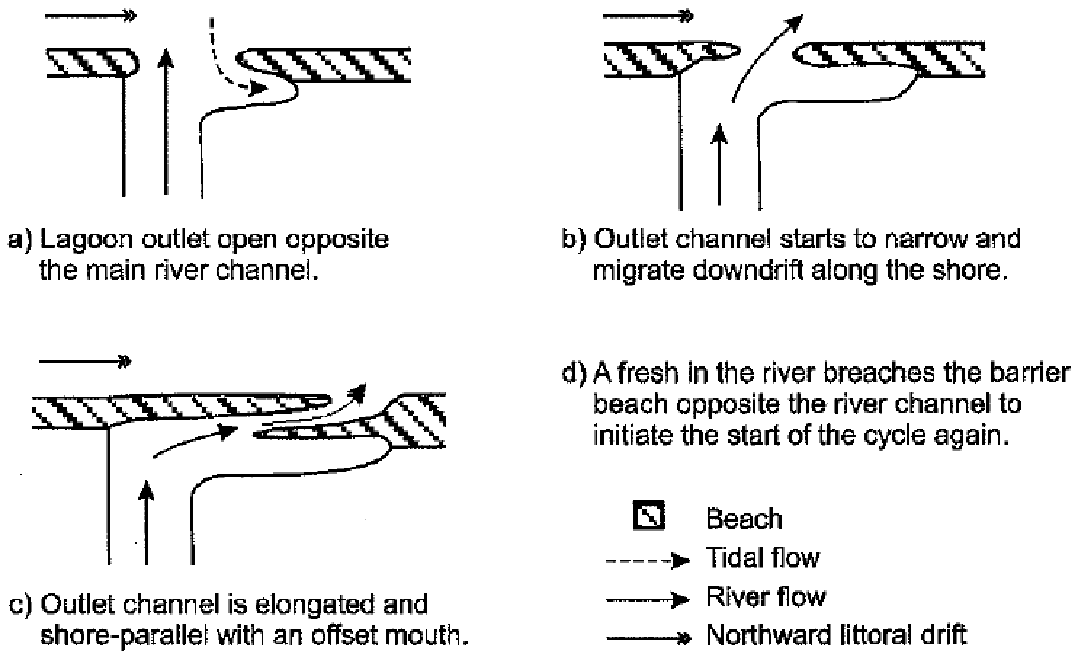

Figure 3.2. A Cycle of river-mouth behaviour and lagoon outlet migration (Source: Todd 1992 pg. 212)

Hart (2009a) found in her study of 11 hapua lagoons on the East Coast of the South Island, that hapua often experience several different morphological states and shifts between states. Figure 3.3 shows the cycle of behavioural changes observed in hapua. The dominance of wave over fluvial processes tends to produce the most significant shifts in lagoon phases (i.e. average sea conditions and low fluvial flows, or storm sea conditions and all but peak fluvial flows), inducing narrow and extended migrating outlets, closed outlets and barrier beach overtopping. In contrast, fluvial dominated phases cause primary and secondary barrier breaches, but less regularly. Hart (2009a) found that phase changes between states were reflected in the differences in flow regimes of the river. Of the 11 rivers reviewed in this study, the mean annual fluvial flows varied between 373 m^3 s^{-1} and <3 m^3s^{-1}, which reflected the size of the rivers and their catchments. It was found that hapua experiencing low river base flows were more likely to undergo prolonged periods of lagoon outlet closure, whilst hapua that experience medium size river base flows often exhibited long outlet channels and more frequent phase changes. In contrast, hapua with high river base flows were able to maintain more stable lagoon phases, as their fluvial flows were better at balancing the high energy marine environment.

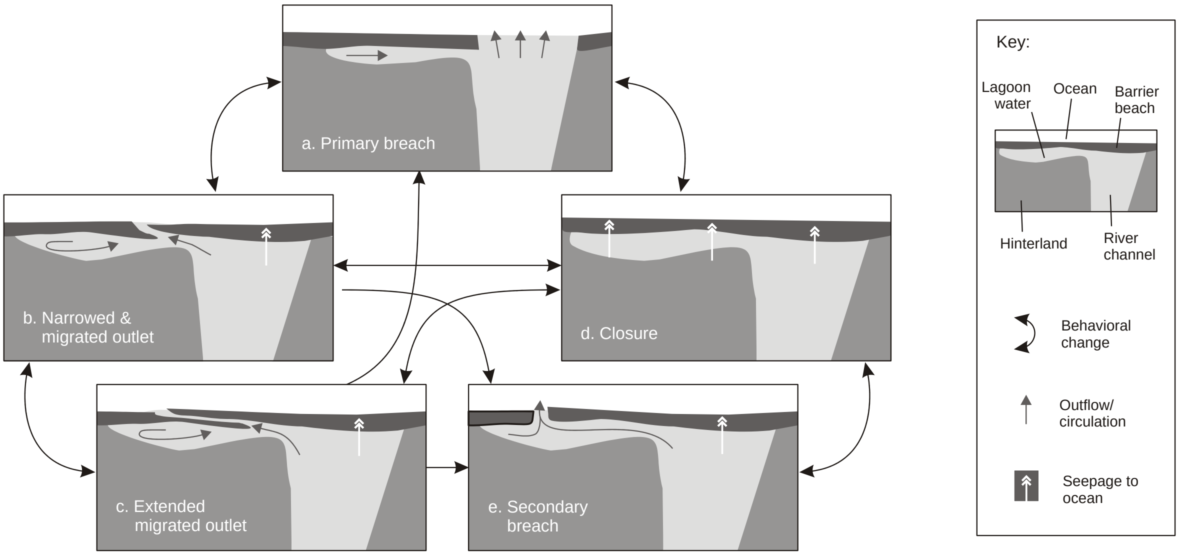

Figure 3.3. Range of states and changes between states exhibited by different East Coast hapua due to the balance between marine wave processes and different levels of river flow (Source: Hart, 2009a pg. 1357)

Although all hapua in Hart"s (2009a) study were situated on a wave dominated coastline, they each experienced different sensitivity to change due to their different balances between marine and fluvial processes. This balance is best described by Hart"s (1999) hapua dynamics model shown in Figure 3.4. Her model combines the effects of both river discharge (x-axis) and the impact of wave height (y-axis) on outlet position, barrier morphology and lagoon behaviour. The model defines threshold levels (dashed lines) for changes in morphology, which includes wave and fluvial based changes, as well as the combined effects of both process agents.

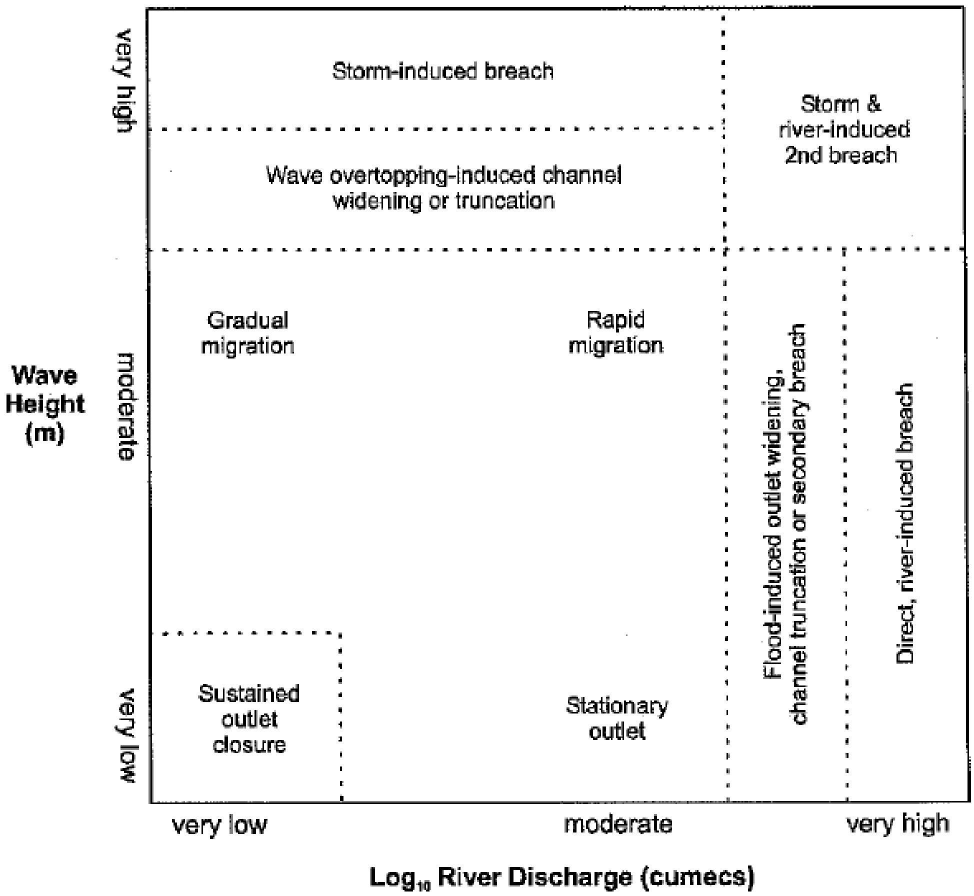

Figure 3.4. Descriptive model of hapua dynamics showing the relationship between marine and fluvial processes (Source: Hart 1999 pg. 198)

Hapua formation and phase changes are also highly dependent on the permeability of the barrier beach, which determines the through-flow of water between the lagoon and the ocean (Kirk, 1991; Todd, 1992; Hart, 1999). In traditional hapua, the barrier beach is often made up of mixed sand and gravel, which is a very permeable substrate. If river flow is less than the rate of barrier through flow then there will be no hydraulic head and the lagoon outlet will close as a result of wave processes. In contrast, during times of higher river flow, where barrier through flow is matched by river base flow, hydraulic head is sufficient to maintain an open lagoon outlet. During periods of medium flow the lagoon outlet is generally more mobile, displaying intermittent periods of opening and closing as well as periods of migration (Hart, 1999, 2007, 2009a). Kain (2009a) suggests that there is a linear relationship between river flow and barrier permeability in the formation of hapua. She found that hapua are capable of forming on rivers of smaller flow volumes when the barrier beach has a less-permeable sandy composition, provided that sediment supply, a high energy wave climate and longshore drift are still present (i.e. traditional hapua on the East Coast of the South Island have permeable mixed sand and gravel barriers and often form at the outlets of rivers with large flow volumes, while hapua on the West Coast can have low permeable sandy barriers and form at the outlets of low flowing rivers). Kain (2009) termed these low-flow hapua as 'sandy hapua'. This concept is important for the New River Lagoon, as it is formed on a composite barrier beach that cycles between being sand and gravel dominated (explained in more detail in Chapter 2, Section 2.3.2).

Management concerns with hapua include the sustained closure often experienced at the lagoon outlet caused by prolonged periods of low river flow. Lagoon outlet closure can cause the river to „back up" leading to the flooding of adjacent low lying land and blockage of fish passage between the river and the ocean (Hart, 2007). In order to avoid lagoon closure, river flows must be maintained above minimum thresholds by reducing anthropogenic influences such as irrigation. Alternatively, anthropogenic management techniques such as engineering excavation can be used to artificially open and relocate lagoon outlet"s to relieve the build up of water during periods of low river flow. However, these management techniques can have implications to the dynamics, hydrology and ecology of a lagoon and only temporarily relieve flooding if river flows remain low (explain in more detail in Section 3.5).

Kirk (1991) produced a model for water resource planning that essentially explains the morphological change and dynamics of hapua in response to periods of high, moderate and low fluvial flow, as shown in Figure 3.5. The model uses the Rakaia River as an example, suggesting that low river base flows (<45 m^3s^{-1}) could initiate lagoon outlet closure and sediment accumulation, moderate river base flows in combination with longshore currents allow for lagoon outlet migration and that high river base flows (>200 m^3s^{-1}) initiates lagoon outlet breach. Although the threshold values in this model have been made specifically for the Rakaia hapua, the concept that low, moderate and high river flows can have different morphological affects on a lagoon outlet can be transferred to other hapua for similar water resource management and catchment wide planning.

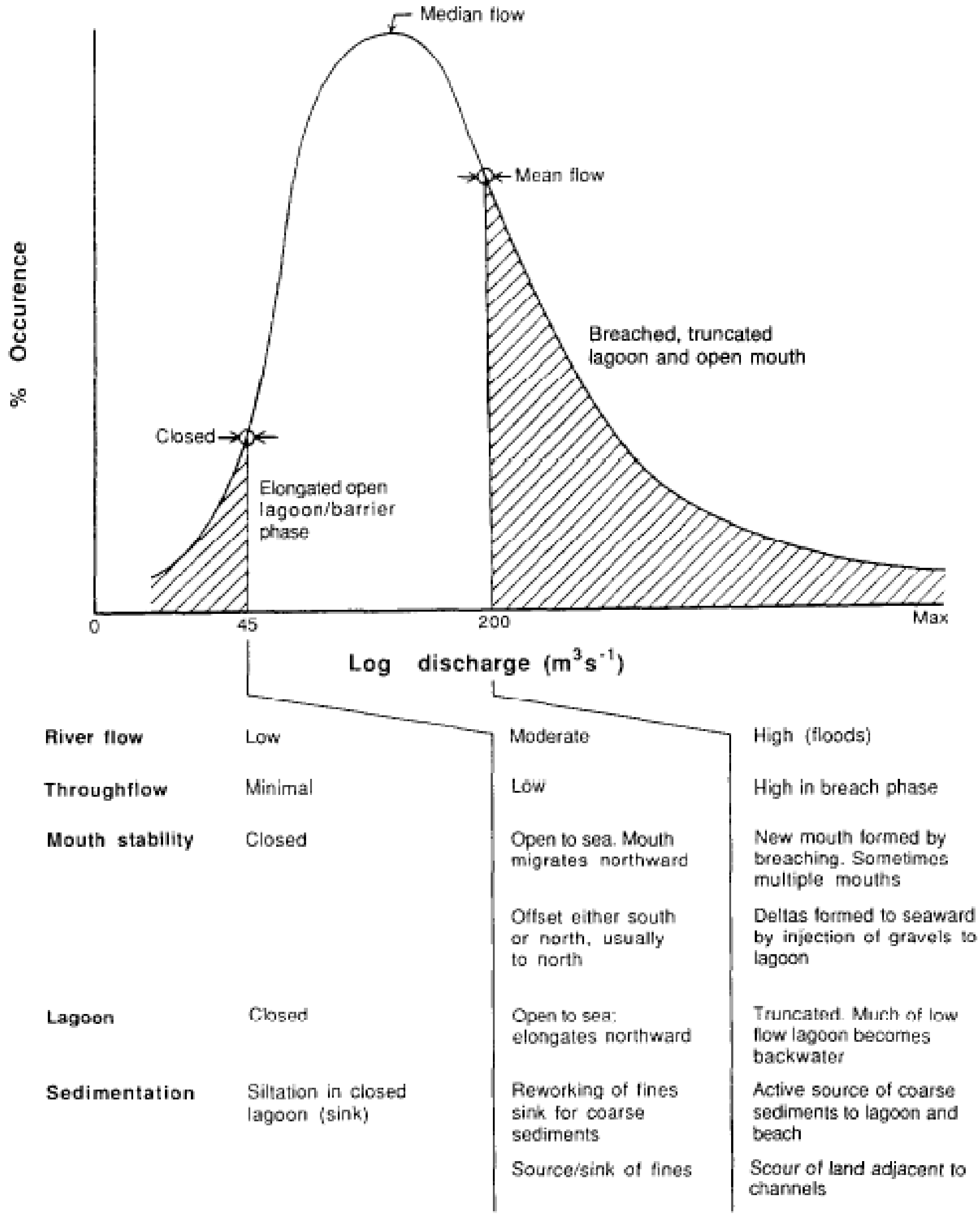

Figure 3.5. Descriptive model of the frequency of lagoon outlet dynamics in response to different levels of river water discharge. Threshold values for low, moderate and high river base flows are set for the Rakaia as a function of river discharge (Source: Kirk 1991 pg. 285)

3.4 Coastal lagoon hydrology and morphodynamics

By definition, coastal lagoons are not tidally-dominated, though some may be subject to tidal mixing and variable salinity gradients depending on the regional hydrological balance and the lagoons entrance dynamics (Kjerfve and Magill, 1989; Kjerfve, 1994). Hapua-type lagoons in particular do not experience any tidal ingress, prism or mixing (Kirk, 1991; Hart, 1999; Kirk and Lauder, 2000). However, they can be exposed to small temporary variations in salinity due to storm wave barrier overtopping (Hart, 1999, 2007), and water quality, as a result of catchment runoff (Kjerfve, 1989). Water circulation and stratification of coastal lagoons is dependent on a series of factors including tides, wind, runoff, weather, storms, sea level and the exchange of heat and water with the atmosphere (Kjerfve and Magill, 1989; Bird, 1994). Generally, choked lagoons are shallow (a few metres deep) so are well mixed, meaning there is often no vertical salinity or temperature stratification. However, vertical density gradients can occur during periods of low freshwater inflow due to surface heat exchange, while horizontal density gradients can dominate during periods of pronounced wind mixing (Kjerfve and Magill, 1989). The main geomorphological factors influencing the hydrology of a lagoon are entrance size and shape, water depth and lagoon orientation to prevailing winds. Furthermore, tidal exchange in a lagoon is controlled by the balance of marine and fluvial processes and the influence this has on the dynamics of the lagoon outlet (Cooper, 2001).

The New River Lagoon in this study has been describes by Neale (2006a) and Neale *et al.* (2007) as a hapua-type lagoon, but is known to have experienced intermittent tidal exchange in the past, particularly in the immediate vicinity of the outlet and now has regular tidal exchange under current management intervention. Other West Coast lagoons, which have been described as hapua, are also known to exhibit tidal exchange (Kain, 2009). Similar constricted, but tidally influenced lagoon systems are also found internationally in south-eastern areas of Australia where they are known as „Intermittently Closed/Open Lagoons" (ICOLs) (Haines, 2006; Haines *et al.*, 2006; Morris and Turner, 2010) and in areas of South Africa where they are known as „Temporally Open/Closed Estuaries" (TOCEs) (Whitfield and Bate, 2007) or „Perched and Non-Perched Estuaries" (Cooper, 2001). For ease of understanding these lagoons will be referred to on the whole as ICOLs, unless stated specifically.

ICOLs are highly dynamic coastal lagoons located on micro-tidal coastlines and exposed to a high-energy swell wave climate (Haines, 2006; Whitfield and Bate, 2007). Outlet hydrodynamics at ICOLs are influenced by the balance of marine and fluvial processes, which means they typically cycle between open, closed and constricted phases (Roy *et al.,* 2001, Haines, 2006) (Figure 3.6). However, ICOLs are generally classified as being mostly open or mostly closed. In

New South Wales, Australia, 70% of ICOLs are mostly closed for more than 60% of the time, whilst 25% mostly open (closed for less than 20% of the time) (Haines, 2006; Haines *et al.*, 2006). Several factors determine whether an ICOL is mostly close or open, which includes catchment size, prevailing wave angle of approach and entrance channel controls (i.e. rock outcrops) (Roy *et al.,* 2001, Haines, 2006). ICOLs are often located adjacent to rocky headlands, with very few positioned mid-way along a beach (Haines, 2006; Haines and Thom, 2007); a situation similar to the current management regime of the New River Lagoon outlet.

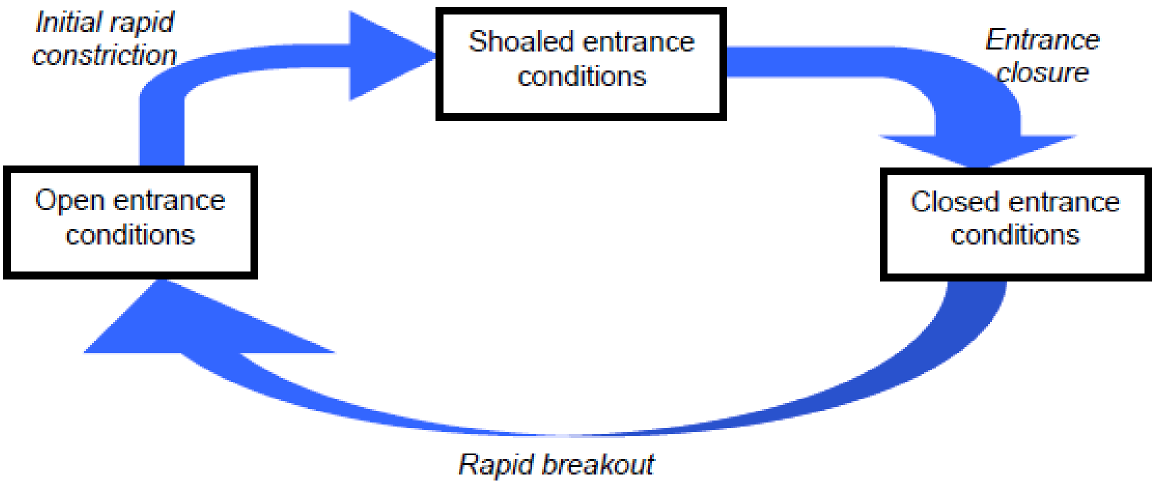

Figure 3.6. Morphodynamic cycle of ICOL entrance processes (Source: Haines, 2006 pg. 109)

The main difference between ICOLs and hapua is that ICOLs experience tidal exchange with the ocean following entrance breaching. Entrance breaching commonly occurs when elevated lagoon water levels exceed the height of the barrier beach or during periods of increased river flow (Gordon, 1990; Haines, 2006; Whitfield and Bate, 2007). Roy *et al.* (2001) and Bell *et al.* (2001) also describe wave overtopping as a second form of entrance breaching. Breaching often results in a 20 to 30 m wide channel cut into the barrier beach down to an elevation at or below mean sea level, allowing for tidal exchange once out-flowing flood waters become steady (Gordon, 1990; Cooper, 2001). Figure 3.7 shows the sequence of events leading to a barrier breach and tidal exchange. Tidal exchange is dependent on riverbed and barrier elevations following the breach, which can vary based on the strength and persistence of river flooding and subsequent down-cutting into the barrier beach (Cooper, 2001; Whitfield and Bate, 2007). In situations where the entrance channel is elevated above high tide level, the lagoon can instead „back up" in its lower reaches due to a damming effect caused by high tide (Cooper, 1990); an affect similar to hapua.

Tidal exchange is greatest at the immediate vicinity of the lagoon outlet, though can increase further into the lagoon if channel morphology and river flow conditions allow for tidal persistence.

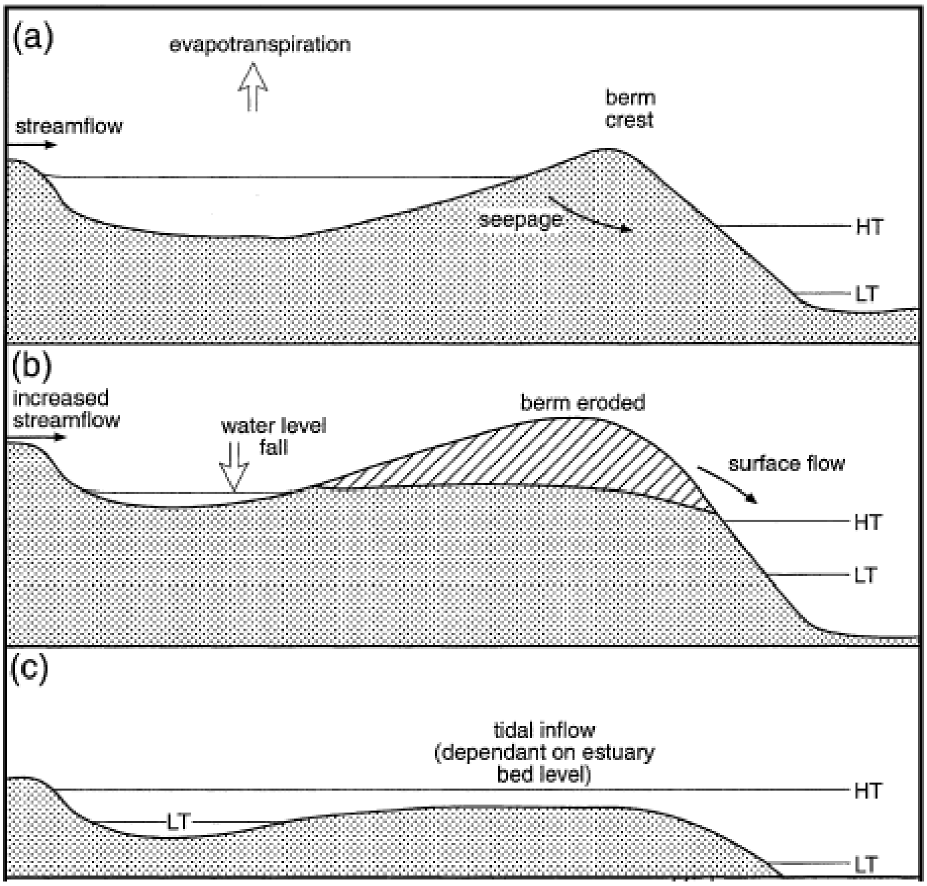

Figure 3.7. General behaviour of ICOLs during barrier berm breach (A-C). Under balanced conditions (A) the stream inflow is balanced by seepage through the barrier and evapotranspiration. During increased streamflow (B) the barrier berm is eroded and lagoon water levels drop as the outlet is opened. Tidal inflow occurs depending on channel bed elevation above sea level (C) (Source: Modified from Cooper, 2001 pg. 113).

The level of tidal influence in ICOLs can be related to the geomorphology of the barrier beach, which subsequently effects estuary bed elevations. Cooper (2001) describes the level of tidal exchange in South African lagoons as a function of bed elevation or whether they are typically „perched" or „non-perched". Perched lagoons are often located in tropical regions on steep, reflective, gravel beaches that are graded to a base level above sea level, so are not as likely to experience tidal ingress following entrance opening. In contrast, non-perched lagoons are located on more dissipative, sandy coastlines with a base level at or near sea level. These estuaries lack a large barrier berm so often undergo wave overtopping and are more susceptible to tidal ingress during entrance barrier breach (Cooper, 2001; Whitfield and Bate, 2007). Perched estuaries show greater similarities to hapua, while non-perched estuaries show more similarities of traditional estuaries.

The influence of tidal processes in ICOLs is often only short lived as the inflow of flood tides transports sediment into the lagoon, which is deposited and acts to close the lagoon outlet. The entrance closure of ICOLs is dependent on the availability of sediment in the nearshore zone and upper beach face following entrance breakout, and the strength of the incident wave climate relative to ebb-currents (Gordon, 1990; Haines, 2006). As lagoon closure progresses, ebb-tidal currents become inefficient at removing sand from the outlet. This is caused by the asymmetry of ebb- and tide-flows through the outlet channel (i.e. flood tides produce higher velocities near peak flow, compared with ebb tides that generate longer lasting but lower flow conditions), which mean ebb-flows cannot balance the removal of sediment with the incoming tidal deposition (Gordon, 1990; Haines, 2006). Closure is usually event driven, associated with a flood tide, storm surge event, elevated wave energy conditions, the spring tide cycle or low rainfall in the catchment (Gordon, 1990). A quick closure of the outlet channel can follow an outlet breakout because of an abundance of nearshore sediment available for distribution during incoming flood tides (Gordon, 1990; Haines, 2006).

Ranasinghe and Pattiaratch (2003) describe the closure of seasonally open tidal outlets, using Figure 3.8, as a function of two different mechanisms, each dependent on the strength of outlet currents (fluvial or tidal) and the dominance of either longshore or cross-shore sediment transport. Closure of the lagoon outlet by longshore currents (Mechanism 1) is common on exposed, high wave-energy coastlines and occurs when strong outlet currents interrupt the longshore transport of sediment, causing it to be deposited as an updrift shoal. The growth of an updrift shoal can force ebb-currents to shift downstream eroding the beach immediately downdrift of the outlet (Ranasinge and Pattiaratch, 2003). If outlet currents remain strong then there will be no progradation of the spit and it will remain open. However, if the outlet continues to accrete and begins to offset in the direction of longshore drift, then the hydraulic efficiency of outlet currents will begin to decrease and the it may eventually become blocked (FitzGerald, 1996; Komar, 1996). In some circumstances the outlet currents remain strong enough for the outlet to maintain an opening whilst sediment continues to accrete, forcing it to migrate in the direction of longshore sediment transport (Fitzgerald *et al.*, 2001). Closure of the lagoon outlet by cross-shore transport of sediment (Mechanism 2) is more common at a sheltered lagoon outlet where longshore currents are weak and when outlet currents are small, often due to either a small tidal prism or weak ebb currents (Ranasinge and Pattiaratch, 2003). Cross-shore currents and swell waves transport nearshore sediment into the lagoon outlet, often following stormy periods or lagoon outlet breach. If outlet currents are weak, sediment will infill the lagoon outlet. If outlet currents are strong, they will obstruct the onshore transport of sediment and the outlet will remain open.

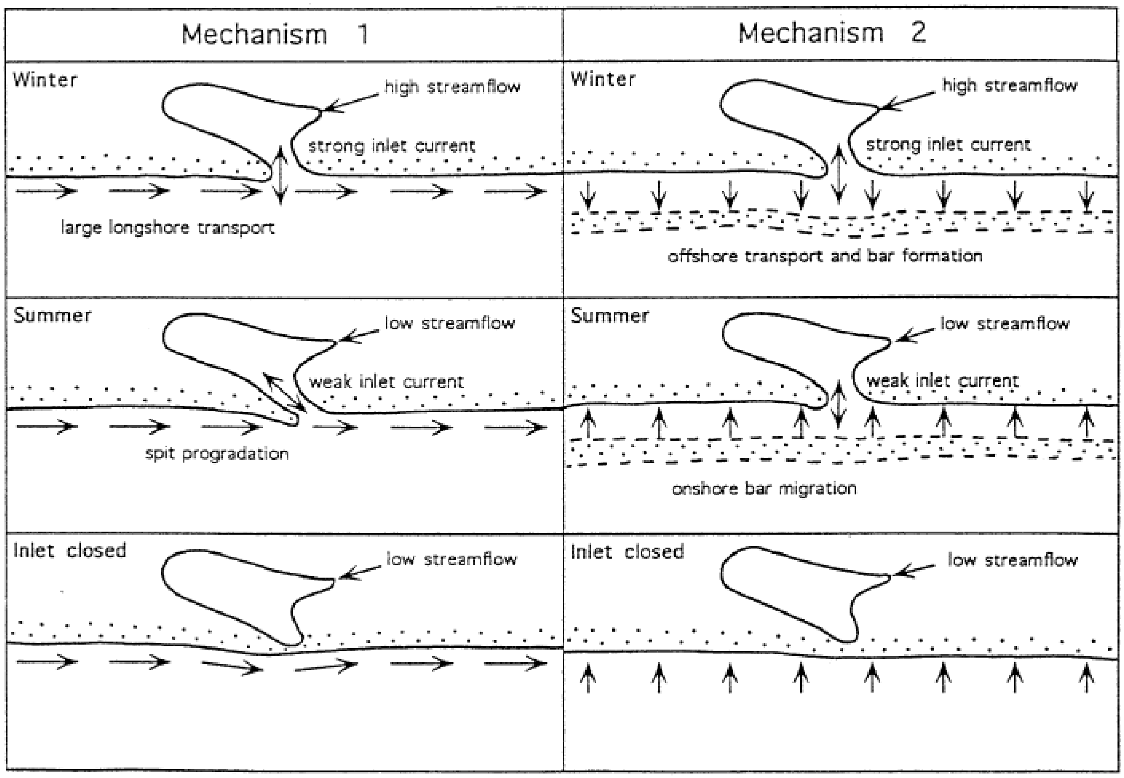

Figure 3.8. Tidal outlet closure via mechanisms of longshore and cross-shore sediment transport (Source: Ranasinghe and Pattiaratchi, 2003 pg. 604).

