Characterising landscape and sea level dynamics to predict shoreline responses over the next 100+ years in a high energy tectonic setting, Kaikoura, New Zealand

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Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

This thesis is

dedicated to the memory of

Terence & Elaine Berger

My grandparents

to whom I owe my love and curiosity

for the natural environment

and to my Mum,

who raised me to believe

that I could accomplish

anything I put my mind to

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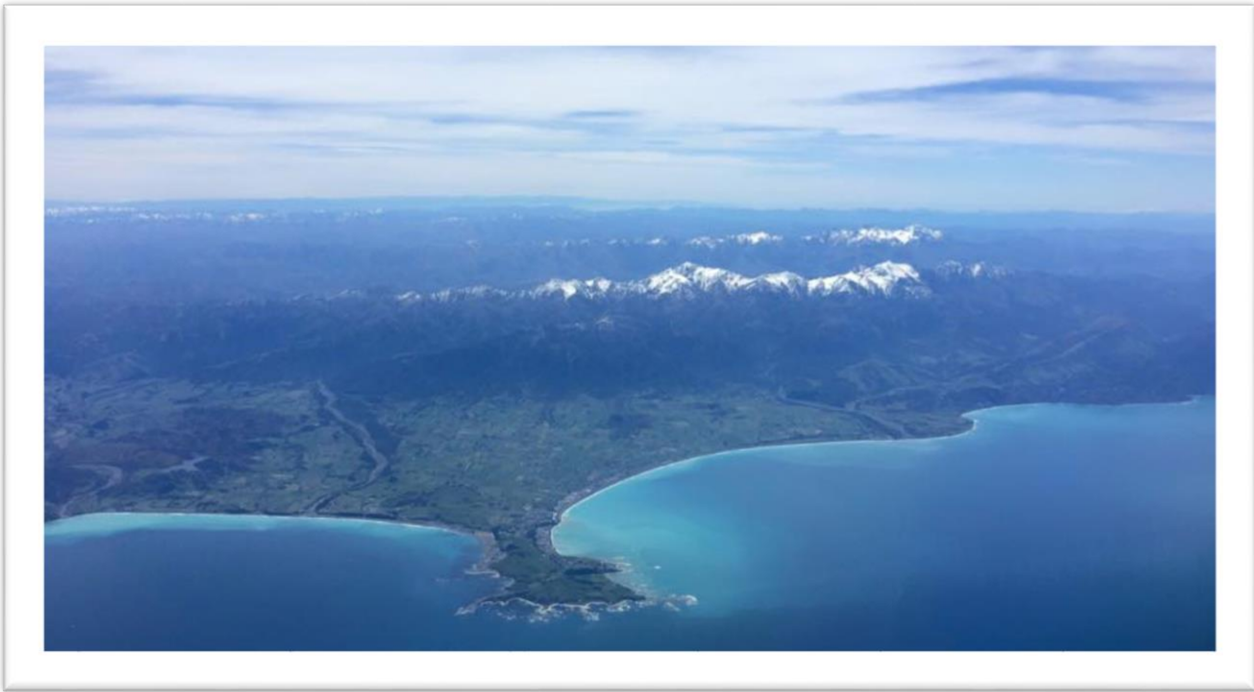

Aerial view of Kaikoura, New Zealand.

Photo credit: H.V Berger

7^{th} November 2015

Abstract

This thesis examines local scale landscape dynamics and coastal responses to climate change along the tectonically active, high energy Kaikoura coastline, South Island, New Zealand.

In New Zealand, the majority of urban infrastructure is built along low-lying coastal plains. As a result, expanding coastal communities face increasing exposure to coastal hazards, which will potentially be exacerbated by climate change-induced adjustments in sediment supply, wave climates and sea levels, amongst other factors. Sea level around New Zealand has been predicted to rise between 0.8 m and 1.0 m by 2115 as a response to increasing global temperatures. In Kaikoura, local relative sea levels may vary from regional projections based on local sediment dynamics in response to; local tectonic uplift and co-seismic sediment delivery, increased rainfall and storm intensity, ocean climate and tides.

Local sediment dynamics are important to consider when managing relative sea-level variations, in terms of assessing erosion response affected by sediment supply. New Zealand Coastal Policy Statement (NZCPS, 2010) Policy 24 states that the effects of climate change on coastal sediment dynamics should be factored into 100 year hazard risk assessments. To this date there has been no combined assessment on tectonic, climatic, and anthropogenic controls on local sediment dynamics, to predict mixed sand and gravel morphology response to future climate change and sea level variation along the Kaikoura coastline.

The main objective of the research is to predict how coastal geomorphology in Kaikoura is likely to respond to local tectonic and climate change- induced adjustments in landscape and sea level dynamics over the next 100+ years. In order to fulfil the research objective, the primary focus of this research was developing a conceptual framework for the preliminary assessment of local sediment dynamics as part of a sea-level rise response matrix. The methodology was developed using a Kaikoura area case study, including the coast between the Hapuku and Kahutara Rivers, Kaikoura Peninsula and the adjacent coastal progradation plain, and Seaward Kaikoura Ranges. This area encompasses key coastal sediment processes and controls in a small well-constrained region that produced findings that can be scalable to other areas in New Zealand and elsewhere.

Tectonics, climate, and human interventions were identified as the main controls on local sediment dynamics in Kaikoura. Key physical (faults, watersheds, landforms) and anthropogenic (hard/soft engineering structures, regulatory frameworks) factors influencing the sediment dynamics were assessed at different temporal and spatial scales. Various climate, river gauge, and beach survey data alongside local tectonic assessments were used to characterise and assess each control.

Determining how each control influences local scale sediment dynamics proved challenging in a relatively sparse data context. Rainfall, ocean climate, and beach profile data analyses provided sufficient information to construct a conceptual model for the preliminary assessment of local sediment dynamics, how tectonic and climate change-induced adjustments could affect sediment supply and how future relative sea level may manifest in the Kaikoura region.

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Chapter One

Introduction

This thesis examines local scale landscape dynamics and coastal responses to climate change along the tectonically active, high energy Kaikoura coastline, South Island, New Zealand.

1.1 The Significance of Mixed and Gravel Beaches in the Study Area

In New Zealand, mixed sand and gravel beaches are common along sections of the south south-eastern coast, North Island and the east coast, South Island (Kirk, 1980). This beach type is rare at a global scale where the majority of coastlines are either made up of sand or pure gravel beaches (Kirk, 1980; Dawe, 1997). The West Coast of both North and South Islands also feature mixed sand and gravel beaches (Dawe, 1997). As a result, there has been growing research on mixed sand and gravel beach morphology exclusive to New Zealand since the mid 1960's (Dawe, 1997). Some of this research has been conducted along the Kaikoura coast, between the Hapuku and Kahutara Rivers, where mixed sand and gravel beaches occur along the coast north and south of the Kaikoura Peninsula. McLean and Kirk (1969) described the relationships between grain sizes, size sorting and foreshore slope along South Bay and North Beach; McLean (1970) identified the alongshore variation of mixed sand and gravel deposits of South Bay and North Beach, based on the textural properties of the sediment deposits; Dawe (1997) re-assessed Mclean's research, verifying the study and linking Late Quaternary tectonic and geomorphic processes to the present day morphology along North Beach; Boorer (2002) described the geomorphic evolution of the South Bay coast by re-examining research by McLean (1970) and assessing the roles of tectonic processes and sediment supply in the development of South Bay.

Other studies of the area include tectonic and geomorphic assessments on alluvial fans Suggate (1965), Chandra (1968), Davies & Bull (2005); and marine terraces and shore platforms of the Kaikoura Peninsula Suggate (1965), Chandra (1968), Ota et al (1996), Stephenson and Kirk (1998; 2001).

To this date there has been no combined assessment on tectonic, climatic, and anthropogenic controls on local sediment dynamics, to predict mixed sand and gravel morphology responses to future climate change and sea level variation along the Kaikoura coastline.

1.2 Research Rationale

Accelerated sea level rise as a result of climate change is a global issue. Global eustatic mean sea level rose to a rate of 1.7 mm per year between 1901 and 2010, and over the latter part of this time frame from 1993 to 2010 the rate increased to approximately 3.2 mm per year between 1993 to 2010 (Intergovernmental Panel on Climate Change (IPCC), 2013, p. 1139). Average global temperature increased by approximately 0.85 °C from 1880 to 2012 (IPCC, 2013), resulting in the following processes that are contributing to sea level rise: expansion of sea water; glacial melt and retreat; and loss of polar ice sheets. These processes are predicted to continue over the next century. The IPCC estimate the global eustatic mean sea level will rise 0.52 m to 0.98 m by 2100, with the current rise rate of 3.3 mm per year (Cazenave et al. 2014, p. 358) increasing to 8 to 16 mm per year from 2081 to 2100 (IPCC, 2013, p. 1140). Scientists have also predicted that global eustatic mean sea level would continue to rise by an additional 1 m by 2300, or 2 – 3 m if global temperatures continue to increase (Horton et al. 2014). Overall global eustatic mean sea level is highly likely to reach 1 m by 2100.

Global eustatic mean sea level rise projections are based on global climatic processes which result in the expansion of sea water, glacial melt and retreat, and loss of polar ice sheets. Relative sea level is a term that describes the vertical movement of the sea or land which changes the sea level relative to the land (IPCC, 2013). Relative sea level rose at an average of 1.7 mm per year between 1925 and 2010 around the New Zealand, consistent with the global sea level rise average of 1.7 mm per year between 1901 and 2010 (Hannah & Bell, 2012, p. 2; IPCC, 2013, p. 1139). In Canterbury, the port tide gauge in Lyttelton Harbour recorded a relative sea level rise of 1.9 mm per year between 1925 and 2010 (Hannah & Bell, 2012).

Local scale changes in relative sea level can be caused by tectonic uplift or subsidence of land, tides, and climatic variability (Bell, 2001). These changes can either result from: rapid change when there is (i) vertical displacement of land in the event of an earthquake, (ii) a low-pressure weather system over the coast during high tide, or gradual change when there is (i) gradual uplift or subsidence of land along active faults (IPCC, 2013; MFE, 2014). A recent example of rapid relative sea level change in New Zealand is the 2010 - 2012 Canterbury earthquake sequence. Land near rivers and the coast in Christchurch had subsided causing the relative sea level to rise approximately 0.5 m (Tonkin & Taylor, 2013, p. 15).

In New Zealand, the relative sea level rise is an important issue as the majority of urban infrastructure, development, and settlements are situated on low-lying coastal plains. In the context of the research area of focus in this thesis, the topography in Kaikoura tends to slope seaward from Mt Fyffe and the Seaward Kaikoura Range to the coast. Along the mixed sand and gravel coastline are raised beach ridges and storm berms, which elevate parts of the coastal strip in front of the township's CBD and along the coast of North Beach and South Bay (Chandra, 1969; Boorer, 2002). The slope of the progradational plain is relatively inclined, narrow, and was formed from active avulsion by the Kowhai, Waimangarara, and Hapuku Rivers 2500 years B.P as a result of relative sea level fall and tectonic uplift of the Seaward Kaikoura Range (Chandra, 1969; Dawe, 1997; Boorer 2002; Davies & Bull, 2005). The majority critical infrastructure Kaikoura is built along the coastal strip, including shore platforms north and south of the Kaikoura Peninsula, and progradational plain formed by the Kowhai, Waimangarara, and Hapuku Rivers. Here, the community face increasing exposure to fluvial and coastal hazards, which will likely be exacerbated by (i) tectonic adjustments in fluvial and coastal morphology, and (ii) climate change-induced adjustments in rainfall intensity and storms, wave climates and sea levels, amongst other physical and human factors.

A rise of absolute sea level between 0.8 m and 1.0 m is predicted for New Zealand coastlines over the next 100 years, based on the IPCC global mean sea level rise projections (MFE, 2014). In Kaikoura, local relative sea levels may vary from regional projections based on local sediment dynamics in response to; local tectonic uplift, rainfall and storm intensity, ocean climate and tides. Local sediment dynamics are important to consider when managing relative sea-level variations, in terms of assessing erosion response affected by sediment supply. New Zealand Coastal Policy Statement (NZCPS, 2010) Policy 24 states that the effects of climate change on coastal sediment dynamics should be factored into 100 year hazard risk assessments.

1.3 Research Aim and Objectives

The main objective of the research is to predict how coastal geomorphology in Kaikoura is likely to respond to local tectonic and climate change-induced adjustments in landscape and sea level dynamics over the next 100+ years.

In order to fulfil the research objective, the primary focus of this research is to develop a conceptual framework for the preliminary assessment of local sediment dynamics as part of a sea-level rise response matrix, which can be scalable to other mixed sand and gravel coastlines in New Zealand and elsewhere.

1.4 Thesis Structure

The structure of this thesis is based on examining the following set of questions in order to achieve the research objective:

- What are the potential impacts of local tectonic activity on (i) coastal sediment supply, and (ii) land elevation relative to the sea in Kaikoura over the next 100+ years?
- How will regional-scale climate change impact (i) rainfall and storms, and (ii) relative sea level?
- How could tectonic and atmospheric-ocean climate processes affect the geomorphology of the Kaikoura coastline over the next 100 years+? And what are the ongoing management implications of this?

This introductory chapter provides, (i) an overview of the case study area, (ii) a foundation for the research by identifying problems associated with the paucity of knowledge on local sediment dynamics, and (iii) the rationale behind identifying how local scale coastal responses to projected relative sea-level rise might vary under different tectonic and climate scenarios. It also sets out the main aim and objective of the research and describes the format of the thesis chapters.

Chapter 2 provides a summary of the case study location, including key features in the fluvial and coastal environment. Key tectonic, climatic, and human controls are introduced in relation to sediment dynamics and the time and space scales in which they operate in.

Chapter 3 defines local tectonic controls on fluvial and coastal processes, within the regional context of the Marlborough Fault System. It then summarises active faults and their impacts on land elevation from compressional uplift and vertical displacement, as well as determining co-seismic effects on coastal sediment supply over the next 100+ years.

Chapter 4 identifies key climatic controls on fluvial and coastal processes. The main aim of this chapter is to assess how regional-scale climate change impacts local-scale (i) rainfall, (ii) wave and wind climate, (iii) tides, and (iv) storms over the next 100+ years in Kaikoura, New Zealand.

Chapter 5 describes coastal geomorphic evolution along the Kaikoura coastline based on previous studies on paleo climate and tectonic history in the area. Local sediment supply and foreshore volumes are assessed in relation to tectonic and climate controls to determine spatial and temporal variabilities for local sediment dynamics.

Chapter 6 identifies coastal hazards, shoreline modelling approaches, and management solutions. It provides an overview of coastal erosion, inundation, and tsunami hazards. It then critiques shoreline modelling techniques previously used to model coastal responses to sea level rise.

Chapter 7 summarises and discusses the main concepts of the thesis raised throughout the preceding five chapters. It discusses the limitations of this study and finishes off by suggesting future research.

Chapter Two

Case Study Area

2.1 Setting

2.1.1 Location

Kaikoura is located on the north-eastern coast of the South Island (Figure 2.1). The main geomorphic features in this area are the Kaikoura ranges, fluvial plains, coastal landforms, and offshore shelf and canyon physiography.

2.1.2 Fluvial environment

There are three main braided river catchments that drain from the Seaward Kaikoura Range (Figure 2.2). The Kahutara, Kowhai, and Hapuku Rivers (Chandra; 1968; Bull, 1991; Dawe, 1997; Boorer, 2003; Davies & Bull, 2005).

The Hapuku and Puhi Puhi River catchment is approximately 134 km^2. The Hapuku River flows from its headwaters in the Seaward Kaikoura Range to the coast, north of Kaikoura. The Hapuku River discharge increases 2.7 km from the coast due to its confluence with the Puhi Puhi River.

The Kowhai River is a steep, braided river with an estimated catchment area of around 85 km^2 (Environment Canterbury, 2000; Sutherland, 2006). This river flows from its headwaters sourced from northwest siding slopes of Mt Fyffe (1602 m) and south siding slopes of the Seaward Kaikoura Range, with elevations between 2,151 m and 2,212 m (Environment Canterbury, 2000 p. 13). The river flows 27 km from the Seaward Kaikoura Range through an incised gorge and arrives onto a progradational gravel floodplain, which extends to the current coastline north and south of the Kaikoura Peninsula (Environment Canterbury, 2000; Sutherland, 2006, p.1). At present day the Kowhai River continues to flow southeast depositing sediment at the coast south of the South Bay Township (Environment Canterbury, 2000).

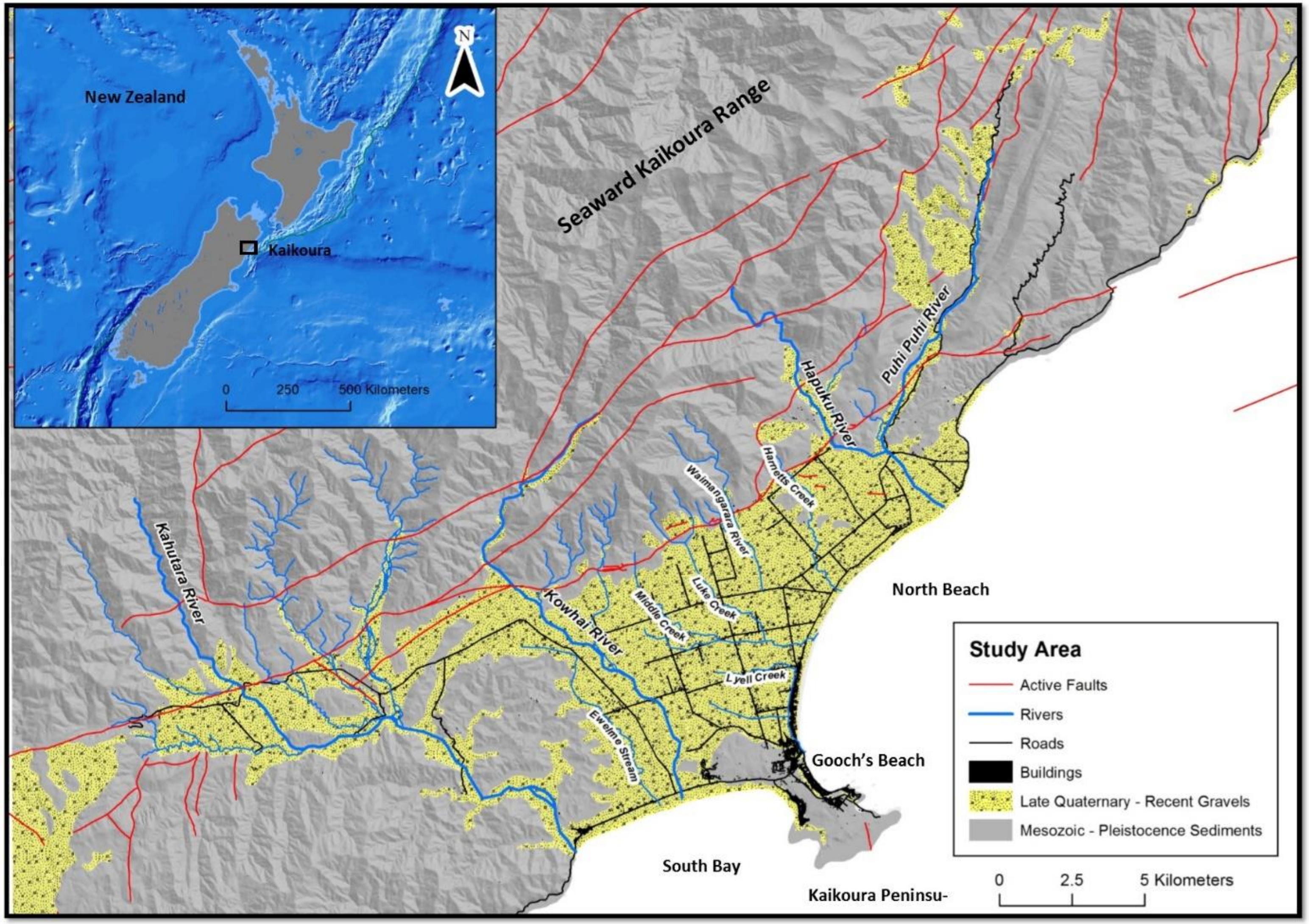

Figure 2-1: Map of case study area

The Kahutara River is another sediment source for the coastline south of the Kaikoura Peninsula, between the mouths of Kahutara River and Kowhai River. The rivers' catchment is located in the Seaward Kaikoura Range and flows to the coast just south of the Peketa settlement.

Goldmine Creek, Floodgate Creek, Luke Creek and the Waimangarara River erode and drain down Mt Fyffe and contribute to the deposition of sediment across the Kowhai and Waimangarara fans. The Mt Fyffe streams (Harnetts Creek, Swan Creek, Middle Creek and Lyell Creek) incise and erode the alluvial fan materials and deposit sediment at the coast north of the Kaikoura Peninsula (Dawe 1997; Boorer, 2003; Davies & Bull, 2005). During past flood events, the Kowhai River has aggraded over its flood plain depositing material into Lyell Creek, which transports larger gravels north of the Peninsula (Dawe, 1997; Bull, 2009). Elms Creek and Stoney Creek (also known as Ewelme Stream) are situated between the Kahutara and Kowhai Rivers. Elms Creek flows from the southeast siding slope near Lake Rotorua to the coast and Ewelme Stream flows from tributaries draining the northeast to southeast slopes of Rangamahoe (327 m) to the coast (Boorer, 2003).

2.1.3 Coastal environment

The beaches north and south of the Kaikoura Peninsula are made up of coarse sediment derived from eroded Greywacke basement rock of the Seaward Kaikoura Range and Quaternary alluvial deposits (Cotton, 1916; Mclean, 1970). North Beach, Gooch's Beach, and South Bay are classified as mixed sand and gravel (MSG) beaches (McLean, 1970; Kirk, 1980). MSG beaches are formed in high energy coastal environments, dominated by wave run-up due to the steeply reflective nature characterised by MSG morphology (Jennings & Shulmeister, 2002). During storms, high tides, or storm tides (combination of both events occurring over the same time) increased wave run-up can lead to overtopping of berms and inundation (Kirk, 1980). Run-up is a process used to describe the interaction between waves and the slope of the beach. Waves rework and remove the finer sediment component of the profile forming gravelly cusp horns (Kirk, 1975). Cusp horns are coarser-grained features formed from run-up processes of waves and can be used to identify the extent of run-up along the foreshore. The position of relict cusps to newer cusps can be used as a guide to determine periods of regression and relative sea level fluctuations (Shulmeister & Kirk, 1993; Nolan et al. 1999).

Figure 2-2: Mixed Sand and Gravel Beaches discussed in this thesis. 1. South Bay – North of the Kahutara River. 2. South Bay – North of the Kowhai River. 3, Gooch's Beach looking towards the Township. 4. North Beach – South of the Hapuku River Mouth.

Coastal cliffs, marine terraces, raised beaches and intertidal shore platforms are uplifted geomorphic features of the Peninsula (Cotton, 1916; Jobberns, 1928; Chandra; 1968; Ota et al. 1996; Rattenbury et al. 2006). The geology of the Kaikoura Peninsula consists of; Palaeocene – Eocene (65 – 35 million years) Amuri limestone, and Oligocene (55 million years) mudstone. The shore platforms are inter-tidal and cover an area of approximately 0.74 km^2 around the Peninsula (Suggate, 1965; Duckmanton, 1974; Ota et al. 1996; Stephenson & Kirk, 2001; Rattenbury et al. 2006). Limestone platforms are exposed along the southeast side, and mudstone platforms are exposed northeast and southwest of the Peninsula due to local scale folding (Rattenbury et al. 2006). Sub-tidal reef structures also occur around the Peninsula (Stephenson & Kirk, 2001). The Peninsula also consists of five marine terraces and beach deposits that have been uplifted during the Holocene (100,000 kya – recent). These marine terraces are features that can indicate the position of past relative sea level by determining the height of eustatic sea level and local tectonic uplift (Ota et al. 1996).

Figure 2-3: Southern side of the Kaikoura Peninsula looking south towards Haumuri Bluffs. Limestone and mudstone intertidal shore platforms below.

2.1.4 Marine environment

The continental shelf, continental slope, Hikurangi Trough and the Chatham Rise are the four dominant marine physiographic features offshore Kaikoura (Rattenbury et al. 2006). The continental shelf exists approximately 10 km wide at a depth less than 400 m close to the Kaikoura Peninsula. Many canyons and basins are carved into the continental slope (Rattenbury et al. 2006). The Kaikoura Canyon is a deeply incised submarine feature of the continental shelf (Lewis & Barnes, 1999; Barnes & Audru, 1999). It has formed 500 m off the coast from Goose Bay, south of the Kaikoura Peninsula. Here, the canyon's bathymetry drops to 1,000 m deep and captures northward drifting sediment (Lewis & Barnes, 1999).

The Hikurangi Trough reaches depths around 2,500 m off the Kaikoura coastline, trending northeast and extending towards the east coast of the North Island, where it exists at 3,500 m deep (Lewis & Barnes, 1999).

2.2 Assessment Framework

2.2.1 Conceptual Modelling

The key controls that will be discussed in this thesis are: Tectonic Controls, Climate Controls, and Anthropogenic Controls in relation to sediment dynamics (Figure 2-4).

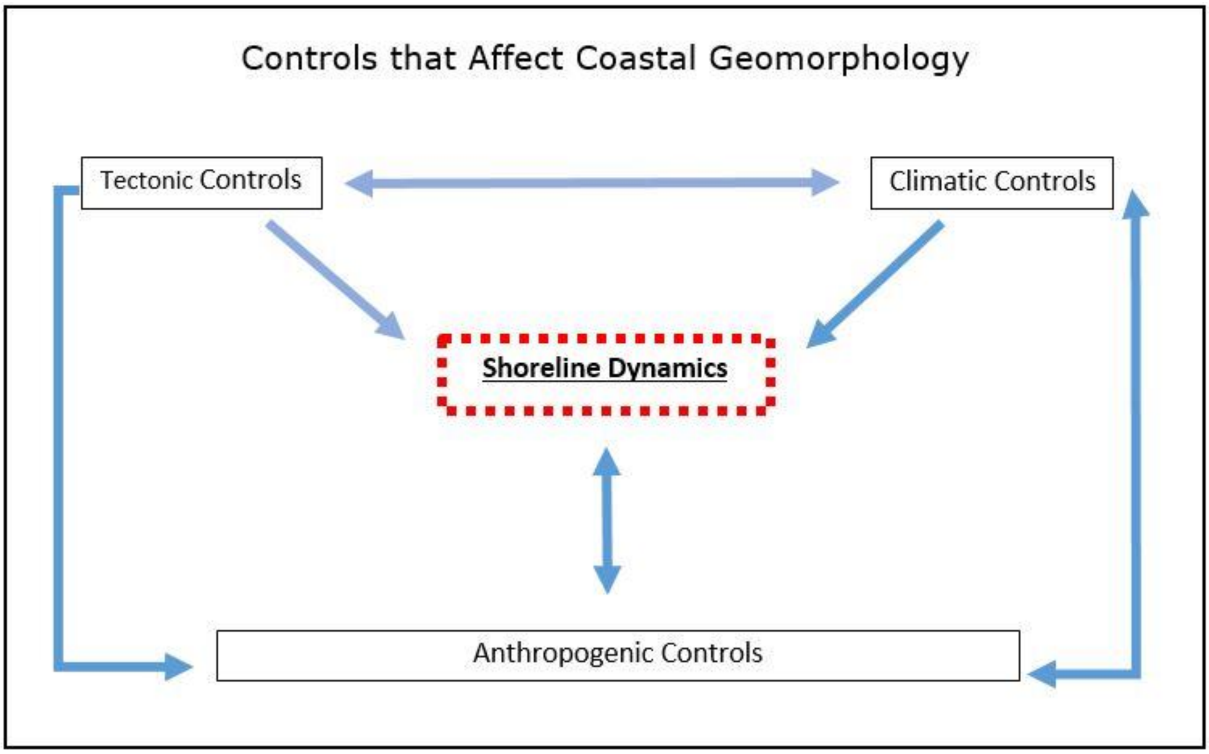

Figure 2-4: Overall conceptual framework.

Figure 2-5 demonstrates the time frames at which various controls operate within relation to the coastal environment. Geological timeframes are assessed to develop the knowledge of the geomorphic evolution of the Kaikoura coastline in Chapters 3, 4 and 5. Whereas historical and event timeframes are used to review hazard management approaches.

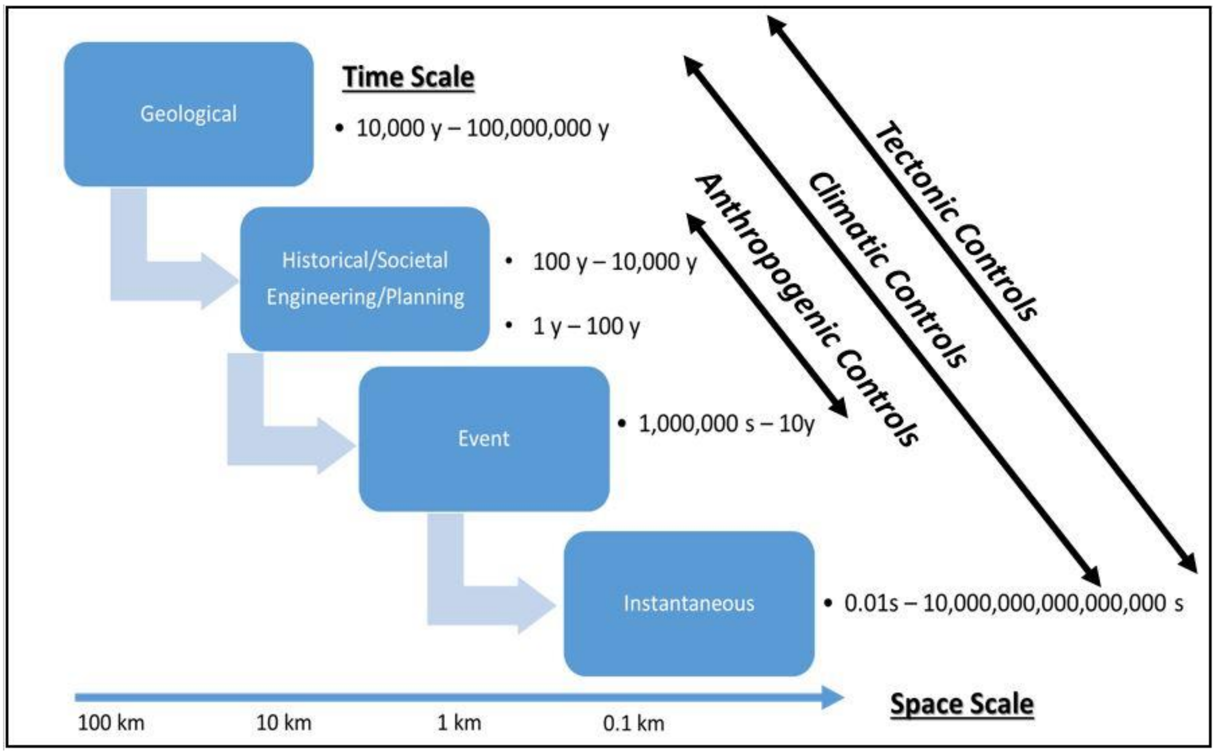

Figure 2-5: A schematic representation of examples of key controls that influence coastal sediment dynamics at different time and space scales. Adapted for a coastline in a high-energy, tectonically active setting. Adapted from (Cowell & Thom, 1994; Woodroffe, 2003).

Chapter Three

Tectonic Effects on Coastal Systems

3.1 Introduction

3.1.1 Tectonic Framework

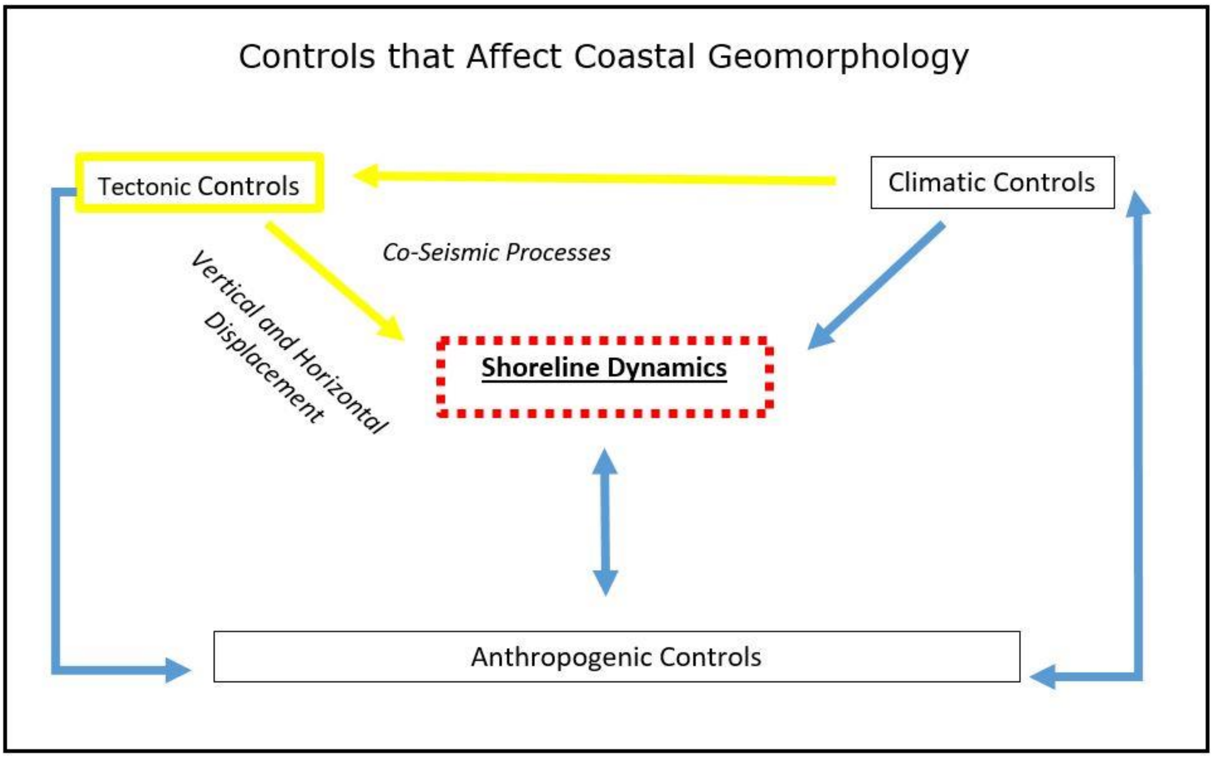

Figure 3-1: Controls that affect coastal geomorphology.

Figures 3-1 and 3-2 conceptual frameworks outline tectonic effects on coastal systems. Figure 3-2 framework takes into consideration vertical displacement in terms of uplift of mountain ranges and in some cases subsidence of river basins depending on the nature of a fault. Horizontal displacement across a fault can displace watersheds and drainage networks. The framework also accounts for seismic events which can lead to sudden horizontal and/or vertical displacement of landforms and rapid changes in fluvial and coastal morphology.

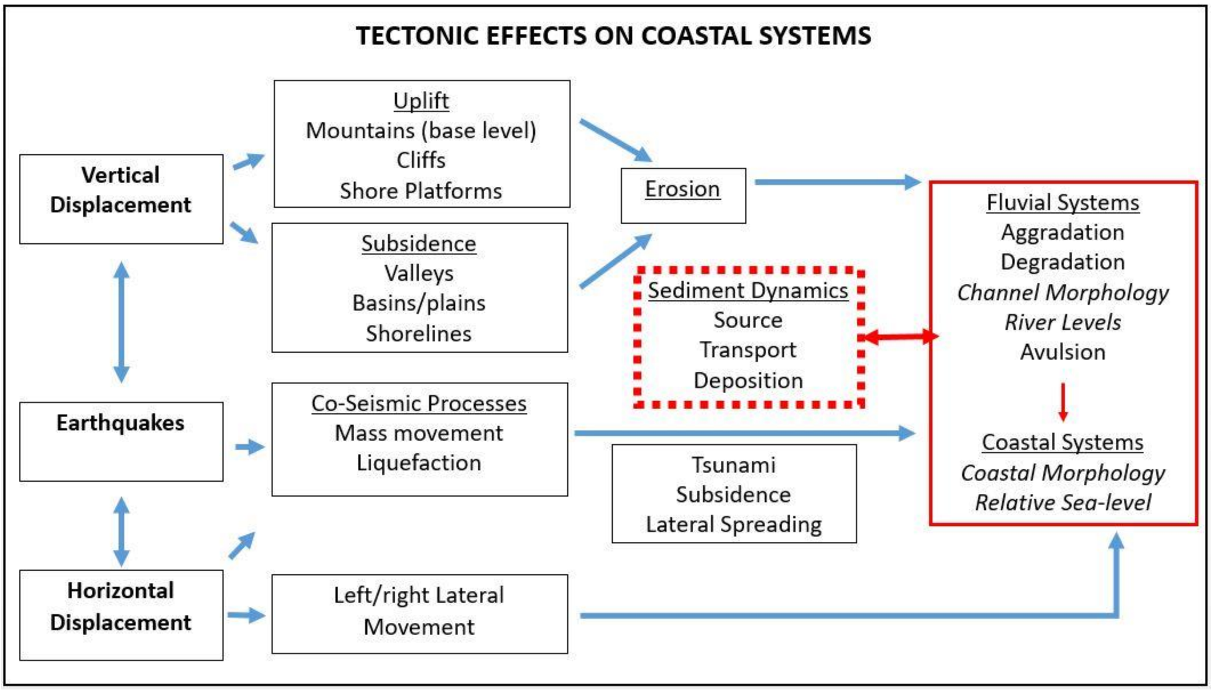

Figure 3-2: Conceptual framework for tectonic effects on coastal systems.

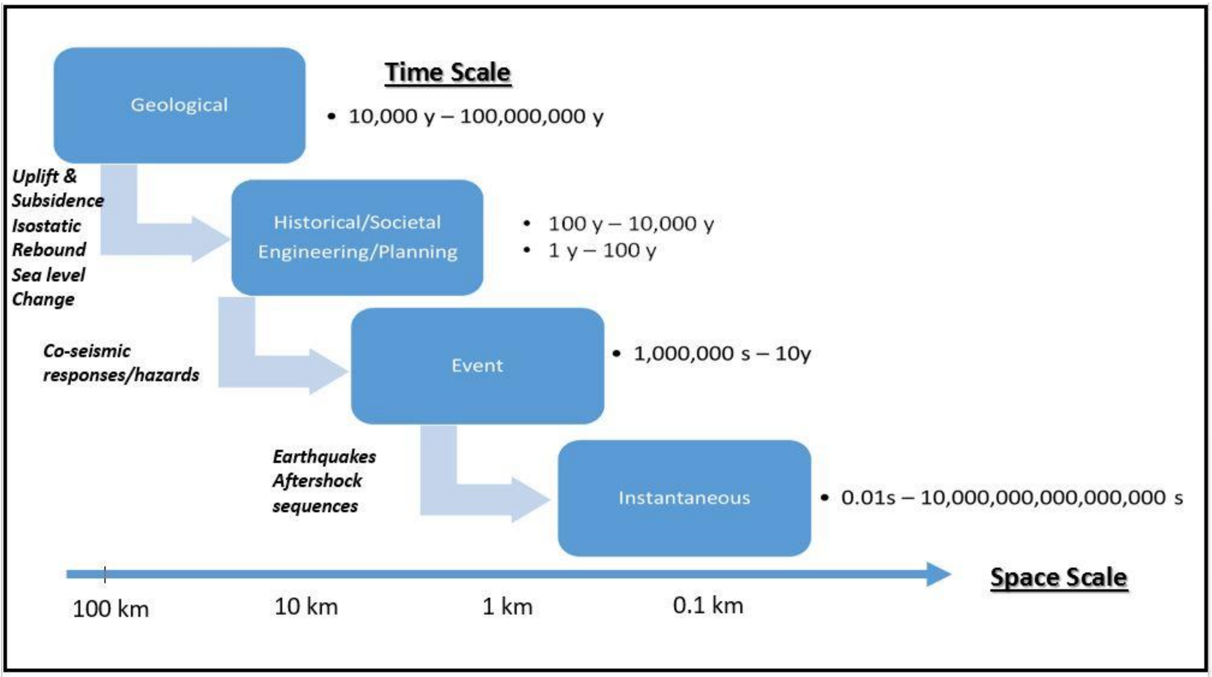

Figure 3-3: A schematic representation of examples of key tectonic controls and drivers which influence coastal sediment dynamics at different time and space scales. Adapted for a coastline in a high-energy, tectonically active setting. Adapted from (Cowell & Thom, 1994; Woodroffe, 2003).