As mentioned above, tidal asymmetry contributes to outlet closure of ICOLs. Tidal asymmetry can vary with different channel morphologies such as outlet size, shape and depth. Consequently, some tidal systems can be ebb-tide dominated or flood-tide dominated. A study by Blanton *et al.,* (2002) found that tidal asymmetry on a narrow, shallow-channelled estuary was more pronounced in comparison with estuaries composed of wider tidal flats. These findings are supported by Speer and Aubrey (1985) who also found a relationship between water depth and tidal asymmetry. They suggest that shallow estuaries are more likely to experience longer ebb-tides and stronger flood-tides, while deep estuaries will experience the contrary. An increase in channel bed slope can also cause tidal asymmetry, as the energy required for a flood-tide to work its way up-stream is considerably greater than the energy for an ebb-tide to work its way down-stream (Masselink *et al.,* 2009).

Salinity regimes can oscillate between freshwater and hypersaline in ICOLs depending on outlet dynamics. Snow and Taljaard (2007) provide on overview of water quality in South African ICOLs. They found that salinity gradients are generally longitudinal during outlet opening, with the position of haloclines depending on the strength of river flow. During periods of closure the authors found saline levels were generally homogenous, although could be horizontally or vertically stratified immediately following outlet closure. River flow can also determine the level of influence that tidal flows have on estuarine and lagoon environments, which subsequently effects salinity and temperature mixing. Using field data and model simulations, Vaz *et al.* (2005) found that when river flow is weak, tidal intrusion is strong, generating mixed levels of salinity and temperature within a tidal channel. By contrast, during high river flows, tidal ingress is weak, which results in more stratified channel conditions.

3.5 Coastal management

The pressure put on the coastline is forever increasing with the development of land and nearshore coastal areas. Moreover, with increasing coastal development comes the need for protection of infrastructure and property. Coastal engineering protection is based around the manipulation of a natural system, whether it is by „hard" engineering techniques such as the construction of breakwaters, groynes and barriers, or „soft" engineering techniques such as beach nourishment and outlet relocation. The design and use of coastal engineering structures is based primarily on preventing erosion of the shoreline and flooding of coastal hinterland. Although engineering structures can also be used to shelter harbour outlets from waves, stabilise navigation channels and in the case of the New River Lagoon, it is hoped it will stabilise and maintain an artificial lagoon outlet. Recently, the implementation of „soft" engineering techniques has become more widely used because they tend work with the natural environment rather than opposing it (Gao and Collins, 1995; Hillyer, 1996).

The morphology, dynamics and location of lagoon and estuarine outlets are of primary concern to coastal management because they have potential to create hazards for local communities. A natural hazard is defined by Burton *et al.* (1978 pg. 10) as "*the release of energy or materials that threatens humans or what they value*", which in the context of coastal environments can vary temporally and spatially. Fundamentally, humans create hazards with their presence and desire to live alongside the coastline, which is why modification of the coastal environment for protection is of such importance. Flooding and erosion are two major hazards associated with lagoon and river outlets and are caused mostly by outlet blockage and outlet migration. For the purposes of this study, the following section will focus primarily on the different soft and hard engineering techniques used to manage hazards associated with dynamic coastal outlets, as well as the physical effects that these techniques can have on manipulating the natural environment.

3.5.1 'Soft' engineering management of lagoon outlets

In New Zealand, flooding is especially common in hapua-type lagoons similar to the New River Lagoon due to the dynamic nature of the lagoon outlet (Kirk and Lauder, 2000; Kain, 2009; Hart, 2009b). Consequently, one of the greatest issues surrounding the management of coastal lagoons in New Zealand, in particular on the West Coast of the South Island (Kain, 2009), is the artificial opening of lagoon outlets to reduce the risk of flooding, as well as promote certain recreational uses such as whitebaiting (Kirk and Lauder, 2000; Kain, 2009; Hart, 2009b). Similar issues are common in areas of south-eastern Australia, where many Intermittently Closed/Open Lagoons (ICOLs) are also artificially opened to reduce the effects of flooding and improve lagoon flushing characteristics (Roy *et al.*, 2001; Haines *et al.*, 2006). Flooding hazards are also of concern at the New River Lagoon and are explained in more detail in Chapter 1, Section 1.3.1.

Artificial outlet opening and relocation are common soft engineering management techniques that can be applied to a variety of different environments such as estuaries, lagoons, barrier islands and deltas as a temporary form of relief from an outlet that is prone to closure induced flooding or outlet migration. As with many soft engineering management techniques, one of the disadvantages of outlet opening and relocation is the limited duration of effect. Generally, once relocated and opened, the outlet will tend to close or migrate down-drift again until it reaches a point where it requires re excavation. Despite this disadvantage, outlet relocation and opening is a soft protection technique that is designed to work with natural processes. The effectiveness of outlet relocation can be modelled on several factors including, but not limited to, the duration in which the artificial outlet maintains a modified position (Goodwin, 1996; Vila-Concejo *et al.*, 2004); the effectiveness of flood mitigation; and its level of environmental impacts on a lagoon system. This study investigates the effectiveness of engineering management at reducing flood risk at the New River Lagoon, while imposing minimal impacts to the physical lagoon environment.

Vila-Concejo *et al.* (2004) analyse the changes at two large barrier island tidal outlets in Portugal following their artificial outlet relocation. The authors conclude that to improve the success of artificial outlet relocation, it is inherently important to gain knowledge of outlet behaviour before and after the relocation (Figure 3.9). They emphasise the importance of choosing an appropriate artificial outlet location in order to maximise the success of relocation. Some of the important features that must be understood before a relocation point is found are: historical migration paths, typical outlet width and the hydrology and morphology of the back barrier (Vila-Concejo *et al.,* 2004). Although such barrier outlet systems are of a much larger scale than most West Coast river-mouth lagoons, the principles of this research still applies to lagoon outlet relocation.

Kain (2009) reinforces the importance of preparing knowledge of a lagoon system prior to outlet relocation in her study of the Totara and Waikoriri Lagoons, in Westland, New Zealand. Both lagoons have a history of artificial outlet opening and relocation to relieve flooding hazards and enhance whitebait migration. Although her study was not solely directed at lagoon outlet management, Kain (2009) did notice the potentially negative effects of inappropriate artificial opening in response to high lagoon water levels in November 2008, causing an artificial barrier breach directly opposite the river outlet. The artificial breach caused a dramatic decrease in lagoon water levels and disruption to the natural lagoon hydrology and ecology, including a decrease in ecotourism values.

In contrast, Kain (2009) mentions that an artificial outlet is maintained opposite the river mouth at the Totara Lagoon without any obvious morphological effects to the present system. However, she does speculate that artificial opening may have had an effect on Totara Lagoon‟s hydrological regime. Totara lagoon has been considered a hapua-type lagoon; however, Kain‟s (2009) study showed the lagoon to be going through an „estuarine phase‟ of tidal exchange with the open ocean. Kain (2009) speculates that this tidal exchange may be, in part, a consequence of repeated artificial opening directly opposite the river outlet for two reasons: 1) the outlet channel experiences enhanced scouring and channel currents, carving it deeper below sea level, as opposed to a naturally offset outlet at an angle that does not allow fast moving water flow, and; 2) the location of the outlet in front of the river mouth means the angle of wave approach is oriented directly into the lagoon. It is unknown whether this change in hydrological regime has had any adverse effects on the lagoon environment since the opening was first maintained artificially many years ago. What can be learnt from these contrasting responses to artificial opening is that all lagoon systems need to be assessed on a case-by-case basis before management decisions are made.

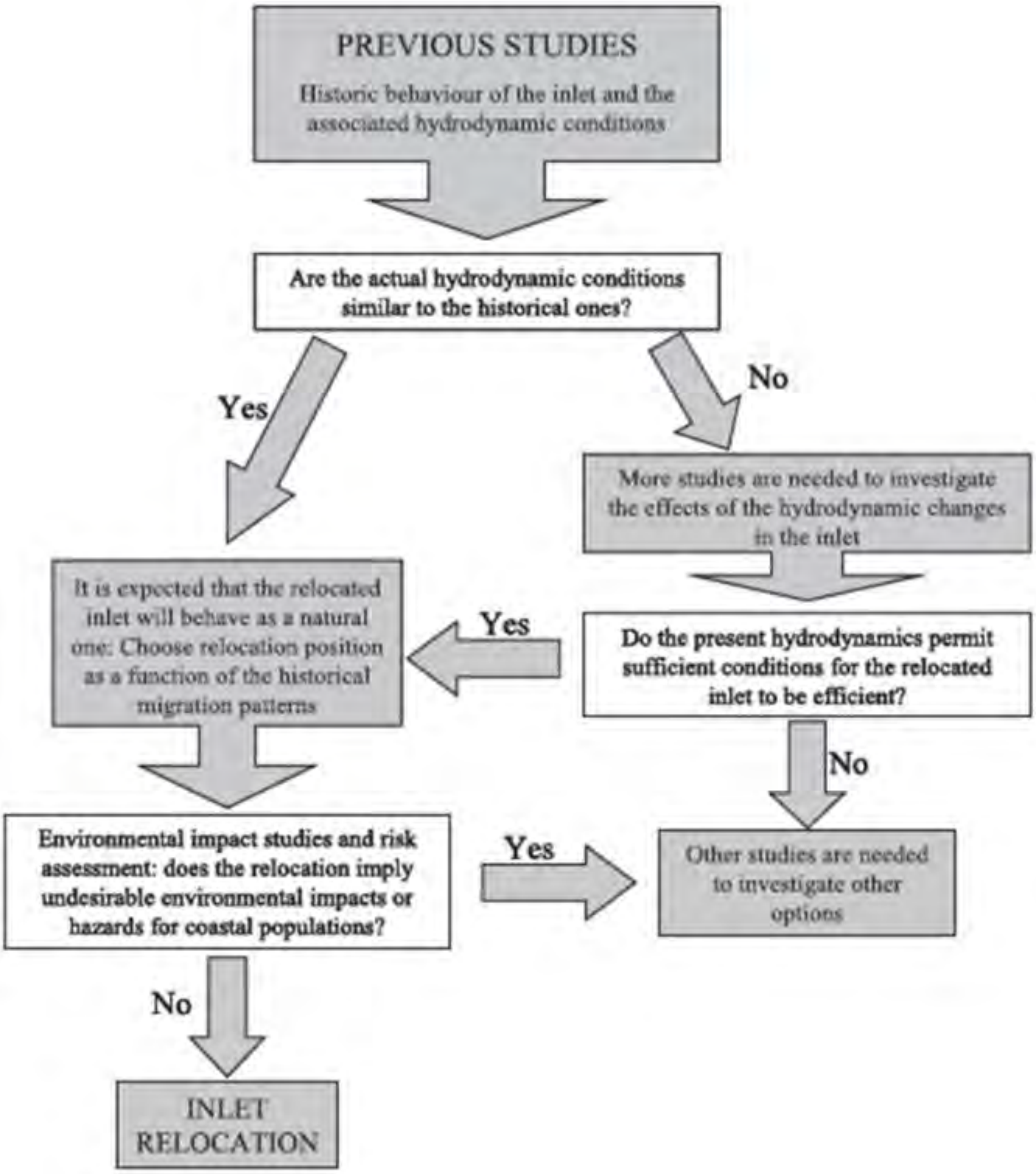

Figure 3.9. Recommended procedures for outlet relocation (Source: Vila-Concejo *et al.,* 2004 pg. 987)

3.5.2 'Hard' engineering management of lagoon outlets

Coastal structures such as jetties, sea walls, breakwater and groynes have long been used to maintain coastal outlets to a desirable water depth and location for flood control purposes (Tanaka and Lee, 2003). In the case of the New River Lagoon, a rubble-mound breakwater is used to support an artificial lagoon outlet in an attempt to better control the lagoon outlet from blockage and migration. Jetties and breakwaters are most commonly utilised at large, deep, tidal outlets that require stability and protection from waves for navigational purposes. Hard engineering structures are rarely employed in smaller choked and restricted lagoon and estuarine outlet systems, for which there is very little published literature. It seems that the implementation of this type of engineering works in smaller lagoon environments is avoided, which is likely due to their sensitive response to change (Haines *et al.,* 2006). Therefore, the following section will look at the use of engineering management on larger lagoon and estuarine outlets; concepts and ideas that are likely transferable to smaller scale systems like the New River Lagoon.

There are various advantages and disadvantages to the construction of jetties and breakwaters for the purpose of outlet stability. As mentioned in Sections 3.3 and 3.4, outlets have a tendency to become a sediment sink, accumulating sediment that moves along the coastline due to the dominance of marine wave processes over outlet currents. The advantage of engineering structures is their ability to obstruct the bypassing of littoral sediment that moves along the coastline, thus minimising sediment accumulation in and around the outlet. In doing so, flow through the outlet is more confined allowing the outlet to remain open by maintaining a more consistent depth (Brunn, 1995).

The disadvantages of using jetties and breakwaters for outlet stability are the adverse controls they have on longshore and flood tidal sediment transport. By intersecting natural sediment bypassing, engineering structures cause sediment to accumulate on updrift beaches, but prevent the supply of sediment to downdrift beaches, which can suffer erosion and shoreline retreat as a result (Pilkey and Wright, 1988; Brunn, 1995; Komar, 1996). The further the structure protrudes into the sea, the more effective it is at obstructing the longshore drift of sediment and the more detrimental it will be to the downdrift coastline.

The objective of stabilising an outlet is to maintain a constant opening between the ocean and the estuarine or lagoon system. A study by Fortunato and Oliveira (2007) on the stability of the Obidos Lagoon outlet in western Portugal revealed that stabilising the lagoon outlet using a breakwater significantly increased the tidal prism, which consequently increased sedimentation in the lagoon due to tidal flooding. Sedimentation occurs if ebb-tide current sediment transport out to sea cannot balance the rate of infilling, which can led to the demise of an estuary or lagoon system. An increase in tidal prism also causes greater fluctuations in lagoon water levels and salinity (Goodwin, 1996; Roy *et al.*, 2001; Gunaratne *et al.*, 2011).

In some circumstances, such as at the New River Lagoon, only one breakwater is used to stabilise a migrating outlet. Having only one side of the outlet stabilised allows for one of the shorelines to move, which can lead to problems of maintaining a stable outlet. Studies by Kieslich (1981), Komar and Terich (1976) and Seabergh (1974) describe the morphological changes to tidal outlets as a result of single jetties, which include the formation of a narrow, deep channel against the jetty wall and a large ebb-tidal shoal updrift of the outlet. This change in outlet morphology is comparable to natural situations where a rock or a headland stabilises one side of the outlet such as in Tauranga Harbour (Komar, 1996).

3.6 Summary

This chapter has outlined the process environments controlling the morphology and dynamics of regional and international coastal lagoon systems. The balance between marine and fluvial processes environments is identified as a key factor in determining the characteristics of a coastal system, which is highlighted in the level of connectivity between each system. As such, estuaries and hapua can be described as being at two opposite ends of a hydrological continuum; one exposed to a tidally dominated process environment and the other restricted in its fluvial/marine connectivity. The New River Lagoon, similar to international lagoon systems such as ICOLs, shows characteristics of both systems, so sits somewhere between estuaries and hapua on a continuum. Where exactly along this continuum the lagoon sits at present is difficult to determine until more is known about the dynamics of the lagoon itself.

Knowing the process environments affecting a coastal system is important when making informed management decisions. Different management techniques have different implications for the natural dynamics of a system and, if not applied appropriately, can cause detrimental effects for an environment and its inhabitants. Soft management techniques aim to work with the natural environment, rather than opposing it. In contrast, hard engineering management techniques are permanent structures used for coastal protection and can often have detrimental effects on the natural processes of a system if used inappropriately. The New River Lagoon has been exposed to a combination of soft and hard engineering management techniques in an attempt to maintain an open outlet.

The following results sections use a methodological framework to describe the physical process environments affecting changes to the New River Lagoon both pre- and post-engineering management. Figure 3.10 provides an overview of the structure for the following results chapters, including data sources, measured process environments and determined lagoon characteristics.

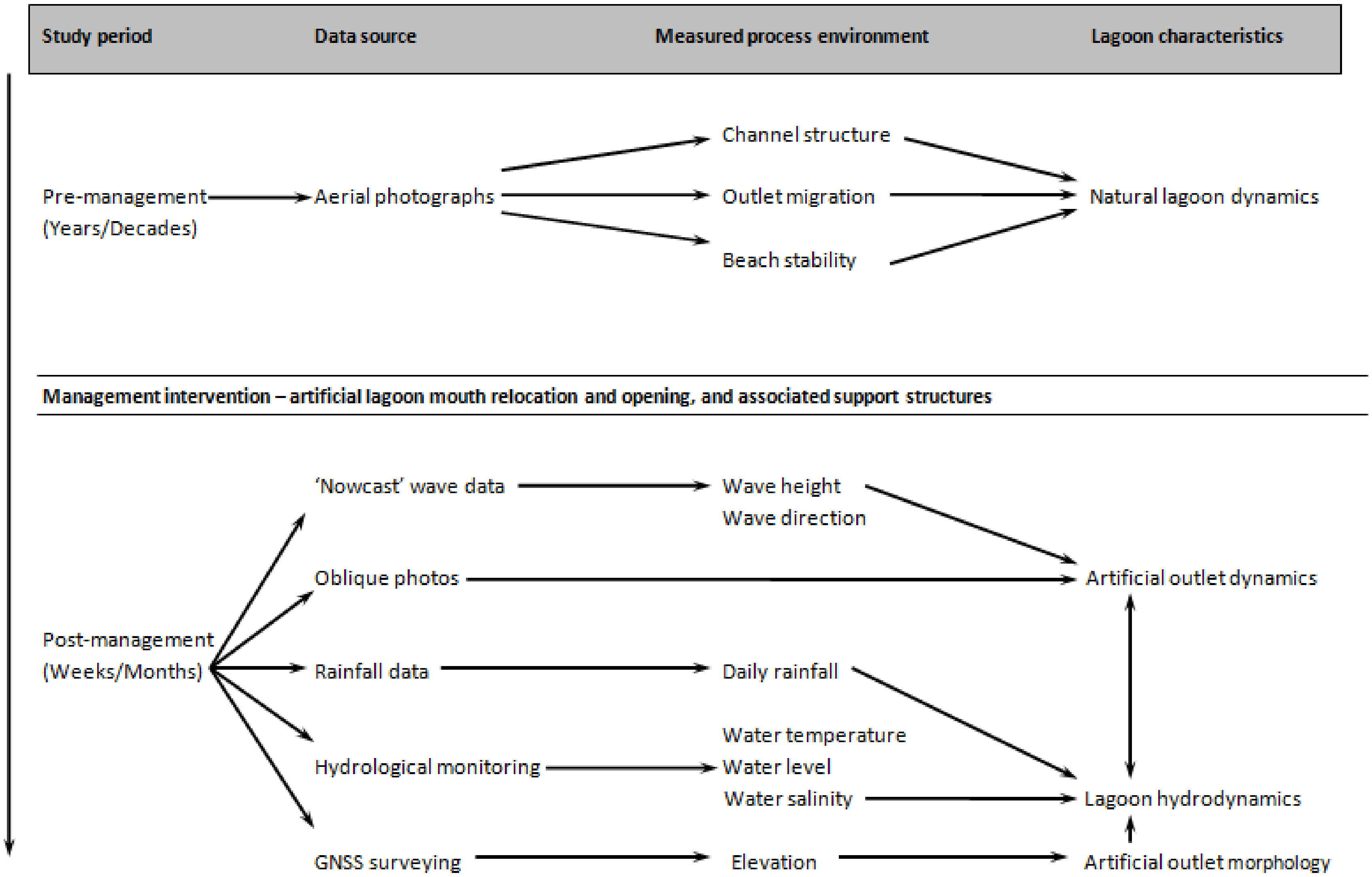

Figure 3.10. Data source, measured process environments and resulting lagoon characteristics assessed in the following results chapters, which are split into periods that are pre- and post- management intervention.

Chapter 4 : Past Lagoon Morphology and Dynamics

4.1 Introduction

In order to fully understand the morphology and dynamics of the New River Lagoon system, it is important to have a detailed record of outlet migration, channel structure and beach stability. This chapter investigates the morphology and dynamics of the study site prior to the 2010 management intervention, by comparing aerial photographs taken over a 67 year period. The photographs were taken roughly on a decadal time scale, with an additional few that allow changes to be identified at shorter intervals. Qualitative analysis was undertaken initially to compare and describe visual changes between photographs. Following qualitative analysis, quantitative measurements of net changes in outlet and shoreline position were calculated using *ArcGis*. In addition, some photographs that showed a clear progression were used to measure the net rates of change. It is important to note that aerial photographs produce a snapshot in time from which changes can be inferred. Therefore, changes that may have occurred between surveying years are not recorded.

The information from the analysis of aerial photographs is divided into three sections; methodology, presented in Section 4.2, results, presented in Section 4.3 and discussion and interpretation, presented in Section 4.4. The following research objectives are addressed:

- investigation of lagoon outlet and channel migration, and changes to shoreline position and vegetation cover, by comparing aerial photographs taken over a 67 year period,
- determination of quantitative measurements of approximate net change and rate of change in outlet and shoreline position where possible, and
- an explanation of the processes driving morphological change and the dynamics of the system.

4.2 Methodology

4.2.1 Aerial photograph analysis

Aerial photography is the capturing of images above the earths surface providing a 'snapshot' at a specific instant in time. They can be taken either vertically or obliquely, for which the former is more common in GIS applications. Collection of vertical aerial photography of the coastline around the world began in the 1920s, but it was not until the 1930s that stereo aerial photographs became readily available for mapping purposes (Boak and Turner, 2005). The major advantages with aerial photographs are the wide spatial coverage of the coastline, the relatively low cost, and high spectral and spatial resolution (Heywood *et al.,* 2006). Recently, satellite imagery is considered the most suitable form of imagery for environmentally sensitive regions, due to its ability to cover a large spatial scale. However, high costs mean there are often spatial and temporal limitations with its accessibility and its ability to cover large spatial areas means pixel resolution can be low when the focus is small coastal features such as the New River Lagoon (Boak and Turner, 2005). Therefore, in the case of the New River Lagoon, aerial photography is a more valid option for monitoring change.

Before aerial photographs can be used for mapping purposes, distortions that are obtained during their capture must be accounted for and removed. These can include radial distortions (generally in older lenses) and relief distortions caused by variation in topography; changes in tilt and pitch of the aircraft; and scale variations caused by changes in altitude along a flight path (Gorman *et al.*, 1998; Boak and Turner, 2005; Heywood *et al.*, 2006). In most cases coastal environments tend to consist of relatively flat topography so are not considered to be susceptible to large scale relief distortions (Al-Tahir and Ali, 2004). This flat topography means photographs are almost vertical so there is also minimal tilt and pitch displacement (Al-Tahir and Ali, 2004). In preparing aerial photographs for mapping they are georeferenced to remove many of these potential errors.

Other factors that must be considered when analysing aerial photographs on the coast are the changes in sea, lagoon and estuary water levels due to tides, river flows and rainfall. These factors are particularly influential when assessing positional changes of a shoreline and changes in the areal extent of coastal water bodies.

4.2.2 Data collection and orthorectification

This study utilised several aerial photographs taken between 1943 and 2010 to determine changes to the lagoon outlet, channel structure and beach stability of the New River Lagoon. High resolution digital aerial photographs were available in colour for 2005, 2009 and 2010, and black and white for 1995. Black and white vertical photographs from 1943, 1970, 1973, 1979 and 1983, were scanned at 600 psi resolution from hard copy unorthorectified aerial photographs and saved as digital (.tif) files for the purpose of GIS analysis. All photographs were imported into *ArcMap 4.0* for analysis. In some cases several photographs were required to cover the full extent of the lagoon and in others, the photographs available did not cover the full extent of the lagoon. The details of these photographs are provided in Appendix 1.

Before analysis could be undertaken, all scanned photographs were orthorectified in *ArcGis* by georeferencing each photo to a common orthorectified photograph. In this case the 2010 photograph was used as the baseline image. Georeferencing involved selecting stable control points on the scanned photograph and matching them with the same points on the orthorectified photograph. By doing so, the scanned photograph was warped and distorted so that it overlayed the orthorectified photograph. Structures such as buildings were most commonly used for control points, as they often remained permanent for many years, so featured in a wide range of photographs. At least 4 control points were used on each photograph and were spaced out as evenly as possible over its full extent to ensure accurate orthorectification. Unfortunately, the most suitable control points were often located on the hinterland of the lagoon due to the dynamic nature of the coastal area. In some instances this made it difficult to cover a representative area of each photograph.

4.2.3 Data analysis

Following georeferencing, all images were compared qualitatively and quantitatively with one another to determine changes in outlet position, channel structure and beach stability. Change in lagoon channel structure and outlet position was determined qualitatively by digitising lagoon channels and vegetation cover into polygon shapefiles using „Spatial Data Analyst" in *ArcGIS.* These shapefiles were compared visually with one another to describe the changes to the lagoon over the study period. In addition, change in lagoon outlet position was assessed using quantitative analysis, which involved measuring the distance of lagoon outlet movement north/south of a reference line that was projected perpendicular from the New River Bridge to the coastline. These measurements were made directly onto the georeferenced aerial photographs in *ArcGIS* to avoid any potential errors that may have occurred during the digitising process.

Qualitative analysis of beach stability involved measuring the changes to shoreline position over the entire study period. The railway line (present in all photographs), located on the hinterland of the lagoon, was used as a fixed referenced point from which 11 parallel profiles extended to the coastline forming longshore cross-sections (Figure 4.1). The profiles cover the coastline from South Beach in the north to Camerons in the south. From the reference points, measurements were made along each profile to the shoreline. Due to the complex nature of the lagoon, measurements were made to both the seaward vegetation line and the beach crest. The vegetation line is a commonly referenced shoreline used in this type of beach analysis (Boak and Turner, 2005). However, at times the barrier beach could range from completely covered in vegetation in some areas, to almost completely stripped of vegetation in others. Vegetation cover was also often only temporary due to the dynamic movement of the lagoon outlet; therefore, vegetation cover did not always give an accurate representation of beach stability. Because of these inaccuracies it was also decided to plot the beach crest position, as this was readily identifiable in all images where the backshore was characterised by washover lobes and the foreshore was characterised by the wetted line and a comparatively smooth, even surface. In many of the later high resolution photos the beach crest was a distinct line, while in some of the earlier small scale photos the crest was determined based on adjacent debris, vegetation and wetted lines. The beach is relatively narrow, so the margin of error determining the beach crest was considered to be minimal (+/- 5 m). In some cases, the photographs did not cover the full extent of the beach or obstruction of the lagoon outlet made it difficult to determine a shoreline position. Therefore, not all profiles covered every year of photographs.

Figure 4.1. Beach profiles 1 to 11 covering the extent of the coastline between Camerons (in the South) and South Beach, north of the Paroa Hotel

4.2.4 Limitations

There were several limitations involved with the orthorectification/georeferencing caused largely by the quality of aerial photographs and the nature of the study site. One limitation often found with georeferencing images from a coastal zone is finding adequate features to use as ground control points that are evenly distributed around the photograph. To ensure accurate georeferencing, it is important that a sufficient number of ground control points are used and distributed evenly around the photograph (Shoshany and Degani, 1992; Al-Tahir and Ali, 2004). Fortunately the New River Lagoon is situated in an area that is relatively populated, so there were many stable structures (e.g. houses) available to use as control points. However, these structures were often situated on the hinterland of the lagoon; in some places a long distance from the features of interest. The dynamic nature of the lagoon meant it was difficult to find stable, close surrounding control points, which made it hard to cover the photograph evenly. A minimum of 3 control points were used on each photograph and spaced as evenly over the photograph and as close to features of interest as possible.

Accurate human interpretation of features is another common limitation associated with the analysis of aerial photographs and is often related to photograph resolution. This could have created errors during georeferencing, digitisation of lagoon features and shoreline mapping, particularly in some of the earlier low resolution photographs. Shade, shape, texture, pixel size and tone are all important factors to consider when performing analysis (Boak and Turner, 2005). To minimise errors of interpretation, analysis was undertaken by one person to maintain a consistent approach to identifying features.

In addition to photographic limitations, potential errors interpreting lagoon dimensions and lagoon outlet positions may also have arisen due to the fluctuation in lagoon water levels caused by tidal ingress, rainfall, and river flow and lagoon outlet dynamics. Similarly, the interpretation of beach characteristics, thus shoreline position, can become obscure due to neap and spring tidal variations and other weather factors. All quantitative results were rounded to the nearest 50 m to take into consideration these potential errors.

4.3 Results

The following section presents the results from the analysis of aerial photographs and is divided into three sub-sections: Section 4.3.1 presents the results on outlet migration, Section 4.3.2 presents the results on channel structure and Section 4.3.3 presents the results on beach stability. Figure 4.2 shows all 11 orthorectified photographs from 1943 to 2010 used in this analysis and

Figure 4.3 shows individual digitisations of the lagoon area derived from orthorectified images from each year.

4.3.1 Lagoon outlet position

The position of the lagoon outlet varied significantly over the 1943 to 2010 period, fluctuating between 4270 m north of the New River Bridge and 575 m south (Table 4.1, Figure 4.2, 4.3). The lagoon outlet spent similar amounts of time in all sections of the lagoon; being in section A for 1959, 1970 and 1973; section B for 1979, 1983 and 1995; section C for 1943, 2005 and 2009; and migrating its farthest recorded distance north to section D in 2010 before an artificial lagoon outlet was created.

In 1943, the lagoon outlet was situated in section C, 3515 m from the New River Bridge. Following this, no data is available until 1959, whereby the lagoon outlet had relocated 4090 m south to section A. This large scale movement was event driven, consequential of pronounced flooding that caused barrier breaches on two separate occasions: first between the 23 and 24 January 1958 and again on the 3 December 1958 (Benn, 1990). From 1959 through to 2010, the lagoon outlet followed a distinct pattern of northerly migration, with exception to three years between 1970 and 1973, where the outlet moved 200 m southwards.

The continuous northward movement of the lagoon outlet from 1973 to 2010 allows for rates of change to be calculated. In this case, over approximate 10 year intervals. Net annual rates of northward outlet migration were relatively similar over the intervals between 1973 and 2010 (Table 4.1). Between 1973 and 1983 the lagoon outlet migrated 965 m northwards, which equates to 95 $m.yr^{-1}$. The outlet moved a further 670 m by 1995; a net annual rate of 55 $m.yr^{-1}$. Northward migration increased to its highest rate of 135 $m.yr^{-1}$ between 1995 and 2005, having moved 1360 m north. By 2010 the annual rate of movement was 85 $m.yr^{-1}$ after moving 1045 m.

Table 4.1. Outlet migration of the New River Lagoon measured north and south of the New River Bridge. Net change is denoted as + for northward movement and – for southward movement.

Survey Date	Years between photographs	Outlet offset (m)	Net change (m)	Net rate of change (m.yr^{-1})
June 1943	-	+3515	-	-
October 1959	16	-575	-4090	-
February 1970	11	+610	+1185	-
March 1973	3	+410	-200	
August 1979	6	+1130	+720	
November 1983	4	+1375	+245	+95
January 1995	12	+2045	+670	+55
March 2005	10	+3405	+1360	+135
2009*	4	+4090	+685	
2010*	1	+4270	+180	+85

*Month that image was taken is unknown

4.3.2 Channel structure

In addition to lagoon outlet migration was the substantial change in channel structure and channel orientation over the study period. These changes were controlled largely by the location of the lagoon outlet and its ability to forge new channels and abandoning old ones. The major lagoon channels of New River and Saltwater Creek remained active and relatively unchanged for the duration of the study period. The following interpretations are determined from Figure 4.3, which shows digitised images of the occupied and unoccupied channels of the lagoon and the seaward extent of vegetation cover. It is split into four sections: A, B, C and D, for ease of interpretation.

The changes to channel structure of Section A of the lagoon can be separated into two distinctive periods: 1943 to 1983 and 1983 to 2010. From 1943 to 1983 the New River channel flowed diagonally southwards from the bridge on State Highway 6 and adjacent to the Camerons community, before making a „U‟ turn and flowing parallel northwards along the coastline. This channel remained stable until 1958 when flooding caused a primary barrier breach (breach directly opposite the river-mouth) at the southern extremity of the lagoon. An abandoned lagoon channel, visible to the south of the lagoon outlet in the 1959 image, was likely formed during the initial barrier breach, especially considering the southward diagonal angle of approach of New River with the coastline. This remnant channel suggests the breach may have occurred further south of the 1959 position of the outlet and then subsequently migrated northwards during the 11 months between the December 1958 flooding and the October 1959 photograph.