In terms of assessing sediment dynamics, all these variables need to be considered due to the number of active faults in Kaikoura. Understanding co-seismic processes are particularly important for assessing sediment dynamics since seismic events are highly likely to occur in the next 100 years. These co-seismic impacts will not only affect sediment budget by providing large amounts of sediment into river catchments but also affect how this sediment is transported to and along the coastline.

3.2 Tectonic Setting

3.2.1 Regional convergence and uplift

The study area is located along the east coast of the South Island within the active Marlborough Fault system (Rattenbury et al. 2006). This area represents the boundary transition zone where the Australian and Pacific plate convergence rate is 41 mm/yr (DeMets et al. 1990; Anderson & Webb, 1994). The faulting associated with this convergence results in the uplift of the Seaward Kaikoura Range by 6 to 10 mm/yr, a rate at which is similar to the Southern Alps (Van Dissen & Yeats, 1991).

3.2.2 Geological History

This section summaries major geological events and the formation of regional – local scale lithological groups and paleo environments over the last 145 million years. Figure 3.4 shows the main lithological units in Kaikoura case study area.

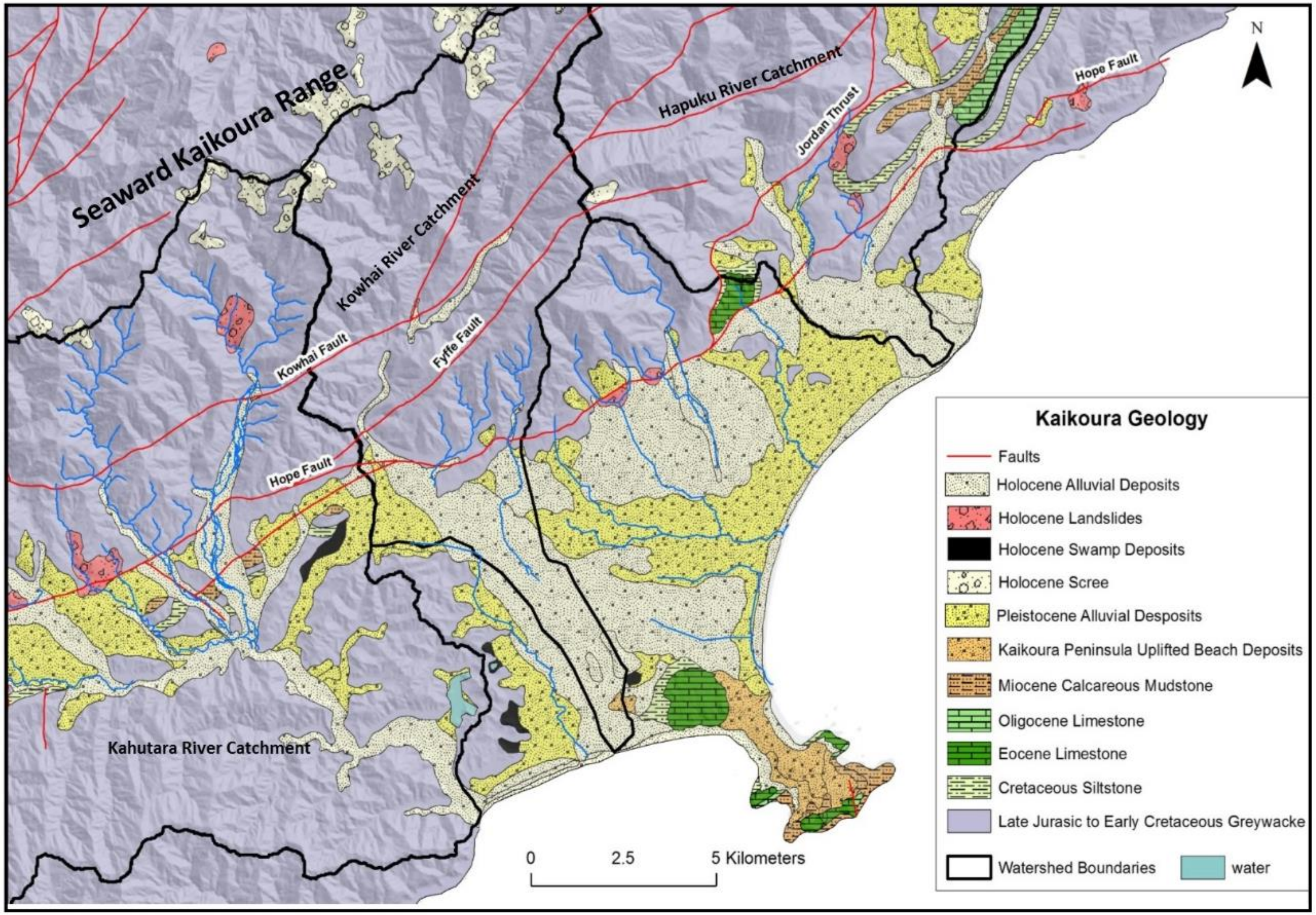

Figure 3-4: Main lithological units in Kaikoura case study area.

Late Jurassic to Early Cretaceous:

The Pahau terrane Greywacke is the dominant basement rock that forms the Seaward and Inland Kaikoura Ranges. This bedded sand and mudstone formed between 142 – 99 million years ago in an ocean basin environment during the Early Cretaceous rifting of the Tasman Sea (Rattenbury et al. 2006). The Rangitata orogeny was the first major mountain building event throughout New Zealand from the Late Jurassic to the Palaeocene, as a result, convergent tectonics along the plate boundary margins that formed Gondwanaland (Kingma, 1959). Regional uplift of the Pahau terrane Greywacke in the Marlborough and North Canterbury and the formation of Seymour Group siltstone occurred in the Late Cretaceous followed by a period of rapid erosion (Kingma, 1959; Rattenbury et al. 2006).

Palaeocene to Oligocene:

Tectonic stability in the region occurred during the Palaeocene (65 mya) through to the Oligocene (25 mya). This was a period of active subsidence and marine transgression, which resulted in extensive marine sedimentation and the formation of Muzzle Group and Motunau Group Limestones (Rattenbury et al. 2006). Muzzle Group Amuri Limestone was formed in the region during the Palaeocene and Eocene (65- 35 mya). The earliest formation (55 – 35 mya) overlays the Seymour Group Siltstone as part of the Kaikoura Peninsula (Rattenbury et al. 2006). Motunau Group Spyglass Formation Limestone formed during the Oligocene (35 – 25 mya) following a period of erosion evident from unconformable deposition on top of the older Amuri Limestone Peninsula (Rattenbury et al. 2006).

Miocene to Pliocene:

Deposition of the Waima Formation Mudstone occurred during the Miocene, approximately 25 – 5 million years ago (Rattenbury et al. 2006). The Kaikoura Orogeny was the second major mountain building event to occur in New Zealand from the Miocene through to the Quaternary (Kingma, 1959). Rapid uplift of the Seaward Kaikoura Range occurred from the Late Pliocene (3 mya) as a result of plate boundary compression due to the convergence between the Pacific and Australian Plates (Kingma, 1959; Rattenbury et al. 2006). This event created a subsequent erosion of material and a period of shoreline regression (Ota et al. 1996; Shulmeister & Kirk, 1993; Rattenbury et al. 2006).

Pleistocene:

Early Quaternary Pleistocene alluvial and beach deposits are characterised by poorly to well-sorted gravels, sand and silt originating from Pahau Terrane Greywacke (Rattenbury et al. 2006). These deposits formed between 5 – 2 million years ago as a result of river aggradation during a period of relative sea level stability and shoreline regression (Bull, 1991; Shulmeister & Kirk, 1993).

Holocene:

Holocene deposits during the Late Quaternary formed in correlation with regional climate and sea level fluctuations between glacial and interglacial periods and active uplift of the Seaward Kaikoura Range and Kaikoura Peninsula (Cotton; 1916; Jobberns, 1928; Bull, 1991; Shulmeister & Kirk, 1993; Dawe, 1997; Boorer, 2003; Davies & Bull, 2005). Alluvial fan and scree deposits are the most recently deposited gravels derived from the active uplifting and eroding Seaward Kaikoura Range and previous Pleistocene alluvium (Rattenbury et al. 2006). Swamp deposits in this area consist of peat material locally confined by aggrading fans (Rattenbury et al. 2006). Landslide deposits shown in Figure tend to cover an area >1km^2. Smaller scale mass movements are not represented in this map but frequently occur in the Seaward Kaikoura Range. The composition of the Holocene landslides is course brecciated Pahau Terrane Greywacke (Rattenbury et al. 2006). Landslides of this scale have most likely been triggered by severe seismic shaking from earthquake events over the last 100,000 years (Rattenbury et al. 2006; Stirling et al. 2007; Yetton & McCahon, 2009; Robinson, 2014).

3.3 Active Faults

3.3.1 Introduction

The stresses involved with plate convergence are transferred through north – northeast trending oblique, right lateral (dextral) strike-slip Alpine, Awatere, Kekerengu, Clarence, Hope Faults, and reverse faults such as the Jordan Thrust, Kaikoura and Kekerengu Bank Faults (Kingma, 1959; Van Dissen, 1989; Van Dissen & Yeats; 1991; Knuepfer, 1992; Yetton & McCahon, 2009).

3.3.2 Overview: fault movements

As previously mentioned, the Marlborough Fault Zone is an area of convergence and transition between a transform and convergent plate boundaries (DeMets et al. 1990; Anderson & Webb, 1994). Vertical displacement in this region is attributed to thrust and oblique-slip faulting. Whereas horizontal displacement occurs along dextral strike-slip and segments where there is a component of oblique-slip movement (Suppe, 1985). The Marlborough Fault Zone and the North Canterbury Fold and Thrust Belt are two major faulting domains classified by Stirling et al. (1999 & 2007). These two domains are referred to by Yetton & McCahon (2009) as the most relevant to the Kaikoura district in relation to large-scale displacement and considerable seismic hazard. The majority of vertical and horizontal displacement of river catchments in the Kaikoura case study area is attributed to movement across Hope and Jordan Thrust Faults within the Marlborough Fault Zone. Whereas vertical movement along the coast relates to northeast trending offshore thrust faults associated with the Northern Canterbury Fold and Thrust Belt (Van Dissen, 1989; Van Dissen & Yeats, 1991; Ota et al. 1996; Stirling et al. 1999 & 2007; Yetton & McCahon, 2009).

3.3.3 Horizontal displacement

Horizontal displacement across the Seaward Kaikoura Range primarily occurs along the 230 km long Hope Fault. There are four major segments along the Hope Fault (Taramakau – Hope River, Conway – Kahutara, Mt Fyffe, and Seaward segments). The Conway-Kahutara, Mt Fyffe and Seaward segments accommodate the majority of strain in the study area, and contribute to both horizontal and vertical slip along 100+ km of the fault (Van Dissen, 1989; Van Dissen & Yeats, 1991; Bull, 1991 & 2009; Yetton & McCahon, 2009).

3.3.4 Vertical displacement

Uplift in the Kaikoura case study are can be spatially classified into two areas: (i) Seaward Kaikoura Range (ii) Kaikoura Peninsula (Yetton & McCahon, 2009; Beavan & Litchfield, 2012).

1. Plate boundary uplift of the Seaward Kaikoura Range from crustal shortening locally accommodated by strain along the Hope and Jordan Thrust Faults.
2. Fault block uplift of the Kaikoura Peninsula, shore platforms, and reefs associated with offshore thrust faults across the continental shelf

3.4 Earthquakes and Co-Seismic Impacts

3.4.1 Future scenario

A survey report written by Yetton and McCahon (2009) identifies major local and regional faults likely to produce a significant seismic hazard for the Kaikoura District, using probabilistic data from Stirling et al (2007).

Table 3.1 below is a summary of the major active onshore faults that are likely to cause significant seismic hazards on land and off shore near Kaikoura. The Hope Fault and the Jordan Thrust are defined as the two most active faults in the Kaikoura case study area (Yetton & McCahon, 2009). The majority of slip from the Mt Fyffe segment is transferred to the Jordan Thrust Fault (Van Dissen & Yeats, 1991). In terms of assessing the scale of co-seismic impacts from rupture along these faults the likelihood of an earthquake occurring, the amount of energy released and displacement are important variables to consider (Yetton & McCahon, 2009). The Conway-Kahutara segment of the Hope Fault is of particular focus because it has a very high probability of rupturing within the next 100 years. The fault segment is also the main morphological control on the morphology of the Kahutara and Kowhai rivers (Bull, 1991; Davies & Bull, 2005). Based on a rupture scenario occurring within the next 100 years, the magnitude of the rupture will be between 7.3 and 7.5 Mw along the Conway-Kahutara section of the Hope Fault. Lateral displacement is likely to be 7 m across the fault. The shaking intensity will be MM9 – MM10 and the Peak Ground Acceleration will range from 0.6 to 0.7g (Stirling et al. 2007; Yetton & McCahon, 2009).

An event of scale would cause many landslides and rock falls into the main river catchments in the Seaward Kaikoura Ranges. Large co-seismic sediment input is likely to create landslide dams, which can lead to channel avulsion further downstream (Robinson, 2014). Previous landslide deposits from past earthquake events over the last 100,000 years, occur along the shear zone of the Hope Fault (Figure 3.5). This shear zone runs through major drainage zones and these previous deposits indicate is likely to occur in these active valley systems (Rattenbury et al. 2006). Liquefaction susceptibility in Kaikoura is relatively low (Figure 3.6), however, lateral spreading may occur where the water table is high near rivers and streams, in areas of recent flooding (Yetton & McCahon, 2009).

Table 3-1: Active Onshore Faults that are likely to cause significant seismic hazards on land and offshore Kaikoura (Stirling et al. 2007; Rattenbury et al. 2006; Yetton & McCahon, 2009; GNS Science, 2015).

Fault	Length	Fault Sense	Slip Rate (mm/yr.)	Mw	Recurrence Interval yrs.	Last Event yrs.	Single Event Displacement (m)
Alpine	400	dextral	> 10	7.1-7.5	< 2,000	160-1,000	> 5
Alpine/Wairau	110 - 120	dextral	1-5	7.3-7.7	< 2,000	1,000-10,000	
N: Awatere	65 - 70	dextral	5-10	7.5	< 2,000	160	
Clarence	175	dextral	1-10	7.7	2,000 – 3,500	1,000-10,000	
Kekerengu	20	dextral/ reverse	> 10	7.2	< 2,000	1,000-10,000 *	
HF: Hope River - Taramakau	90 - 110	dextral	11 - 17	>7.0	81 - 490	<1,000	
HF: Conway - Kahutara	60 - 90	dextral/ reverse	18 - 35	7.2-7.6	120	128	
HF: Mt Fyffe	12 - 15	dextral/ reverse	11 - 21	>7.0	< 2,000	<1,000	
HF: Seaward	10 - 25	dextral/ reverse	3 - 5	>7.0	< 2,000	<1,000*	
Jordan Thrust	25	reverse	1-10	7.1	< 2,000	1,000-10,000 *	1-5
Hundalee	53	reverse	0-1.5	7.0	2,000-3,500	< 10,000 *	1 – 5

*Recent rupture (14/11/2016 Kaikoura EQ) Clark et al. 2016

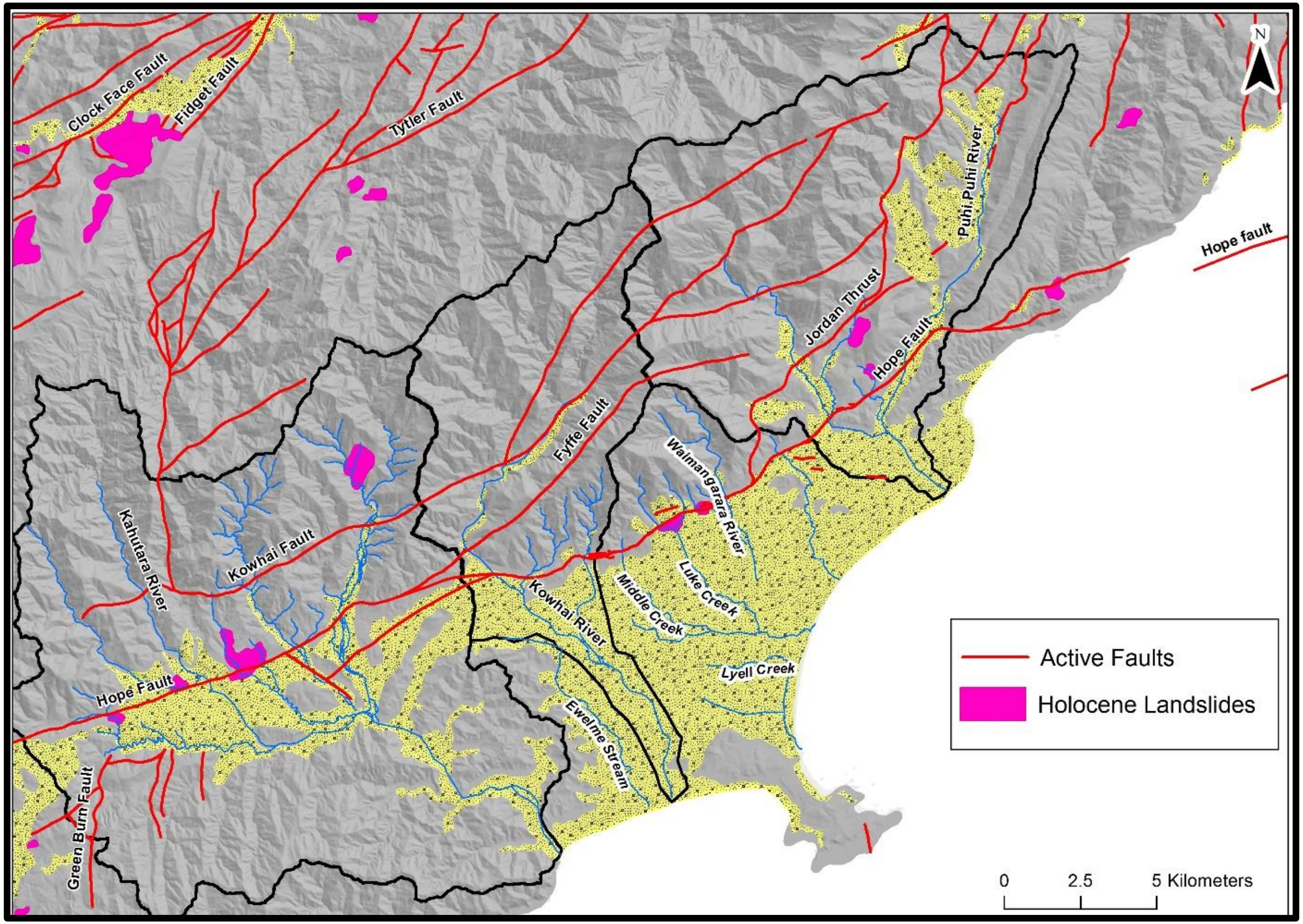

Figure 3-5: Map showing Holocene landslide deposits >1km2 along active faults in Kaikoura (Rattenbury et al. 2006).