Following barrier breach in section A of the lagoon, the outlet proceeded to migrate northwards, which straightened out the channel parallel with the beach and created an especially tight turning bend in the river. Consequently, this decreased the size of the island separating the southward flowing New River and the northward flowing Lagoon channel.

By 1983, the New River had cut a new channel perpendicular to the coastline, disregarding its southward flowing channel in favour of a more direct route. It is uncertain if this shortening was a result of long-term erosion and subsequent breach of the island divider, or if it had been artificially excavated to reduce the risk of flooding to the Camerons community. Figures 4.2 and 4.3 show slight erosion of the New River true right bank, which over the four years between 1979 and 1983 could have resulted in a breach after a flood event. However, the island divider was highly vegetated and approximately 100 m wide, which suggests the latter scenario. Remnants of the southward flowing channel are present in all later images, residing as a swampy lake.

From the photographs of 1983 to 2010, the lagoon channel structure in section A remained relatively stable, with the lagoon outlet at a northerly location. Small-scale channel migration, caused by the build up of sediment bars, occurred within the New River channel. Scouring of the true left river bank where the New River turns and flows parallel with the coastline was persistent over the 27 years, although did not appear (from the available images) to have contributed to another primary barrier breach.

The most significant changes to channel structure in section B occurred between 1979 and 1995. During this time lagoon outlet migration formed a long elongated channel parallel to the southward flowing Saltwater Creek channel and separated by a densely vegetated island. Subsequently, the confluence of New River and Saltwater Creek moved northwards and remained stagnant until 2005, whereby it shifted to Section C along with the opening of a new lagoon outlet. Remnants of a similar phase of lagoon outlet migration are also evident in Section B of the 1943 image. Based on the remnant lagoon channel and lack of seaward vegetation cover, there is evidence to suggest that prior to the 1943 image a similar lagoon channel ran parallel to the main New River – Saltwater Creek channel, likely caused by a similar phase of lagoon outlet migration.

Channel structure in section B remains relatively unchanged from the 2005 image onwards due to the continued northward migration of the lagoon outlet. Remnants of the old parallel lagoon channel remain wetted as water is diverting from the flow of the New River. However, it does not appear in any images to have become reinstated as a primary outlet channel.

The most significant changes in channel structure to section C of the lagoon occur from 1943 to 1959 and 2005 to 2010. As such, these two periods are when the lagoon outlet resides at a northerly position. The development of a channel parallel to the southward flowing Saltwater Creek occurs during both periods, much the same as in section B. In both instances the channel is separated from Saltwater Creek by a densely vegetated island. The channels are created by the progressive northward migration of the lagoon outlet, which is enhanced by its oblique angle of approach to the coastline. The confluence of the New River and Saltwater Creek channels shifts northwards along with the migration of the lagoon outlet.

Remnant channels in section D of the images shows the northern most extent to which the lagoon migrated since 1943. None of the images show the lagoon outlet at this northern extent and it is unlikely that lagoon channels in section D were utilised when any of these photos were taken. However, the pattern of vegetation loss in section C and D between 1943 and 1959 suggests the outlet migrated northwards during this 16 year period and the remnant channel, still in part present today, is a result of this movement. The presence of a similar channel in the 1943 image also suggests that this is not the first time that the outlet has migrated this far north. Southward migration of the lagoon outlet in 1959 would have left these channels unoccupied. However, had artificial opening of the lagoon outlet not been undertaken in late 2010, it is likely these channels would have been reinstated; or if not, a new channel created, due to the progressive northward migration of the lagoon outlet

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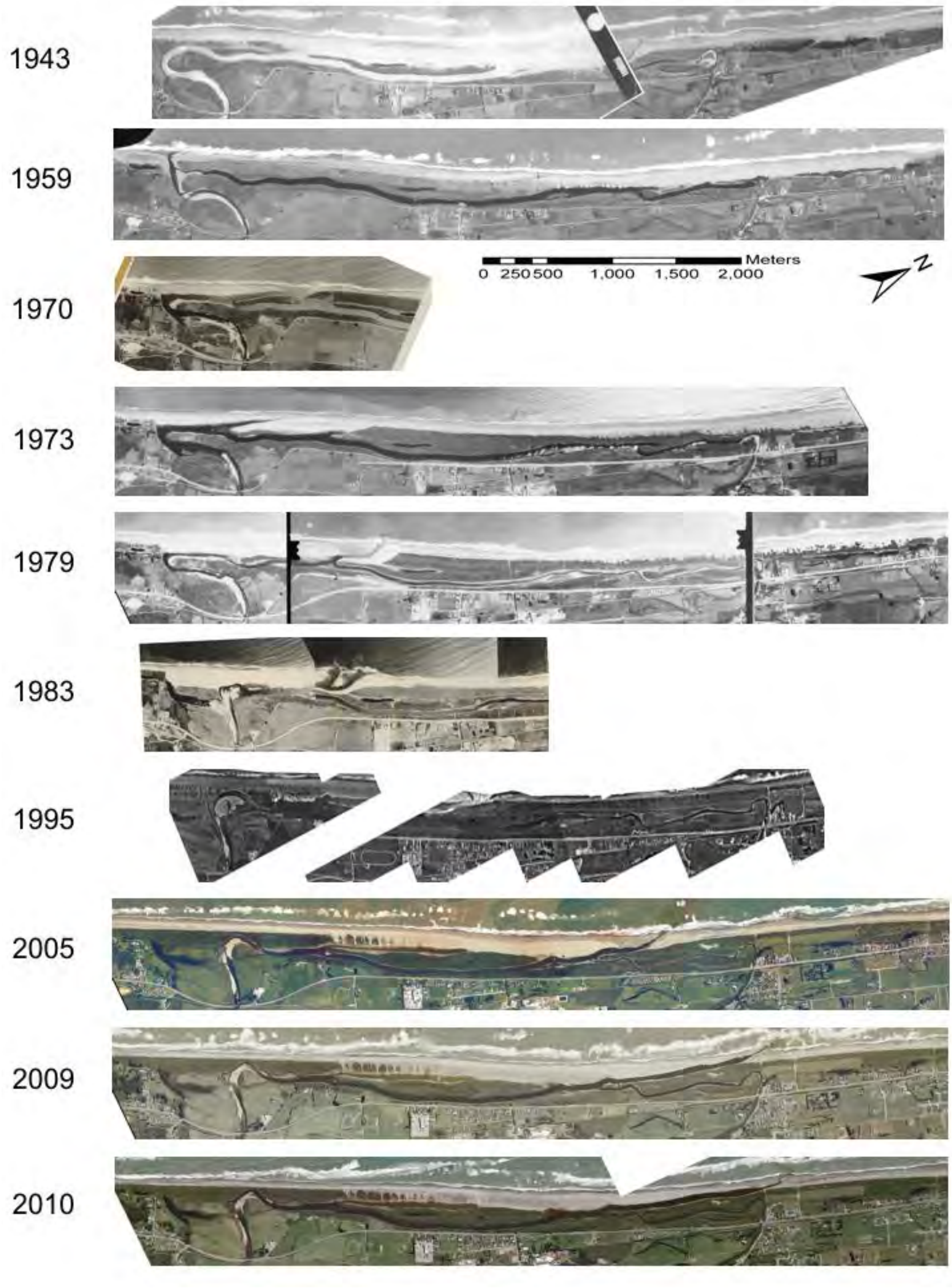

Figure 4.2. Orthorectified aerial photographs of the New River Lagoon obtained from the West Coast Regional Council, the Grey District Council and the Department of Conservation Hokitika respectively.

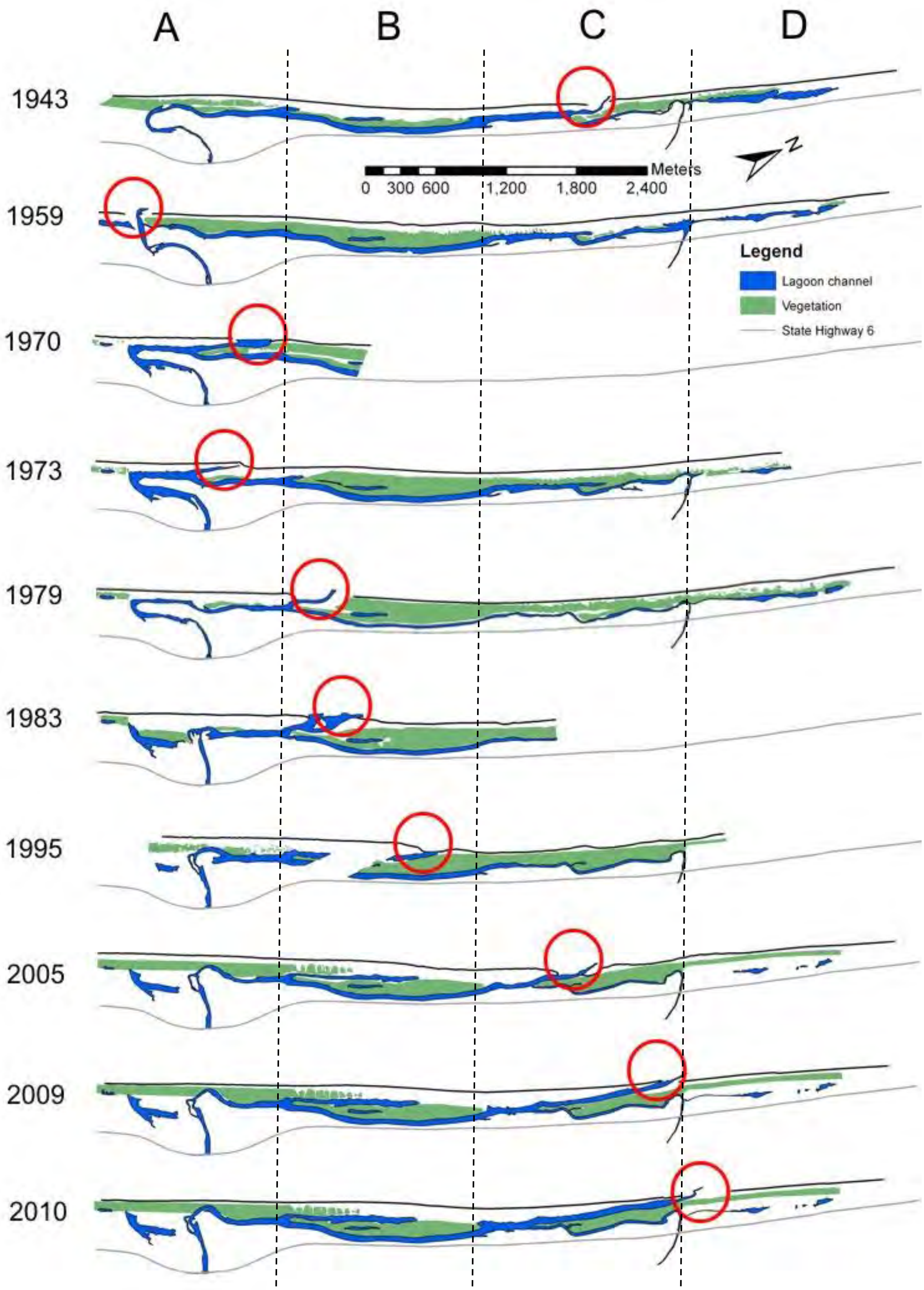

Figure 4.3. New River Lagoon occupied and unoccupied channels and the seaward extent of vegetation cover from 1943 to 2010. Images have been digitised from a 2010 orthorectified aerial photograph and outlet positions circled in red.

4.3.3 Beach stability

This section describes the changes in shoreline position of the coastline between South Beach and Camerons, fronting the New River Lagoon. Beach stability is important for determining the longevity of a lagoon system and in the case of the New River Lagoon, beach stability and the dynamics of the lagoon outlet are closely related. Figure 4.4 shows change in beach crest horizontal position for 11 different profiles positioned north to south. All beach profiles show an overall trend of progradation from 1943 to 2010, ranging from +11.4 m at profile 1 and +133.6 m at profile 8. The detailed measurements are presented in Appendix 2.

The trend of progradation is not always stable, as some beach profiles fluctuate with periods of landwards or seawards movement of the shoreline. Figure 4.4 shows that profiles 1-6 all experience an initial period of landward retreat between 1943 and 1959, whilst profiles 7-11 all undergo varying degrees of progradation. Profiles 2-6 experience steady progradation between 1959 and 1979, whilst profiles 10 and 11 retreat, and profile 1 remains relatively unchanged. From 1983 to 2005 all profiles show a relatively steady period of progradation. Profiles 1-8 continue to prograde until 2010, while profiles 10 and 11 show distinct retreat, particularly between 2005 and 2009.

Despite all sites recording overall figures of progradation, there are distinct differences in overall net change, and thus beach stability between different sections of the coastline. Profiles 1-3, located at the northern most extent of the lagoon and 10-11, located at the southern most extent of the lagoon, all record net progradation of lease than +50 m over the 67 years. In contrast, profiles 4-9 all recorded net progradation above +50 m over the study period. Figure 4.4 shows profiles 7 and 8 recorded the highest overall net progradation of +96.6 m and +133.6 m respectively, while profiles 10 and 1 recorded the lowest overall net progradation of +19.6 m and +11.4 m respectively.

The seaward extent of vegetation cover at the New River Lagoon fluctuated rapidly over the entire study period, due to migration of the lagoon outlet (Figure 4.3). In contrast, the landward extent of vegetation at the New River Lagoon remained stable throughout the entire study period. Figure 4.3 shows that between 1943 and 1995, vegetation recovery following northward migration of the lagoon outlet was relatively quick in all sections of the beach. In contrast, between 2005 and 2010, vegetation re-growth in sections B and C was minimal. In particular Section B begun regrowth in 2005 but ceased to continue, as it had done in the past, over the 10 years that the outlet was situated at the northern extent of the lagoon.

Quantitative analysis of shoreline stability, based on changes to the vegetation line, was difficult to determine for profiles 4-10, because of its continuous fluctuation caused by migration of the lagoon outlet. However, profiles 1-3 north of the Paroa Hotel and profile 11 south of the New River Bridge were not directly influenced by the lagoon outlet after 1973. Therefore, they are considered to represent the true state of vegetative shoreline stability without fluvial disturbances. Figure 4.5 shows change to the vegetation line for profiles 1-3 between 1979 and 2010, and profile 11 between 1973 and 2010. The detailed measurements are presented in Appendix 3. All profiles show an overall trend of progradation. Profiles 1 and 11 each showed the least amount of net change, advancing +34 and +38 m respectively. While profiles 2 and 3 each recorded higher net changes of +45 and +65 m respectively. Figure 4.6 shows the extent of vegetation progradation between 1979 and 2010 at sites north of the Paroa Hotel.

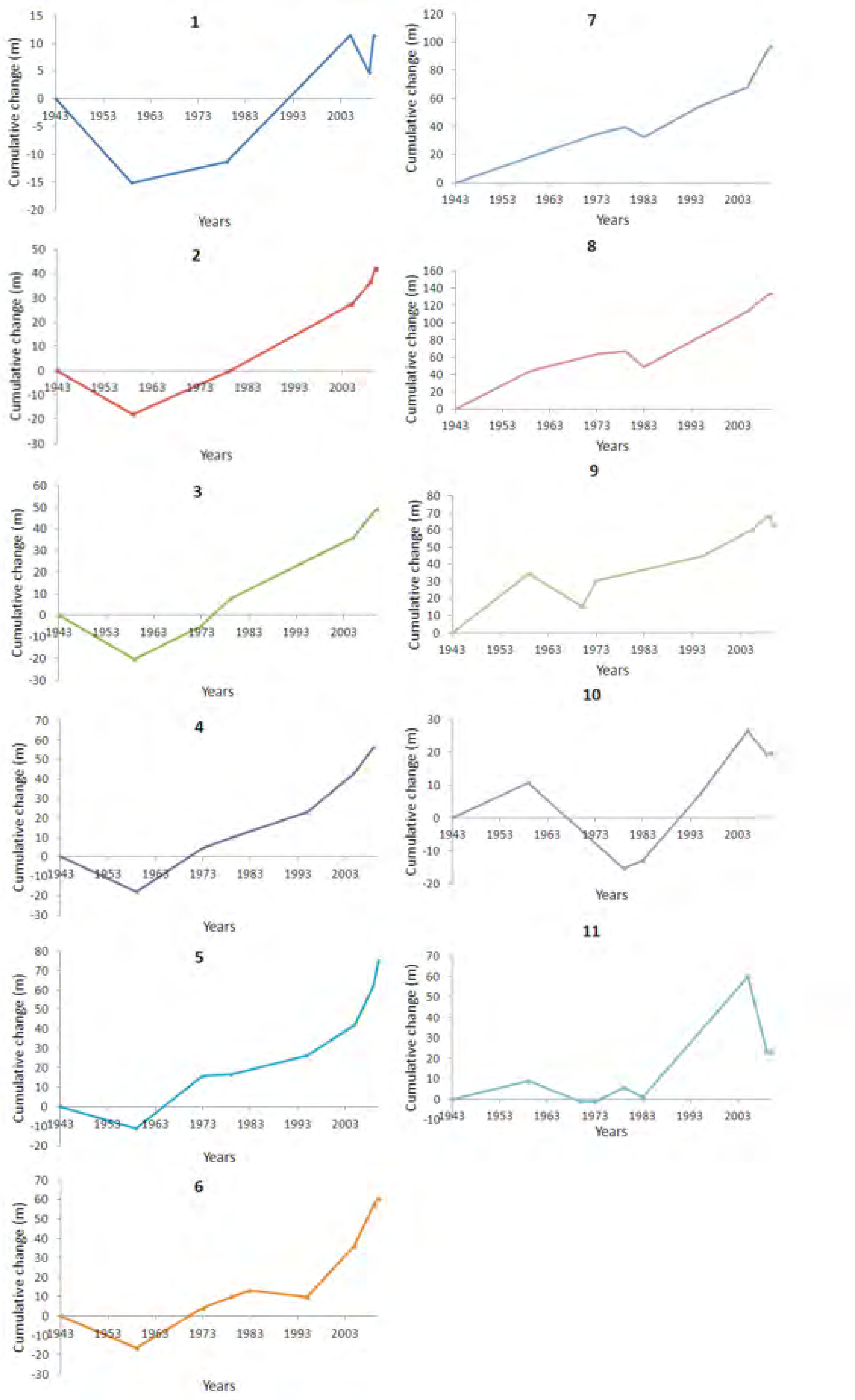

Figure 4.4. Cumulative change in the beach crest position of profiles 1 to 11 from 1943-2010. Note: positive slope of lines show progradation (seaward movement), while negative slopes indicate retreat (landward movement) of the berm crest.

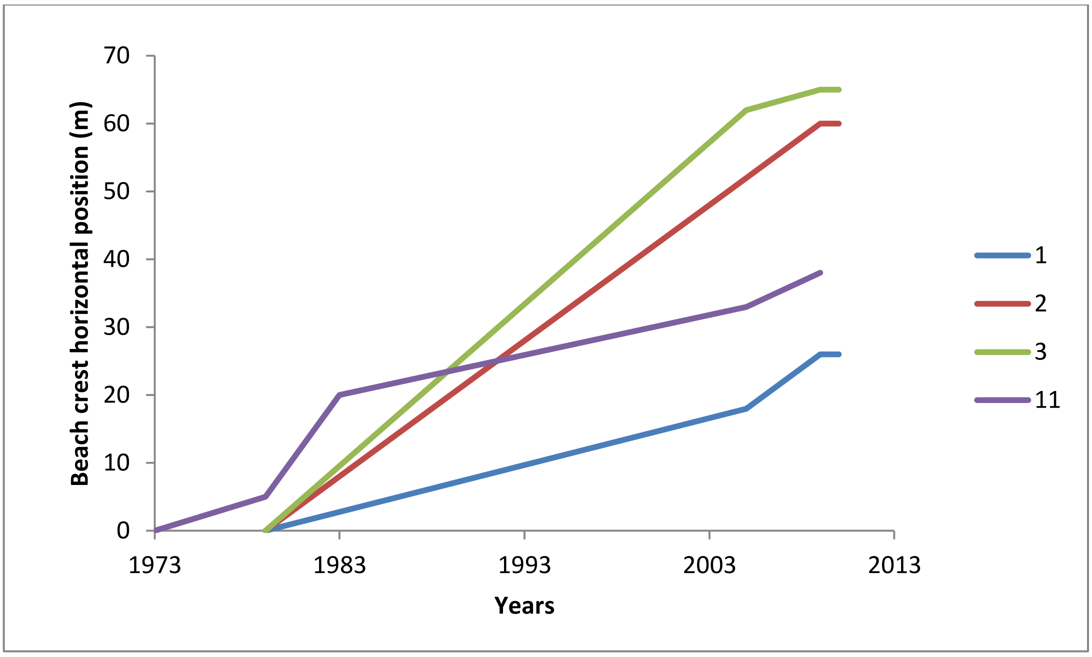

Figure 4.5. Cumulative change of the vegetation line of profiles 1-3 from 1979-2010 and profile 11 from 1972-2010. Note: positive slope of lines show progradation (seaward movement) of the position of the seaward edge of vegetation.

Figure 4.6. 2010 orthorectified photograph overlying a 1979 orthorectified photograph shows the progradation of the vegetation line at profiles 1 to 3, north of the Paroa Hotel.

4.4 Discussion and Interpretation

This section discusses the dynamics of the New River Lagoon and associated beach environment based on the results found in aerial photograph analysis. Interpretations are then made between these characteristics and literature regarding coastal lagoon dynamics.

4.4.1 Lagoon outlet dynamics

There is a clear trend of outlet migration at the New River Lagoon, particularly between 1973 and 2010, when the outlet progressively moved position from 410 to 4270 m north of the New River Bridge. Kirk (1991) and Hart (1999) describe the direction of hapua outlet migration as being dependant on a strong longshore drift of sediment, which is inherently reliant on the prevailing wave climate. Figure 4.7 shows an overview of outlet and channel positions during the study period in relation to wave height and wave direction, using *NIWA wave hindcast* data simulated over a 20 year period between 1979 and 1999 (Gorman *et al.*, 2003a). The figure shows a high frequency of waves travel in an E-NE direction, forcing the drift of sediment northwards and causing migration of the lagoon outlet. It is likely that sediment from the Taramakau River, located immediately south of the New River Lagoon, is the major source of sediment to the shoreline fronting the lagoon (Benn, 2004).

The steady northward migration of the lagoon outlet, in the direction of longshore drift of sediment, is likely to follow a similar process of hapua outlet offsetting, explained in detail by Kirk (1991) and Hart (1999). They explain outlet offsetting as a process of marine sediment accumulating on the updrift bank of the lagoon outlet, whilst the down drift bank is eroded in the direction of longshore drift. Eventually a barrier is formed that separates the ocean from the lagoon channel. Figure 4.4 show that the lagoon outlet often approaches the coastline at an oblique angle, which enhances erosion of its down drift bank, allowing it to move in the direction of longshore drift. It is unclear if the northward migration of the lagoon outlet is a continuous process or if it jumps between positions in response to fluvial and/or marine events. The southward movement of the lagoon outlet during a 3 year period between 1970 and 1973 suggests that although in the long-term the outlet is trending northwards, it may jump back and forth during the short-term.

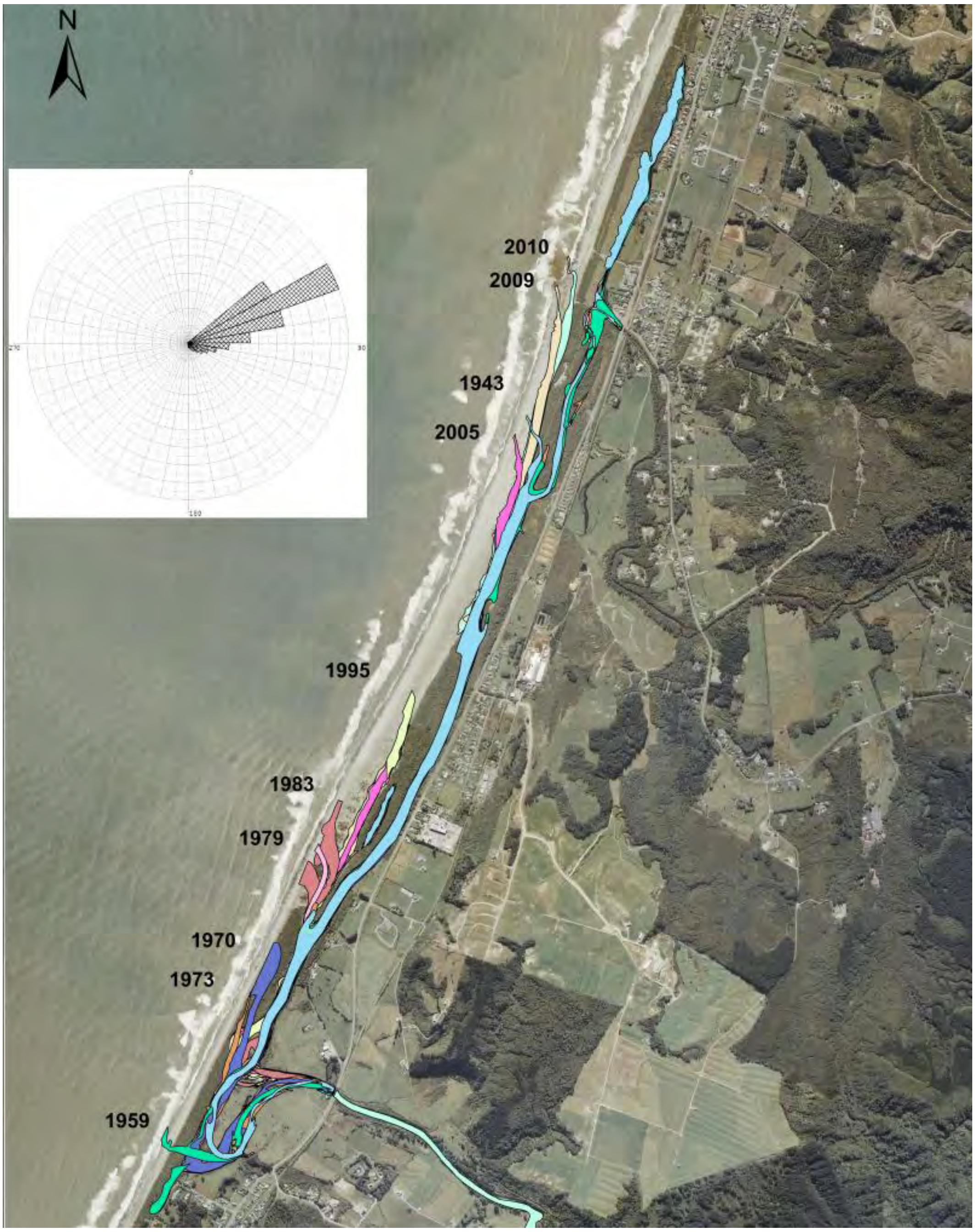

Figure 4.7. Northward movement of lagoon outlet positions from 1943 to 2010 and a wave rose showing a high frequency of waves traveling in an E/NE direction causing northward migration of the lagoon outlet.

Possibly the most significant event to have affected the dynamics of the New River Lagoon during the study period, was the primary barrier breach at the southern end of the lagoon. This breach was caused by pronounced flooding on two separate occasions. The initial breach occurred between the 23 and 24 January 1958 and then again on the 3 December 1958 (Benn, 1990). Benn (1990) describes flooding to have been prominent at the confluence of the New

River and Saltwater Creek channels, at the time located in section C closest to Saltwater Creek. This resulted in the New River breaching the barrier beach while floodwaters affected the Camerons community. It is likely that lagoon outlet blockage contributed to flooding at the confluence of the two river channels, causing the New River to back up and put pressure on the barrier beach. Outlet blockage is common in hapua-type lagoon systems when marine wave processes supplying sediment to the barrier beach are dominant over the flow of river water through the lagoon outlet (Kirk, 1991; Hart, 1999). It is unclear exactly why the breach occurred at the southern end of the lagoon, but it was likely caused by the build up of pressure behind the barrier beach, combined with the dominant flow of the New River. Blowouts in the barrier beach and old outlet channels could have made the southern end of the lagoon more susceptible to barrier breach, along with the characteristic decrease in height of the barrier beach south of the New River Bridge, allowing for easier overtopping (Benn, 2004).

The New River Lagoon is a unique environment in that it is made up of two conflicting waterways; one more dominant than the other. Primary breach shifted/reset the phase of lagoon outlet migration to the southern extremity of the lagoon from its previous northward location in Section C. Subsequently, this would have changed the hydrological dynamics of the lagoon, shifting the exchange between marine and fluvial systems closer to the New River and farther from Saltwater Creek. As a result, water from Saltwater Creek would have had to travel approximately 5 km parallel to the coastline before exiting the lagoon outlet. Similarly, in 2005 the confluence of both channels shifts to section C as a result of lagoon outlet migration, once again relocating the fluvial-marine interface. Kain (2009) found that the Totara lagoon was exposed to significant tidal influences during outlet opening immediately opposite the river-mouth, caused by enhanced scouring of the outlet channel lowering bed elevation; a concept possibly applied to the New River Lagoon during its 1959 outlet location.

Aside from the lagoon outlet forging new channels parallel with the coastline, the length and area of the active lagoon did not appear to have changed much over the study period. Instead it stayed relatively well confined between Camerons and the Paroa Hotel. However, it is likely that sometime between 1943 and 1959 and also prior to 1943, the lagoon outlet was situated further north than the 2010 position, as depicted by old channels and patterns of vegetation growth.

The lagoon outlet was not recorded to have been located in its current artificial position prior to engineering management, based on this aerial photograph analysis. However, it is likely it was located at the confluence of both New River and Saltwater Creek channels during northward migration prior to 1943 and between 1995 and 2005. The suitability of the artificial lagoon outlet location is discussed in detail in Chapter 6, along with its effectiveness at flood management.

4.4.2 Beach stability

All beach profiles show an overall trend of progradation over the study period, which suggests the New River Lagoon is located on a coastline that is in a long-term state of progradation. However, there is definite spatial and temporal variability in beach stability along the coastline. Profiles 5-9, located in the central, most active vicinity of the lagoon, experienced more distinct fluctuation in phases of shoreline retreat and progradation than profiles 1-4 and 10-11, located north and south of the lagoon.

This variability in beach stability can first be related to a convex beach shape that allows for more sediment to be deposited in front of the lagoon and less updrift and downdrift. As a result, the central section of coastline experienced more progradation, which is evident in the barrier beach termini being fixed roughly between the New River Bridge and the Paroa hotel. Secondly, the lagoon outlet moves mostly between the New River Bridge and the Paroa Hotel. As the outlet migrates it forges a new channel which erodes the barrier breach and strips vegetation cover. This is then followed by barrier overtopping and channel infilling, which further explains periods of beach retreat, but then also initiates beach progradation. Profiles 1-6 all experience a period of landward retreat between 1943 and 1959, which was when the lagoon outlet was situated in section C and likely moved through section D of the beach. Similar periods of instability occur at profile 9 between 1959 and 1970 and at profile 8 between 1979 and 1983.

In contrast, the lagoon outlet did not as often affect the sections of coastline north of the Paroa Hotel and south of the New River Bridge, so land based vegetation extended much closer to the beach. However, berm crest profiles 10 and 11 south of the New River Bridge, have recorded landward retreat since 2005, which is likely due to less sediment accumulation caused by the beaches convex shape, allowing for greater removal of barrier volume during storm conditions, with less sediment renewal. Despite vegetation recording prograding conditions, Figure 4.8 shows that low berm elevations have resulted in landward erosion north of the New River Bridge during storm conditions in recent times.