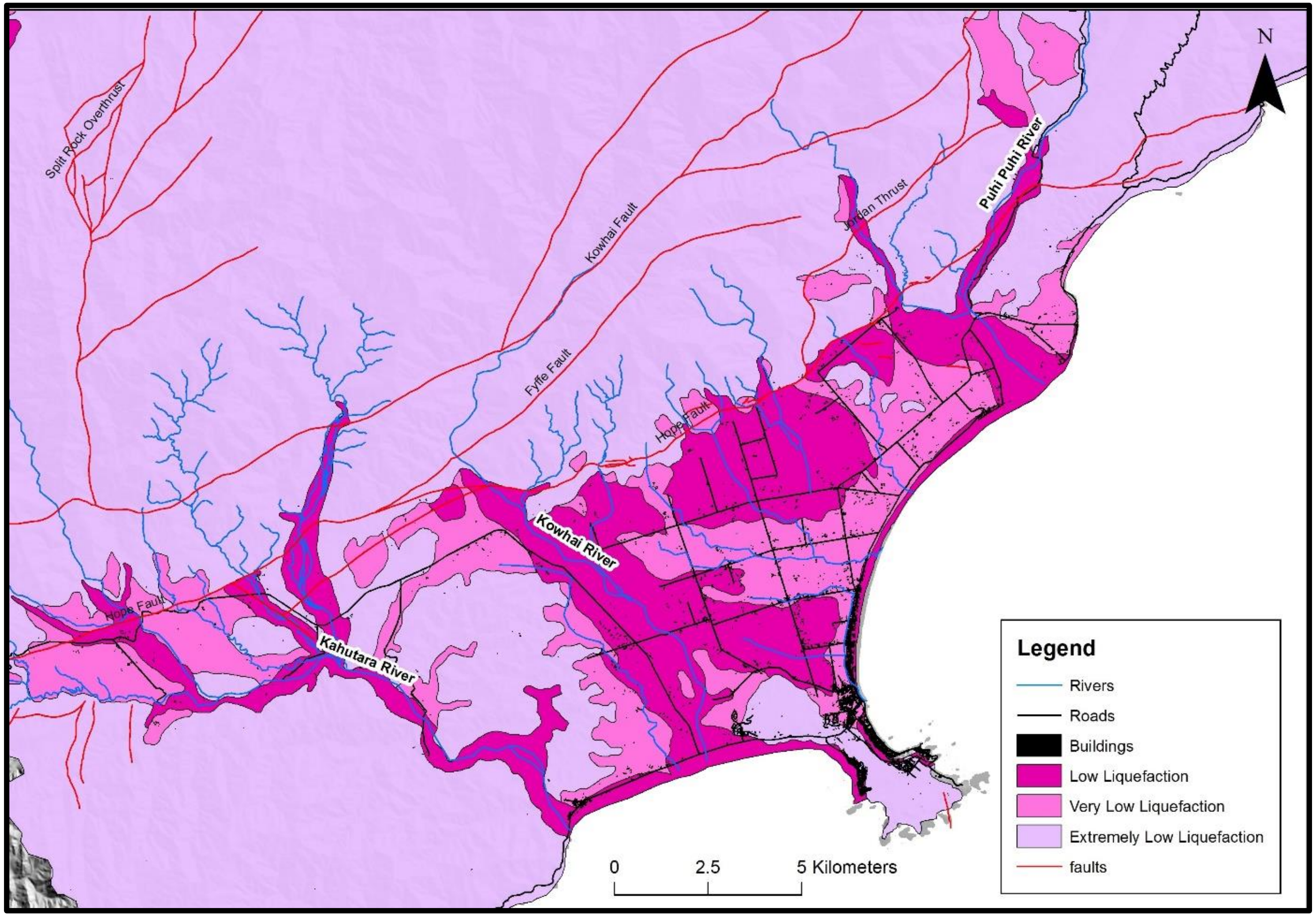

Figure 3-6: Map showing liquefaction susceptibility in the Kaikoura area. Liquefaction potential is low in general and is likely to limited to active river and stream channels and recent flood deposits (Yetton & McCahon, 2009; Environment Canterbury, 2015a).

3.5 Relative sea level along tectonically active coastlines

3.5.1 An overview

A change in land elevation relative to sea level results in an increase or decrease in relative sea level (RSL). Regional to local scale changes in relative sea level are due to: (i) geological (long term) uplift or subsidence of land as a result of fault movement and sedimentary compaction in drainage basins, (ii) seismic displacement along an active fault resulting in uplift or subsidence, (iii) co-seismic liquefaction-induced subsidence and settlement, (iv) subsidence due to groundwater withdrawal and sediment compaction (Yetton & McCahon, 2009; Beavan & Litchfield, 2012). Relative sea level also changes in relation to shoreline aggradation and erosion, which is locally affected by fluvial transport of sediment to the coast and alongshore transportation and deposition along the coast (Shulmeister & Kirk, 1993). In a tectonically active region, the rate of accretion and erosion is likely to be controlled by tectonic uplift and co-seismic processes in both fluvial and coastal systems.

In the Kaikoura study area, the elevation along the coastline around the Kaikoura Peninsula is affected by: (i) long-term tectonic uplift, and (ii) vertical displacement accompanying seismic events associated with offshore thrust faults in the North Canterbury Fold and Thrust Belt (Stirling et al. 2007; Yetton & McCahon, 2009; Beavan & Litchfield, 2012). Shoreline accretion along coastal sections north and south of the Kaikoura Peninsula is attributed to fluvial aggradation in response to erosion of the uplifting Seaward Kaikoura Range, co-seismic sediment delivery, and increased rainfall producing ample sediment supply (Cotton, 1916; Bull, 1991; Shulmeister & Kirk, 1993; Davies & Bull, 2005; Rattenbury et al. 2006).

The inferred long term uplift rate along the Kaikoura Peninsula coastline is >1 mm/yr, based on an uplifted 125,000 year old marine terrace (Ota et al. 1996; Beavan & Litchfield, 2012).

Until recently there had been no major uplift event along the Kaikoura coastline associated with any documented historical earthquake occurring in either the Marlborough Fault Zone or North Canterbury Fold and Thrust Belt (Yetton & McCahon, 2009). On the 14th of November 2016 rapid uplift of intertidal reefs and platforms, ranging between 0.5 to 5.7 m, occurred along the Kaikoura and Marlborough coastline during the 7.8 Mw Kaikoura Earthquake (Clark et al. 2016). Based on the measurements from preliminary surveying and long-term uplift rate of the Kaikoura Peninsula, 1,000 years of uplift occurred within one seismic event and relative sea-level fall (Ota et al. 1996; Beavan & Litchfield et al. 2012; Clark et al. 2016). The opposite occurred along the Christchurch coastline during the 2011 February earthquake, where coastal land subsided and relative sea-level rose by 0.5 m to 1 m (Hughes et al. 2015). On the northern side of the Kaikoura Peninsula 0.9 m of uplift occurred based on tidal gauge measurements. Helicopter surveying measured uplift between 0.5 m to 1.5 m along the southern side of the Peninsula (Clark et al. 2016). Surface fault ruptures were observed along the Hundalee, Hope (seaward segment), Papatea, Jordan Thrust and Kekerengu Faults. The sense of movement along these faults during the rupture caused significant uplift (Clark et al. 2016). Significant co-seismic landsliding into the upper Hapuku, Kowhai and Kahutara River catchments also occurred. The large amount of co – seismic sediment created many landslide dams in the Seaward Kaikoura Range. An example is a 150 m high dam in the Hapuku River which poses a dam break and local flooding hazard in the study area (Canterbury Maps, 2016; Canterbury Civil Defence, 2016). The geomorphic consequences are likely to result in increased fluvial aggradation across the Kowhai, Waimangarara and Hapuku fans (Robinson, 2014).

3.6 Summary

This chapter identified local tectonic controls and their impacts on (i) land elevation relative to the sea due to compressional uplift and vertical displacement, and (ii) assesses co-seismic effects on coastal sediment supply over the next 100+ years.

Chapter Four

Climate Effects on Coastal Systems

4.1 Introduction

This chapter focusses on key climatic controls on fluvial and coastal sediment processes. The main aim of this chapter is to assess how regional-scale climate change impacts local-scale (i) rainfall, (ii) wave and wind climate, (iii) tides, and (iv) storms over the next 100+ years in Kaikoura, New Zealand.

4.1.1 Climate within a local case study context: Framework methodology

The balance between sediment input and coastal processes determines shoreline stability (Bell, 2001). Therefore, it is necessary to understand past climate and current climate variability to assess future climate change impacts. This is particularly important for local scale coastal hazard management in New Zealand when assessing the coastal responses caused by local sediment transport to and along the coast.

This chapter assesses the main atmospheric and ocean climate controls on local sediment dynamics in terms of sediment transport to and along the Kaikoura coastline by fluvial and coastal processes. The interaction between tectonic and human controls (Figure 3.1), over different time and space scales (Figure 3.2) is also accounted for. Variables that will be discussed are shown in Figure 3.3.

The following atmospheric controls are evaluated:

i) Local rainfall and temperature in relation to fluvial processes in sediment delivery to the coast.

ii) Storms and tide levels in conjunction with ocean climate controls on wave energy and alongshore sediment delivery.

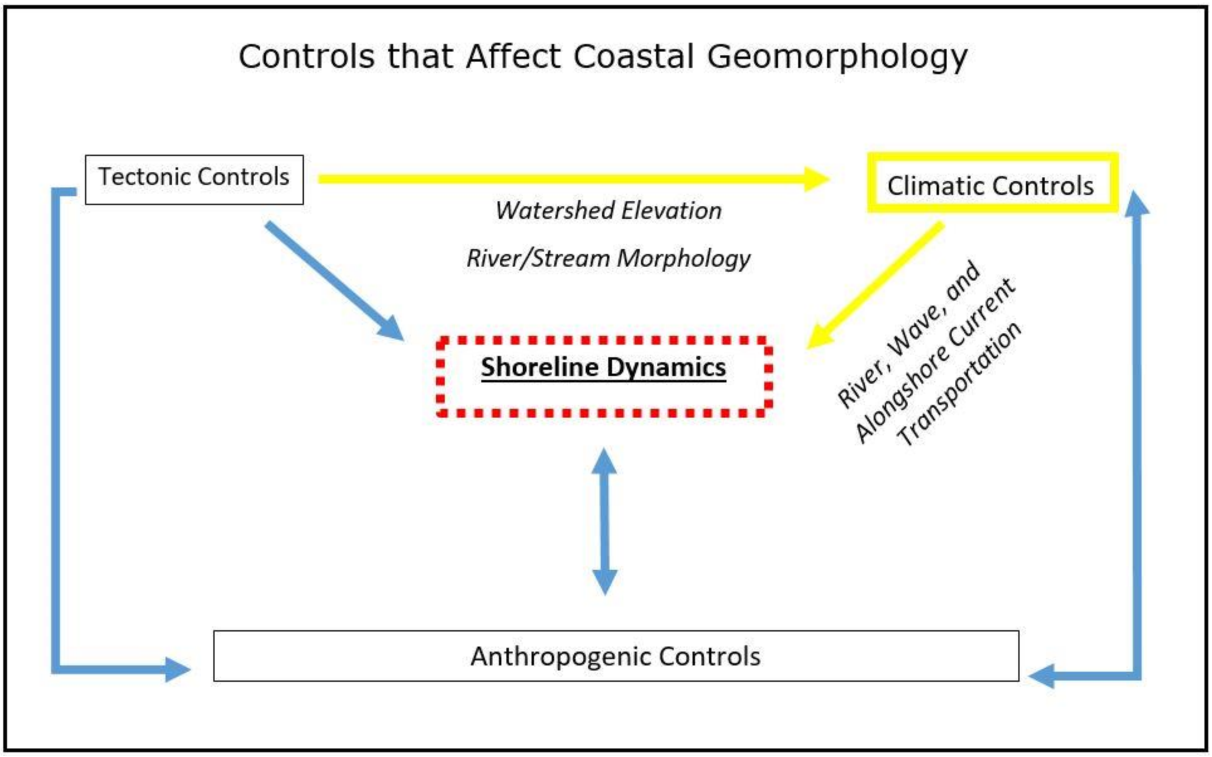

Figure 4-1: Controls that affect coastal geomorphology.

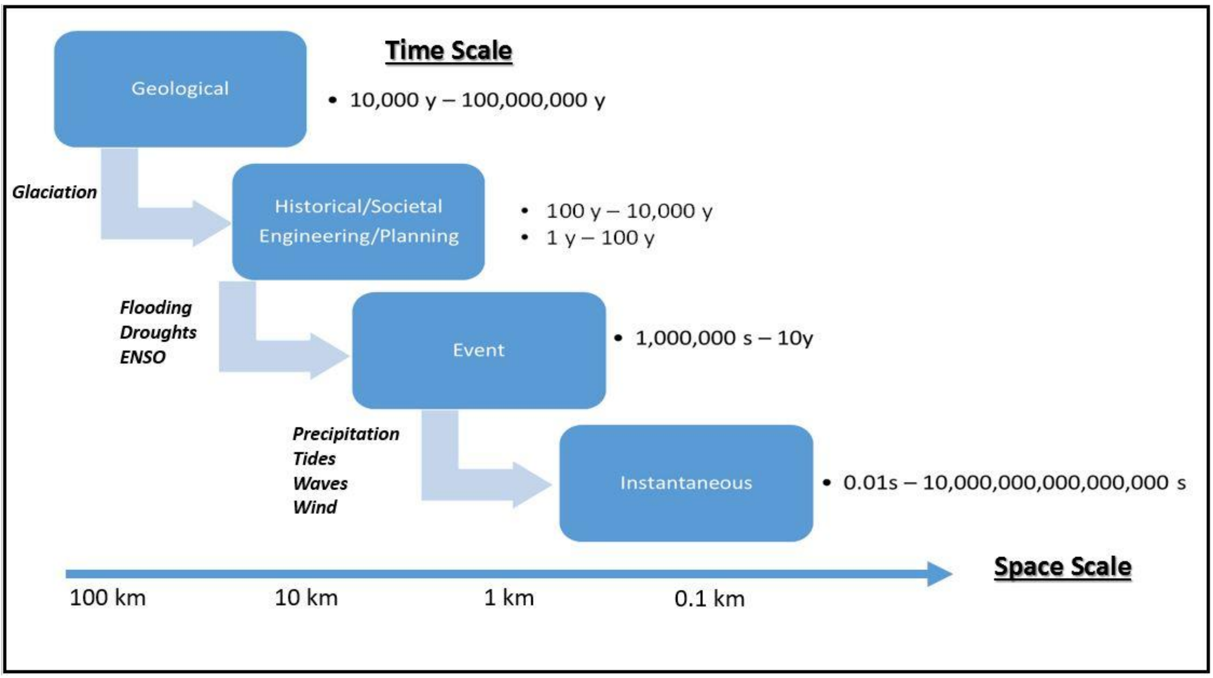

Figure 4-2: A schematic representation of examples of key climate controls and drivers which influence coastal sediment dynamics at different time and space scales. Adapted for a coastline in a high-energy, tectonically active setting. Adapted from (Cowell & Thom, 1994; Woodroffe, 2003).

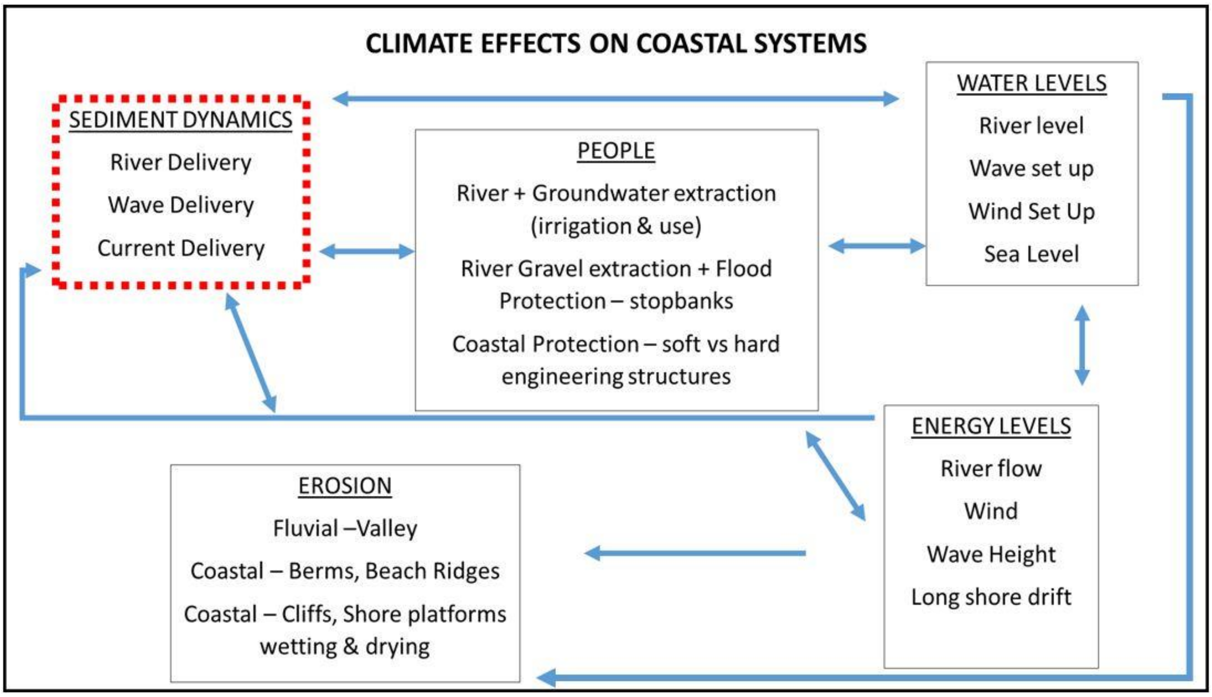

Figure 4-3: A schematic representation of examples of key coastal geomorphic responses to sediment dynamics influenced by tectonic and climate controls over different time and space scales. Adapted for a coastline in a high-energy, tectonically active setting. Adapted from (Cowell & Thom, 1994; Woodroffe, 2003).

4.2 New Zealand Climate: An Overview

4.2.1 Paleoclimate

Large scale temporal variations in climate are important to assess. Coastal mountain ranges and plains paleoclimate along the east coast of the South Island during the late Quaternary (25ka to present) has been assessed using geomorphological evidence, ecological data and sedimentological data (McGlone, 1988; Bull, 1991; Sturman & Tapper, 2006).

Ecological evidence in changing plant populations has provided an understanding of climate conditions over the last 25,000 years (McGlone, 1998). During the last glacial maximum (25,000 – 15,000 years B.P) the climate was dry, cold and windy, based on the lack of vegetation growth. The climate throughout the late glacial periods (15,000 – 10,000 years

B.P) went from dry to wet as the environment began to significantly warm and rainfall increased, resulting in shrub and grass growth. Between the early and mid to late Holocene (9,500 – 2,500 years B.P) temperatures rapidly increased and rainfall increased towards current values, which lead to the fast growth of Podocarp and Beech Forests. Evidence of deforestation due to naturally occurring fire from the late Holocene (2,500 years B.P) is indicative of intensified north-westerly foehn winds creating droughts during summer months (McGlone, 1988; Bull, 1991).

4.2.2 Present-day climate

New Zealand is situated in the Southern Hemisphere between latitudes 34° S and 47° S, approximately 1,600 km east of Australia and 2,200 km north of Antarctica. The country is very isolated surrounded by the vast Pacific and Southern Oceans. These large water bodies not only provide copious amounts of moisture, they also modify the majority of westerly and southerly air masses resulting in temperate and polar maritime influences on regional climate and weather patterns (Maunder, 1970; Sturman & Tapper, 2006).

Some examples of major air-mass types affecting regional scale air flow and precipitation in New Zealand described by Sturman and Tapper (2006) are:

- Modified polar maritime (NPm): An unstable, cold, and moist air mass from Antarctica, which produces a southerly airflow following a low pressure system (cold front) affecting the southern regions of New Zealand with low levels of snow and sleet during winter months.
- Southern Maritime (Sm): A cold and moist air mass originating from the Southern Ocean, which creates heavy rainfall in regions of New Zealand where orographic lifting occurs.
- Tropical maritime Tasman (tTm) and Tropical maritime Pacific (pTm): these two warm and moist air masses produce rainfall in northern parts New Zealand. The pTm is formed over the western Pacific Ocean and produces heavy rainfall that can affect northern New Zealand coinciding with tropical cyclones. The tTm originates from the Tasman Sea, which creates westerly airflow across the country and heavy orographic rainfall along the West Coast of the South Island.