Figure 4.8. Landward erosions north of the New River Bridge (27/11/2011)

4.5 Summary

This chapter presents the results of aerial photograph analysis of the New River Lagoon using images from 1943 to 2010. Lagoon outlet dynamics, channel structure and beach stability are assessed using qualitative and quantitative analysis. The results describe the morphology and dynamics of the New River Lagoon and its associated beach environment prior to engineering management intervention.

The lagoon outlet has a tendency to migrate northwards in the direction of littoral sediment drift; a characteristic typical of hapua systems described in the literature. The lagoon outlet reached a maximum distance of 4270 m north of the New River mouth and moved at rates between 0 and 135 $m.yr^{-1}$. Waves on this coast travel mostly in an E/NE direction creating a northerly longshore drift, carrying sediment that is likely from the Taramakau River, located immediately updrift of the New River Lagoon.

Change in channel structure was minimal for the two major New River and Saltwater Creek channels over the study period. However, lagoon outlet migration forged long, elongated outlet channels and shifted the confluence of New River and Saltwater Creek north and south. The majority of channels forged during this period are still remnant today, although are unlikely to be reinstated under current management intervention.

The coastline from South Beach to Camerons fronting the New River Lagoon, is in a long-term state of progradation. However, beach stability is variable along the coastline. The beach immediately fronting the New River Lagoon tends to exhibit greater fluctuation in net sediment due to its convex shape and phases of landward retreat and progradation caused by migration of the lagoon outlet. While updrift and downdrift of the lagoon fluvial disturbances are minimal and land based vegetation extends much closer to the beach.

Chapter 5 : Current Lagoon Hydrology and Morphological Dynamics

5.1 Introduction

In general, the characteristics of coastal river-mouth lagoon systems are controlled by the interaction between fluvial and marine environments, which are each linked with one another through different feedback mechanisms controlled largely by the dynamics of the lagoon outlet. The New River Lagoon is an interesting case, in that the lagoon outlet has been modified by engineering management works in an attempt to control the feedback mechanisms between marine and fluvial systems. Complementary to Chapter 4, this chapter investigates the current controlled hydrological and morphological dynamics of the New River Lagoon with specific emphasis on changes at the artificial lagoon outlet. This chapter investigates the current hydrology of the New River Lagoon using water level, temperature and conductivity recordings taken at four sites in the lagoon between August 2011 and March 2012. In addition, this chapter investigates lagoon outlet morphology and explains the relationship between morphological changes at the artificial lagoon outlet and changes in hydrological dynamics and wave climate. This is done by combining oblique photographs and Global Navigational Satellite Surveying (GNSS) of the lagoon outlet, with local wave and rainfall data. Information from this analysis of modified lagoon dynamics is used later to determine the functional effectiveness of engineering management intervention.

This chapter is divided into three sections: methodology in Section 5.2, results in Section 5.3 and discussion and interpretation in Section 5.4. The following research objectives are addressed:

- documentation of the hydrological dynamics of the New River Lagoon by assessing changes in water level, conductivity and temperature over long and short periods of time,

- description of the local wave and climate conditions within the area of the New River Lagoon, and

- an explanation of the relationship between morphological changes at the artificial lagoon outlet and changes in lagoon hydrology, wave climate and precipitation.

5.2 Methodology

The following section provides information on the data collection and analysis methods used to determine the hydrology and morphological changes of the New River Lagoon. Section 5.2.1 explains the use of water level recorders to measure lagoon hydrological dynamics; Section 5.2.2 explains the source of local rainfall data used to determine river flow characteristics; Section 5.2.3 explains the source of local wave data used to determine changes at the lagoon outlet due to sediment transport and wave overtopping processes; Section 5.2.4 explains the use of GNSS ground surveying techniques to measure elevation levels of the lagoon outlet in relation to sea level; and Section 5.2.5 explains the use of oblique aerial photography to document morphological changes to the lagoon outlet over time. Figure 5.1, provides a conceptual view of how each method used in this chapter combines to provide data for understanding different lagoon process environments.

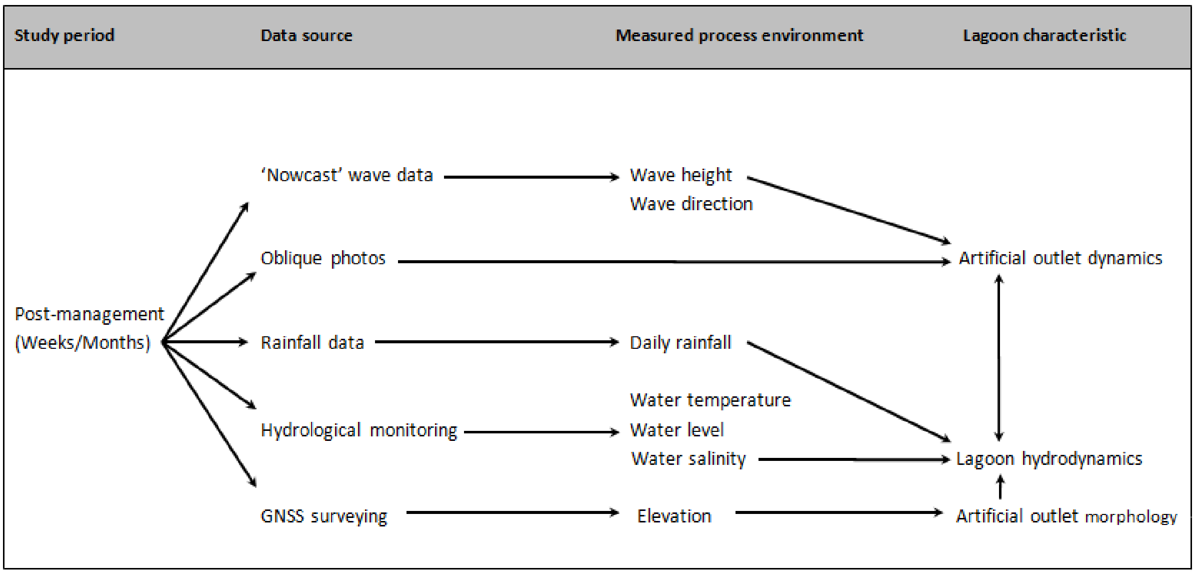

Figure 5.1. Different data sources and data measurements used together to determine outlet morphology and dynamics and hydrodynamics of the New River Lagoon.

5.2.1 Lagoon hydrological monitoring

Conductivity, temperature and water pressure (converted to water depth) are three common variables for measuring characteristics and changes to the hydrology of a coastal system. This study utilises water level recorders to monitor the hydrological dynamics of the New River Lagoon over a 7 month long-term period and a 5 day short-term period. Coastal lagoon hydrology and channel dynamics are largely controlled by the interaction between the incoming tide and outgoing river flows, as well as other factors such as catchment land use and ecology.

The tidal cycle, river flow and the opening/closing of the lagoon outlet can all have effects on the water levels of a coastal lagoon, particularly dynamic coastal lagoons like hapua and ICOL that are often intermittently open/closed (Kirk and Lauder, 2000; Haines, 2006). Variations in lagoon water levels are often the cause of morphological changes to the lagoon outlet, such as closure, opening and migration (Kirk, 1991).

Conductivity is commonly used as a proxy for measuring the salinity of lagoon water (Fernandes *et al.*, 2004; Lucus *et al.*, 2006). Water conductivity levels can increase and decrease in a lagoon environment in response to variable levels of tidal ingress, catchment runoff and soil composition, flow rates and evaporation/dilution (Lucus *et al.,* 2006). Conductivity can also vary spatially in the water column, ranging from vertical and horizontal gradients to well mixed waters. Monitoring salinity levels is especially important in coastal lagoons as it determines the degree of water exchange between the ocean and the lagoon, which can determine the balance between marine and fluvial processes (Kirk, 1991). However, it is important to mention that change in lagoon conductivity is not always attributed to the influence of marine waters, as some may be due to the above factors. It is possible to calculate absolute salinity from conductivity and temperature data, but this was not considered necessary for this study. Therefore, the ranges of electrical conductivity for different water types are presented in Table 5.1

Water temperature is affected largely by the heat produced by solar radiation, but can also increase or decrease depending on local hydrodynamics such as fluvial and marine inflow into a coastal lagoon (Vaz *et al.*, 2005; Lucus *et al.*, 2006). Temperature gradients can also vary in the water column, similar to water conductivity.

Table 5.1. Electrical conductivity ranges of different water types (Source: modified from Sutter, 1990)

Water Type	**Electrical conductivity range (mS cm^{-1})**
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

5.2.1.1 Data collection

Two sets of water level, conductivity and temperature data were taken across the New River Lagoon: a long-term record, taken in both Saltwater Creek and New River channels and a short-term record, taken only in the New River channel. The locations of these recorders are shown in Figure 5.2 and GPS coordinates given in Appendix 4. A long-term water level logger was placed in the northern section of the New River channel, approximately 600 m from the outlet and in the Saltwater Creek channel, approximately 1500 m from the outlet. Two short term water level recorders were placed in the central and southern sections of the New River channel, approximately 1400 m and 3000 m south from the lagoon outlet respectively. The locations of short term recorders were selected so comparisons could be made along the full extent of the New River channel.

Long term records were taken using two different types of *Odyssey Data Recorders* manufactured by Dataflow Systems Pty Limited. Odyssey water pressure and temperature data recorders measured water pressure (psi) and temperature (^{0}C) at 10 minute intervals from the 5th August 2011 until 5th March 2012; and Odyssey high range (0-80 mS cm^{-1}) conductivity and temperature data loggers measured water conductivity (mS cm^{-1}) and temperature (^{0}C) at 10 minute intervals from the 21st September 2011 until 5th March 2012. Conductivity recorders were installed at a later date to the water pressure loggers due to a delay in their availability. Therefore, changes in water pressure, caused by tidal exchange prior to the 21st September 2011, could only be determined based on changes to water temperature or obvious tidal water level trends. Each recorder was encapsulated in a steel bracket for protection and fastened vertically to a steel pole, which was driven into the muddy bed of the lagoon channel (Figure 5.3). These were installed at low tide in an attempt to ensure that water levels did not drop below the height of the sensors. The New River recorder was positioned 440 mm above the bed of the river and the Saltwater Creek recorder was positioned 330 mm above the bed of the river.

Short term records were taken using *CT2X* water level loggers manufactured by Instrumentation Northwest Inc. They recorded water pressure (psi), temperature (^{0}C) and conductivity (µS cm^{-1}) at 5 minute intervals from March 1st to March 5th 2012. Each recorder was mounted vertically on a steel pole, which was driven into the muddy bed of the lagoon channel (Figure 5.3). The New River South recorder was positioned 90 mm above the bed of the river and the New River Central recorder was positioned 350 mm above the bed of the river.

The long term *Odyssey* water level recorders automatically converted the difference between barometric pressure and water pressure through a tubular vent that connected the recorder to a steel pole positioned a few metres away on the river bank. In contrast, the short term *CT2X* recorders required separate measurements of barometric pressure. This was achieved using a *PT2X-BV* barometric pressure sensor, which was positioned at a nearby building on Rutherglen Rd.

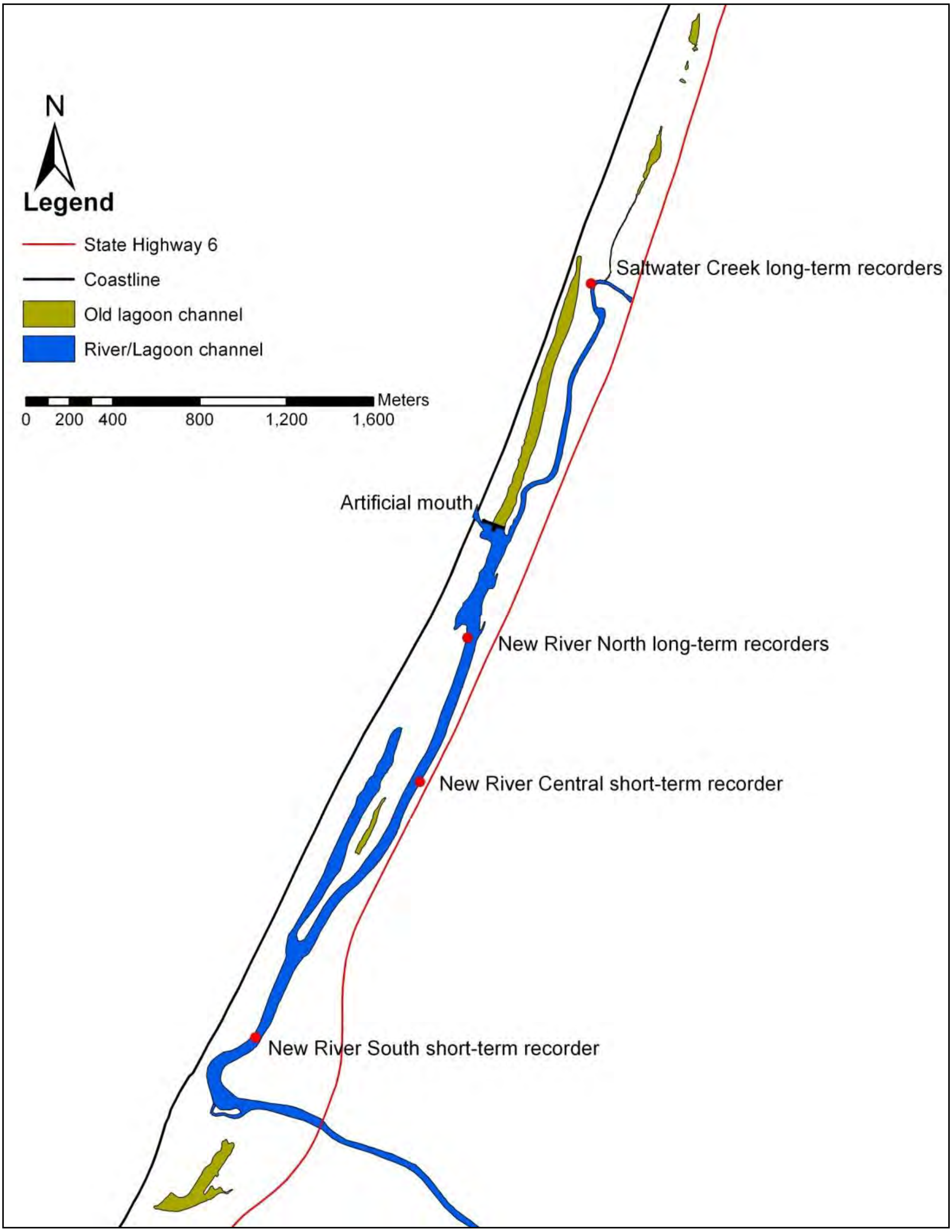

Figure 5.2. Location of long- and short-term water level recorders

Figure 5.3. To the left is the short term water level, temperature and salinity recorder fastened to a steel pole and to the right is the long term water level, temperature and conductivity recorders, both encapsulated in steel brackets and fastened on either side of a steel pole (05/03/2012).

5.2.1.2 Data analysis

Water pressure, temperature and conductivity readings were downloaded from the long term *Odyssey* recorders using *Odyssey* data logging software and the short term *CT2X* recorders using *Aquasoft*. Similarly, barometric pressure readings were also downloaded for the short term pressure records using *Aquasoft*. All data was exported into Microsoft Excel for further analysis.

Units of measurement were standardised across all recordings with all pressure measurements converted to mmH_20 and all conductivity measurements converted to mS cm^{-1}. Pressure measurements for the short term recorders were manually corrected by subtracting the recorded barometric pressure readings from the recorded water pressure readings. Distance from the bed of the river to the pressure sensor was measured for each long term recorder and added to all data entries to give absolute values of water depth. All data that was recorded whilst the recorder was out of the water (before and after sampling or as a result of unusually low water levels) or when water levels dropped to a depth that pressure and conductivity differences were negligible (< approximately 100 mm) was removed prior to data analysis. These periods were identified by data pressure recordings of less than 0.0 mmH_20 and conductivity recordings of less than 0.0 mS

cm^{-1}. In the case of the New River North long term pressure and conductivity recorders, this included removing large amounts of data due to artificial opening and several periods where flushing of the lagoon outlet caused lagoon water levels to drop considerably. Temperature data from the New River North site was disregarded due to inconsistent results caused by the recorders frequent exposure to air temperature and conductivity data from the New River Central site was unattainable due to malfunctioning of the conductivity sensor. Appendix 4 provides details of all recorders used at each site and the data recorded and used in this investigation.

Data was graphed over time to assess the trends in water level, conductivity and temperature measurements and to compare the measurements from long term and short term monitoring sites. Data was then used in combination with oblique photographs, wave and rainfall data to determine the causes of morphological change to the lagoon outlet.

5.2.1.3 Limitations

On several occasions during low tide, water levels dropped below a recordable level of the New River North recorders, initially as a consequence of artificial opening of the lagoon outlet and then subsequently following breaches of the lagoon outlet directly to sea. Moving the recorders deeper into the New River channel was considered too great a risk for collecting data when water levels were to rise again, especially when considering the unpredictability of the lagoon outlet to become blocked. As a result, blocks of water depth and conductivity data were removed from the analysis, and the full extent of tidal water level fluctuation, in particular the drop in water level at low tide, was not able to be recorded. Furthermore, all temperature data at New River North was removed due to inconsistent results.

In addition, it is thought that the rise and fall of water levels may have caused an air bubble to form in the conductivity sensor (Richard O"Brien, Engineering Supervisor at Dataflow Systems Ltd, pers. comm., 31/01/2012), thus explaining some unusually negative conductivity readings whilst the pressure sensor was recorded to be well submerged. These negative readings occurred randomly and for up to a day at a time, but did not have an effect on the overall long term conductivity trends.

Conductivity data from the New River Central recorder was unattainable due to malfunctioning of the conductivity sensor, meaning the extent of tidal exchange in the New River channel could only be measured as far as the New River North recorder.

5.2.2 Local rainfall

Rainfall is an important factor to consider when determining lagoon outlet dynamics because it has a direct link to river flow; the fluvial balance of a lagoon system. River flow has a large bearing on the morphology of the lagoon outlet due to the balance between marine and fluvial processes. Low river flows are often associated with a closed lagoon outlet and high river flows associated with an open lagoon outlet (Kirk, 1991). River flow also has an influence on tidal ingress, with high river flows restricting the level of tidal propagation and diluting the concentration of lagoon salinity (Vaz *et al.,* 2005).

5.2.2.1 Data collection and analysis

Total daily rainfall data was obtained from the National Institute of Water and Atmospheric Research (NIWA) and recorded at the Greymouth Aero Earthquake and Weather Station, at latitude, longitude, -42.46022 S, 171.19157 E (Figure 5.4), from the 1st August 2011 to 5th March 2012. The rain gauge is located approximately 6 km north of the New River Lagoon site, so is considered to experience a similar degree of rainfall.

Rainfall data was used to determine river flow conditions at the New River Lagoon, in particular high flow events and periods of low flow that might have influence on the balance between fluvial and marine processes at the lagoon outlet. Rainfall on the West Coast is highly spatially variable (Garnier, 1958; Hessel, 1982), therefore, this rainfall data can only being used as an estimate of the rainfall occurring in the New River and Saltwater Creek catchments. Rainfall data was uploaded into Excel for processing.

5.2.3 Local wave climate

Wave climate is an important factor to consider when determining lagoon outlet dynamics because it can cause landward lagoon barrier breach and because it has a direct link to sediment transport in the coastal littoral zone and across the beach. Wave height is the most common wave parameter for analysing the energy received at the beach and in combination with wave angle of approach to the coastline, can determine the strength of marine sediment transport (Ashton *et al.*, 2001; Masselink *et al.*, 2011). In general, large waves exert more pressure on the beach environment and generate more energy for sediment transport. Wave direction is the most common parameter for determining the direction of wave currents, thus the direction of sediment transport (Masselink *et al.*, 2011).

Sediment transport is particularly important for the morphological change of a lagoon outlet, as an outlet tends to act as a sediment sink, intercepting marine sediments that are transported by wave currents. Therefore, the strength and direction in which waves travel influence the changes in morphology of a lagoon outlet. Wave climate at the New River lagoon is high in energy, so is particularly influential on the morphology of the lagoon outlet

5.2.3.1 Data collection and analysis

Virtual „nowcast" wave data was obtained from *MetOcean Solutions Ltd* from 1st August 2011 to 5th March 2012. Data was generated by their NZ scale wave forecast model at 1 hour intervals, from latitude, longitude, -42.420 S, 171.100 E (Figure 5.4) (Johnson *et al.*, 2008). This NZ scale forecast model essentially runs a 5 km resolution SWAN domain over New Zealand that is nested within the 0.5 degree global W3 for spectral boundaries. The SWAN model is also forced with wind from a 6-18 km WRF forecast model. Significant wave height and peak wave direction were used to explain the wave climate effecting morphological changes at the New River Lagoon outlet during the study period.

Data was uploaded into Excel for processing, whereby frequencies of significant wave height and wave direction were calculated. In addition, frequencies of wave heights travelling in a northerly and southerly direction were also calculated to loosely determine the strength of longshore sediment transport.

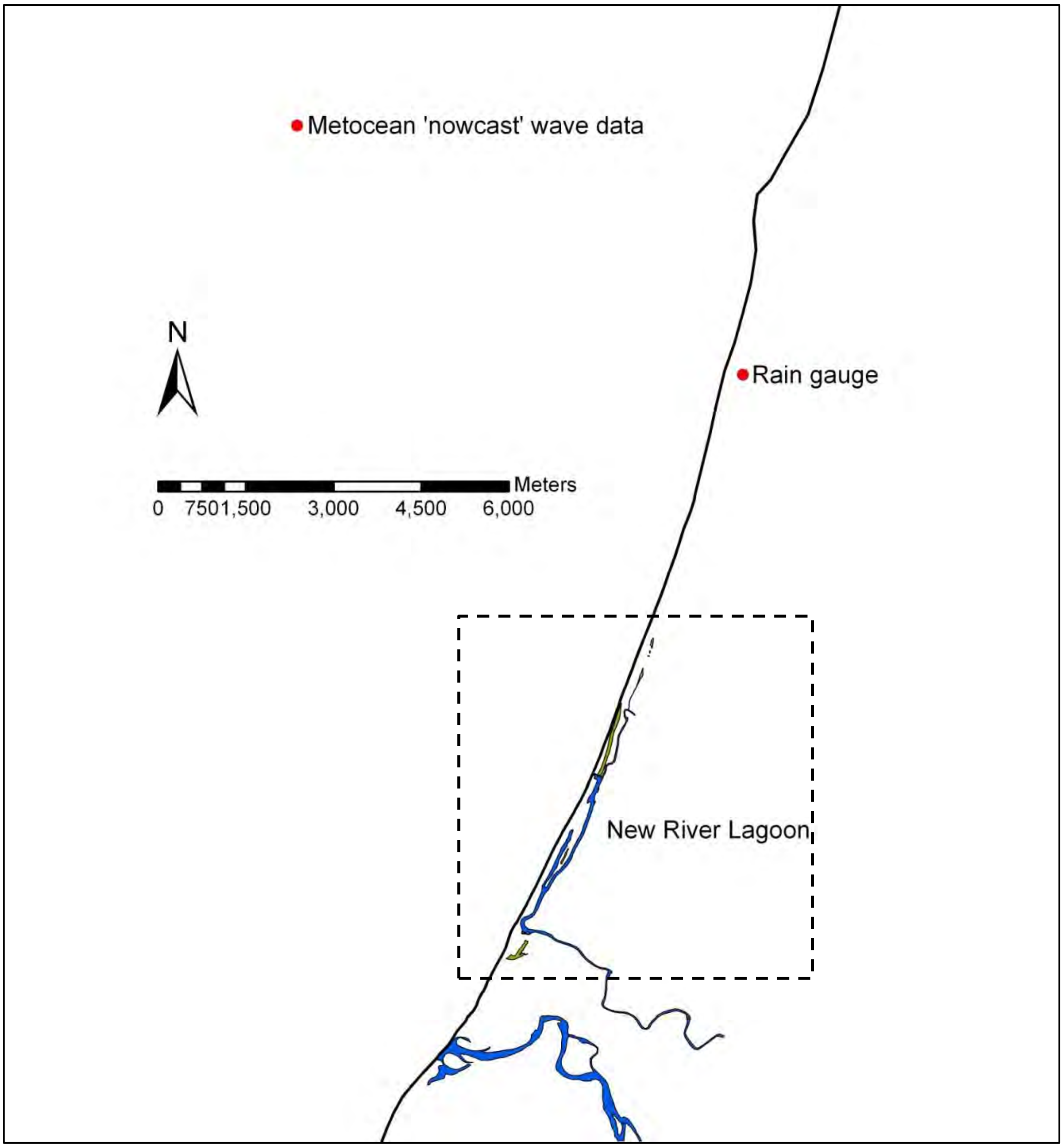

Figure 5.4. Location of Metocean nowcast wave data collection and Greymouth Aero Club rain gauge in relation to the New River Lagoon. Dashed lines indicated the area of the New River Lagoon shown in Figure 5.2.

5.2.4 Lagoon outlet morphology

Coastal areas are complex environments exposed to ocean, river, fluvial and anthropogenic influences that can cause dynamic and often extreme changes. As such, ground surveying of coastal areas is a fundamental technique for investigating coastal geomorphology and for assessing geomorphological change (Morton *et al.*, 1993). Surveying can be a time consuming and costly monitoring option, thus it is important to balance the desire for detailed topographical analysis with the need to gather information for a large geographic area. This balance has been made easier with the development of ground surveying technology. In the past, basic total station surveying was potentially very accurate, but also labour intensive and time consuming. Today, more complex Geographic Information System (GIS) and Global Navigation Satellite Surveying (GNSS) techniques are capable of covering larger areas, more efficiently and thoroughly (Pardo-Pascual *et al.*, 2005).

Ground surveying is site specific with the dimensions of coastal features determining the number of sampling points and pattern of sampling needed to accurately portray a landform (Andrews *et al.,* 2002). For example, abrupt, steep slopes require a greater density of points than gentle, gradual sloping terrain.

Following data collection, the spatial characteristics of data points can be displayed geographically using a range of techniques. The development of GIS technology has permitted both two- and three-dimensional representation of spatial data. A Digital Elevation Model (DEM) is a three dimensional representation of point elevation values. DEMs are constructed using grid cells of equal size that are interpolated to form a continuous surface. To create a continuous surface, unknown elevation points must be interpolated by fitting a model to known elevation points. Therefore, it is important to select an appropriate interpolation method to fit the set of data. Some common interpolation methods include inverse distance weighting, kriging, spline and nearest neighbour (Andrew *et al.*, 2002; Heywood *et al.*, 2006). It is recommend that a variety of interpolation methods are trialled for individual datasets, as there is no set formula to determine which model will producing the most accurate DEM.

Another form of three dimensional model commonly used is a Triangular Irregular Network (TIN). A TIN model is a mosaic of irregular triangles that form planes between elevation points to form a continuous flowing surface that does not require data interpolation (Andrews *et al.,* 2002; Heywood *et al.,* 2006). TIN models work best when data points are spaced irregularly, rather than in a grid and when they are dense, giving good spatial coverage (Andrews *et al.,* 2002).

5.2.4.1 Data collection

Ground surveying of the lagoon outlet and immediate updrift and downdrift beaches and back barrier environment of the New River Lagoon was undertaken on the 1 December 2011 using a *Trimble R8* GNSS. Surveying was undertaken during low tide when most of the beach was exposed. The purpose of surveying the lagoon outlet and surrounding areas was to determine elevation levels in relation to mean sea level that could be used to help explain the prominent tidal influences present at the lagoon. Areas of marine sediment deposition updrift and downdrift of the breakwater could also be inferred.

Surveying was undertaken using a *Trimble R8* GNSS system. Consistent cellphone reception was available over the full extent of the lagoon, which allowed for the surveying rover to be connected to a LINZ base station receiver located in Hokitika, using a wireless bluetooth connection on a cellphone. Surveying was performed using Real Time Kinematics (RTK), which provides centimetre accurate surveying in the field without having to make any post-surveying corrections.

The NZGD 2000 Hokitika map grid was used for all surveys. Surveying was carried out on foot with the surveyors wearing backpacks with surveying rovers attached, which recorded their position and elevation at 2 second intervals using the „continuous topo" function. This type of surveying meant large areas could be covered efficiently and effectively.

In order to link ground surveying elevations to mean sea level, a known geodic survey point (B8e6, latitude, longitude, -42 32 40.54225 S, 171 08 87.86668 E) in the area was occupied using a *Trimble R8* GNSS system. The point occupied was a first order vertical marker; the most accurate known measurement of elevation available. Using *Trimble Business Centre*, the surveyed point was calibrated to within 10 cm of the elevation and position of the known point. The calibrated point was then averaged over all ground surveying elevations to transform their elevations to above mean sea level.

5.2.4.2 Data analysis

Data collected in the field was transferred onto a laptop and converted into ASCII format using *Trimble Geomatics Office* program. The ASCII files were then made compatible with *ArcGIS* software by transformed them into shapefiles (.shp), database files (.dbf) and *ArcGIS* database index files (.shx).

Once data had been processed it was imported into *ArcGIS* to produce a digital elevation model (DEM). Several interpolation methods were experimented with including Inverse Distance Weighting, Kriging and Triangular Irregular Network (TIN) 3D modelling. TIN modelling proved to produce the best suited DEM for the available dataset.

5.2.4.3 Limitations

Fortunately lagoon water levels were abnormally low during surveying allowing for areas close to the channel to be surveyed. However, even so, the main outlet channel was too deep for safe surveying practice, which meant actual elevation levels of the channel bed in these areas could not be measured.

5.2.5 Lagoon outlet dynamics

Oblique photography is a basic method of monitoring environmental change and in this instance is used to document changes in lagoon outlet morphology during the study period. Hart (1999) used a similar method to document changes at the Ashburton River outlet.

Oblique photos showed the change in outlet states due to river flow and wave processes and were also used to determine changes in lagoon hydrology and the effectiveness of engineering management at maintaining a stable outlet. It is important to note that photographs only provide a snap shot in time, from which changes can be inferred. Therefore, changes that may have occurred between photographs were not recorded.

5.2.5.1 Data collection and analysis

Oblique photos were taken roughly once a week from July 2011 until March 2012 by Charlie Teasdale and Karl Tolley of Rutherglen Road, Greymouth. Photos were taken at low tide when the beach morphology was most exposed and from two different angles that documented change in outlet morphology seaward of the breakwater and the corresponding change in water levels adjacent to the breakwater (Figure 5.5).

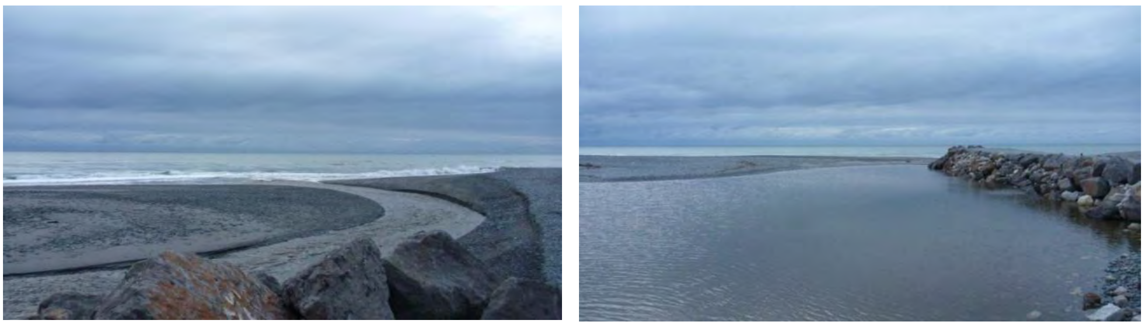

Figure 5.5. Oblique photos were taken at two angles that showed changes to outlet morphology seaward of the breakwater and associated changes in lagoon water levels adjacent to the breakwater (05/07/2011, photos courtesy of Charlie Teasdale).

5.2.5.2 Limitations

Several weeks of photographs were missed over the study period and no photos were taken in February 2012. Furthermore, on some weeks photographs were only taken at one of the two angles. These errors mean there are gaps in the photographic record. However, these were human errors and largely uncontrollable.