The typical weather pattern associated with these air mass influences are a series of anticyclones and low pressure troughs (Maunder, 1970). The occurrence of anticyclones effect the direction of regional air flow and rainfall distribution across the country. Air flow behaves differently on the western and eastern sides of anticyclones (Maunder, 1970). On the eastern side, cooler maritime air flow tends to originate between the southeast and southwest. The western side of an anticyclone is warmer maritime air associated with north-north westerly air flow, which develops as the anticyclone moves further east across New Zealand (Garnier, 1958; Maunder, 1970). Low pressure troughs form when cooler westerly – southerly airflow by another anticyclonic system, replacing the warmer north-westerly air flow as moves west-east across New Zealand (Watts, 1947). The troughs are generally, but not always linked to cold fronts and how these systems behave depends on the direction of airflow behind each system. Westerly airflows tend to create rainy conditions in western regions and drier conditions in eastern regions. Northerly to easterly airflows produce rainfall in northern and eastern regions. Whereas easterly-southerly flows result in rainfall in eastern and southern regions (Garnier, 1958; Maunder, 1970).

An important physical aspect that influences regional weather patterns is how mountain terrain modifies airflow and rainfall distribution (Maunder, 1970; Sturman & Tapper, 2006). In the South Island, the high elevation of the Southern Alps creates significant rainfall variation west and east of the main divide, where annual rainfall averages around 6,000 mm in Fiordland in comparison with areas in Central Otago averaging around 330 mm (Maunder, 1970). This variation in west-east rainfall gradient is due to orographic effects, where prevailing westerly airflow brings moist air which is then forced upward creating a band of heavy rainfall on the western slopes, reducing the amount of rainfall on the eastern (lee) side of the mountain range (Watts, 1947; Sturman & Tapper, 2006). The opposite occurs in eastern areas of the North Island, where heavy rainfall occurs due to the orographic effect from easterly – southerly airflows (Maunder, 1970).

4.2.3 Climate regions

In order to assess regional to local scale climate, previous literature has characterised dominant climate controls and how each control varies across New Zealand (Garnier, 1958; Maunder, 1970). In a geographical survey, Garnier (1958) divided New Zealand into nine climatic regions to spatially define controlling climate factors based on large scale atmospheric systems (Table 4.1).

The Upland South Island region is of particular focus to assess regional to local scale climate controls in Kaikoura, particularly with regards to precipitation in the upper river catchments of the Seaward Kaikoura Range, as well as controls on local ocean climate. This region, defined by Garnier (1958), encompasses the Southern Alps, which are high mountain ranges extending the length of the South Island from Fiordland in the southwest towards Marlborough in the northeast. These mountain ranges formed during the Kaikoura Orogeny, where significant uplift resulted in rapid erosion and alluvial progradation (Garnier, 1958). The varying topography, high peaks, exposed rock and scree slopes, large ice-fields, and incised valleys of this region are very dissimilar compared to other regions characterised by Garnier (1958). This geomorphic dissimilarity is created by a distinct climatic footprint controlled by the high elevations across these mountain ranges that surpass a general height of 1,220 m (4,000 ft.). Elevation varies between south-western, central, and north-eastern ranges. The north-eastern Inland and Seaward Kaikoura Ranges rise to 2,440 m (8,000 f.t) compared to peaks exceeding 3,050 m (10,000 f.t) in the central ranges, and 1,830 m (6,000 f.t) in the south-western ranges (Garnier, 1958).

In general, the climate of this region is characterised by westerly and southerly (polar) airflows which bring heavy rainfall, snow, and cold temperatures particularly during the winter months (Tables 4-1 and 4-2). During summer, drier ‘drought’ conditions can occur on the eastern side of the Southern Alps due to north-westerly foehn winds (Garnier, 1958; Maunder, 1970; Sturman & Tapper, 2006). The east coast receives heavier rainfall due to frontal systems moving in from south or southeast, compared with frontal systems originating from the northwest, west or southwest (Watts, 1997). However, areas elevated above 1,220 m (4,000 f.t) situated to both the west and eastern sides of Mountain Ranges can receive heavy precipitation (Garnier, 1958).

Table 4-1: New Zealand’s nine climatic regions as defined by Garnier (1958).

Controlling Factors	Description: Climate Characteristics
W	• Dominated by ‘Westerly’ influences • Abundant rainfall • Small mean annual temperature range
E	• Dominated ‘Easterly’ influences • High rainfall variability • Large mean annual temperature range
T	• Subtropical conditions occur
A	• Polar conditions occur
X	• Occasionally affected by polar and/or subtropical conditions
I	• Inland controls • High rainfall during summer • Large seasonal range in temperatures
M	• Elevation effects • High rainfall • Cold temperatures during winter
M*	• High elevation of Mountain Ranges • Orographic effects • Extreme precipitation
D	• Categorised by large variety of climatic variables
H	• Homogenous climate
K	• Defined by a moderate variety of climate variables

Table 4-2:

Regions	Factors										
	W	E	T	A	X	I	M	M+	D	H	K
Middle NZ[1]	*				*						*
Western South Island[2]	*				*			*		*	
Northern NZ[3]	*		*							*	
Southern NZ[4]	*			*						*	
Eastern North Island[5]		*		*						*	
Eastern South Island[6]		*		*						*	
Central North Island[7]	*				*	*	*				*
Inland South Island[8]				*		*			*		
Upland South Island[9]	*			*			*		*		

Variation of lower wind flow occurring below 1,220 m (4,000 ft.) can lead to differences in localised precipitation due to the orientation of mountain ranges (Garner, 1958). An example of this is during a south-westerly along the West Coast of the South Island. The wind flow is concentrated and funnelled through Cook Straight and curves around the northern part of the South Island, appearing as a north-easterly along coastal Marlborough as far south as Kaikoura (Garnier, 1958).

Localised precipitation contrasts are due to the differential exposure of the area to prevailing wind and other climatic influences. This contrast can occur where a high mountain range exists within close proximity to a coastal plain (Garnier, 1958). Temperature also varies considerably in these areas, where temperature values can rapidly decrease with an increasing altitude. This tends to result in snow fall at high elevations close to the coast (Garnier, 1958).

A limitation with classifying distinct climate regions is that boundaries defined are not representing transition zones between each region to account for local variabilities (Sturman & Tapper, 2006). Whilst the upper fluvial drainage systems in Kaikoura exist at high elevations in the Seaward Kaikoura Ranges. The major rivers, which flow across a section of the northern Canterbury plain and coastline are exposed to easterly influences similar to central and southern Canterbury locations. These influences are classified as the 'Eastern South Island' climatic region by Garnier (1958). Westerly and easterly systems result in seasonal and temporal variations in local scale atmospheric and ocean climate. This local climatic variability becomes challenging to manage due to the likelihood of increased seasonal floods, droughts, and coastal storms over the next 100+ years due to climate change.

4.2.4 The effects of the El Niño Southern Oscillation (ENSO) on regional climate

Changes in local sediment dynamics driven by climatic controls on fluvial and coastal processes are likely to be influenced by phases of El Niño and La Niña (Bryan et al. 2008).

The El Niño Southern Oscillation (ENSO) a climatic irregularity within the large scale atmospheric and ocean system over the Pacific. The Walker circulation is an ocean-atmospheric system that consists of easterly trade winds pushing warmer water towards the western Pacific resulting in the upwelling of cooler water along the coast of South America.

This process leads to moist warm air conditions in the western Pacific, which circulates to cold dry air in the eastern Pacific. This process is a neutral phase. El Niño phases are the opposite and occur as a result of easterly trade winds weakening, resulting in the decline of cold water upwelling in the eastern Pacific and warmer water moving eastward, and creating a south-westerly flow over New Zealand. La Niña phases occur as a result of easterly trade winds increasing above normal. Upwelling of colder water becomes intensified in the eastern Pacific and spreads towards the western pacific. Warmer water is pushed further westward over Australasia, producing north-easterly flows over New Zealand (Gordon; 1986; Sturman & Tapper, 2006).

ENSO phases are the main control over inter-annual and inter-decadal variations in New Zealand. These phases tend to last between 2 to 10 years. The strength of the El Niño and La Niña phases is measured by the surface pressure gradient differences between Darwin and Tahiti. The strength of each phase is represented by the Southern Oscillation Index (SOI). The high and low positive values indicate strong and weak La Niña phases, whereas high and low negative values indicate strong and weak El Niño phases (Gordon, 1986). Figure 4.4 shows the SOI over the last 130 years (1885 – 2015).

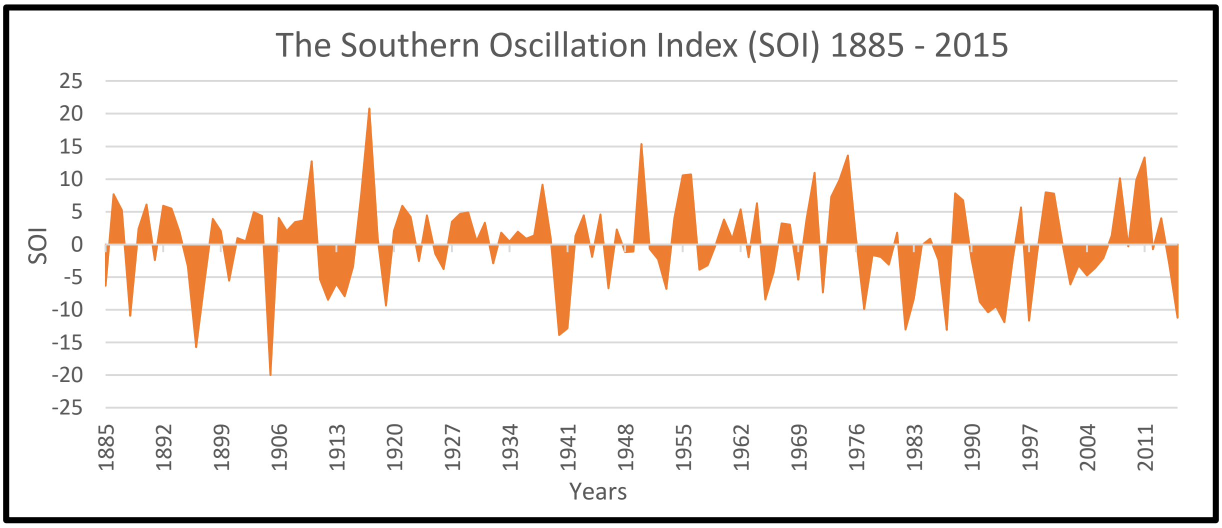

Figure 4-4: SOI showing average annual positive and negative values of ENSO from 1885 – 2015. Data sourced from: Australian Bureau of Meteorology (2016).

In New Zealand, negative ENSO phases cause south westerly wind systems which increase rainfall along the west coast, resulting in below normal rainfall along the east coast particularly in the South Island. Seasonal variations during El Niño include increased westerlies during summer and southerlies in winter. Positive ENSO phases enhance north easterly systems, producing higher than normal rainfalls along the east coast (Gordon, 1986).

In terms of ENSO effects on ocean climate, relative mean sea levels tend to decrease during the negative phases of El Niño and increase during the positive phases of La Niña (Bell, 2001). Southerly swells may be enhanced with an increase of westerlies during El Niño, and north easterly swells correlating with north-easterlies during La Niña (Pickrill & Mitchell, 1979; Gordon, 1986; Gorman et al. 2003; Godoi, et al. 2015).

The Interdecadal Pacific Oscillation (IPO) is another large scale climatic anomaly that affects regional climate across New Zealand. Positive and negative phases of IPO reflect 20 – 30 year climate variability resulting in sea level pressure changes and sea surface temperature fluctuations across the North and South Pacific Ocean. This system has the tendency to modify interannual El Niño and La Niña ENSO phases (Bell, 2001, p. 3). Since the early 1920's there have been three phases of IPO recognised (Figure 4.5): (i) 1922 – 1944 (positive phase), (ii) 1946 – 1977 (negative phase), and (iii) 1978 – 1998 (positive phase). Since 1998 it is apparent that the IPO has shifted back to a negative phase (Bell, 2001; O'Donnell, 2007; Bryan et al. 2008). Positive IPO phases strengthen El Niño events, whereas negative IPO phases strengthen La Niña events (Bell, 2001).

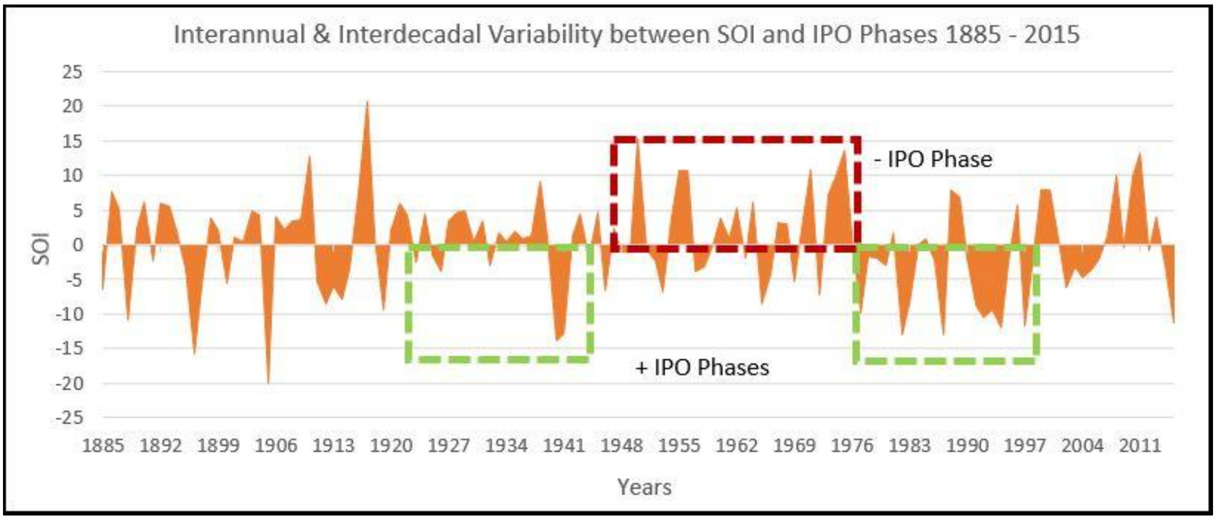

Figure 4-5: Plot showing interannual and interdecadal variability between SOI and IPO occurring from 1885 – 2015. Data sourced from: Australian Bureau of Meteorology (2016).

At a regional scale, negative IPO phases relate to an increase in average temperatures and weaker rainfall gradient across the country from the west to east. Positive IPO phases correspond with increased rainfall during winter across the South Island and during summer in the southeast of the South Island (O'Donnell, 2007). Transition periods between positive and negative IPO phases tends to coincide with an increased rate of sea level rise around the country, which poses future risks of coastal erosion and inundation during storm events which may occur over that period (Bell, 2001; O'Donnell, 2007).

4.3 Locale Scale Atmospheric Climate

4.3.1 Classification

The local climate in Kaikoura is influenced by westerly, southerly, and north-easterly weather systems controlled by coastal and mountainous topography (Garnier, 1958; Maunder, 1970; Garr & Fitzharris, 1991). Despite the area being situated along the east coast, the local climate is distinctive compared to the rest of the Canterbury Plains due to the close proximity of the Seaward Kaikoura Ranges and the coast (Garnier, 1958; Dawe, 1997). Rainfall recorded at three weather stations over the last thirty years (see Appendix A for weather station location) has varied between the foothills and the coast. Between 1984 and 2014, rainfall recorded in the foothills at Hapuku Grange averaged 1,360 mm per year, 357 mm higher than Sawyers Downs station located to the southwest which recorded 1,003 mm per year. Rainfall near sea level averaged 866 mm per year, decreasing across the plains by 137 - 494 mm (Figure 4.6). Monthly temperature averages recorded at a station located on the Peninsula over the same decadal timeframe were between 16°C and 8.6°C (Figure 4.7).

The drainage basins in the Seaward Kaikoura Range are classified as weakly seasonal humid environments using rainfall from Hapuku Grange and Sawyers Downs stations (Figure). Humid environments are classified by a mean annual precipitation range of 1,000 – 2,000 mm (Bull, 1991). The mean annual temperature range of 8 – 15°C recorded at a different station at the coast is classified as moderately seasonal frigid to mesic. Despite annual temperatures not being recorded at similar locations to rainfall, the classification is fairly representative of the Charwell River drainage basin, which neighbours the Kahutara basin, southwest of the study area (Bull, 1991). The seasonality indexes can be worked out using equations 4.1 and 4.2 (Bull, 1991):

$$S_p = \frac{P_w}{P_d} \tag{4.1}$$

and

$$S_t = T_h - T_c \tag{4.2}$$

Where S_p is the precipitation seasonality index, which represents the ratio of average total precipitation for the three wettest (P_w) consecutive months divided by the average total precipitation for the three driest (P_d) consective months. Equation 4.2 is the temperature seasonality index (S_t), calculated by subtracting the mean temperature of the coldest (T_c) month by the mean temperature of the hottest (T_h) month) (Table 4.3).

Table 4-3: Classification of Climates. Adapted from Bull (1991).

Class	**Mean Annual Rainfall range (mm)**	**Class**	**Mean Annual Temperature (°C)**
Extremely Arid	<50	Pergelic	>0
Arid	50 – 250	**Frigid**	**0 – 8**
Semiarid	250 – 500	**Mesic**	**8 – 15**
Subhumid	500 – 1000	Thermic	15 – 22
Humid	**1000 – 2000**	Hyperthermic	>22
Extremely humid	>2000	11.4 – 13.3 (Fig 4.7)	
Hapuku Grange Hill	1,360 (Fig 4.7)		
Sawyers Downs	1,000		
Class	Seasonality Index *(Sp)*[a]	Class	Seasonality Index *(St)*[b] *(°C)*
Nonseasonal	1 – 1.6	Nonseasonal	<2
Weakly seasonal	**1.6 – 2.5**	Weakly seasonal	2 – 5
Moderately seasonal	2.5 – 10.0	**Moderately seasonal**	**5 – 15**
Strongly seasonal	>10	Strongly seasonal	>15
Hapuku Grange Hill	1.2	7.5	
Sawyers Downs	1.6		

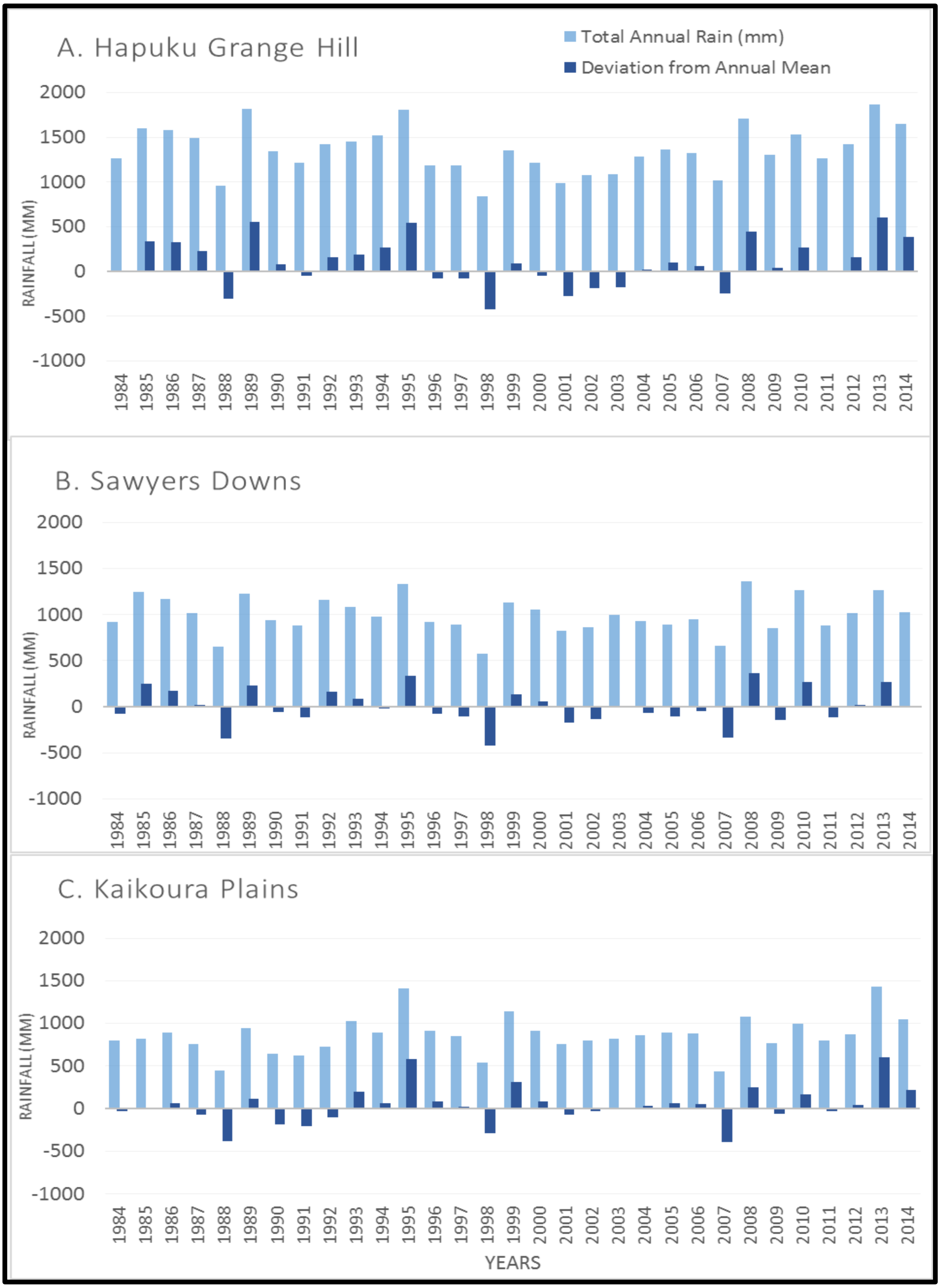

Figure 4-6: Total Annual Rainfall across three weather station locations in Kaikoura. Total Annual Rainfall was deviated from the annual mean in order to assess above and below normal rainfall per year. Rainfall data sourced from NIWA CliFlo (2016).