5.3 Results

The current dynamics of the New River Lagoon are controlled by several different factors that form a relationship through various feedback mechanisms. The following section identifies lagoon hydrodynamics (including tides), rainfall, wave climate, and outlet morphology as four separate influential processes. Section 5.3.1 describes the current hydrological dynamics at the New River Lagoon; Section 5.3.2 describes wave climate from of a site located immediately updrift of the lagoon; Section 5.3.3 describes the climatic conditions at the lagoon; Section 5.3.4 describes lagoon outlet morphology; and Section 5.3.5 identifies relationships between these processes and morphological changes at the lagoon outlet.

5.3.1 Lagoon hydrological dynamics

This section describes the long and short term changes in water level, conductivity and temperature recordings in relation to the tidal cycle at four different sites in the New River Lagoon during the study period. Tidal data was obtained from NIWA.

Water Level

During the short term study period, water level variation in the New River channel followed the tidal cycle (Figure 5.6). The range of water levels at each recorder reduced from north to south along the channel due to a diminishing tidal influence at greater distances from the lagoon outlet. Water levels at New River Central fluctuated from a maximum of 1717 mm, to a minimum of 794 mm, with a mean water level of 1204 mm and a range of 923 mm. Water level at New River South fluctuated less, reaching a maximum of 1228 mm, to a minimum of 478 mm, with a mean water level of 688 mm and a range of 750 mm. Water level maximums and minimums at each logger were reached within 30 minutes of one another, but were on average 2 hours behind high and low tide. There was evidence of tidal current asymmetry between incoming and outgoing tides, with water levels increasing quicker during incoming tides and draining slower during outgoing tides. Changes in water level at New River North were similar to those at New River Central during the short term study period fluctuating from a maximum of 1316 mm, to a minimum below recordable level (440 mm), with a mean recorded water level of 783 mm and a range of >876 mm. Water levels at Saltwater Creek were much more stagnant in comparison (Figure 5.6).

During the long term period, water level variation at New River North was largely influenced by the tidal cycle, due to its close proximity to the lagoon outlet. Water level fluctuated dramatically over the study period, from a maximum level of 2846 mm, to falling to a minimum level below the logger height (440 mm) several times as a result of extremely low water levels (Figure 5.7). The mean recorded water level over the 7 month period for New River North was 1282.5 mm and the range of >2406 mm. Overall, change in water level was intermittent on a daily basis and on seven separate occasions water levels rouse to elevations above 2000 mm.

During the long term period, water level variations at Saltwater Creek followed the tidal cycle, although not to the extent or frequency as water levels in the New River channel (Figure 5.7). Water level fluctuated from a maximum depth of 2580 mm, to a minimum depth of 513.4 mm, with a mean water depth of 875 mm and a range of 2066.6 mm (Figure 5.7).

Conductivity

Conductivity levels decreased in strength and variability with distance from the lagoon outlet (Figure 5.6). During the short term study period, New River North conductivity fluctuated largely with the tidal cycle, recording a maximum of 52.8 mS cm^{-1} and a minimum of 0.1 mS cm^{-1}, with a mean value of 31.2 mS cm^{-1} and a range of 52.7 mS cm^{-1}. In contrast, New River South conductivity did not fluctuate by as much, recording a maximum of 0.86 mS cm^{-1} and a minimum of 0.03 mS cm^{-1}, with a mean value of 0.16 mS cm^{-1}. For comparison, Saltwater Creek recorded a maximum conductivity level of 0.3 mS cm^{-1} and a minimum of 0.5 mS cm^{-1}. Note that during March 1st and 2nd New River North recorded negative salinity readings, which was likely due to a trapped air bubble associated with the rise and fall of lagoon water levels (as indicated in Section 5.2.1.3).

During the long term period, New River North conductivity fluctuated largely with the tidal cycle, from a maximum level of 57.8 mS cm^{-1} to a minimum of 0.1 mS cm^{-1}, with a mean value of 31.5 mS cm^{-1} (Figure 5.7). In contrast, Saltwater Creek conductivity remained relatively stable for the duration of the study period, recording a maximum level of 42.7 mS cm^{-1} and a minimum level of 0.2 mS cm^{-1}, with a mean value of 2.2 mS cm^{-1} (Figure 5.7). Saltwater Creek underwent occasional spikes in conductivity levels, most prominently during 5-8 day periods in December, January and February (Figure 5.8). Between the 25th and 30th of December conductivity levels loosely fluctuated with the tidal cycle, similar, but to a lesser extent, to New River North. In contrast, between the 8th and 12th of January and the 9th and 15th of February, conductivity levels were at high levels for unusually long periods, which coincided with consistently high conductivity levels at New River North. Note that negative conductivity records between the 25th and 30th of December have been removed for when the recorder was exposed.

Temperature

Temperature records followed a similar pattern at all locations during the short term study period (Figure 5.6). New River Central showed the warmest temperatures ranging from 19.2 ^{0}C to 14 ^{0}C, with a mean of 15.8 ^{0}C, while New River South was similar ranged from 17.9 ^{0}C to 13.4 ^{0}C, with a mean of 15.3 ^{0}C. Saltwater Creek temperature recordings were around 2 ^{0}C colder than the New River sites ranging from 15.6 ^{0}C to 11.5 ^{0}C, with a mean of 13 ^{0}C. There were no obvious temperature increases due to tidal ingress.

Long term temperature records at Saltwater Creek showed a large degree of variation ranging from 24.7 ^{0}C to 2.3 ^{0}C, with a mean of 13 ^{0}C (Figure 5.7). Water temperatures were coldest during the winter months of August and September but increased over the summer months of December and early January, before decreasing again in late February and March. During late January there is an unusual decline in temperature.

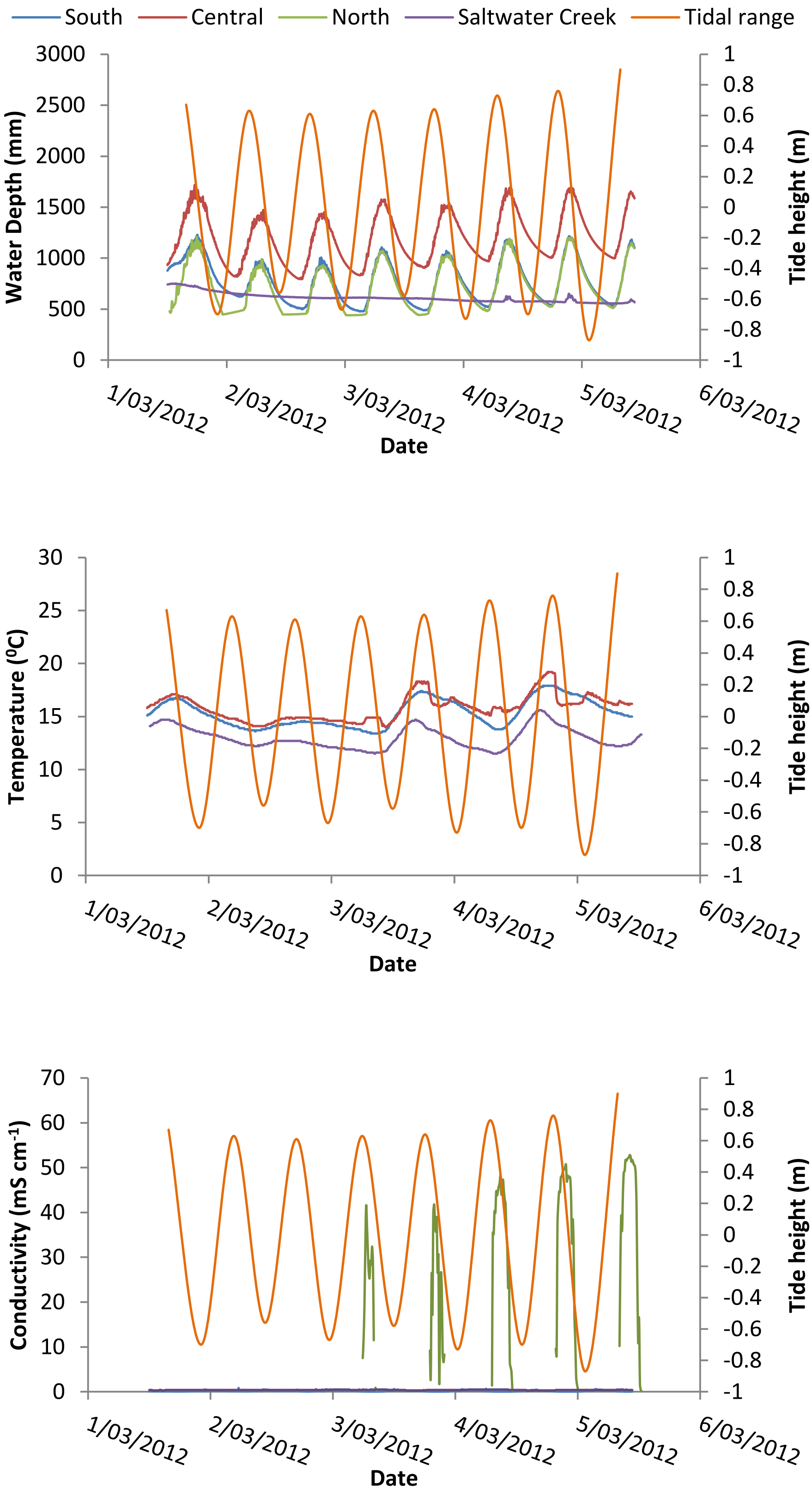

Figure 5.6. Short term water level, temperature and conductivity recordings in relation to tidal range, between the 1st March and 5th March 2012 for the recorders in the New River Lagoon. Note that negative values of tidal height indicate low tide and positive values of tidal height indicate high tide.

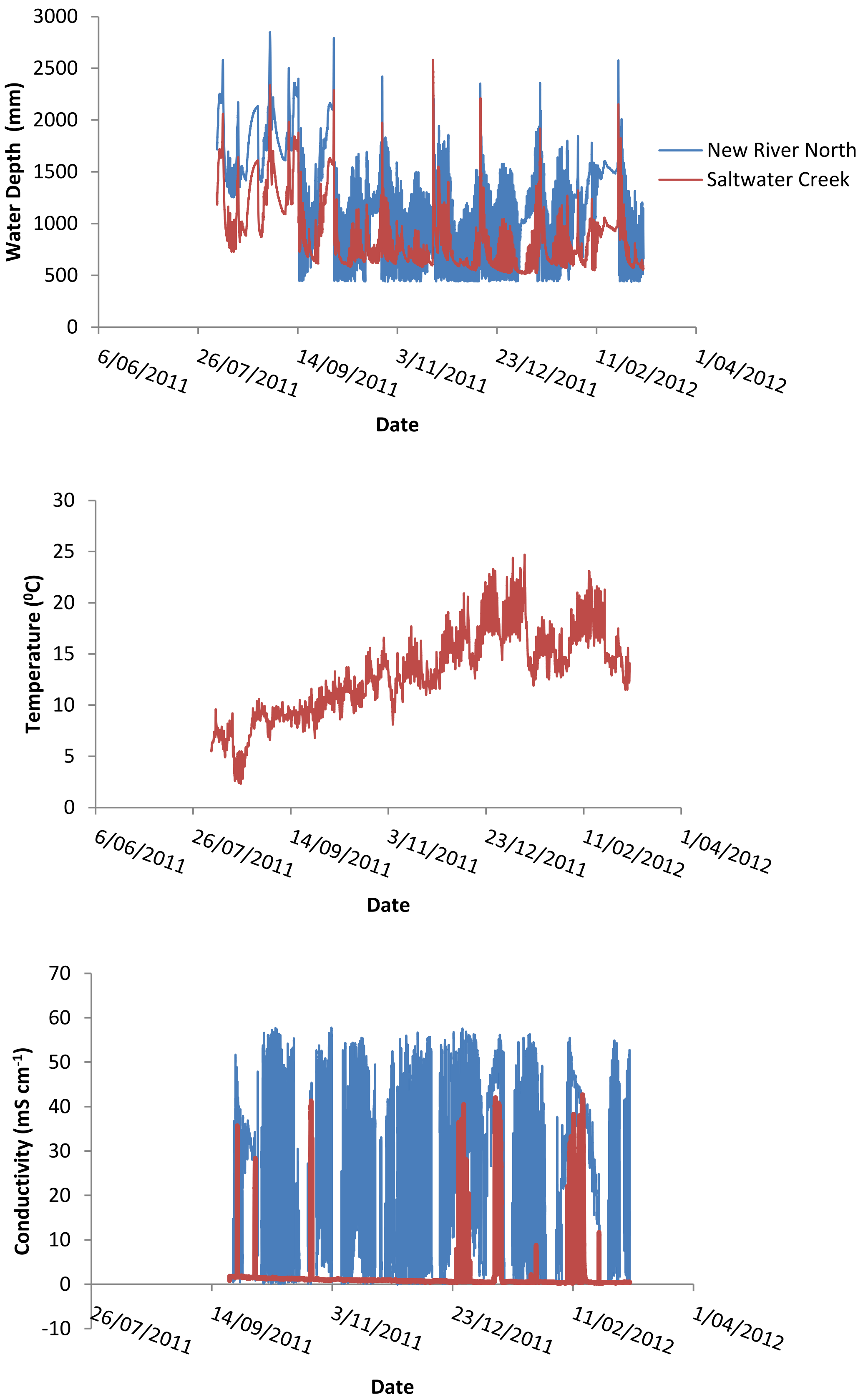

Figure 5.7. Long term water depth and temperature recordings between 4th August 2011 to 6th March 2012, and conductivity readings between 21st September 2011 to 6th March 2012, at Saltwater Creek and New River North

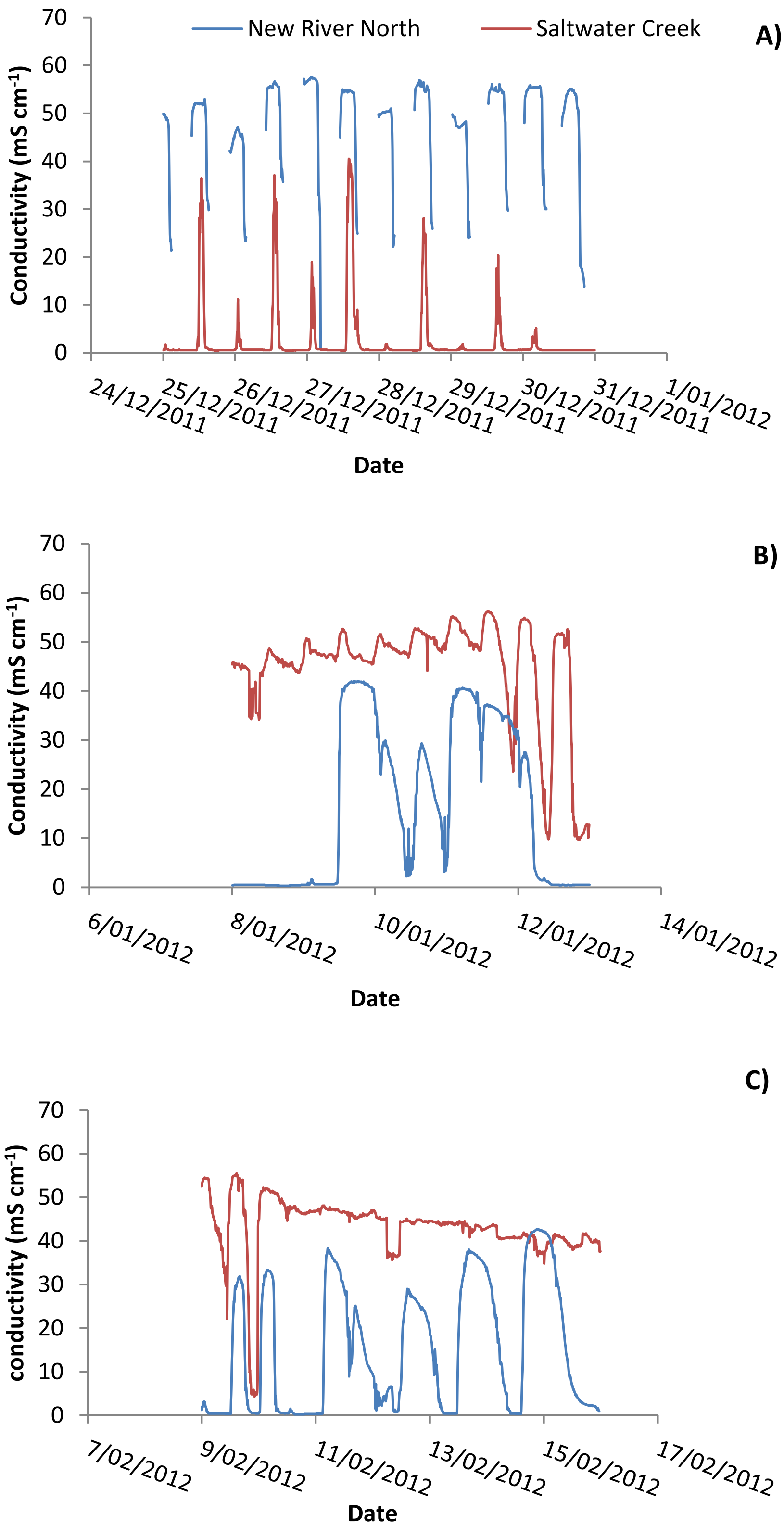

Figure 5.8. Periods of increased conductivity levels at Saltwater Creek and New River North. Image A shows distinct tidal influences at both recorders between the 25th and 30th December and images B and C show conductivity levels to be unusually high for prolonged periods at Saltwater Creek, whilst New River North has consistently high conductivity levels, between the 8th and 13th January and 9th and 15th February.

5.3.2 Local rainfall

Table 5.2 shows that daily rainfall varied considerably, from a maximum of 81.6 mm to a minimum of 0 mm. The mean daily rainfall of 5.1 mm. Total level of rainfall over the study period was 1413 mm, while November received the highest monthly total of rainfall at 329 mm and August received the lowest at 75.4 mm. The mean monthly rainfall was 197 mm. Approximately one third of total rainfall for the study period fell over 13 separate days in which total daily rainfall levels exceeded at least 20 mm.

Table 5.2. Total daily rainfall from August 2011 to 6th March 2012 recorded at the Greymouth Aero Club by NIWA

Day	August	September	October	November	December	January	February	March
1	0	4.2	0	0	0	0	11.6	9
2	0	1.4	19.4	7.4	0	0	5.2	0
3	0	0.2	26	9.2	0	0	0.4	5.4
4	0	1	6.2	11.2	10.6	1.6	0	0
5	1	0	0	15.6	3.4	0	0	1.4
6	0.2	0	0	2.6	0	0	0	0.2
7	16.2	0	0	0.4	3.6	2.8	0	
8	5	0	0	0.4	0	0.4	0	
9	1.6	23.6	0.2	9.8	0	0	0	
10	0	0.4	0.6	5	0	0	9.8	
11	0	1.2	8.4	0	0	0	0	
12	0	6.6	3.2	3	1	19.2	0	
13	0	10.6	11.6	0	6	57.6	0	
14	4.4	8	15.6	0	16.4	59.4	2.6	
15	0.2	21	3.8	0	48	10.4	0.8	
16	0	13.8	6.4	7.8	17.6	10	0	
17	0	5.2	0	10.6	1.2	0	0	
18	0	0.6	15.2	6.8	0	0	0	
19	0	12.6	4.2	0.8	0	0	0	
20	0	2.2	0	0	0	5.8	0.6	
21	0	0	0	81.6	0	0	3.2	
22	0.4	0	4.4	4.4	0	12	40.6	
23	0.2	0	0	8.2	0	0.4	37.4	
24	3	0.4	0.8	38.6	0	0	10.6	
25	6	9.2	1.4	4	0	0	17.6	
26	1.2	5.2	34	1.4	0	0	0.8	
27	2.8	2	0.6	0	0	15.4	0.6	
28	0.4	2.4	0	10.8	0	0	0	
29	0.2	0	4.2	7.8	0.4	0.6	0	
30	2.2	0	4	0	8	0		
31	15.2		0		21.6	0		
Min	0	0	0	0	0	0	0	0
Max	16.2	23.6	34	81.6	48	59.4	40.6	9
Mean	1.9	4.4	5.5	8.2	4.4	6.3	4.9	2.7
Total	76.4	155.4	204.2	329	185.8	255	182.4	25

5.3.3 Local wave climate

The maximum and minimum recorded total significant wave heights during the study period were 4.9 m and 0.4 m respectively, with a mean wave height of 1.9 m. Wave heights between 1 m and 3 m occurred most frequently and were variable over the study period reaching higher than 4 m on eight separate occasions (Figure 5.9). The direction in which waves travelled also varied, with 78 % of waves travelling in an E/NE direction, 3 % of waves traveling in a N/NE direction, 13 % of waves traveling in an E/SE direction and 6 % of waves traveling in a S/SE direction (Figure 5.9).

Table 5.3 shows that only 32 % of waves traveling in a NE direction (between 0 and 90^0) were of a greater height than 2 m, whilst 47 % of waves traveling in a SE direction (between 90 and 180^0) were over 2 m. Therefore, the proportion of SE waves greater than 2 m was higher than the proportion of NE waves greater than 2 m, while the actual percentage of all waves greater than 2 m traveling in an SE direction and NE direction was 9 % and 26 % respectively. Periods when wave directions trended SE were only short lived, lasting no more than 5 continuous days at a time.

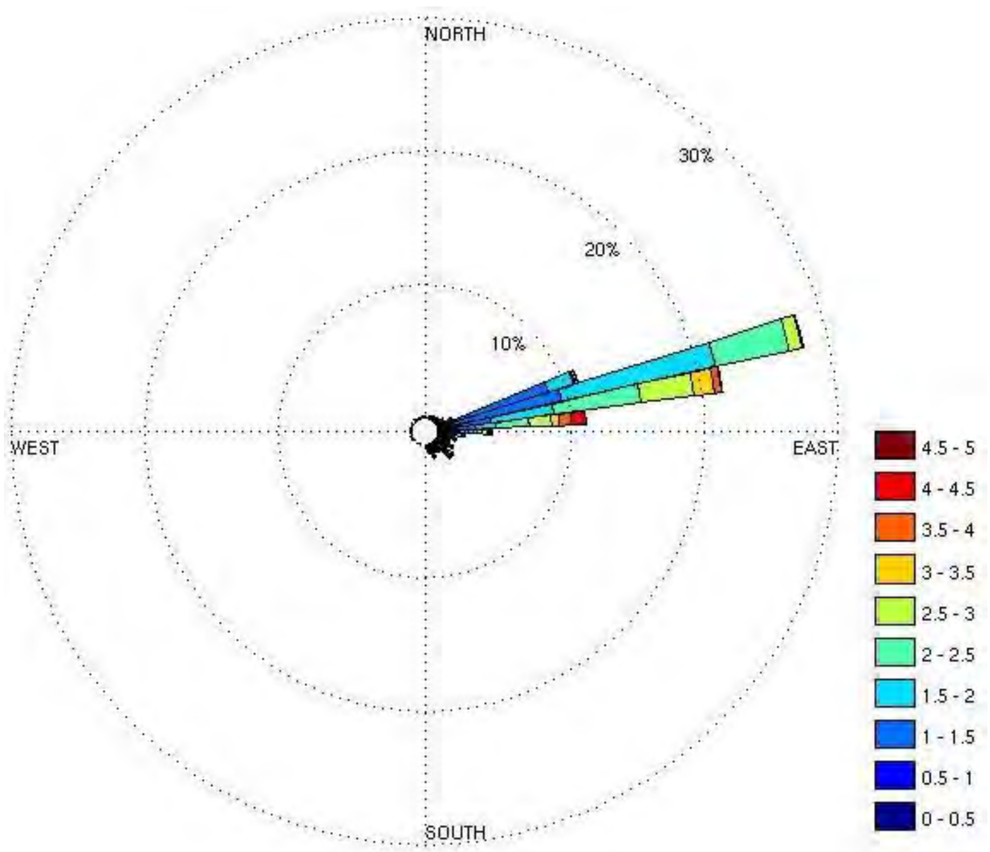

Figure 5.9. Percentage frequency wave height and wave direction from the 1st August 2011 to 5th March

Table 5.3. Proportion of wave heights for waves traveling in a NE direction (between 0 and 90^0) and a SE direction (between 90 to 180^0) between the 1st August 2011 and 5th March 2012

Wave height (m)	Proportion (%) of NE waves	Proportion (%) of SE waves
1	10	6
2	58	47
3	26	35
4	5	8
5	1	4
5+	0	0

5.3.4 Lagoon outlet morphology

Figure 5.10 shows a DEM of the New River Lagoon outlet and immediate updrift and downdrift beaches surveyed on the 1 December 2011 when the lagoon outlet was open. The DEM shows elevation heights relative to mean sea level. The main area of the outlet channel has been highlighted in dark blue as it was not able to be surveyed because water levels were too deep. Therefore, the depth is considered approximately below the lowest elevation of the closest surrounding surveyed areas. The remnant northward flowing lagoon channel and breakwater have also been highlighted. The following section provides a qualitative analysis of lagoon outlet morphology, which can be used to explain the lagoon"s hydrological characteristics.

Figure 5.10 shows the lagoon outlet oriented in a slight southerly direction due to the build up of a nearshore sediment bar directing water flow. The lagoon outlet is initially thin and elongated before dispersing into the sea. An updrift bar has formed across the lagoon outlet pushing the flow of water hard-up against the breakwater. This has created a deep scoured reservoir landward of the outlet channel. During periods of lagoon outlet closure, sediment has been observed to accumulate seaward of the breakwater structure forming a „plug" over the outlet. Water then accumulates in the reservoir until the outlet is breached. During periods of heavy rainfall the outlet widens, scouring through the updrift bar and deepening to allow for more water to exit the lagoon. Lagoon outlet dynamics are discussed further in Section 5.3.5.

For around 150 m downdrift of the breakwater there is an obvious reduction in the height of the barrier beach. Migration of the lagoon outlet, evident by a past lagoon channel at a depth of 1 to 2 m above sea level, separating the back barrier breach from the recovering beach berm, is the cause of sediment erosion along this section of beach. Maximum elevation levels of the barrier beach updrift and downdrift of the outlet are mostly between 4 and 5 m above mean sea level.

On both sides of the nearshore sediment bar and further into the lagoon outlet, elevation levels were surveyed at, or below, mean sea level. The main outlet channel, highlighted in dark blue, landward of the head of the breakwater was estimated at being at least 2 m deep at its deepest point, making it well below mean sea level, relative to surrounding measured elevations. Sediment was built-up to a higher elevation seaward of the breakwater and water depth was estimated at around 1 m, decreasing seaward.

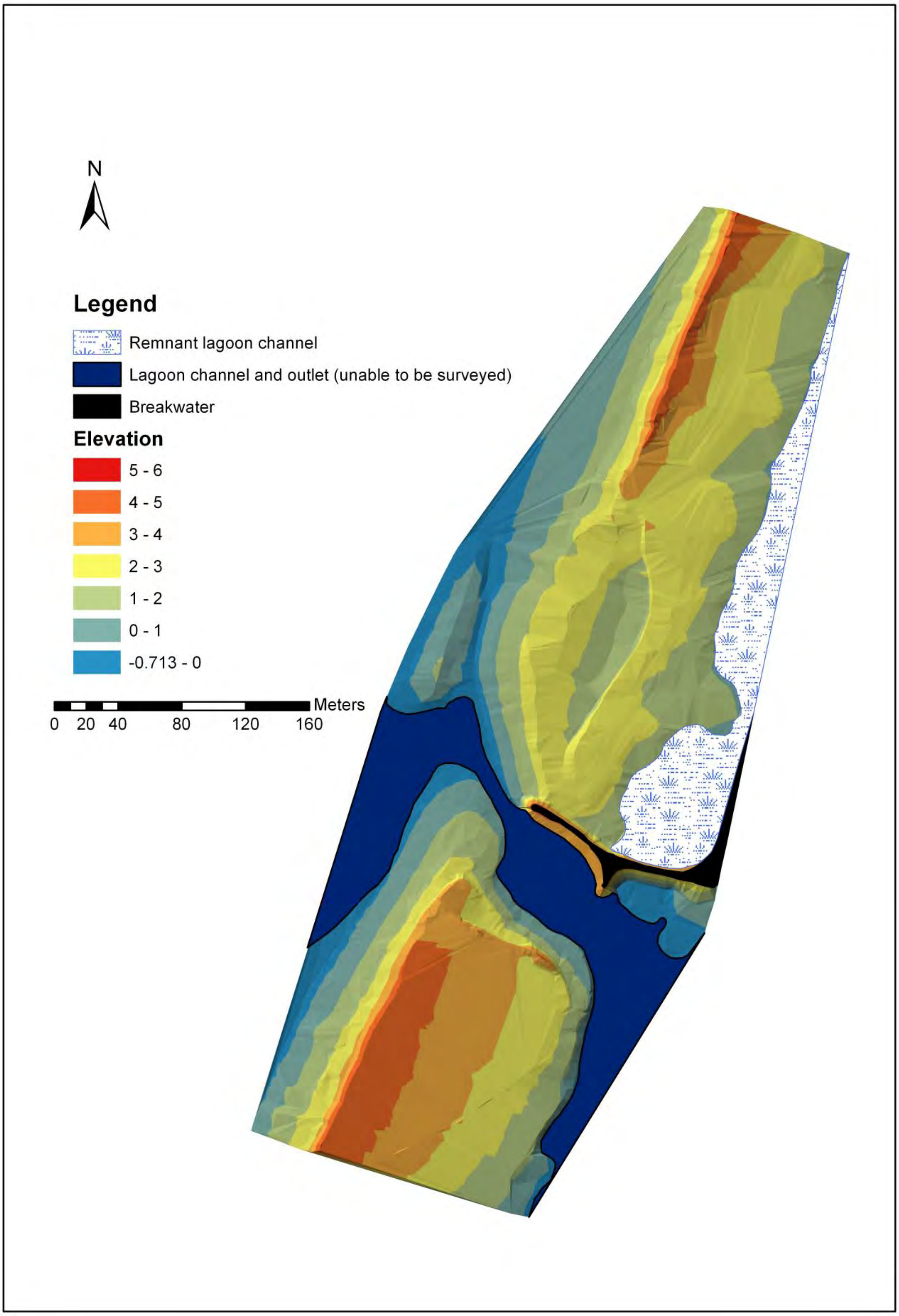

Figure 5.10. Topography of the New River Lagoon outlet and immediate updrift and downdrift beaches relative to mean sea level

5.3.5 Lagoon outlet morphological dynamics

The New River Lagoon outlet was observed to cycle between several different morphological phases due to changes in river flow, tides and wave climate. These included: northward outlet migration, southward outlet migration, outlet blockage and a stable direct outlet. In this instance, outlet blockage was considered when the outlet did not have a free flowing tidal connection with the ocean and when lagoon water levels began to rise above the influence of the tides (Goodwin, 1996). Subsequently, changes in outlet morphology had affects on the hydrology of the lagoon. Using oblique aerial photographs taken on a rough weekly timescale, the following section provides a qualitative analysis of morphological change at the lagoon outlet between the 5th July 2011 and 5th March 2012 and determines links between changes at the lagoon outlet and changes in lagoon hydrology and wave conditions. Figure 5.11 shows a timeline of morphological outlet behaviour and process drivers and associated hydrological dynamics at the New River Lagoon. Appendix 5 shows a timeline of all photographs taken during the study period.

Between 05/07/2011 and 10/09/2011 the lagoon outlet migrated approximately 150 m north of the breakwater, before artificial outlet opening occurred on 14/09/2011, relocating the outlet to a direct route to sea. Outlet migration occurred as a steady outflow of the river water caused progressive erosion of the outside banks of the outlet, whilst longshore drift in a NE direction deposited a sediment bar on the inside bank of the outlet. By 10/09/2011, the outlet channel had turned 90^0 around the breakwater structure and flowed parallel with the coastline (Figure 5.12). During outlet migration, tidal fluctuation of water levels cessed to exist, and on 30/09/2011 the lagoon outlet became blocked, with gravel over-wash causing an obvious restriction in the flow of water through the outlet. Consequently, water levels at New River North reached 2845 mm, the highest level over the study period. Following outlet opening water levels dropped below the logger at New River North and tidal exchange through the lagoon outlet increased dramatically, with water levels rising above and dropping below the logger in cycle with the tide; a characteristic unseen in the 40 days of monitoring prior to artificial outlet opening (Figure 5.12).

Between 22/09/2011 and 02/10/2011 water levels in the lagoon began to slowly increase and on 25/09/2011, 11 days after artificial outlet relocation, the lagoon outlet was again blocked, allowing for the build-up of water behind the barrier beach (Figure 5.12). Subsequently, conductivity levels at New River North were consistently high around 30 mS cm^{-1}, whilst conductivity at Saltwater Creek remained low, but spiked to an unusual concentration of 28 mS cm^{-1} on 01/10/2011. By 02/10/2011 rainfall had caused water levels at New River North to reach 2794 mm before the barrier was breached, resulting in an outlet directly to sea (Figure 5.12). This again caused a large decrease in lagoon water levels and initialised a significant increase in tidal exchange through the lagoon outlet.

During mid-late October the lagoon outlet uncharacteristically migrated southward, against the prevailing northward direction of longshore drift. Between 17/10/2011 and 24/10/2011 a bar progressively formed on the outside banks of the lagoon outlet, forcing the outlet channel to migrate southwards (Figure 5.13). Consequently, lagoon water levels began increasing on 18/10/2011, until they reached 1785 mm at New River North on 25/10/2011. Rainfall on 26/10/2011 caused a further increase in water levels at New River North to 2421 mm, causing the barrier to breach and forcing the lagoon outlet directly to sea. A similar situation of southward outlet migration also occurred between 03/03/2011 and 06/03/2011 (Figure 5.13), restricting tidal exchange through the lagoon outlet. Surprisingly, wave direction was mostly in a NE direction during both these periods of southward outlet migration, though changed to a continuous SE direction intermittently for up to 1 day at a time.

Subsequent to outlet breach on 26/10/2011, high levels of rainfall on the 20/11/2011 and 14/12/2011 caused flooding of the lagoon, with water levels at New River North reaching 2582 mm and 2353 mm respectively. Consequently, between 26/10/2011 and 02/01/2012, the lagoon outlet flowed direct to sea and lagoon water levels fluctuated freely with the tidal cycle (Figure 5.14). A 13 day period of no rainfall and a mean wave height of 1.2 m between 18/12/2011 and 30/12/2011, following flooding and flushing of the lagoon outlet on 14/12/2011, meant river flow and sediment transport into the lagoon outlet were low. As a result, tidal fluctuations were large, propagated as far as the Saltwater Creek recorder. This is evident in Figure 5.8 where conductivity levels loosely fluctuate with the tidal cycle.

Images in Appendix 5 show the lagoon outlet to be positioned relatively straight to sea for January and March. However, between January and March 2012, there were several changes to lagoon water and conductivity levels that suggest changes in outlet morphology not captured on camera.

Following the late November and December period of fluvial dominance, lagoon water levels at New River North increased to 2353 mm between 03/01/2011 and 14/01/2012. During this time high levels of conductivity at New River North were consistent and conductivity levels at Saltwater Creek became unusually high for prolonged periods (Figure 5.8). A similar situation occurred between 10/02/2011 and 22/02/2012, where water levels at New River North increased to 2577 mm and conductivity levels decreased from 50.8 mS cm^{-1} to 3 mS cm^{-1} as the lagoon slowly became diluted with fresh river water. Again, conductivity levels at Saltwater Creek increased for prolonged periods (Figure 5.8). These two periods of increasing water levels and relatively stagnant salinity levels suggest further blockage of the lagoon outlet.

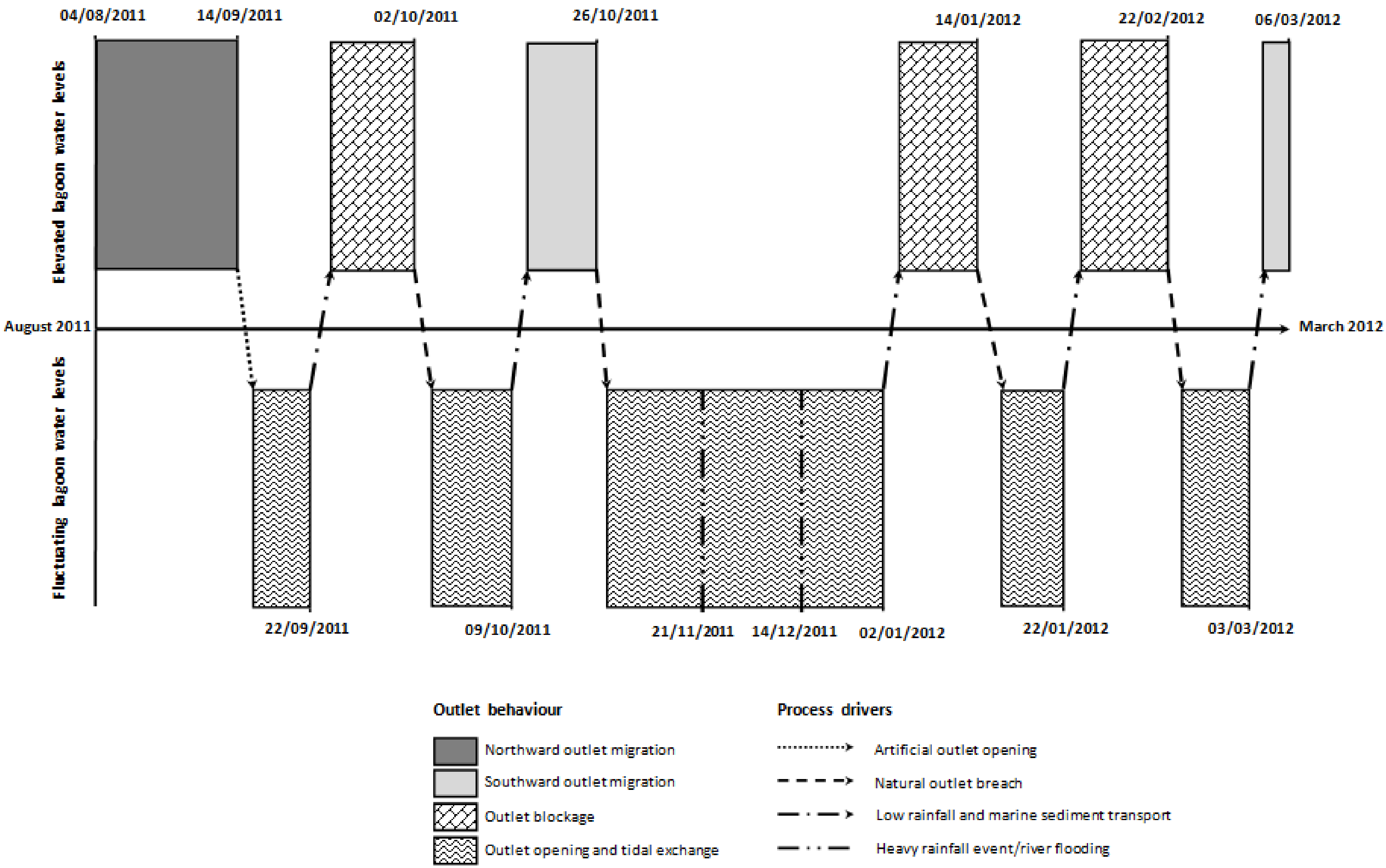

Figure 5.11. Timeline of morphological outlet behaviour and process drivers and associated hydrological dynamics at the New River Lagoon between August 2011 and March 2012

Figure 5.12. Outlet morphology on 10/09/2011 (A, B), 18/09/2011 (C, D), 25/09/2011 (E, F), and 02/10/2011 (G, H) (Photos courtesy of Karl Tolley). Images A and B show northward drift of the lagoon outlet and the subsequent high water levels in the reservoir of the lagoon outlet. Images C and D shows the lagoon outlet 4 days after artificial opening whereby lagoon water levels decrease considerably. Note the nearshore sediment bar in the background of photo B that likely contributed to outlet blockage. Images E and F show blockage of the lagoon outlet 11 days after artificial opening whereby high water levels pond behind the barrier beach. Images G and H show natural lagoon breach following lagoon blockage

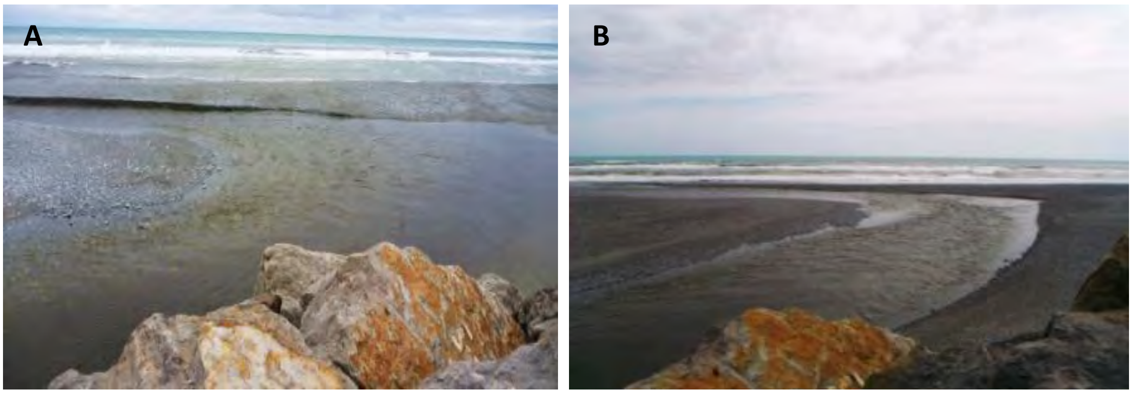

Figure 5.13. Southward outlet migration on the 24/10/2011 (image A) and 06/03/2012 (image B) (Photos courtesy of Charlie Teasdale)

Figure 5.14. Outlet morphology on 20/11/2011 (A, B), 21/11/2011 (C, D), and 02/12/2011 (E, F) (Photos courtesy of Charlie Teasdale). Images A and B show the general direct outlet position for November and December 2011. Images C and D show flooding of the lagoon causing increased water levels and widening of the outlet and images E and F show the lagoon outlet following flooding.

5.4 Discussion and Interpretation

This section discusses the hydrology and outlet dynamics of the New River Lagoon prior to engineering management based on the results from this chapter. Interpretations are then made between the observed characteristics and relevant literature.

Fluctuations in lagoon water levels lessened with greater distance from the lagoon outlet due to a reduction in the direct influence of the tidal cycle. The full extent of the New River channel underwent more dramatic fluctuations in water level than the Saltwater Creek because it is more dominant and drains a larger catchment, so is influenced more directly by the tidal cycle and has a higher peak flood level. Fluctuations in water level at Saltwater Creek and New River South, due to the tidal cycle, can be linked to a tidal backwater effect caused by the interaction of opposing flows between outgoing river water and incoming sea water.

Tidal asymmetry was observed to occur in the New River channel, which can be related to outlet and channel morphology. Speer and Aubrey (1985) and Blanton *et al.* (2002) describe tidal asymmetry to be more pronounced in narrow shallow estuaries, like the New River Lagoon, as opposed to deeper, wider tidal flats. Intermittently Closed/Open Lagoons (ICOLs) with tidal asymmetry, particularly those with larger incoming tides, can have greater difficulty maintaining an open lagoon outlet, as ebb-currents are less efficient at removing sediment (Gordon, 1990; Haines, 2006); a concept possibly applied to the New River lagoon.

Changes in water level had implications for the morphology of the lagoon outlet. Recurring flood events during late November and December meant the lagoon outlet remained open and tidal exchange was prominent. In contrast, during other months of the study period, high river flows were less common and the lagoon outlet cycled through phases of lagoon outlet blockage and a subsequent increase in water levels, followed by outlet breach and an increase in tidal exchange. Provided that river flows remained low, tides and waves worked to close the outlet and repeat the cycle. This cycle of outlet opening and closure is similar to that seen in ICOLs, whereby closure often occurs quickly after an outlet breach, during which there is an abundance of sediment in the nearshore zone (Gordon, 1990; Haines, 2006). This sediment is then deposited into the outlet channel by longshore and cross-shore wave processes and tidal currents (Ranasinghe and Pattiaratch, 2003). On four separate occasions at the New River Lagoon outlet closure began within 12 days of outlet breach, during which tidal exchange was prominent through the outlet.

Artificial outlet opening and barrier breach, following periods of outlet blockage and/or migration, caused lagoon water levels to drop dramatically and tidal exchange to increase. When the outlet blocked, water built up in the outlet channel behind the barrier until water overtopping and/or a rainfall event releases the build up of pressure. The increase in tidal exchange following outlet breach is behaviour common in ICOLs and is related to outlet channel bed elevation (Cooper, 2001; Gordon, 1990). The outlets at many ICOLs are naturally located hard-up against rock outcrop and headlands, causing the scouring of a deep outlet channel (Haines, 2006). The low elevation of the outlet channel at the New River Lagoon is caused by the natural northward drift of the lagoon outlet that forces the outlet channel against the breakwater structure, scouring a deep channel. Essentially, this is how a breakwater is supposed to work, as a deeper channel allows for better flushing of flood water. In the lagoons natural state it is not likely that the outlet channel would have resided at such a low elevation, thus tidal exchange would not have been as prominent.

Conductivity levels also reduced with greater distance from the lagoon outlet, due to a reduction in the direct influence of the tidal cycle. Over the short term study period, conductivity levels at Saltwater Creek and New River South remained at fresh water concentration, whilst at New River Central and New River North they fluctuation with the tidal cycle. Change in morphology of the lagoon outlet had a large influence on the conductivity levels of the lagoon. During periods when the lagoon outlet was open, conductivity levels at New River North constantly fluctuated with the exchange of tidal waters due to its close proximity to the lagoon outlet. As a result, conductivity levels could range from completely saline to fresh water in one tidal cycle. During periods when the lagoon outlet was blocked, tidal exchange was cut off and conductivity levels were consistently high, with the exception of slight dilution due to fresh water inflow. Homogenous salinity levels are common in ICOLs during outlet closure and can often remain that way until the outlet is breached (van Niekerk *et al.*, 2005).

At Saltwater Creek conductivity levels remained at fresh water concentration for the majority of the study period. However, on several occasions there were spikes in conductivity levels that coincided with particular morphological changes at the lagoon outlet. During periods when the lagoon outlet was blocked, saltwater was recorded to back-up as far as the Saltwater Creek logger, causing prolonged increases in conductivity levels. This suggests that during periods of outlet blockage, salt water, located in abundance in close proximity to the lagoon outlet, can back-up into the higher reaches of the lagoon and remain stagnant or fluctuate depending on the level of fresh water influx. In contrast, during a long period of no rainfall and subsequently low river water levels, and when the lagoon outlet was open direct to sea, conductivity levels at Saltwater Creek loosely followed the tidal cycle. This suggests the lagoon has potential to drain to very low levels during low tide, following which tidal waters can then penetrate into the higher reaches of the channel during high tide. This type of behaviour is consistent with Vaz *et al.*

(2005) and Snow and Taljaard (2007) who describe stronger tidal ingress and mixed salinity levels during low river flows, and week tidal ingress and stratified salinity levels during high river flows.

Local rainfall had a large control on the opening and closing of the lagoon outlet. Periods of consistently high rainfall during November, meant the outlet was open consistently. In contrast, during dry periods such as August, where rainfall was less than half the mean monthly rainfall amount for the study period, marine wave processes and tidal transport of sediment worked to close the lagoon outlet. The influence of river flow for maintaining on open outlet is common for lagoon systems, located on high energy coastlines, particularly hapua (Kirk, 1991), river-dominated (Cooper, 2001) and wave-dominated estuaries (Roy *et al.,* 2001), and ICOLs (Haines, 2006; Whitfield and Bate, 2007).

Wave climate off the coast of the New River Lagoon was relatively consistent throughout the study period with the majority of wave heights recorded between 1 to 3 m and traveling in a northerly direction. This was expected, based on previous studies and when considering the lagoon outlets past tendencies to migrate in a northerly direction. Waves were recorded to travel in a southerly direction, but these periods did not last more than 5 days at a time. The predominant northerly wave direction causes a northerly longshore drift of sediment, which was obvious during the beginning of the study period when northward outlet migration was observed to occur, despite the implementation of a breakwater at the lagoon outlet in an attempt to prevent such processes occurring. As a result, water levels rose to their highest level of 2845 mm at New River North for the study period. Had artificial opening of the outlet not occurred to relocate the outlet directly to sea, it is possible that the outlet channel would have re-joined the past lagoon channel to the north and inland of the artificial outlet, currently blocked off by the engineering breakwater.

Brief southward outlet migration was also observed to occur on two separate occasions, causing partial outlet blockage. Surprisingly during these periods southerly directed waves only appeared intermittently and for short periods. However, on average southerly directed waves were recorded to have greater wave heights, and thus wave energy, than northerly directed waves, which suggests enhanced sediment movement during these short periods may have been enough to direct the outlet channel southward and initiate scouring of the outlet channels inside banks. A similar shift in prevailing wave direction, thus direction of sediment transport, can also occur on the East Coast of the South Island, New Zealand, causing hapua to migrate in a southerly direction (Kirk, 1991). Outlet migration against the prevailing direction of longshore drift has also been recorded at the Keurbooms Inlet in South Africa due to the interaction of tides and wave sediment transport (Reddering, 1983).

There are obvious differences in lagoon morphology and dynamics between pre- and post-engineering management periods. In particular, the change in outlet dynamics and the influence this now has on lagoon hydrology. As a result, the New River Lagoon now shows a combination of characteristics distinctive of hapua-type lagoons and ICOLs, with those of the latter shifting its classification on a hydrological scale from being closer to hapua to closer to estuaries. Chapter 6 determines the changes in lagoon characteristics as a result of engineering management and compares these characteristics with the classification of similar lagoon systems in the national and international literature.

Despite unstable morphological changes to the lagoon outlet, that saw periods of lagoon outlet migration and blockage; characteristics both typical of erosion and lagoon flooding, hazard management intervention at the lagoon was relatively effective at reducing the risk of flooding and erosion by controlling the outflow of river water and restricting outlet migration. Chapter 6 discusses the suitability of engineering work to the New River Lagoon system and determines the functional effectiveness it has on reducing flood and erosion risks, while evaluating its impact to the natural dynamics of the lagoon system. Future management options for the New River Lagoon are also discussed.

5.5 Summary

This chapter described the current hydrology and morphological outlet dynamics of the New River Lagoon, and presented the results of water level recorders, local wave and rainfall data, GNSS surveying and oblique photographs. Water depth, conductivity and temperature records were used to explain lagoon hydrology, and DEMs and oblique photos were used to explain and document changes in outlet morphology. Wave and rainfall data were used to explain the balances between marine and fluvial environments and their affects on outlet dynamics.

The hydrology of the New River Lagoon varied both spatially and temporally and was largely influenced by the tidal cycle. Fluctuation in water level and conductivity decreased with distance from the lagoon outlet due to a less direct influence of the tidal cycle and the New River channel experienced more extreme fluctuations in water level than the Saltwater Creek channel because it drains a larger catchment and because it is a more dominant channel. Lagoon outlet dynamics caused variations in lagoon water levels and conductivity due to its control on the exchange of water between fluvial and marine environments.

Local wave climate was relatively consistent during the study period with wave heights between 1 to 3 m, traveling in an E/NE direction, occurring most frequently. As a result northward migration of the lagoon outlet occurred during August influenced by northward longshore drift of sediment. Waves were also recorded to travel in an E/SE direction, but for shorter durations and on average at a greater height. However, there were no strong links between southward wave movement and southward outlet migration.

Local rainfall varied considerably during the study period ranging from total daily levels of 0 mm to 81 mm. August received the lowest level of total rainfall with 75.4 mm, whilst November received the highest level of total rainfall with 329 mm. As a result, the lagoon outlet was least stable during August due to the dominance of marine wave processes and most stable during November due to the balance of fluvial and marine processes. Periods of heavy rainfall often caused outlet breach at the lagoon, whilst periods of low rainfall allowed the lagoon outlet to become blocked or migrate.

Although current engineering management is in place in an attempt to stabilise the lagoon outlet, it continued to cycle through various unstable morphological states, which included north and south outlet migration and outlet blockage. These states were a result of marine wave dominance and occurred during periods of low river flow and high sediment supply. In spite of this, the outlet breakwater managed to control high levels of river flow and for the majority of the study period an open outlet to the sea was maintained.

Chapter 6 : Integrated Discussion

6.1 Introduction

The previous two chapters have presented a detailed description of the geomorphology and dynamics of the New River Lagoon over a 67 year period prior to engineering management, and the results of an investigation of the lagoon hydrology and changes in the outlet morphology in relation to local wave and rainfall climate over a 6 month period following engineering management of the lagoon system. Using this information, the lagoon characteristics during a long term period of natural lagoon development and a short term period of controlled lagoon development were able to be interpreted. The following chapter brings together these results to assess changes in the lagoon characteristics, as a result of engineering intervention and to conceptualise the change in process response mechanisms of the lagoon. Comparisons are made between characteristics of the New River Lagoon and classification of similar lagoon systems in the international literature. The effectiveness of management works, based on performance and effects on environmental integrity are determined, while options for future management are also discussed.

The following chapter is separated into 3 sections: Section 6.2 makes comparisons between lagoon characteristics pre- and post-engineering management; Section 6.3 discusses the classification of lagoons and compares the characteristics of the New River Lagoon with hapua and Intermittently Open/Closed Lagoons (ICOLs); and Section 6.4 determines the effectiveness of engineering management and discusses options for the future.

These following research objectives are addressed:

- identify the changes in lagoon morphology and dynamics between pre- and post-engineering management works,

- evaluate the classification of the New River Lagoon in relation to other similar lagoon systems,

- determine the effectiveness of engineering management works at reducing hazards risk for the local community, whilst imposing minimal adverse effects on the environment, and

- discuss future management options for the New River lagoon

6.2 Comparison of the New River Lagoon pre- and post-management

The results of lagoon morphology and dynamics pre- and post-management have previously been interpreted in detail within chapters 4 and 5 and will not be repeated here. Instead this section draws together and discusses these results as a whole by comparing the dynamics of the New River Lagoon pre- and post-engineering management intervention. The changes that occur to lagoon dynamics as a direct result of anthropogenic influences are important for determining environmental effects and the overall suitability of management works. This is particularly important for the New River Lagoon, as little was known about its characteristics prior to management decisions being made. There are obvious changes in lagoon dynamics pre- and post-engineering management, which are largely related to the implementation of a breakwater that partially obstructs the natural dynamics of the lagoon outlet. In addition, the difference in spatial and temporal scale of pre- and post-engineering periods of analysis reveals different lagoon characteristics.

Prior to management intervention the lagoon outlet was free to move along the beach in response to northward littoral drift, forming long elongated outlet channels parallel to the coastline. The lagoon outlet approached the coastline at an oblique angle, which aided its northward movement and channel formation. The analysis of aerial photographs showed that over decades the northward movement of the lagoon outlet was steady; although over years the outlet could also migrate southwards, suggesting northward movement was not always constant. Overall, the morphology of the lagoon did not appear to undergo large-scale morphological changes, with only one primary breach event over the 67 year study period likely to have any major effects on the dynamics of the lagoon. Therefore, it is reasonable to assume that the hydrology of the lagoon was relatively stable prior to engineering management.

Over a short term temporal scale from weeks to months following engineering management, the lagoon outlet was observed to cycle frequently between different morphological phases that saw it flow directly to sea, become blocked and migrate in both northern and southern directions (Figure 6.1). These morphological changes were mostly restricted to the immediate vicinity of the breakwater, with the exception of one occasion when the outlet migrated northward, similar to its natural dynamics.

Figure 6.2 shows the process agents and associated outlet behaviours observed at the New River Lagoon following engineering management intervention. River flow and wave climate are the major driving forces of outlet change as they balance one another (i.e. periods of high river flow counteract marine sediment supply keeping the outlet open, while periods of low river flow are dominated by marine sediment supply that works to close the outlet). Outlet opening caused tidal influences, which keep the outlet open but also transport and deposit sediment to work it closed. Outlet migration required a balance between river flow and sediment supply and also caused outlet closure. The process agents involved in Figure 6.2 were likely very similar prior to engineering management. However, it is unlikely that tidal influence would have had a direct link with outlet opening and lagoon water levels, and likely that northward outlet migration was more prominent; a characteristic now restricted under engineering management.

The hydrological dynamics of the New River Lagoon were largely unknown prior to engineering management and this study. Neale *et al.* (2007) mentioned that several lagoons on the West Coast experienced restricted tidal ingress, isolated mainly to the immediate vicinity of the lagoon outlet, while Kain (2009) found that the Totara Lagoon was undergoing an estuarine phase of tidal exchange with the sea, caused by artificial outlet opening. Following engineering management the hydrology of the New River Lagoon is now largely influenced by the tidal cycle, controlled by the dynamics and morphology of the lagoon outlet in association with the breakwater. The lagoon outlet channel, restricted against the breakwater, has a bed elevation below mean sea level, due to scouring that has carved a deep channel adjacent to the breakwater. Prior to engineering management, it is not likely that the bed of the outlet channel would have been so low, and tidal exchange would not have been as prominent during periods when the outlet was open.

Frequent morphological changes to the lagoon outlet meant extreme changes to lagoon hydrology occurred on a frequent basis, because of the low bed elevation of the outlet channel. For instance, the outlet would typically cycle through open and closed phases (Figure 6.1 and 6.2), which meant lagoon water levels would deviate from large fluctuations in water level and salinity during an open phase, to water levels that increased in depth and had a homogenous salinity concentration during a closed phase.

Furthermore, the location of the artificial outlet directly in front of the breakwater and at the confluence of New River and Saltwater Creek channels, adds to the enhanced tidal exchange. The contrast between lagoon hydrology under natural outlet conditions and modified outlet conditions was especially evident following artificial relocation of the outlet in September 2011. Prior to relocation, the outlet migrated downdrift (north) of the breakwater, forming an outlet channel parallel with the coastline and discharging at an oblique angle to the coastline; a morphological state comparable to the natural characteristics of the lagoon prior to engineering management.

During the 2 months of outlet migration, overall lagoon water levels were around 1 m higher in the New River channel and did not fluctuate dramatically or consistently with the tidal cycle. This could be explained by two factors: 1) tidal ingress was less prominent when the outlet approached the coastline from an angle away from prevailing northward wave direction, and more prominent when the outlet was oriented directly out to sea, and 2) the location of the outlet at the end of an elongated channel, where hydraulic head had reduced, meant water resided longer before exiting the lagoon, as opposed to the location of the outlet at the confluence of both lagoon channels where water was flushed more effectively to sea.

These characteristics of artificial outlet opening are comparable with the reduction in lagoon water levels that occur during primary outlet breach (barrier breach directly opposite the river mouth) (Kirk, 1991; Kain, 2009); however, unlike lagoons such as hapua, that readily experience primary breach and are elevated above high tide, the New River Lagoon experiences tidal exchange, due to a low channel bed elevation. Kain (2009) describes similar hydrological characteristics during continuous artificial outlet openings opposite the river mouth at the Totara Lagoon.

Inferences can be made about the potential hydrology of the New River Lagoon prior to engineering management based on these characteristics. The hydrological characteristics observed during lagoon outlet migration, following engineering management, would suggest that it is highly unlikely that tidal exchange during outlet migration prior to engineering management would have existed. However during periods when the outlet was located at the confluence of Saltwater Creek and New River channels, or at a location directly opposite the river mouth, it is likely that tidal exchange would have existed, but at less intensity, due to naturally higher outlet channel bed elevations.

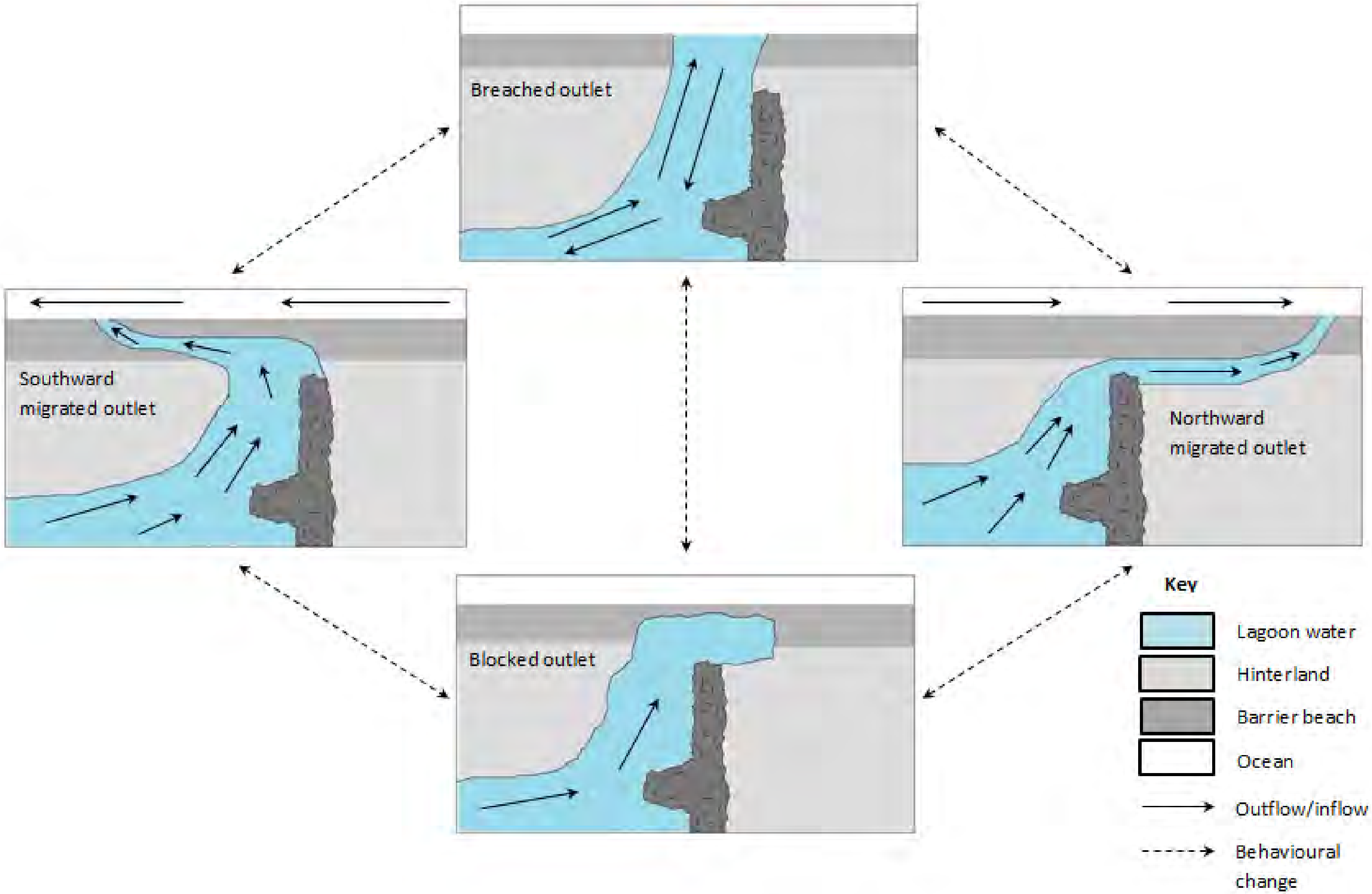

Figure 6.1. Typical outlet states at the New River Lagoon post-engineering management cycled between phases of outlet breach, outlet blockage and outlet migration, which determined inflows and outflows into the system. This is largely controlled by the obstruction of the rubble-mound breakwater.