There is a permanent snowline at 1,220 m above sea level (4,000 ft.) across the Inland and Seaward Kaikoura Ranges during the winter months (Garnier, 1958; Dawe, 1997). However, there is no long term snow fall recordings to assess how much snow falls seasonally per year compared to rainfall, which may affect mean annual precipitation amount during the winter months.

In terms of sediment input and fluvial transportation of sediment to the coast from hillslopes in the Seaward Kaikoura Range, these humid environments have shown large sediment yields and increasing aggradation events across the northern Canterbury plains in the past through to the present (Chandra, 1969; Bull, 2001). This confirms the importance of assessing local climate over large time scales in order to determine likely fluvial changes in sediment input and transportation over the next 100+ years. This will be discussed in Chapter 5.

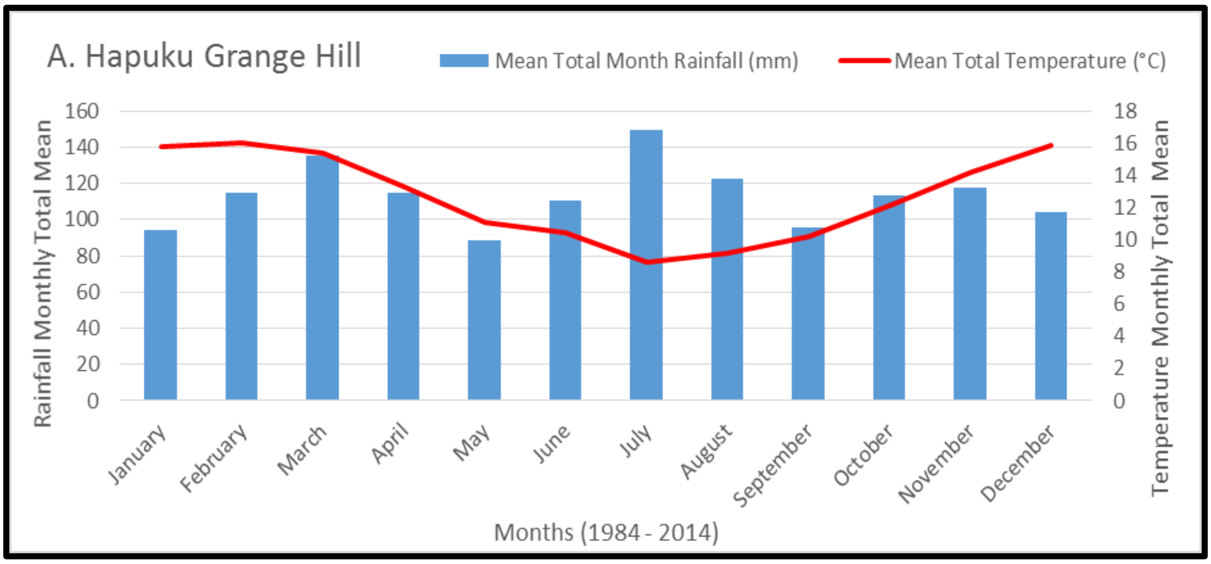

Figure 4-7: Mean Total Monthly Temperature recorded on the Peninsula plotted with Mean Total Monthly Rainfall recorded at Hapuku Grange Hill Station (Appendix A). Data sourced from NIWA CliFlo (2016).

4.3.2 Local climate variations and river flow

The flow and transportation of sediment in the Hapuku, Kowhai, Kahutara Rivers, smaller tributaries and streams is primarily controlled by regional and local scale rainfall (Bell, 2001).

There are approximately seven Environment Canterbury river gauges which have monitored the flow of the Kahutara River, Kowhai River, and Hapuku Rivers between 2001 and 2016 (see Appendix B1). It is important to note that the flow data has been inconsistently recorded, which is why analysis in restricted to two years of consistent daily flow monitoring in the Kowhai River. It is difficult to correlate long term interannual and interdecadal climate controls on local rainfall and river discharge. A table summarising flow recordings is shown in Appendix B2. Figure 4.8 shows a two year correlation between total monthly rainfall and flow in the Kowhai River recorded at Orange Grove in 2012 and 2013.

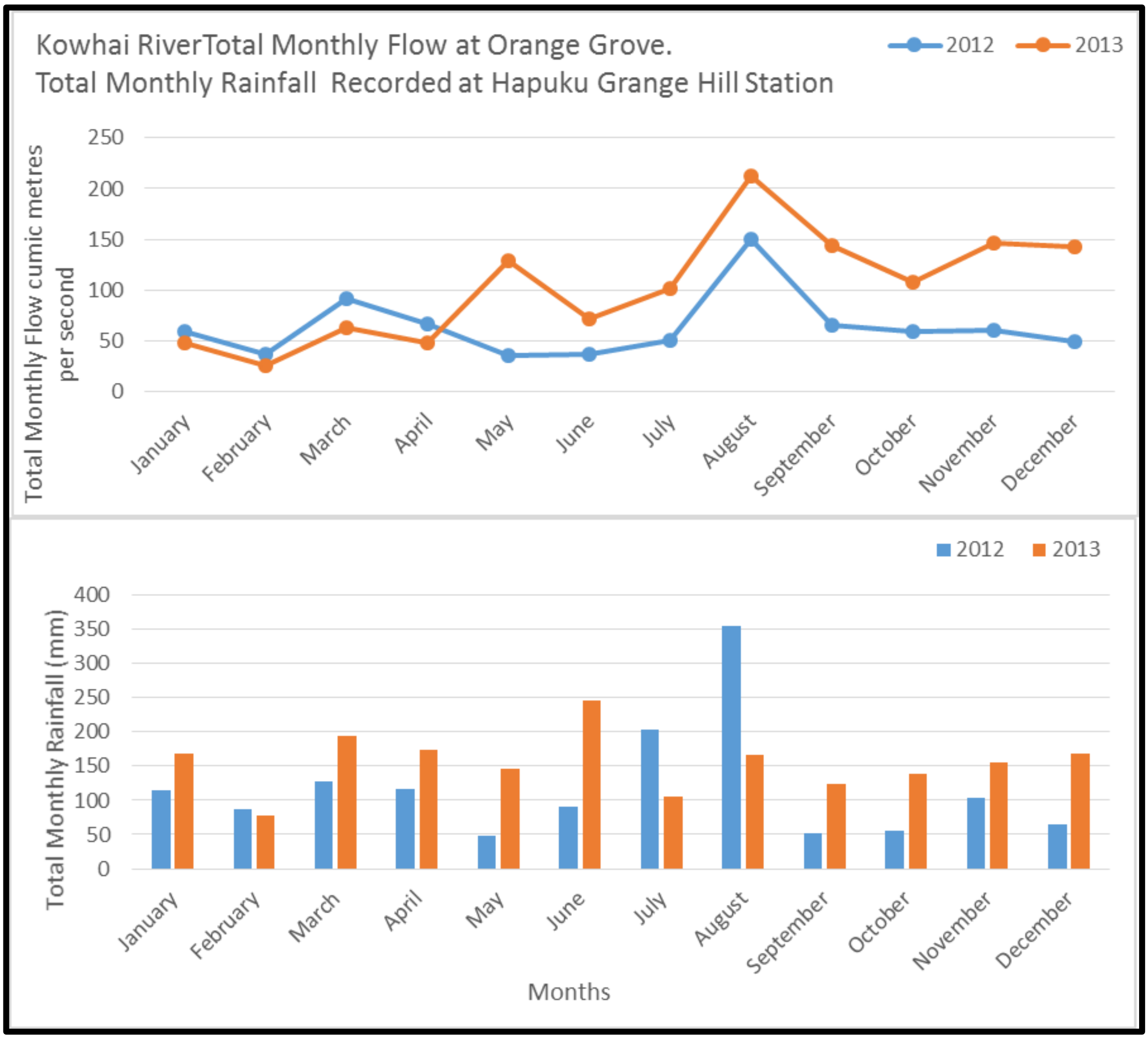

Figure 4-8: Mean Total Monthly Rainfall (mm) correlated with Mean Total Monthly Kowhai River Flow (m3/s). Data sourced from NIWA CliFlo (2016) and Environment Canterbury (2016b).

Based on Figure 4.8, total annual rainfall recorded at the Hapuku Grange weather station was above the normal annual average during both years, with 2013 having much higher rainfall compared to 2012. However, there appears to be too much seasonal variation and without a substantial amount of data; it is difficult to assess long term seasonal and interannual trends in river flow in relation to local rainfall variability in the Kaikoura area.

4.3.3 The effects of the El Niño Southern Oscillation (ENSO) on local climate

Figure 4.9 shows the relationship between SOI and total annual precipitation deviated from the annual mean between 1984 and 2014. The data was analysed over thirty years to account for inter-annual and inter-decadal variability between SOI and local rainfall patterns across Kaikoura. Between 1984 and 2014 there has been approximately five strong El Niño phases. These occurred between: (i) 1984 – 1998, (ii) 1990 – 1995, (iii) 1996 – 1997, (iv) 2001 -2007, and (v) 2014 – 2015. Strong La Niña phases have occurred between: (i) 1988 – 1989, (ii) 1996, (iii) 2007 – 2008, (iv) 2010 – 2011, and (v) 2013 – 2014.

Generally annual rainfall during phases of El Niño tends to fall below normal, however, between 1990 and 1995 there was a strong El Niño correlating to slightly above normal to normal annual rainfall. This is likely due to the strength of El Niño causing stronger westerly and southerly conditions, resulting in higher rainfall. Years where rainfall was significantly above normal levels occurred during La Niña, where north easterlies brought more moisture to the east coast (Gordon, 1986). It is very important to note that in this thesis local rainfall variability and climatic anomaly are compared within a large global scale atmospheric ocean system. The number of lag effects shown on these graphs is likely due to seasonal variability between both rainfall and SOI, which makes it hard to assess at such a localised scale.

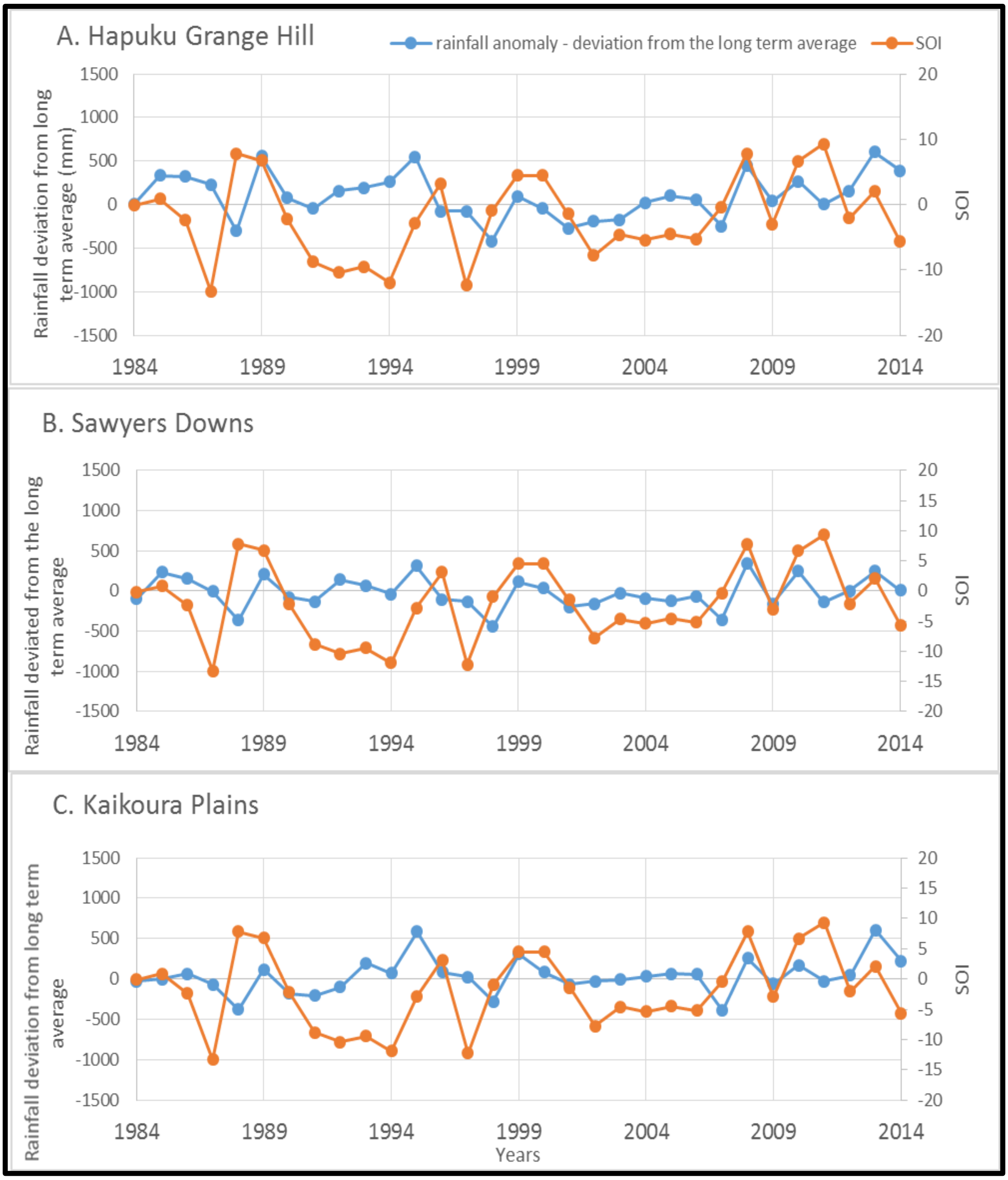

Figure 4-9: SOI and local total annual precipitation deviated from the annual mean between 1984 and 2014 across three sites in Kaikoura. Data sourced from NIWA CliFlo (2016) and Australian Bureau of Meteorology (2016).

4.4 Local Scale Ocean Climate and the Coastal Environment

4.4.1 Currents

Coastal surface currents around New Zealand are controlled by the topography, orientation of the shoreline, offshore bathymetry and can be altered by local wind flow (Brodie, 1960). The major surface current that runs along the east coast of the South Island is the Southland Current (Chiswell, 1996; Hart et al. 2008). This current originates from the southwest coastal region of the South Island, curves eastward through Foveaux Straight, and moves up the South Island along the east coast (Brodie, 1960). Alongshore currents vary north and south of the Kaikoura Peninsula, where local variations in wave climate north of the Peninsula creates southward moving longshore current (Dawe, 1997).

4.4.2 Local coastal process in Kaikoura (north and south of the Kaikoura Peninsula)

The northern Canterbury coastline is very exposed to strong southerly and north-easterly swells generated from the Southern and Pacific Oceans over extensive fetches (Gorman et al. 1993). The dominating southerly swells are generated by strong westerlies, commonly known as the 'roaring forties', as they are formed at 40° S below a belt of high pressure (Watts, 1947).

The wave climate along the east coast of the South Island varies due to the position of the country's landmass trending southwest – northeast (Pickrill & Mitchell, 1979). Along the Kaikoura coastline wind and wave regimes interrelate, where the strength and direction of local wind flow influences the height and direction of waves (Dawe, 1997). Prevailing winds occur from south and southwest 43.2% of the time, compared to wind flow occurring 28.5% of the time from the northeast (Boorer, 2002, p. 20).

North-easterly swells north of the Kaikoura Peninsula average 1.0 m and increase in occurrence during the winter months, compared with south-westerly swells south of the Peninsula at 0.5 – 2 m high and 0.5 – 1.5 m onshore waves, which approach from the south-east (McLean & Kirk, 1969; Pickrill & Mitchell, 1979, p.518; Dawe, 2001, p.268). Figure 4.10 shows variation of local wave climate north and south of the Kaikoura Peninsula influenced by north-easterly wind flow.

Figure 4-10: 1. Image taken from North of the Kaikoura Peninsula along Acova Street and shows strong north-easterly driven waves. 2. Image taken from South of the Kaikoura Peninsula along Kaka Road and shows how the Peninsula 'buffers' north-easterly swell energy,

The tidal regime in Kaikoura is semidiurnal. The microtidal range in is approximately 1.8 m between highest and lowest tide (Table 4.4). This tidal range can exceed 2.5 m during perihelion and perigee states in the tidal cycle (Dawe, 1997 & 2001; Land Information New Zealand, 2015). The occurrence of extreme high tides coinciding with large swells during storms can cause coastal erosion and flooding, resulting in damages to properties and service utilities such as: roads, water pipes, power lines, telecommunication cables (Dawe, 1997).

Table 4-4: Tidal Regime in Kaikoura. Data sourced from LINZ (2014).

Kaikoura: Mean Spring, Neap and Mean Sea Level Heights (m)				
MHWS	**MHWN**	**MLWN**	**MLWS**	**MSL**
2	1.6	0.5	0.2	1.1

4.4.3 Local climate effects on tidal regime and wave height in relation to relative sea level.

High and low pressure systems can temporarily raise or lower relative sea level. The inverse-barometer effect, resulting from a passage of low pressure, raises the sea level during high tide can cause inundation of low lying coastlines. For every 10 hPa drop in atmospheric pressure there is a relative sea level rise of 0.1 m (Bell & Coco, 2005, p. 16). These atmospheric and tidal conditions create storm tides, where high tide is temporarily higher than normal and wave heights also increase to 3 - 5 m (McLean & Kirk, 1969). It is important to note that these high and low pressure systems are synoptic events which only occur over short time scales (Garnier, 1958; Maunder, 1970; Sturman & Tapper, 2006).

4.5 Review

Variations in regional atmospheric conditions can significantly impact local climate in New Zealand. These future impacts can alter processes such as; sediment transport in rivers flowing east of the main divide, and deposition of sediment along the east coast of the South Island (Bell, 2001; MFE, 2014).