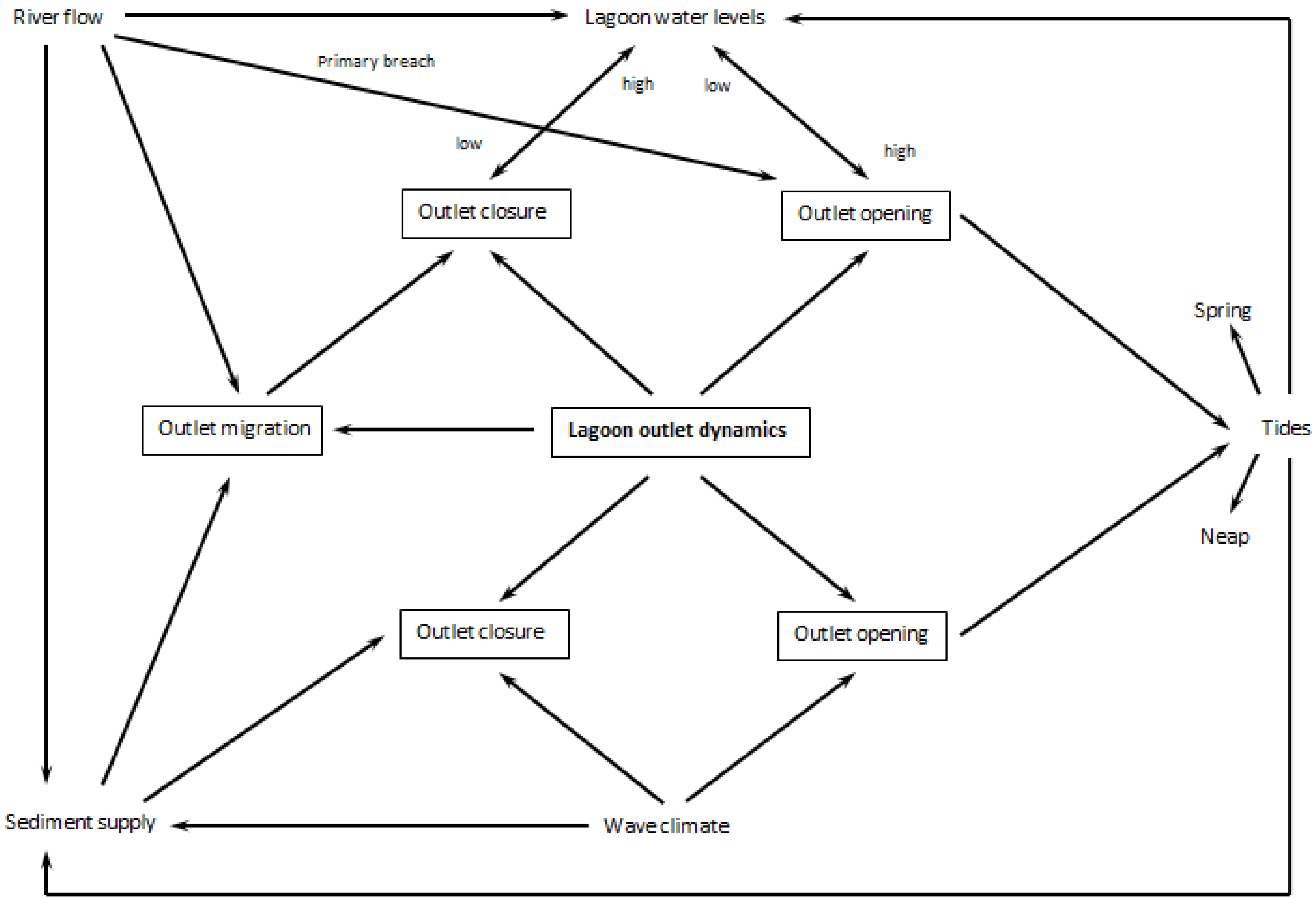

Figure 6.2. New River Lagoon outlet dynamics in response to different process agents following engineering management

6.3 Lagoon classification

The classification of coastal waterbodies has been a topic of discussion and development within literature for decades, but there is still uncertainty of the definition and classification of coastal lagoon systems, which are diverse in nature throughout the world. Much confusion comes from the distinction between coastal lagoons and estuaries, with some authors using the terms as overlapping or interchangeable. For the purpose of this study, definitions with minimal overlap are used in order to clearly distinguish the differences in estuary and lagoon systems. Both types show similar morphological features but are exposed to different process environments, so display different hydrological characteristics. This section examines the classification schemes of different coastal lagoons and uses them as context to understand the morphology and dynamics of the New River Lagoon, and compares them with other similar lagoon systems. The characteristics of the New River Lagoon have developed as a result of anthropogenic influences, so changes to its classification between pre- and post-management environments are also determined.

6.3.1 Coastal lagoons and estuary systems

The physical characteristics of coastal systems have been the primary emphasis of a number of classification schemes. As such, the New River Lagoon fits with the basic definitions of coastal lagoons, described by Phleger (1969) and Kjerfve (1994 pg. 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*". Process environments drive the physical characteristics of a lagoon, but they also cause discrepancies between classification schemes that are based on these characteristics. As such, issues arise when hydrological parameters are introduced, particularly within coastal lagoons, leading to confusion with estuary definitions. Therefore, whilst physical dimensions are important for describing a coastal environment, the process environments and subsequent dynamics of a coastal system are what characterise them and differentiate or relate them to similar systems. Furthermore, changes in lagoon morphology, due to the anthropogenic influences, for example, create changes in the dominance of different process environments and variability of definition for a particular coastal system. In the case of the New River Lagoon, engineering management intervention has changed the lagoon‟s morphology, which has lead to an increase in the dominance of tidal processes.

Prior to engineering management at the New River Lagoon, wave processes dominated morphological changes and the lagoon relied largely on river flow to maintain an open outlet. Consequently, strong northward littoral drift meant the lagoon was prone to outlet closure and migration and was subsequently classified by Neale (2006a) and Neale *et al.* (2007) as a hapua-type lagoon. River-dominated estuaries and wave-dominated estuaries are a similar classification scheme to hapua developed by Cooper (2001) and Roy *et al.* (2001) respectively. Both are used to describe systems located on wave-dominated coastlines that do not have a tidal prism strong enough to maintain an open outlet against longshore drift and cross-shore transport of sediment, so instead rely on sufficient river outflows.

Prior to engineering management the hydrology of the New River Lagoon was largely unknown, although it experienced periods of tidal influence, which was likely dependent on the location of the lagoon outlet. Tidal ingress is a process strictly uncharacteristic of hapua and river- and wave-dominated estuarine classifications (Kirk, 1991; Cooper, 2001; Roy *et al.*, 2001). Thus the New River Lagoon could not be classified primarily as either of these terms. The lagoon"s tidal prism was too weak to maintain an open outlet against the prominent longshore drift, evident by the fact that it is located on a wave-dominated coastline and would typically close under periods of low river flow and strong littoral drift. Therefore, it could not have been classed amongst tidal-dominated estuaries; a classification also developed by (Cooper, 2001).

It can be concluded that the New River Lagoon prior to engineering management was located on a wave-dominated coastline, relied on dominant river flow to balance marine wave processes and showed hapua-like characteristics, but also experienced periods of tidal influence. Therefore, placing it somewhere on a continuum between hapua and estuaries; two coastal waterbodies, arguably at different extremes on the hydrological scale (Kain, 2009). In order to gain context as to how the New River Lagoon functions in relation to similar New Zealand coastal lagoons, Section 6.3.2 discusses the similarities and differences between the New River Lagoon pre-management and hapua.

Classification of the New River Lagoon post-engineering management is difficult to determine, with obstruction of the lagoons natural dynamics exposing it to a variety of processes environments that each show periods of varying dominance. Tidal exchange is now an integral part of lagoon dynamics during periods of outlet opening, assisting it to maintain an open outlet, but also transporting sediment into the outlet contributing to its closure. An increase in tidal exchange at the lagoon during outlet opening has meant lagoon water is now of a brackish concentration for at least 500 m past the lagoon outlet. Despite an increase in tidal prism, the outlet still relies on river flow to remain open, with frequent closure associated mostly with dry periods. Furthermore, tidal exchange is greatest following major rainfall events, during which the outlet channel is deepened. Lagoon outlet migration is still apparent, expressing the lagoons hapua-type nature.

It is difficult to classify the New River Lagoon post-engineering management as it shows clear characteristics of both estuarine and lagoon systems and unless monitoring is carried out over a longer time span, it is unclear exactly which characteristics dominate and where on the hydrological continuum the system sits. Intermittently Closed/Open Lagoons (ICOLs), along with similar intermittently opening systems such as Temporary Open/Closed Estuaries (TOCEs), are primary examples of the debate about the overlapping definition of estuaries and lagoons (Tagliapietra *et al.*, 2009), as sometimes they are influenced by tidal exchange and sometimes they are not, which is controlled by the intermittent nature of the outlet (Roy *et al.*, 2001; Haines, 2006; Whitfield and Bate, 2007). Essentially, this is also the case with the New River Lagoon, which now experiences intermittent outlet opening/closing, exposing it to variable degrees of tidal exchange. Section 6.3.3 discusses the similarities and differences between ICOLs and the New River Lagoon.

Kain (2009) describes a similar situation at the Totara Lagoon, also located on the West Coast of the South Island, New Zealand. She describes the lagoon as being in an estuarine phase, due to pronounced tidal influences during frequent artificial outlet opening and subsequently classifies it in the centre of a continuum between estuaries and hapua. The New River Lagoon is in a similar situation, albeit on a more permanent scale, whilst management intervention exists.

Figure 6.3 is a conceptual diagram that shows the relationship among different estuary and lagoon classification terms. Brackish water conditions is an important boundary to the diagram as it essentially separates coastal systems of freshwater concentration and those exposed to saltwater ingress. Hapua, ICOLs and both pre- and post-management characteristics of the New River Lagoon are roughly considered to be on a continuum between freshwater lagoon environments with no tidal exchange and brackish estuarine environments with at least intermittent tidal exchange. Based on variable tidal dynamics, the New River Lagoon prior to engineering management can be considered at a point of balance between freshwater and brackish conditions, whilst the New River Lagoon following engineering management can be considered closer towards an estuary system than ICOL, based on its higher frequency of outlet opening and subsequent tidal influences (explained further in Section 6.3.3). Hapua is at the opposite end of the continuum, experiencing no tidal exchange and freshwater concentrations.

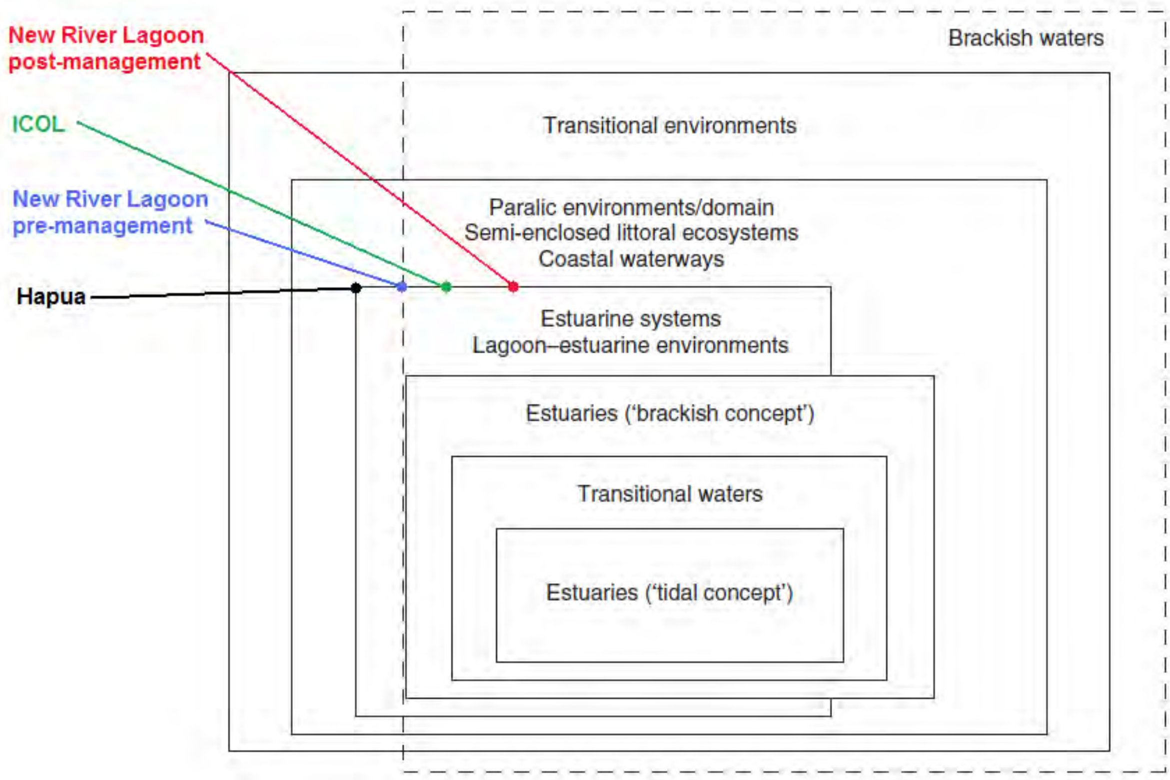

Figure 6.3. Hapua, ICOL, New River Lagoon pre-management and New River Lagoon post-management in relation to one another and other definitions of coastal waterbodies with differing hydrological and physical classifications schemes (Source: modified from Tagliapietra *et al.,* 2009).

6.3.2 The New River Lagoon and Hapua

Chapter 3 describes the characteristics of hapua systems that are found predominantly on the East Coast of the South Island, New Zealand. The New River Lagoon was classified as a hapua-type lagoon by Neale (2006a) and Neale *et al.* (2007), based on geomorphological characteristics such as its parallel movement behind a barrier and its tendency to migrate in the direction of littoral drift. The New River Lagoon also shares a similar high wave energy environment, which produces a strong northward littoral drift. However, there are several differences between the New River Lagoon, pre- and post-engineering management, and hapua. The following section identifies these differences by comparing processes environments and morphological characteristics of both types of systems.

As mentioned in Chapter 4, the New River Lagoon displays similar characteristics of outlet migration to hapua, due to the strong influence of longshore sediment drift and the resulting oblique angle of approach to the shoreline of the outlet channels. However, one of the differing characteristics of outlet migration at the New River Lagoon, prior to engineering management, was that the outlet migrated large distances and formed long, elongated channels parallel to the coastline. Contrasting to the frequent phase changes in morphology often experienced along the outlet channel of hapua (Todd, 1992; Hart, 1999); particularly in Hart"s (2009a) model, referred to in Chapter 3. This can be explained by a combination of different variables including barrier beach permeability, beach stability and river size. Traditionally, hapua form on highly permeable mixed sand and gravel coastlines, in some respects because they are formed by large braided river systems with high flows, in comparison to smaller river systems like the New River and Saltwater Creek (Kirk, 1991; Hart, 1999). Kain (2009) first proposed that hapua are capable of forming on smaller rivers such as the New River, because of the reduced permeability associated with the West Coast"s composite barrier beaches. Low-permeable sediment allows the lagoon outlet to be maintained under lower flows, as rather than loosing large amounts of hydraulic head to seepage through the barrier beach, the lagoon area behind the barrier fills, increasing the reservoir size and hydraulic head between the lagoon and the sea, resulting in more regular outlet channel flow. This makes the development of long outlet channels at the New River more likely, as it is more often able to maintain a relatively consistent flow through the outlet.

Hapua also tend to form on beaches that are in long-term state of erosion, which means the barrier beach and lagoon surface area is often retreating inland and undergoing repeat phase changes in morphology (Kirk, 1991; Hart, 1999). In contrast, the barrier beach systems fronting the New River Lagoon can be considered to be in a state of long-term progradation. This means that when the lagoon outlet changes position, the beach is able to recover quickly by infilling the abandoned channels allowing for the trend of progradation to continue and a growing outlet channel to be maintained. Therefore, the threat of primary and secondary barrier breach, that often re-sets the sequence of hapua phase changes, is reduced.

As mentioned above, the New River Lagoon is fed by two small rivers, with a combined catchment area of 144 km^2, in contrast to many hapua, which are formed on large braided rivers with catchment areas up to 12118 km^2. Therefore, it is reasonable to assume that marine processes dominate morphological change over fluvial processes more so at the New River Lagoon, that is high river flows, capable of primary and secondary barrier breach, occur less frequently. Over the long term study period, prior to engineering management, primary breach occurred only once, due to flooding caused by the confluence of Saltwater Creek and the New River, rather than via direct barrier breach from either river.

Tidal exchange is the major factor distinguishing the New River Lagoon from a hapua system. Hapua do not experience any tidal ingress, which is related to the coarse mixed sand and gravel composition of East Coast beaches that create steep, reflective barriers perched above high tide

(Kirk, 1991; Hart, 1999). In contrast, the New River Lagoon is located on a composite sand and gravel beach, with the majority of sediment closer to sand size particles. As a result, the beach is relatively dissipative and the barrier crest sits at a low elevation relative to sea level. Furthermore, the tidal range on the East Coast of the South Island is micro-tidal, with tidal ranges between 1 and 2 m, while tidal range at Greymouth is predominantly meso-tidal, experiencing tidal range between 1.3 and 2.8 m (NIWA).

6.3.3 The New River Lagoon and Intermittently Closed/Open Lagoons

This section examines links between morphology and dynamics observed at the New River Lagoon, following engineering management, with similar characteristics of ICOLs and TOCEs. An in depth definition of ICOLs was provided in Chapter 3, Section 3.4. But essentially they can be described as lagoons that are intermittently connected to the ocean via an entrance channel, with some mostly open and some mostly closed. During outlet opening ICOLs typically experience tidal ingress and during outlet closure lagoon water levels increase, depending on the level of river input, until the outlet is breached (Roy *et al.*, 2001; Haines, 2006). There a several factors that determine whether an ICOL is mostly open or closed and they all have influence on the balance between marine and fluvial processes at the lagoon outlet. Roy *et al.* (2001) describes the degree of openness as being dependant on the exposure of the outlet to ocean waves and fluvial discharge, whilst Lugg (1996) is more specific, suggesting that longshore drift, catchment size, tidal prism and wave climate conditions all have varying degrees of influence. The artificial or natural stabilisation of an outlet can also have a large influence on outlet openness (Haines, 2006; Whitfield and Bate, 2007).

During the study period following engineering management intervention, the New River Lagoon was observed to cycle through phases where it was closed, accumulating water behind the barrier beach, and open, exchanging water freely with the ocean. As shown in Chapter 5, Figure 5.11, the change in these phases was frequent, with the outlet closing intermittently for short periods, mostly as a result of low levels of rainfall and an abundance of wave transported marine sediment, and open for long periods, due to the stabilising effects of the breakwater structure and the West Coast regions distinctively high levels of rainfall. Based on 7 month monitoring of lagoon hydrology and weekly oblique photographs, the New River Lagoon was observed to have been closed or partially closed for approximately 47% of the study period. As such, the lagoon experienced pronounced tidal exchange with the open ocean for the majority of the study period. The morphology and intermittently closed/open dynamics of the New River Lagoon outlet, along with the pronounced tidal influences during an open outlet, can be related to several similar characteristics seen in ICOLs.

ICOLs are located on high wave energy coastlines (Haines, 2006; Whitfield and Bate, 2007), much like that of the New River Lagoon. Subsequently, at the New River Lagoon, river flow is important for maintaining a balance between marine and fluvial systems, with periods of heavy flow keeping the outlet open and periods of low flow often resulting in outlet closure. ICOLs are no different, although they are affected on a more extreme scale due to catchment size and climate conditions. The catchment size of a lagoon can have a large influence on the volume of water received at the coastline, which works to maintain an open outlet. Catchment size of ICOLs are generally no larger than 200 km^2 and ICOLs that are mostly open are generally located in catchments greater than 100 km^2 with sufficient drainage to maintain an open outlet (Roy *et al.*, 2001; Haines, 2006). The New River Lagoon is made up of two waterways, both exiting the same outlet, with a combined catchment size of 144 km^2. The New River Lagoon"s catchment can be considered relatively large, compared with the size of mostly closed ICOLs, which are generally less than 100 km^2 (Haines, 2006; Whitfield and Bate, 2007), meaning there is a better balance between river outflow and marine wave processes, which allows the outlet to remain open for longer durations and outlet breach to occur more frequently. In addition, rainfall on the West Coast is relatively high compared to south-eastern areas of Australia, which experience unpredictable rainfall events amongst long dry periods, causing lower lagoon water levels and longer periods of outlet closure (Roy *et al.*, 2001).

In addition, to maintaining an open outlet, river flow characteristics in relation to marine wave processes, also influence outlet dynamics beyond basic open/closed processes. Outlet migration is a characteristic still present at the New River Lagoon despite the implementation of a breakwater and occurs when the lagoon outlet offsets in the direction of littoral drift. During outlet migration the lagoon only experienced outflowing water and tidal exchange was inhibited. Outlet migration is generally initiated during marine dominance but is maintained under steady outlet flows (Hart, 1999, 2009b). Outlet migration has not been documented at ICOLs, which is likely related to their severe imbalance between marine and fluvial processes. For instance, low river base flow is not strong enough to maintain a balance with littoral drift and medium river base flow is not sustained for long enough for the outlet to maintain hydraulic head and cause outlet migration, so instead the outlet closes. Furthermore, many ICOLs are located against rock outcrops and headlands (Haines, 2006), restricting any significant movement of the lagoon outlet. If the outlet breakwater at the New River Lagoon was extended further into the nearshore surf zone, outlet migration would be restricted completely.

Recent research into outlet dynamics in small coastal systems such as ICOL and the New River Lagoon, has highlighted a semi-closed outlet state (van Niekerk *et al.*, 2005; Whitfield and Bate, 2007). In a semi-closed state there is still potential for saltwater ingress into the lagoon system during spring tides as well as restricted lagoon outflow through the outlet. A semi-closed outlet should not be confused with wave over-wash during storm events (Whitfield and Bate, 2007). Semi outlet closure was apparent at the New River Lagoon and was associated mostly with the early stages of outlet blockage when water level was still fluctuating due to small volumes of lagoon outflow and tidal inflow. In some instances at the New River Lagoon, changes in water level could cycle from conditions typical of outlet blockage to those of semi-closed fluctuations, as a result of small, short lived breaches to the barrier.

Outlet entrainment is a huge factor to consider when determining the intermittent open/closed nature of outlet dynamics and the potential for tidal exchange (Haines, 2006; Whitfield and Bate, 2007). As mentioned above, many ICOLs are naturally supported by rock outcrops and headlands, providing a similar situation to the breakwater that is being used to stabilise the New River Lagoon outlet. Outlet entrainment increases the duration of outlet opening phases as it reduces turbulence within the outlet, thus lessens the ability of waves to carry sediment into the outlet and cause closure (Whitfield and Bate, 2007). Outlet entrainment can also lower channel bed elevations by confining the flow of water, which in turn scours a deeper channel and allows for tidal ingress (Komar and Terich, 1976; Kieslich, 1981). Since the implementation of a breakwater at the New River Lagoon, outlet bed elevation was measured to be below sea level when open. As a result, tidal exchange was prominent during outlet opening. A similar situation occurs at ICOLs during outlet breach when bed elevation drops below mean sea level, allowing for tidal ingress (Gordon, 1990; Cooper, 2001).

Hydrological characteristics are very similar between the New River Lagoon and TOCEs, located on the coast of South Africa (Whitfield and Bate, 2007). In TOCEs, salinity penetration is reduced during high river flows. Once river flow decreases, saline water can penetrate through the outlet and into the estuary, often forming longitudinal salinity gradients, whereby salinity levels are close to saltwater concentration at the outlet and fresh at the head of the estuary. During outlet closure salinity levels are diluted depending on the level of freshwater inflow, until the outlet is again breached (van Niekerk *et al.*, 2005).

The New River Lagoon outlet following engineering management has an intermittent natural similar to many ICOLs systems, whereby opening causes tidal exchange and closing ceases exchange between the lagoon and the ocean. In addition to this, the New River Lagoon also experiences outlet migration whereby river outflow exist, but tidal inflow is inhibited. The high level of rainfall on the West Coast, coupled with the lagoons larger than average catchment size, means the New River Lagoon in relation to south-eastern Australian ICOLs and South African

TOCEs, is considered mostly open; whether it is open to tidal exchange or freshwater outflow. Despite a change in morphology and dynamics, the lagoon still shows characteristics of hapua, due to the influence that high and low levels of river flow have on the dynamics of the lagoon outlet and the inability the tidal prism to take control of these processes, due to the lagoons location on a wave-dominated coastline. The New River Lagoon post-engineering management can be considered an intermittently open/closed lagoon, but closer to an estuarine system than common ICOLs, due to the higher frequency of outlet opening and subsequent tidal influences (Figure 6.3).

6.4 Outlet Management

The use of soft and hard engineering management intervention at coastal entrances is common practise and has occurred at several different types of coastal lagoons as a form of hazard mitigation, ecological enhancement and recreational amenity. As mentioned in Chapter 1, Section 1.3.2, the New River Lagoon outlet is currently being managed by way of artificial outlet relocation and opening, with added reinforcement of a rubble-mound breakwater in attempt to reduce outlet instability. Little in-depth knowledge was available about the characteristics of the lagoon prior to management intervention. Therefore, using the information about lagoon morphology and dynamics from the past results chapters, this section addresses the following issues: the suitability of chosen management techniques to control hazards at the New River Lagoon; the effectiveness of management works at maintaining a stable lagoon outlet and preventing flooding and erosion to the surrounding land; the effects of engineering management on the lagoon"s environmental integrity; and suggestions for future management.

6.4.1 Suitability of engineering management

Engineering management intervention was implemented at the New River Lagoon in an attempt to reduce the risk of flooding and erosion caused by the lagoons natural morphology and outlet dynamics. Chapter 1, Section 1.3.1 discusses the details of hazard risks for the communities surrounding the New River Lagoon. Engineering management included the relocation and artificial opening of the lagoon outlet, and the construction of a rubble-mound breakwater. Chapter 1, Section 1.3.2 discusses the details of engineering management at the New River Lagoon outlet. Essentially, the breakwater has been put in place to divert water from both Saltwater Creek and New River channels through the artificial outlet and preventing the dominant flow of the New River channel from travelling northward along its past outlet channel. It is also in place to restrict the artificial outlet from migrating northwards. The engineering intervention is aimed at: 1) maintaining an open outlet to drain high flows of water during flood events and 2) eliminating the erosion caused by northward migration of the lagoon outlet, by reducing the effects of longshore drift.

The artificial lagoon outlet was excavated at the confluence of Saltwater Creek and New River Channels. Chapter 4 shows that the lagoon outlet was not located at this position during the 67 years prior to artificial outlet opening. However, during progressive northward outlet migration, prior to 1943 and from 1995 to 2005, the lagoon outlet was likely located at this position for a short time, while progressively migrating northwards. It is known based on Benn"s (1990) flood database that major flooding occurred at the confluence of both lagoon channels, which often ended in Saltwater Creek backing up and flooding the Paroa Hotel and Primary School when the outlet was blocked, due to its less dominant flow in comparison to the New River. Therefore, from a flood mitigation point of view, the location of the artificial lagoon outlet at the confluence of both rivers makes sense, as it allows for excess water in both channels to be funnelled effectively through one outlet, reducing the build-up of hydraulic pressure.

Pressure from marine and fluvial environments must be considered when implementing an engineering structure to stabilise an entrance channel that essentially bears the brunt of both systems. The idea of having the breakwater angled perpendicular to the coastline at the New River Lagoon is to stabilise the lagoon outlet by reducing the natural tendencies of the outlet to migrate northwards in the direction of prevailing littoral drift and constricting the outlet channel to a preferred position at the confluence of both lagoon channels.

There was little planning involved with the design and implementation of the engineering works, which was partly because it was conducted under emergency management provisions following flooding in December 2010. Previous consent applications to modify the lagoon outlet had only dealt with its artificial relocation, so the construction of a breakwater structure was largely un-planned. However, it was looked upon as paramount for the long term stability of the lagoon outlet, especially when considering that the outlet can migrate long distances over short periods of time. Initial plans were to have the breakwater protruding into the nearshore breaker zone to better prevent the outlet from migrating northwards. However, doing so would have caused problems keeping the structure intact, due to the high energy wave environment. Therefore, it was built to a seaward extent that protected the head of the structure from the direct impact of breaking waves (Wayne Foster, GH Foster Contracting in charge of engineering work at the New River Lagoon, pers. comm., 13/03/2012).

The emergency management provisions, in which engineering management was undertaken, would infer that temporary intervention should have taken place at the outlet to reduce flooding, with engineering works implemented once further understanding of the lagoon system was known. However, instead a permanent structure was created over a short periods of time with little planning and prior knowledge of lagoon dynamics. This contradicts Vila-Concejo *et al,* (2004) who state the importance of understanding lagoon dynamics before large scale outlet modifications. Furthermore, management recommendations from a basic engineering report by Smart (2010), regarding management of the lagoon outlet, did not recommend the use of a breakwater structure. Therefore, with little prior knowledge before the implementation of engineering management, the only way to determine its true suitability is through close monitoring.

6.4.2 Effectiveness of engineering management

In terms of the New River Lagoon, effective management, from a performance point of view, is based on the ability of the artificial outlet to reduce flood and erosion risk associated with unstable lagoon outlet dynamics and the ability of the artificial outlet and breakwater structure to maintain structural integrity against both fluvial and marine influences. From an environmental point of view, imposing minimal adverse environmental affects is also important in determining effective management. Section 6.4.2.1 determines the performance based effectiveness of the artificial outlet and Section 6.4.2.2 determines the physical environmental affects associated with the artificial outlet.

6.4.2.1 Performance based analysis

In general, the breakwater was observed to remain structurally sound for the study period, having only minor repairs since being completed (Wayne Foster, GH Foster Contracting in charge of engineering work at the New River Lagoon, pers. comm., 13/03/2012). The most detrimental event to the structural integrity of the breakwater followed a flash flood event on 26 October 2011; the first large amount of rainfall over a short period of time for several months. Flood waters cut an especially deep outlet channel past the breakwater, scouring the underside of the structure and causing its southern side to partially slump into the channel (Figure 6.4). This had no obvious effects to the functionality of the artificial outlet. However, it exposed the detrimental effects capable of occurring to the structure, which can require costly remediation.

Figure 6.4. Slumping of the southern side of the engineering breakwater at the outlet of the New River Lagoon (27/10/2011)

The seaward extent to which the breakwater protrudes means that wave processes caused no obvious structural damage to the breakwater over the study period. The breakwater stabilised and guided the outlet channel, but often only as far as the head of the structure. A deep outlet channel leading into a scoured reservoir, formed landward of the head of the breakwater, due to scouring caused by outflowing river water. This was relatively stable during the study period, as it was sheltered from wave and tide sediment deposition. However, the outlet channel seaward of the head of the breakwater was prone to becoming unstable, which was evident during several periods of lagoon outlet blockage and migration.

Northward outlet migration occurred progressively over approximately 2 months between July and August 2011 forming a long, shore-parallel outlet channel that wrapped around the head of the breakwater structure. By 14 September 2011, the outlet had migrated some 150 m northwards of the breakwater and appeared well established to continue progressing further. During this period, overall lagoon water levels were approximately 1 m higher than when the outlet was located direct to sea, increasing the risk of flooding had a large rainfall event occurred. If the outlet continued migrating, it is possible that it would have re-joined its previous channel, currently blocked by the breakwater. Relocation and re-excavation of the outlet occurred on

September 14 2011 to bring the outlet adjacent to the breakwater structure and minimise the risk of flooding.

Outlet migration also occurred in a southerly direction twice during the study period, again elevating lagoon water levels. However, with southerly wave directions only occurring for short periods at a time and mostly traveling in a northerly direction, southward outlet migration did not establish into a sustainable outlet channel, thus was not a great risk for long-term outlet blockage and flood risk.

Aside from the increase in lagoon water levels during outlet migration, outlet blockage, confined mostly to the immediate vicinity of the breakwater structure, occurred on 3 separate occasions during the study period. Outlet blockage caused lagoon water levels to rise, prevented the free exchange of tidal water and again enhancing the risk of flooding. Blockage often occurred immediately after a large rainfall event, during which tides and wave processes worked sediment from the nearshore zone into the lagoon outlet. Therefore, it is reasonable to assume that the few weeks following large rainfall events is a time the outlet is most susceptible to blockage and potential flood risk.