4.5.1 Wind flow

Over the next 60 to 100 years temperate and equatorial Regions will warm at a higher rate compared to sub-polar and polar Regions, increasing westerlies through New Zealand. The West Coast of the South Island will be exposed to south easterly, westerly, and north westerly flows, while along the east coast, wind flows are likely to intensify from the northwest and northeast (Garnier, 1958; Maunder, 1970, Bell, 2001).

4.5.2 Temperature

By 2080, average monthly temperatures in the Canterbury region are expected to increase by 1.8°C to 2.0°C during winter and by 1.2°C to 1.5°C in summer (Bell, 2001, p. 13). Due to increased westerly systems and the sheltering effects of the Southern Alps, local seasonal variations in temperature may reflect dry foehn effects across the Kaikoura Plains (Garnier, 1958).

4.5.3 Precipitation

Mean annual rainfall will increase in the Southern Alps and foothills on the western and eastern side of the main divide, while east coast Canterbury plains during winter months are expected to receive 20% less rainfall as a result of intensified westerly systems (Bell, 2001, p.17).

4.5.4 Ocean climate

Along the east coast, southerly swells will continue to be the dominant driver of wave climates. Local wave climate and alongshore currents north of the Kaikoura Peninsula are likely to intensify due to increased north easterly wind flow, which may result in southward littoral drift extending further south along the shoreline (Bell, 2001).

4.5.5 Intensity and frequency of storms

Rainfall intensity during storms will rise in frequency over the next 60 to 100 years, increasing river discharge and sediment transport to the coast. While southerly and northerly storm surges intensify along the coast (Bell, 2001).

4.5.6 ENSO

There is currently no scientific unanimity on whether the frequency and intensity of positive and negative ENSO phases will be affected by climate change. Extreme weather events such as floods and droughts are predicted to increase in frequency and intensity regardless of ENSO (Bell, 2001; Sturman & Tapper, 2006; O'Donnell, 2007). Interdecadal scale climate variability influenced by positive and negative phases of IPO may alter predicted trends in regional climate in association with global climate change. An example is a negative IPO phase reducing the strength of westerly systems that are predicted to increase over the next 100 years, resulting in varying local precipitation and temperature in Kaikoura over 20 – 30 year time frames (O'Donnell, 2007).

4.6 Summary

This chapter evaluated present day atmospheric and ocean climate variability in Kaikoura, for the purpose of understanding how local climate is likely to change over the next 100+ years, and the likely impacts on the local fluvial and coastal environment.

The lack of consistent river flow records made assessing the effects of local climate variability on fluvial transportation challenging. The two year daily flow recordings of the Kowhai River at Orange Grove is not a long enough record to be able to deduce inter-annual and inter-decadal above and below normal annual rainfall patterns on river flow. This left a significant gap in the overall assessment and required further reviews on case study material on similar braided river systems in order to assess local sediment dynamics in Chapter 5.

Chapter 5

Coastal Geomorphology

5.1 Introduction

This chapter reviews literature on mixed sand and gravel beach morphologies along the Kaikoura coast, bringing together concepts discussed in Chapters 2 and 3, to assess coastal response over the 100+ years.

5.1.1 Geomorphology within a local case study context: Framework methodology

The mixed sand and gravel Kaikoura coastline is constantly shaped by sediment supply, sediment transport, wave run-up processes, and variations in land elevation and sea levels (Bryan et al. 2008).

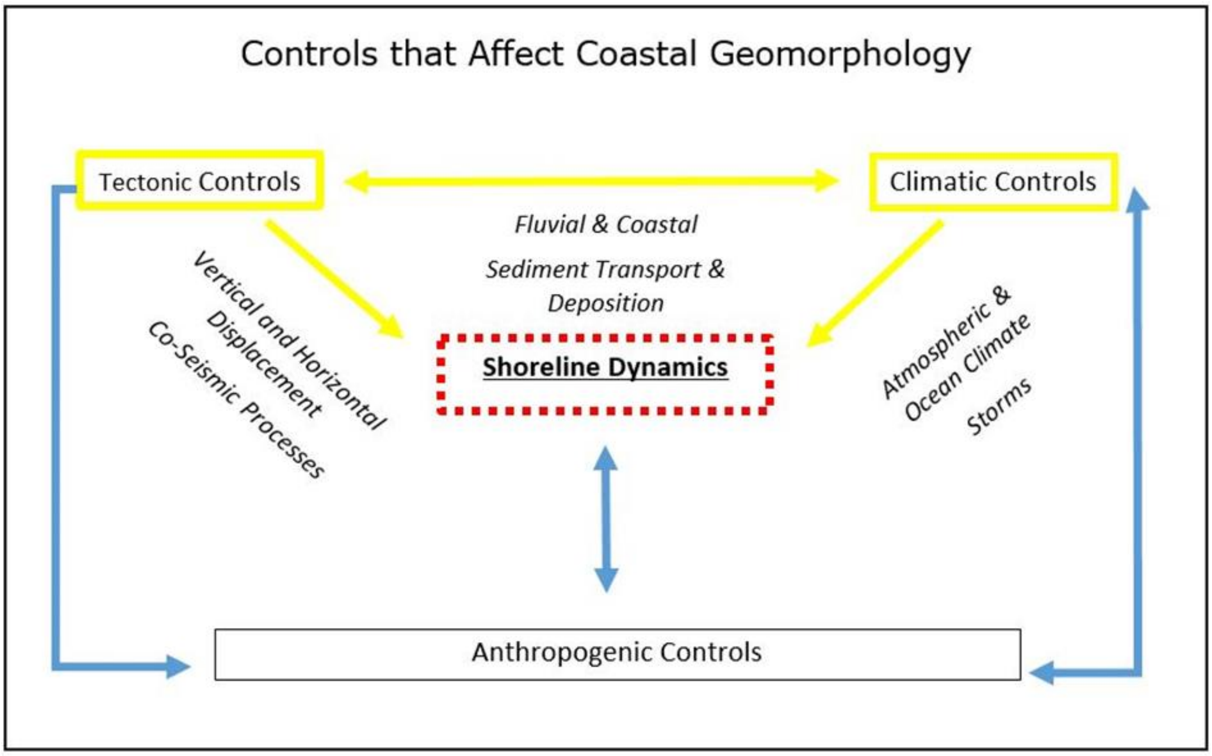

Figure 5-1: Controls that affect coastal geomorphology.

The coastal geomorphology along the coastline has been primarily influenced by tectonic and climatic controls on local fluvial and coastal sediment dynamics since the Late

Pleistocene. Anthropogenic controls on local sediment dynamics by forms of hard and soft fluvial and coastal management structures result in local foreshore changes in sediment volumes along the coast (Figure 5-1). These controls and related processes vary over different spatial and temporal scales (Figure 5-2, N.B Bryan et al. 2008).

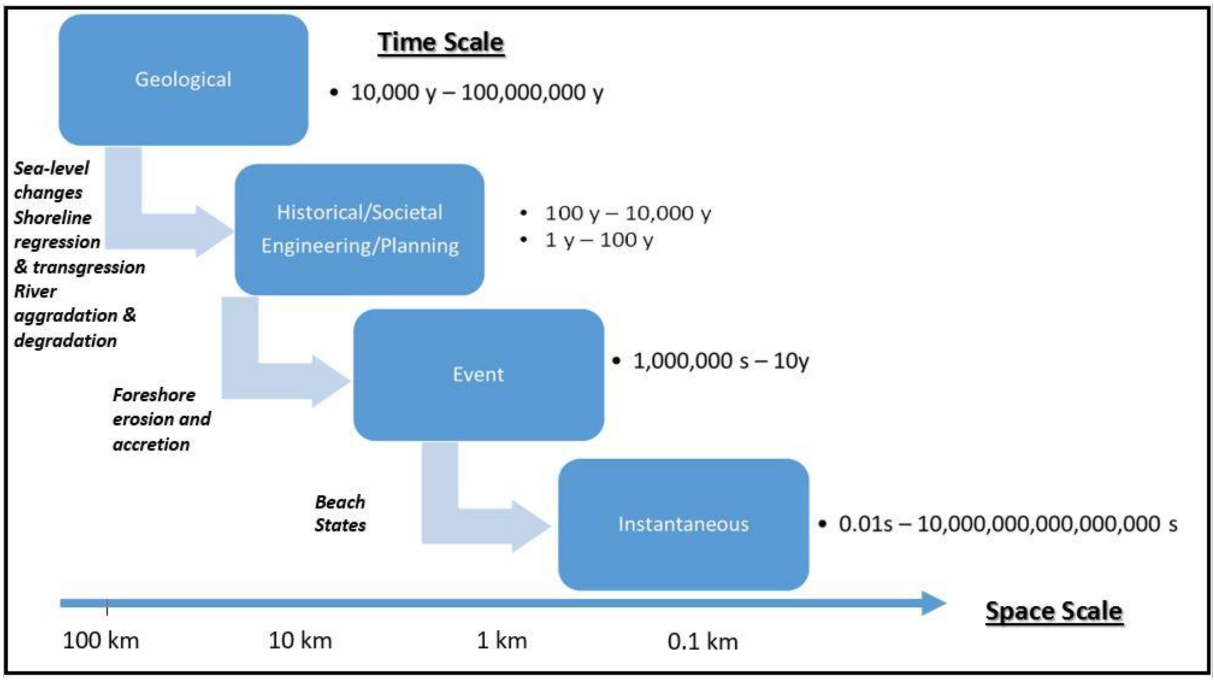

Figure 5-2: A schematic representation of examples of key coastal geomorphic responses to sediment dynamics influenced by tectonic and climate controls over different time and space scales. Adapted for a coastline in a high-energy, tectonically active setting. Adapted from (Cowell & Thom, 1994; Woodroffe, 2003).

5.2 Geomorphic Evolution of the Kaikoura Coastline

5.2.1 Tectonic controls

Tectonic processes in the Kaikoura area have altered the channel morphology of the Hapuku, Kowhai, and Kahutara Rivers (Bull, 2009; Davies & Bull, 2005; Kirk, 1997). Dextral slip along the Hope Fault and co-seismic landsliding has changed the flow directions of all three rivers over the last 1,000 years (Bull, 2009; Davies & Bull, 2005).

Along the progradational plain, the Kowhai River previously supplied sediment to the southern end of North Beach and Gooch's Beach. Uplift of the Kaikoura Peninsula (approximately 1 mm/yr) has resulted in the southerly migration of the Kowhai River

(Environment Canterbury, 2000; Dawe, 1997). The geomorphic response of the Kowhai River channel to tectonic uplift has prevented sediment deposition at the coast along the southern end of North Beach (Figure 5-3). The sediment along the foreshore in front of the Township and Gooch's Beach, are relict deposits and are easily eroded without artificial beach re-nourishment (Dawe, 2001). However, during flood events, the Kowhai River has flowed down old channels north of the Peninsula such as Lyell Creek and supplied sediment to the coast (Dawe, 2001).

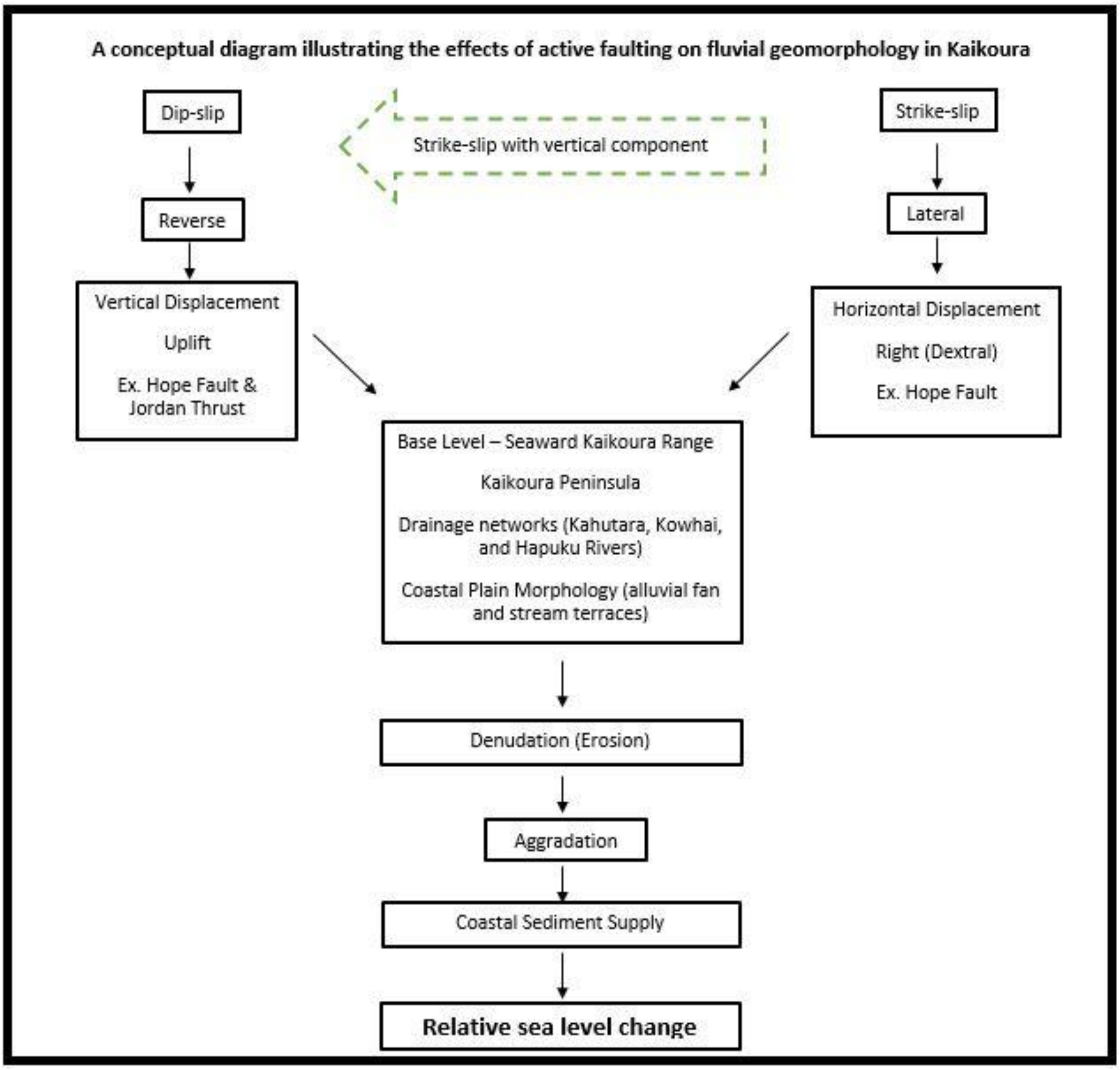

Figure 5-3: A conceptual diagram to show the effects of regional tectonic activity

Tectonic modification to coastal geomorphology (beaches, shore platforms, cliffs) along the Kaikoura coast has led to variations of coastal processes and sediment deposition north and south of the Kaikoura Peninsula. The Kaikoura Peninsula is affected by gradual uplift from offshore thrusts faulting associated with the Northern Canterbury Fold and Thrust Belt Domain, which is located off the coast to the east of the Peninsula (Yetton & McCahon, 2009). The uplifted Peninsula acts as a wave energy buffer on incoming north/north-easterly swells and south/south-easterly swells to beaches north and south of the Peninsula (Dawe, 1997 & 2001). The Peninsula also prevents sediment from the Kahutara and Kowhai Rivers being transported further alongshore north of South Bay (Boorer, 2003).

5.2.2 Climate controls

Geomorphological studies in pre-glaciated drainage basins provide a general understanding of climate systems in terms of precipitation and the effects on fluvial and coastal landforms (Bull, 1991; Sturman & Tapper, 2006). Geomorphic evidence of fluvial aggradation and degradation events during interglacial periods provides insight into relative sea levels along the coast during shoreline regression and transgression events (Suggate, 1965; Bull, 1991).

In the South Island of New Zealand, the majority of mixed sand and gravel barrier beach environments are related to transgressive coasts (Shulmeister & Kirk, 1993). The beach system along the Kaikoura coastline has been formed by paramarine processes during periods of sea level transgression between 10,000 - 6,000 years before present and regression 6,000 years to recent (Shulmeister & Kirk, 1993; Boorer, 2003). Paramarine is a term used by Shulmeister and Kirk (1993) to describe a mixed sand and gravel barrier system formed by fluvial processes and influenced by alongshore currents and wave climate within the littoral environment. Between the mid to late Holocene (9,500 – 2,500 years ago) temperatures and rainfall increased, which resulted in a period of rapid erosion (McFadgen, 1985; McGlone, 1988; Bull, 1991). River aggradation increased with large amounts of sediment eroding from the Seaward Kaikoura Range, which eventuated into coastal progradation (Bull, 1991; Dawe, 1997; Boorer, 2003)

5.3 Local Sediment Supply

At present, there is a lack of knowledge on how local scale coastal responses to relative sea-level rise might vary under different sediment budget scenarios, which hinders the ability to adapt to climate change effects. This is partly due to insufficient sediment budget data available for coastal assessments of climate change effects, and a shortage of past examples of methodologies for such assessments. This thesis section addresses this gap in methodologies for assessing the sediment budget component of coastal hazard assessment in Kaikoura.

The sediment budget for a specific length of coastline is determined primarily by the input source of sediment, as well as how and where the sediment is transported and deposited along the coast (Woodroffe, 2003). The sediment budget for a particular beach does not always behave as a simple system if there are complex variables to consider. Along the Kaikoura coastline, the primary sediment source is the Seaward Kaikoura Ranges. The denudation rate has been estimated by Davies & Bull (2005, p. 143) and is around 1.8 m/ky. The dominant lithologies of the Seaward Kaikoura Ranges are Miocene Greywacke and Argillite's. Around 1,000 t km^2 of sediment is eroded annually from the Seaward Kaikoura Ranges, however sediment yield can range from 44 – 1740 t km^2/yr (Hicks et al. 1996). The majority of this sediment is transported down the Hapuku, Kowhai, and Kahutara Rivers (Davies & Bull, 2005; Boorer, 2003; Dawe, 1997). Sediment is also continuously eroded from the Kowhai, Waimangarara, and Hapuku alluvial fans by a number of streams: Floodgate Creek, Lyell Creek, Waimangarara River, Harnetts Creek, Swan Creek, Luke Creek, and Middle Creek (Boorer, 2003; Dawe, 1997). Coastal sediment sources are limestone and mudstone clasts eroded from the Peninsula cliffs and marine terraces (Ota et al. 1996; Stephenson, 1997). This sediment input is limited to bays around the Peninsula such as Spaniards and Whalers Bay. Limestone clasts from the Peninsula's cliffs form the beach along Kaka Road in South Bay. The shore platforms of Kaikoura peninsula erode around 3.6 mm/yr (Stephenson & Kirk, 1998, p. 1071). The sediments that are predominately from mudstone and limestone lithologies are a very fine grainsize that they are transported offshore rather that reworked into beaches (Stephenson and Kirk, 1998).

5.3.1 Sediment load assessment methodology

The majority of braided rivers channels in New Zealand are unstable during large flood events. Increased river discharge during periods of heavy rainfalls results in the movement of large gravels downstream (Adams, 1980). The transport of well-sorted gravel in a braided river system can be estimated from the Einstein Brown formula:

$$\emptyset = 0.115 \times 10^6 G_i b^{-1} d^{-3/2} \tag{5.1}$$

$$\varphi = 1.65 d y^{-1} S^{-1} \tag{5.2}$$

$$G_i = 6.07 \times 10^6 b y^{3/2} S^{3/2} \tag{5.3}$$

Where $\emptyset$ and φ are non-dimensional parameters. The symbol $\emptyset$ represents the transport of sediment particles and φ represents the sediment particles resistance to transportation. In equations 5.1 and 5.3 G_i is sediment transport (g/s), b is the river channel width (m), y is river channel depth (m), d is median grainsize (m), and S is the slope of the river channel in radians (Adams, 1980). Hicks (1998) explains how Adams (1980) assumption in equation 5.3 suggests that there is a linear relationship between the bedload size and channel depth for a river with a given slope. The bedload size in braided rivers increases as the channel depth increases, with the bedload size being independent of the transport rate. This can lead to underestimating sediment load transport during peak flows and underestimating transport at low flows if bedload size does not change but the channel depth and slope increases (Hicks, 1998).