However, despite periods of outlet blockage, the artificial outlet appeared to provide an effective mechanism for flushing large amounts of rainfall to sea, particularly in November 2011, during which 329 mm of rainfall fell throughout the month; the highest of the study period. Similarly, the outlet responded well to heavy rainfall events during periods of outlet blockage in January and February, when water levels were already elevated. This effective flood control is largely due to efficient flushing characteristics with the location of the outlet at the confluence of both lagoon channels. Improved flushing of the outlet helped maintain it relatively open and reduced the capacity of marine sediment transport to control outlet dynamics, where prior to engineering management an established barrier was capable of forming strongly across the outlet.

Currently, the biggest risk of flooding at the New River Lagoon is a flash flood, following a dry period when marine processes have formed a substantial barrier across the lagoon outlet and lagoon water levels are elevated. The regular levels of rainfall experienced at the New River Lagoon during the majority of the study, with exception to August, meant periods of outlet blockage were only short lived as barrier development could not become established. The lagoon was at its highest risk of flooding during August, due to outlet migration forming a well established barrier.

Large waves and elevated sea levels during storm events also have potential to heighten the risk of flooding at the lagoon, especially when coupled with periods of heavy rainfall (Hunt, 2005) and outlet blockage. During the study periods heavy rainfall did not occur in combination with high seas. However, Figure 6.5 shows the conflict of high levels of outflowing river water and calm wave conditions for a relative comparison.

Figure 6.5. Seaward view of from the breakwater at the New River Lagoon showing opposing outflowing river water during flood conditions and inflowing marine waves (photo courtesy of Charlie Teasdale, 21/11/2011)

6.4.2.2 Environmental based analysis

Essentially, the implementation of coastal engineering management work is designed to modify a system in order to prevent undesired affects such as flooding and erosion, associated with its natural dynamics and progression. Therefore, when making decisions to use engineering management intervention, rather than preventing inevitable changes to a coastal system, emphasis is based largely on minimising adverse affects to its natural dynamics.

As mentioned in Section 6.2, engineering management has caused several changes to the New River Lagoon‟s natural dynamics. Of particular note is the increase in tidal exchange through the lagoon outlet leading to brackish water concentrations and overall lower lagoon water levels. These changes in lagoon hydrology are caused by the location of the outlet at the confluence of Saltwater Creek and New River channels, the deepening of the outlet channel due to concentrated flows past the breakwater and restriction of outlet migration, caused by the breakwater and re-excavation of the outlet. These are relatively common changes to lagoon hydrological dynamics associated with artificial outlet opening and the use of engineering structures to stabilise lagoon outlets (Roy *et al.*, 2001; Fortunato and Oliveira, 2007; Kain, 2009; Gunaratne *et al.*, 2011).

The dramatic drop in lagoon water levels and increase in tidal exchange between pre- and post-engineering management was particularly obvious when the lagoon outlet was artificially relocated following substantial northward outlet migration. The artificial relocation of the outlet provided a contrasting view of lagoon hydrology between unstable, natural outlet dynamics, and stable, controlled outlet dynamics, as discussed in Section 6.2. However, greatest fluctuations in lagoon water levels often occurred as a result of outlet breach when elevated river flows scoured a deep outlet channel along the breakwater. Figure 6.6 shows the variation in lagoon water levels during high river flows, extremely low river flow conditions following outlet breach and normal open outlet conditions.

Prior to engineering management, when the outlet was located at the confluence of New River and Saltwater Creek, it is likely that it also experienced tidal exchange, due to the combined flow of water from both channels enhancing outlet scouring. However, these conditions would have only been short lived as the outlet migrated north and to less effect compared with enhanced outlet scouring now involved as a result of the breakwater. Therefore, this suggests that having the outlet at this location is effectively only enhancing and prolonging tidal exchange.

The effect of artificial opening on the ecosystems of a small lagoon environment such as the New River Lagoon is beyond the content of this study. Be it that there is also very little literature describing the environmental implications of artificial opening, particularly the impact of increasing water level and salinity fluctuations in lagoon systems that are naturally freshwater dominated. Therefore, in order to fully understand the environmental impacts on the New River Lagoon, in-depth research into the effects on plant biodiversity and lagoon ecology must be carried out.

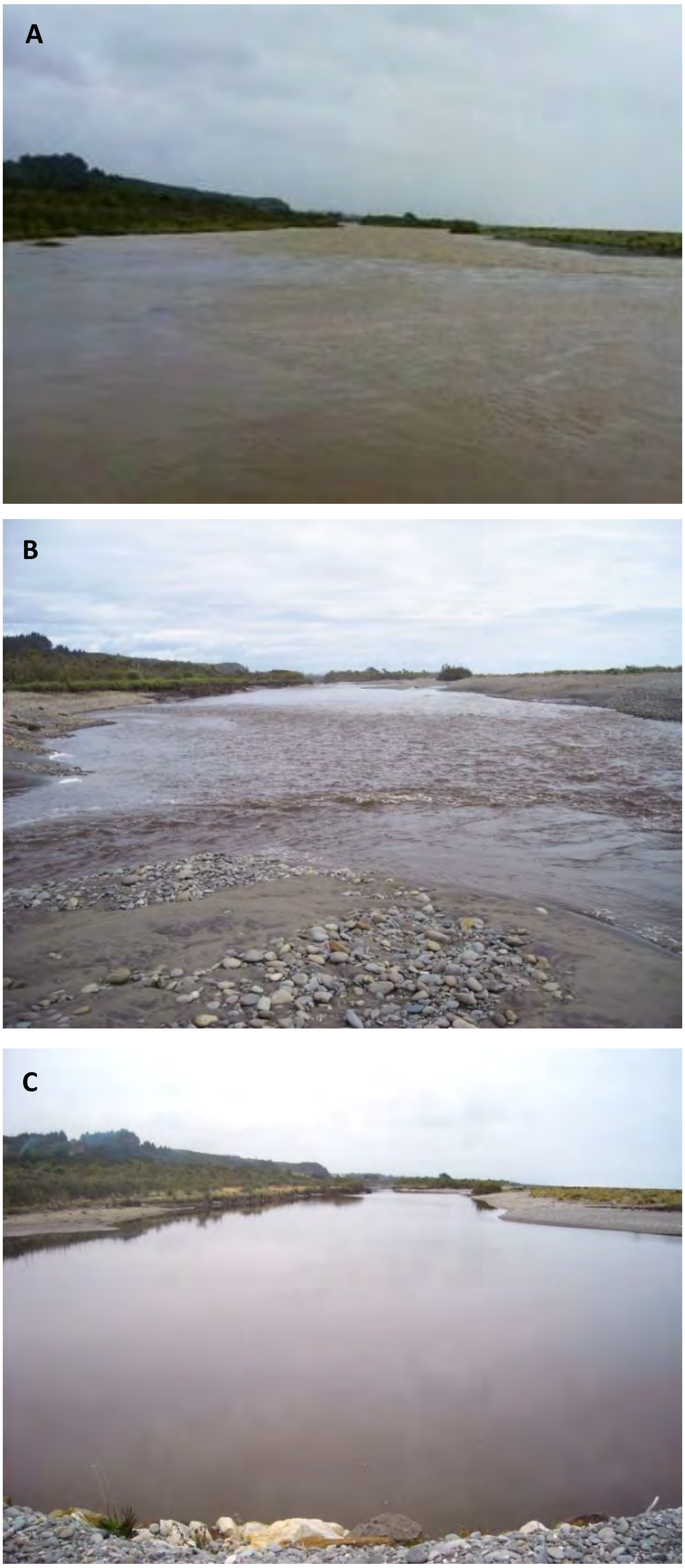

Figure 6.6. Change in lagoon water levels at the New River lagoon during flood conditions (image A, 14/12/2011, Photo courtesy of Charlie Teasdale), following flooding (image B, 27/10/2011) and during steady open outlet conditions (image C, 2/3/2012).

6.4.3 Future management options

There are several options available for management of the lagoon outlet, which have both positive and negative environmental and performance related aspects. Figure 6.7 provides a diagram showing management options for the New River Lagoon and associated performance and environmental responses. From a performance perspective, having the breakwater protruding further into the nearshore surf zone would be detrimental to its structural integrity, but would better stabilise the lagoon outlet by reducing outlet blockage and migration. Less excavation would need to take place and there would be less potential for flooding. However, additional cost would also incur with the inevitable maintenance of the structure, which would certainly offset the savings of re-excavation. Increasing the length of the breakwater would have negative environmental effects on the natural dynamics of the lagoon with longer periods of unnatural outlet opening and consistent levels of tidal exchange, as well as greater obstruction of sediment supply to the downdrift beach.

Removing the breakwater all together would allow the lagoon outlet to progress naturally, which would see it continue its trend of northward migration and return to restricted tidal influences. This would be the best environmental option for the lagoon, but it would also mean there is again potential for flooding at the confluence of both rivers and potential landward erosion if the outlet migrated too far north. As an alternative to the use of a breakwater, threshold opening of the lagoon at the confluence of both rivers is an option for situations when the outlet reaches a certain distance north, or when there is a threat of flooding. A similar management regime is currently carried out at the Totara Lagoon (Kain, 2009).

There is also potential for implementing the artificial outlet opening at the point that both channels intersected in 1979, 1983 and 1995; further south towards the New River. If artificial opening was to occur here there would be minimal hazards when the outlet migrated north, as this is the widest section of beach. However, there might be problems accessing the beach during times when the outlet needed relocating and re-excavating.

Furthermore, taking into consideration the lagoons natural oblique angle of approach to the coastline, environmental integrity would benefit from artificial outlet opening excavated at an angle away from prevailing wave conditions to reduce un-natural tidal influences.

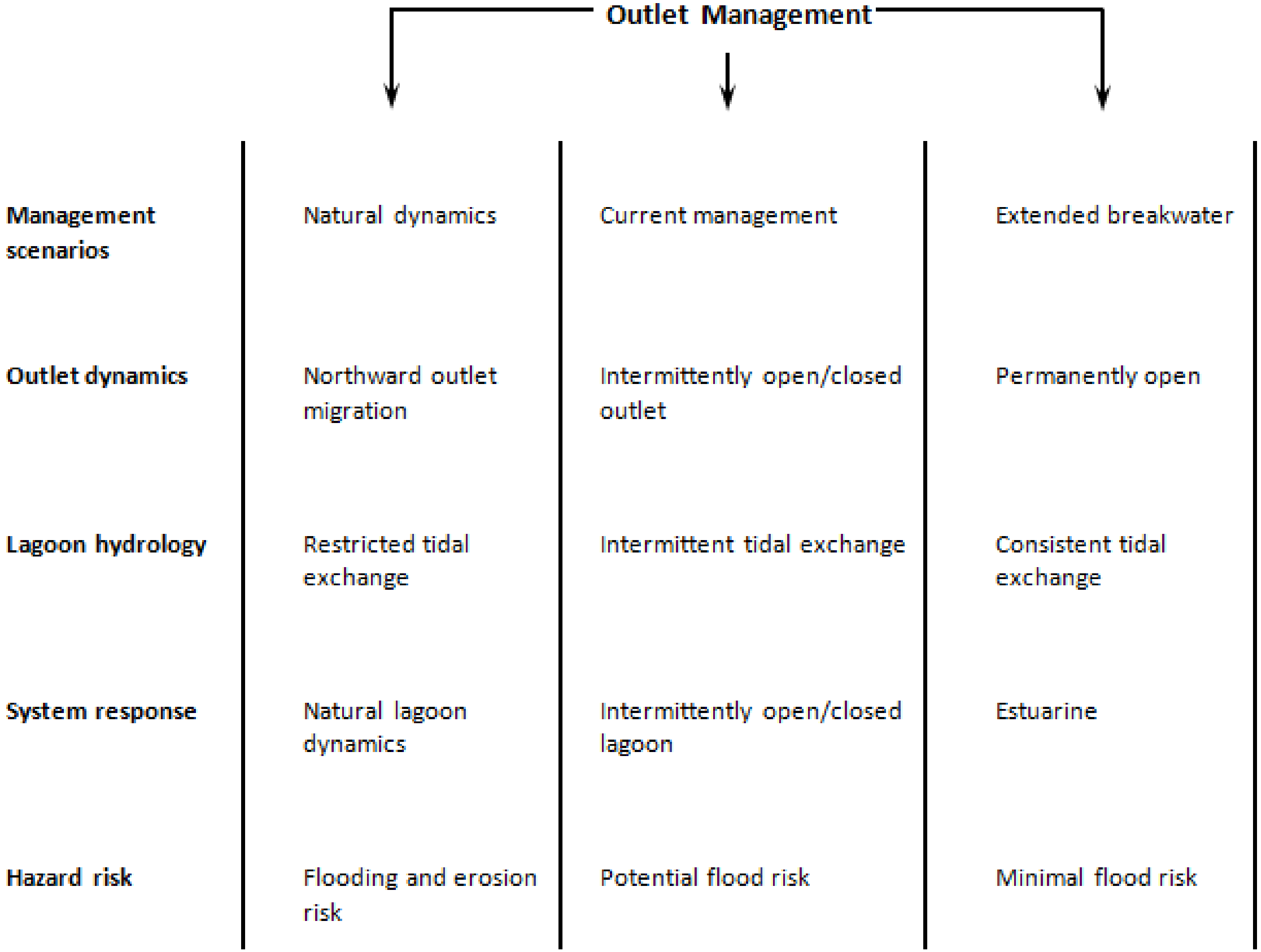

Figure 6.7. Potential management options for the New River Lagoon outlet and their associated performance and environmental responses

6.5 Summary

The purpose of this chapter was to provide an integrated discussion of results presented in the previous two chapters and to assess the changes in characteristics of the New River Lagoon between pre- and post-engineering management. These changes in characteristics were then put into context of similar national and international lagoon classification schemes. The effectiveness of engineering management intervention was assessed and future management options discussed.

Outlet morphology and dynamics has a large bearing on the hydrology of the New River Lagoon, which has changed as a result of engineering management intervention. Prior to engineering management the lagoon showed various outlet and barrier dynamics that are near consistent with existing models of hapua dynamics. However, hydrologically it experienced an unknown level of tidal ingress at the immediate vicinity of the lagoon outlet, by definition excluding it from hapua. Therefore, it was considered to be located on a hydrological continuum somewhere between hapua and estuary.

The New River Lagoon outlet following engineering management has an intermittent nature similar to Intermittently Closed/Open Lagoons (ICOLs). Outlet dynamics typically cycle between opening causing prominent tidal exchange, closing ceases exchange between the lagoon and the ocean and outlet migration allowing for only outflowing water. The high level of rainfall on the West Coast, coupled with the lagoons catchment size, means the New River Lagoon in relation to south-eastern Australian ICOLs and South African TOCEs, is considered mostly open.

Despite a change in morphology and dynamics the lagoon still shows characteristics of hapua due to the influence that high and low levels of river flow have on the dynamics of the lagoon outlet and the inability the tidal prism to take control of these processes. Despite the New River Lagoons hapua-like characteristics, the lagoon in its current state is considered more of an estuarine system than ICOL, due to the higher frequency of outlet opening and subsequent tidal influences.

The artificial lagoon outlet and associated breakwater was effective at flushing high flows of water during the study period. However, the lagoon outlet could still become unstable, causing blockage and migration, two morphological states prone to causing flooding. Outlet migration in particular can still become well established necessitating further outlet relocation and re-excavation. Flash floods are the greatest risk at the New River Lagoon, particularly if they follow dry periods of no rainfall when marine processes have the chance to build a solid barrier over the lagoon outlet and water levels are already elevated.

Management implications associated with the attempt to stabilise the lagoon outlet include deepening of the outlet channel to below mean sea level and flushing of freshwater from both Saltwater Creek and New River channel, meaning the lagoon experiences significant tidal ingress during an open outlet and overall lower lagoon water levels.

Extension of the breakwater structure further into the nearshore zone and removal of the breakwater in place of a threshold artificial opening regime are two potential options for future outlet management. Extension of the breakwater would increase lagoon stability and further reduce flood risk, but the high energy wave climate would hinder its structural integrity. In addition tidal influences would become increasingly dominant and the lagoon would reside as an estuary system. Removing the breakwater and implementing threshold opening would allow the lagoons natural dynamics to continue, but would increase the risk of flooding and erosion.

Chapter 7 : Conclusions

Coastal lagoon systems are complex and dynamic environments that respond rapidly to the changes in fluvial, marine, climatic and anthropogenic process environments. The purpose of this research was to investigate the geomorphology and dynamics of the New River Lagoon, using a methodological framework to analyse active process environments and their changes before and after engineering hazard management. This information was then used to determine the functional effectiveness of engineering management at reducing the risk of flooding and erosion to the local community and imposing minimal impacts on the environmental integrity of the lagoon system.

The primary objectives of this research were:

- To document morphological and positional changes to the New River Lagoon prior to engineering management intervention, including lagoon outlet and channel migration, and changes to shoreline position,

- explain the processes driving morphological change,

- investigate the current lagoon hydrology and explain the relationship between morphological changes to the artificial lagoon outlet and changes in lagoon hydrology, local wave climate and local precipitation levels,

- make comparisons between lagoon characteristics pre- and post-engineering management and draw links between these and similar national and international lagoon systems,

- assess the functionality of the current artificial lagoon outlet at managing lagoon outlet migration and flood hazard control and imposing minimal physical effects on the surrounding environment, and

- recommend future management options at the New River Lagoon where they are needed

The following chapter presents a summary of the main findings, limitations of this study, and suggested areas for future research.

7.1 Summary of main findings

7.1.1 Lagoon morphology and outlet dynamics prior to engineering management

The New River Lagoon is long, narrow, river-mouth lagoon system fed by two waterways: New River, flowing from the south and Saltwater Creek, flowing from the north. Both waterways flow parallel along the coastline and converge to from one lagoon and outlet system that actively spans approximately 4.2 km. Morphology and outlet dynamics of this system, prior to engineering management works, were investigated by analysing aerial photographs taken between 1943 and 2010. Qualitative assessments of lagoon change and quantitative measurements of net change in outlet and shoreline position were determined.

As a consequence of a high-energy wave environment and strong net northward direction of littoral drift, the New River Lagoon outlet had a strong tendency to migrate in a northerly direction. Measurements from aerial photographs showed the lagoon outlet reached a maximum distance of 4270 m north and moved at rates between 0 and 135 $m.yr^{-1}$. Over shorten timespans the lagoon outlet was also observed to migrate in a southerly direction.

Change in overall channel structure was minimal for the two major Saltwater Creek and New River channels, which stayed relatively confined between Camerons and the Paroa Hotel. However, migration of the lagoon outlet forged long, elongated outlet channels parallel with the coastline and shifted the confluence of New River and Saltwater Creek channels north and south. The majority of these channels are still remnant today, residing as small swampy lakes.

Analysis of aerial photographs showed that the beach fronting the New River Lagoon is variable in stability alongshore, but can be considered in a long term state of progradation. Lagoon outlet migration affected the stability of the beach, initiating instances of landward retreat and seaward progradation of the shoreline depending on its location. The prograding coastline, in association with its typically fine grained composition, contributed to the formation of long lagoon outlet channels by infilling abandoned channels as the outlet progressively moved along the coastline.

The long term outlet dynamics and behaviour of the New River Lagoon prior to engineering management supports the classification of this system as a hapua-type lagoon. However, it is likely that the lagoon also experienced tidal influences when the outlet was located in areas of concentrated river flow. This suggests the lagoon shifted between hydrological states and existed on a continuum between hapua and estuary.

7.1.2 Lagoon hydrology and outlet dynamics following engineering management

Lagoon artificial outlet relocation and opening and the construction of a rubble-mound breakwater were implemented at the New River Lagoon in December 2010 in an attempt to minimise the risk of flooding and erosion caused by the outlets dynamic nature. Following engineering management the hydrology of the lagoon was investigated and the relationship between morphological changes to the artificial lagoon outlet and changes in lagoon hydrology, local wave climate and local precipitation levels assessed. Water depth, conductivity and temperature records were used to explain lagoon hydrology and Global Navigational Satellite Surveying (GNSS) and oblique photographs were used to explain and document changes in outlet morphology. Wave and rainfall data were used to explain the balances between marine and fluvial environments and their affects on outlet dynamics.

The hydrology of the lagoon varied both spatially and temporally and unlike lagoon hydrology prior to engineering management was largely influenced by the tidal cycle. Fluctuations in water level and conductivity decreased with distance from the lagoon outlet due to a decrease in the direct influence of the tidal cycle and the New River channel experienced more extreme fluctuations in water level than the Saltwater Creek channel because it drains a larger catchment and because it is the more dominant channel.

An increase in the intermittent nature of lagoon outlet dynamics controlled water level and conductivity variations in the lagoon, deviating between states of outlet closure, opening and migration, which meant lagoon hydrology was very much unstable. Outlet closure was associated with an increase in water levels and homogenous salinity levels, while outlet opening allowed tidal fluctuations in water level and salinity and outlet migration allowed for lagoon outflows but prevent tidal inflows.

Outlet dynamics were based on the balance between marine and fluvial processes, which was determined by rainfall and subsequent freshwater inputs to the lagoon. Periods of low rainfall were associated with a closed outlet due to the dominance of marine sediment transport and periods of heavy rainfall associated with an open outlet or breach of a closed outlet. Outlet migration was associated with low rainfall and occurred in the direction of littoral drift.

Although the New River Lagoon still shows some characteristics of hapua-type lagoons, an increase in tidal influences between pre- and post-engineering management has meant it is now more closely related to an estuarine system. The intermittent nature of the lagoon outlet and pronounced tidal influences during outlet opening, classifies the New River Lagoon as an intermittently closed/open lagoon, similar to Intermittently Open/Closed Lagoons (ICOLs) and

Temporary Open/Close Estuaries (TOCEs) found in areas of Australia and South Africa respectively. The lagoon has a high frequency of outlet opening/closing phases, due mostly to the West Coast wet climate, which means the New River Lagoon is mostly open and closer to the definition of estuary than most common ICOLs and TOCEs.

7.1.2 Effectiveness of hazard management and future management options

The artificial lagoon outlet and associated breakwater was effective at flushing high flows of water during the study period. However, the lagoon outlet could still become unstable, causing blockage and migration; two morphological states prone to causing flooding. Outlet migration, in particular, can still become well established necessitating further outlet relocation and re-excavation. The greatest risks to flooding at the lagoon are flash floods following dry periods where marine sediment has established a solid barrier across the outlet, during which water levels are already elevated.

Increases in tidal influences and overall lower lagoon water levels at the lagoon are a direct result of engineering management intervention. An increase in lagoon flushing, due to the artificial outlet being located at the confluence of Saltwater Creek and New River channels, has caused overall lower lagoon water levels and deepened the outlet channel to well below sea level, allowing for pronounced tidal influences during outlet opening. Restriction of the lagoon outlet from forming a natural migration outlet channel in the direction of littoral drift has meant the outlet is most often oriented perpendicular to the sea, as appose to at an angle away from the direction of incoming waves and currents, further increasing tidal influences.

There are several alternatives for continued management of the New River Lagoon outlet including extension of the breakwater structure further into the nearshore zone and removal of the breakwater in place of a threshold artificial opening regime. Extension of the breakwater would increase lagoon stability and further reduce flood risk, but the high energy wave climate would hinder its structural integrity. In addition tidal influences would become increasingly dominant and the lagoon would reside as an estuary system. Removing the breakwater and implementing threshold opening would allow the lagoons natural dynamics to continue, but would increase the risk of flooding and erosion.

7.2 Limitations and areas for future research

The major limitations with this research are the spatial and temporal scale in which much of the data was captured, particularly the 7 month period following engineering management, which only touches on the short term dynamics of the current artificial lagoon outlet, providing a snapshot of conditions during the time of monitoring.

This is particularly apparent of hydrological measurements in the New River Lagoon and morphological changes at the lagoon outlet, where long term monitoring would allow for better understanding of recurring trends and seasonal patterns of lagoon response and the dominance of tidal influence could be better linked with variable morphological changes at the lagoon outlet. Covering the hydrodynamics of a higher spatial resolution of the lagoon would also allow for better inferences to be made about the long term patterns of salinity and water level fluctuations through the full extent of both lagoon channels.

As with any form of coastal engineering management works, long term monitoring of the integrity, performance and environmental impacts of the artificial outlet is the only true indicator of its effectiveness. The New River Lagoon would benefit from long term monitoring due to the dynamic nature of the lagoon outlet and its continued ability to become unstable, and create flood risk.

There is a large gap for understanding the effect that changes in the hydrological regime of lagoon and estuary systems has on plant biodiversity and lagoon ecology, not only at the New River Lagoon, but in other small waterbodied systems elsewhere. In particular, the affects that both permanent and temporary artificial outlet opening has on the sensitivity of naturally freshwater lagoon environments.

There is a large gap for evaluating the success of coastal hazard management on the West Coast from a legislative perspective, in particular the effectiveness of the Resource Management Act 1991, New Zealand Coastal Policy Statement and West Coast Regional Coastal Plan at facilitating sustainable, environmentally conscious coastal hazard management.

There is a need for greater understanding of coastal environments, particularly the process environments that determine the dynamic nature of many systems in New Zealand. This is especially important for areas of the West Coast of the South Island, New Zealand, where funding is often unavailable, but where coastal science can benefit from understanding these inherently different systems. Furthermore, in order to make informed management decisions of coastal environments such as the New River Lagoon, it is fundamental to have full understanding of environmental processes and dynamics before informed management decisions can be made. Such understanding can only come about by monitoring and valuable ongoing data collection.

There is potential to expand on the current research of coastal lagoons in New Zealand, for which there is much diversity away from the more commonly understood East Coast systems.

Moreover, there is greater potential to determine links between New Zealand lagoons and those internationally, in order to contribute to a wider understanding of these diverse coastal systems

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Appendices

Appendix 1: Aerial photographs used

Date	Survey number	Run and Frame	Scale	Source
1/06/1943	SN 816/1			Department of Conservation, Hokitika
	SN 817/2			
7/10/1959	SN 2648/7			Department of Conservation, Hokitika
10/02/1970	SN 912/1	S1		West Coast Regional Council
14/03/1973	SN 3652	B/1		Department of Conservation, Hokitika
28/08/1979	SN 2977	B3/1		Department of Conservation, Hokitika
		C1/1		
		C2/2		
23/11/1983	SN 912/5	S1	1:8000	West Coast Regional Council
17/01/1995	SN 12156 B	A33-A37	1:5000	Grey District Council
		B31-B35		
		C29-C33		
		D29-D31		
		T43		
		T44		
		U42-U44		
		V41-V44		
		X38-X42		
		Y37-Y40		
		Z35-Z38		
03/2005	SN 50499 C	J32 1103	1:30000	Grey District Council
		J32 1202		
		J32 1203		
		J32 1302		
20/04/2009	SN 13209	AJ37	1:35000	West Coast Regional Council
03/2010	SN 50850 X	BU19 0103	1:25000	Grey District Council
		BU19 0203		
		BU19 0303		

Note: Not all information was available for each photograph, particularly those of earlier dates

Appendix 2: Details of change in berm crest position from aerial photograph analysis

Profile	Period	Period change (m)	Period rate (m.yr^{-1})	Net change (m)	Net rate (m.yr^{-1})
1	1943-1959	-15.1	-0.94		
	1959-1979	+3.8	+0.19		
	1979-2005	+22.7	+0.87		
	2005-2009	-6.7	-1.68		
	2009-2010	+6.7	+6.7	+11.4	+0.17
2	1943-1959	-17.9	-1.12		
	1959-1979	+17.5	+0.88		
	1979-2005	+27.7	+1.07		
	2005-2009	+9.1	+2.28		
	2009-2010	+5.4	+5.4	+41.8	+0.62
3	1943-1959	-20.5	-1.28		
	1959-1973	+15.3	+1.09		
	1973-1979	+12.7	+2.12		
	1979-2005	+28.5	+1.10		
	2005-2009	+11	+2.75		
	2009-2010	+2.2	+2.2	+49.2	+0.73
4	1943-1959	-18.1	-1.13		
	1959-1973	+22.6	+1.61		
	1973-1979	+5.3	+0.88		
	1979-1995	+13.1	+0.82		
	1995-2005	+8.9	+0.89		
	2005-2009	+20.3	+5.08	+52.1	+0.79
5	1943-1959	-11.1	-0.69		
	1959-1973	+26.9	+1.92		
	1973-1979	+0.7	+0.12		
	1979-1995	+9.9	+0.62		
	1995-2005	+15.8	+1.58		
	2005-2009	+20.4	+5.10		
	2009-2010	+12.3	+12.3	+74.9	+1.12
6	1943-1959	-16.6	-1.04		
	1959-1973	+20.7	+1.48		
	1973-1979	+5.7	+0.95		
	1979-1983	+3.3	+0.83		
	1983-1995	-3.4	-0.28		
	1995-2005	+26.6	+2.66		
	2005-2009	+20.6	+5.15		
	2009-2010	+3.5	+3.5	+60.4	+0.90
7	1943-1959	+18.5	+1.16		
	1959-1973	+16	+1.14		
	1973-1979	+5.1	+0.85		

	1979-1983	-6.9	-1.72		
	1983-1995	+21.7	+1.81		
	1995-2005	+13.6	+1.36		
	2005-2009	+24.9	+6.23		
	2009-2010	+3.7	+3.7	+96.6	+1.44
8	1943-1959	+43.7	+2.73		
	1959-1973	+19.8	+1.41		
	1973-1979	+3.7	+0.62		
	1979-1983	-18.3	-4.58		
	1983-2005	+64.5	+2.93		
	2005-2009	+18.3	+4.58		
	2009-2010	+1.9	+1.9	+133.6	+1.99
9	1943-1959	+34.5	+2.16		
	1959-1970	-19.3	-1.75		
	1970-1973	+15.4	+5.13		
	1973-1995	+14.1	+0.64		
	1995-2005	+14.9	+1.49		
	2005-2009	+8.8	+2.20		
	2009-2010	-6.3	-6.3	+62.1	+0.93
10	1943-1959	+10.7	+0.67		
	1959-1979	-26.1	-1.31		
	1979-1983	+2.3	+0.58		
	1983-1995	+20.2	+1.68		
	1995-2005	+19.6	+1.96		
	2005-2009	-7.4	-1.85		
	2009-2010	+0.3	+0.3	+19.6	+0.29
11	1943-1959	+8.9	+0.56		
	1959-1970	-10	-0.91		
	1970-1973	0	0.00		
	1973-1979	+6.3	+1.05		
	1979-1983	-4.5	-1.13		
	1983-2005	58.9	+2.68		
	2005-2009	-36.5	-9.13		
	2009-2010	-0.6	-0.6	+22.5	+0.34

Appendix 3: Details of change in vegetation line position from aerial photograph analysis

Profile	Period	Period change (m)	Period rate ($m.yr^{-1}$)	Net change (m)	Net rate ($m.yr^{-1}$)
1	1979-2005	+29	+1		
	2005-2009	+5	+1.3		
	2009-2010	0.0	0	+34.0	+1
2	1979-2005	+37	+1		
	2005-2009	+8	+2		
	2009-2010	0.0	0	+45.0	+1
3	1979-2005	+62	+2.4		
	2005-2009	+3	+0.8		
	2009-2010	0	0	+65.0	+2
11	1973-1979	+5	+0.8		
	1979-1983	+15	+3.8		
	1979-2005	+13	+0.5		
	2005-2009	+5	+1.3		
	2009-2010	0.0	0	+38.0	+1

Appendix 4: Location and recording period of short and long term water level recorders

Location	NZTM Northing	NZTM Easting	Data recorded and used	Recording period
Saltwater Creek	5291795.627	1449274.393	Pressure/temperature	04/08/2011-05/03/2012
			Conductivity	21/09/2011-05/03/2011
New River North	5290161.252	1448704.152	Pressure	04/08/2011-05/03/2012
			Conductivity	21/09/2011-05/03/2011
New River Central	5289497.234	1448484.905	Pressure/ temperature	01/03/2011-05/03/2011
New River South	5288317.057	1447727.193	Pressure/conductivity/temperature	01/03/2011-05/03/2011