Adams (1980) notes that when a river channel transports a mixture of sediment sizes, the formula from equation 5.2 is used for every separate grain size and the rates of transport are added together to give the total rate. The total rate of sediment transport in braided river systems reflect on the relationship between (i) a low rate of transport for the largest sediment (boulders – pebbles) and (ii) a high rate of transport for the fine sediment (course sands – silts and clays). The larger sediment tends to be transported downstream during large floods compared with the finer sediment that is continuously moved under normal flow (Adams, 1980).

The Mannings formula can be used to assess sediment transport rates by incorporating total water discharge and channel roughness in the following equations (Adams, 1980):

$$Q_i = b y^{5/3} S^{1/2} n^{-1} \tag{5.4}$$

$$G_i = 6.07 \times 10^6 Q_i S n y^{-1/6} \tag{5.5}$$

If y is based on an average New Zealand braided river depth of 0.91 m, then

$$G_i = 5.52 \times 10^6 Q_i S n \tag{5.6}$$

Where Q_i represents the total river discharge (m^3/s) and n is the Mannings roughness coefficient for river channels (Adams, 1980). Hicks (1998) suggests that equations 5.4 and 5.5 tend to represent transport rates during floods and are likely to over calculate the transport rate of rivers during periods of lower flows. The functions of G_i and Q_i in equations 5.4 to 5.6 used in Adams (1980) are clearly summarised by Hicks (1998). Sediment transport, G_i (g/s) is a linear function of total river discharge, Q_i (m^3/s). Therefore, to estimate the average bedload of a braided river over time, is to replace the function of Q_i by the mean river discharge, Q (m^3/s). Hicks (1980) also acknowledged Adams (1980) recognition of the threshold-motion-effect to combine equation 5.5 with a formula of the flow duration curve (5.7):

$$f = e^{aqb} \tag{5.7}$$

$$q = \frac{Q_i}{Q} \tag{5.8}$$

Where f represents the cumulative proportion of time that the river flow exceeds the given dimensionless flow of q within the parameters of a and b. The threshold-of-motion includes flood flows and excludes lower flow rates (Adams, 1980; Hicks, 1998). To determine mean river transport, G (g/s), equations 5.6 to 5.8 are adjusted to give formulas 5.9 and 5.10:

$$G_i = 5.52 \times 10^6 QSnq \tag{5.9}$$

$$G = 5.52 \times 10^6 QSn \int_0^\infty q \left(d - \frac{df}{dq}\right) dq \tag{5.10}$$

The long term annual bedload capacity can finally be calculated using:

$$Y_b = 31.56 \times 10^6 G \tag{5.11}$$

$$Y_b = 174 \times 10^6 nSQ \frac{1}{ae^b} \tag{5.12}$$

Where Y_b is the long term annual bedload capacity (t/yr), and $1/ae^b$ is the flow style which is used in the formula to remove sediment transportation during low flows in order to assess bedload materials which tend to be transported in rivers during floods (Adams, 1980; Hicks, 1998).

Table 5-1: Annual bedload calculations by Adams (1980). Runoff and flow style estimated from neighbouring rivers (Clarence and Conway Rivers).

River	Site	Catchment Area (km^2)	Runoff (m/y)	River flow (m^3/s)	River slope (10^{-4} radians)	a	b	$\frac{1}{ae^b}$	Bedload (t/yr)	Bedload Erosion rate (t/km^2/yr)
Clarence	Coast	3,150	0.7	*	74	*	*	0.2	540,000	171
Hapuku	**Coast**	**140**	**0.7**	*****	**265**	*****	*****	**0.2**	**86,000**	**610**
Kowhai	**Coast**	**55**	**0.7**	*****	**110**	*****	*****	**0.2**	**14,000**	**254**
Kahutara	**Coast**	**180**	**0.7**	*****	**110**	*****	*****	**0.2**	**46,000**	**254**
Conway	Coast	505	0.7	*	60	*	*	0.2	70,000	140

*No local data available Q, a and b for each of these sites

Table 5-2: Annual suspended load calculated by Griffiths and Glasby (1985) based on the same area used in Adams (1980) (Hicks, 1998).

<table>
<tr><th>River</th><th>Catchment Area (km^2)</th><th>Suspended load (t/yr) (Griffiths & Glasby 1985)</th><th>Suspended load Erosion rate (t/km^2/yr) (Griffiths & Glasby 1985)</th></tr>
<tr><td>Hapuku</td><td>140</td><td rowspan="3">1,150,000</td><td>8,210</td></tr>
<tr><td>Kowhai</td><td>55</td><td>20,910</td></tr>
<tr><td>Kahutara</td><td>180</td><td>6,390</td></tr>
</table>

The suspended sediment yield is calculated by:

$$Y_s = 224A^{0.26}R_{mf}^{0.54} \tag{5.13}$$

Where Y_s represents suspended sediment yield (t/km^2/yr), A is drainage basin area (km^2), and R_{mf} is the runoff from the Mean Annual Flood (m^3/s/km^2) (Hicks, 1998). Based on this equation Griffiths and Glasby (1985) have estimated that the suspended sediment yield for the Hapuku, Kowhai and Kahutara River is 1,150,000 t/yr. Hicks (1998) compares Adams (1980) bedload's and Griffiths & Glasby (1985) suspended loads together based on Adams (1980) catchment area for each of the three main rivers in Kaikoura. The suspended load erosion rate for each river catchment was calculated by dividing the suspended load (t/yr) by the catchment area (km^2) used in Adams (1980) to give suspended sediment yield in ($t/km^2/yr$).

Table 5-3: Suspended sediment yield (t/km2/yr) from Hicks et al. (1996) has been calculated based on mean annual rainfall (mm/yr) and catchment lithology.

Lithological group	**Mean annual rainfall range (mm)**	**Coefficient value range**	**Suspended sediment yield range ($t/km^2/yr.$)**
Granite, gneiss, marble	3,700 – 8,400	1.0×10^{-7} to 3.5×10^{-7}	17 – 350
Greywacke, argillite	1,060 – 8,100	2.1×10^{-6} to 3.3×10^{-5}	44 – 1,740
Schist, semi-schist (phyllites)	660 – 11,200	6.0×10^{-6} to 6.7×10^{-5}	22 – 29,600
Weak marine sedimentary	1,200 – 2,400	5.2×10^{-5} to 4.0×10^{-4}	1,200 – 20,000

Table 5-4: Ranges of sediment yield (S) calculated for selected greywacke, argillite river catchments in Kaikoura from mean annual rainfall data (P) and coefficient (a) in Ys = aP2.3 used in a publication by Hicks et al. (1996). Mean annual rainfall at locations

Catchment (Greywacke, argillite)	**Mean annual rainfall (*P*) mm/yr.**	**Coefficient (*a*)**	**Suspended sediment yield (*Ys*) $t/km^2/yr.$**
Example (Hicks et al. 1996)	1,060 – 8,100	2.1×10^{-6} to 3.3×10^{-5}	44 – 1,740
Kaikoura, Hapuku Grange Hill (HGH)*[30]	1,360	2.1×10^{-6} to 3.3×10^{-5}	34 – 530
Kaikoura, Sawyers Downs (SD) *[30]	1,002	2.1×10^{-6} to 3.3×10^{-5}	17 - 260

The following is the method used in Hicks et al. (1996) to calculate minimum and maximum suspended sediment yields, Ys (t km^{-2}yr^{-1}) from greywacke, argillite lithology represented by coefficient, *a* based on mean annual rainfall, *P* (mm) using equation:

$$Y_s = aP^{2.3} \quad (5.14)$$

Minimum sediment yield calculated using mean annual rainfall (*P*) and coefficient, *a* as 2.1×10^{-6} in equation:

$$Y_s = 2.1 \times 10^{-6}P^{2.3} \quad (5.15)$$

Maximum sediment yield calculated using mean annual rainfall (*P*) and coefficient 3.3×10^{-5} in equation:

$$Y_s = 3.3 \times 10^{-5}P^{2.3} \quad (5.16)$$

Calculating Suspended sediment yield, Y_s for an entire River Catchment (t/yr)

$$Y_s = DA\theta \quad (5.17)$$

$$Y_s = 0.0018 \times A \times 2.65 \quad (5.18)$$

Where *D* is the denudation rate of the Seward Kaikoura Ranges in (m/yr), A is catchment area (m^2), and θ is sediment density (t/m^3). The catchment area for each of the three main rivers was calculated using spatial analyst tools in GIS. The ratio of bedload to suspended load tends to range from 4% to 26% (Hicks, 1998).

Table 5-5: Calculated suspended sediment yield values using equation 5.18 for each main river catchment using the areas in GIS.

River	Catchment Area (km^2) GIS	Suspended Sediment yield (t/yr) Calculated from equation 5.18	Suspended Sediment yield (t/ km^2/yr)
Hapuku	134	640,000	4,780
Kowhai	85	406,000	4,780
Kahutara	231	1,102,000	4,770

Table 5.5 shows suspended sediment yields calculated using equation 5.18 have higher values compared with the suspended yield range calculated using Hicks (1996) formula, and have lower values compared to Griffiths and Glasby's (1985) yield value. According to Hicks (1998) Griffiths and Glasby's values tend to be overestimated.

5.3.2 Critique

This section has outlined the process for calculating sediment load delivery using methods previously applied by researchers. Where detailed flow gauge data for the rivers becomes available from the study area the method can be applied quantitatively. From a qualitative perspective the Hapuku, Kowhai, and Kahutara river channel sizes vary with length and depth, and therefore their sediment delivery to the coast varies across the alluvial plain north and south of the Peninsula (Davies & Bull, 2005). The lack of reliable flow data is attributed to the inability for practical river flow and water level recording due to the steep catchment terrain and highly mobile channel bedloads (Ecan, 2000; Sutherland, 2006, p.2). However, without this local data it is difficult to make assumptions on actual bedload yields for each river. This is crucial for future assessments for determining future co-seismic sediment yield input and aggradation events during peak flood events that are likely to increase in frequency and intensity over the next 50 to 100 years.

5.4 Foreshore Sediment Volumes

5.4.1 Beach profile analysis

Beach profiles are affected by the erosion and accretion of sediments. This can be indicative of interannual and interdecadal climatic variations. These relationships can be investigated by looking at measured beach profiles and how these change with time (Bryan et al. 2008).

Beach profiles have been annually surveyed along the Kaikoura Coastline by Environment Canterbury since 1997 (Gabites, 2016). The location of these surveys are shown in Figure 5.4. For purpose of illustration in this thesis, representative sites have been analysed to determine the erosion and accretion responses to alongshore sediment transport mechanisms. Additional data for the other beach profile sites shown in Figure 5.4 have been tabulated in Appendix C1, C2, C3 and C4.

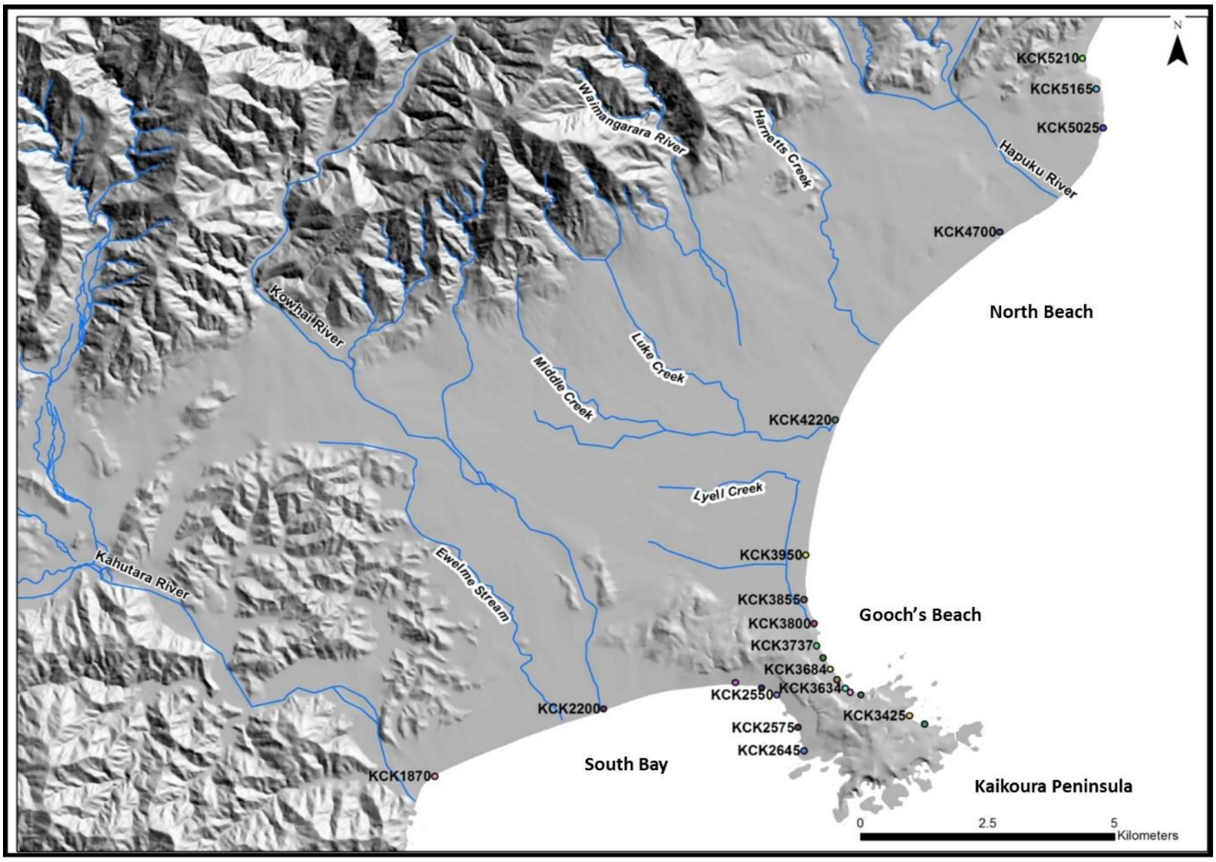

Figure 5-4: Map showing the location of Environment Canterbury Beach Profile Surveys.

Figures 5.5 and 5.7 show profiles from sections along North Beach and variation in sediment volume changes over time relative to the horizontal change of the MSL contour. Both sites show an accretion trend since 1997.

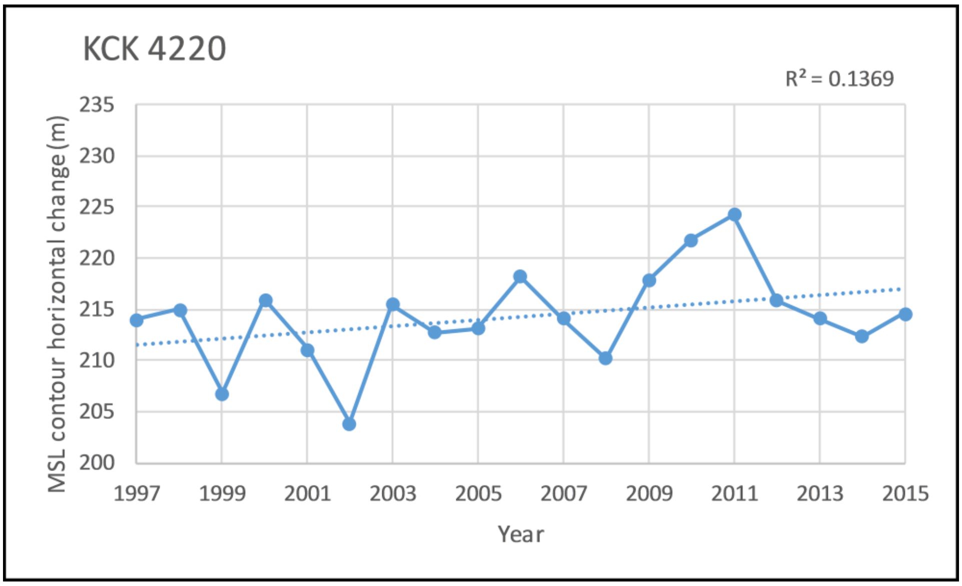

Figure 5-5: North Beach profile, KCK 4220.

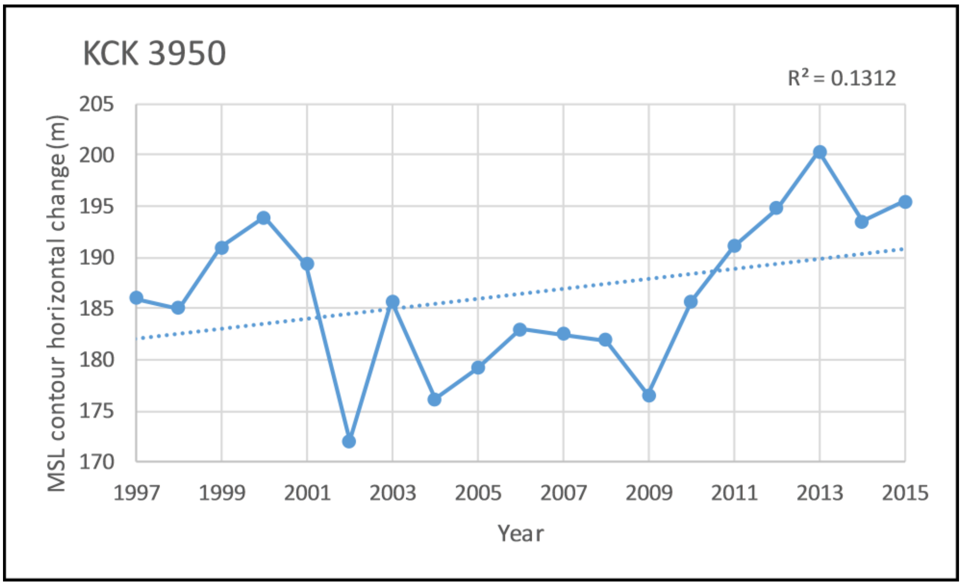

Figure 5-6: North Beach profile, KCK 3950.

Figures 5.7 and 5.8 show profiles from sections along Gooch's Beach, little variation in sediment volume changes over time are observed, relative to the horizontal change of the MSL contour. Site KCK 3659 shows slight erosion trend over this time. While a small accretion trend can be noted in profile KCK 3684. Gooch's Beach is subject to regular re-nourishment, without which the profiles would be actively eroded (Gabites, 2016).

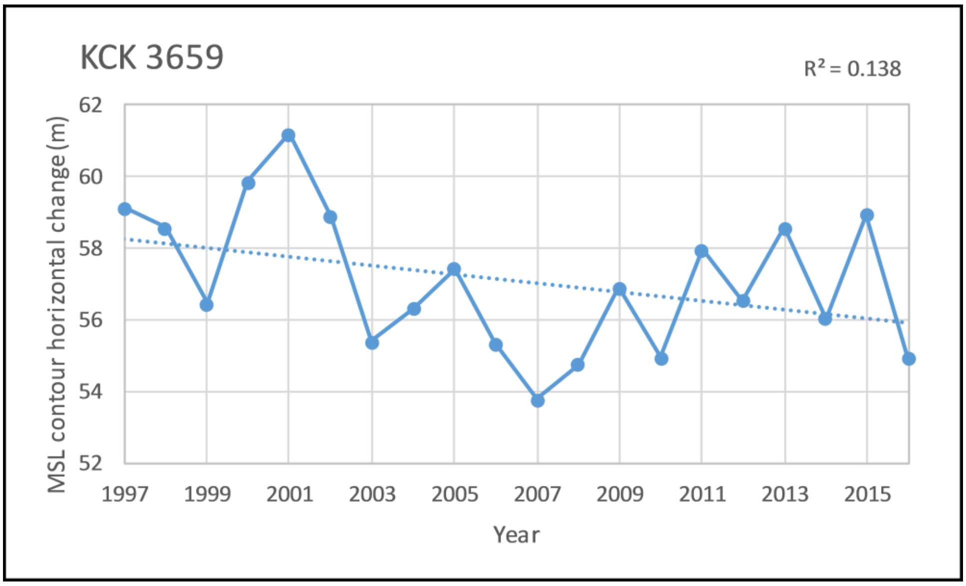

Figure 5-7: Gooch's Beach, Profile KCK 3659.

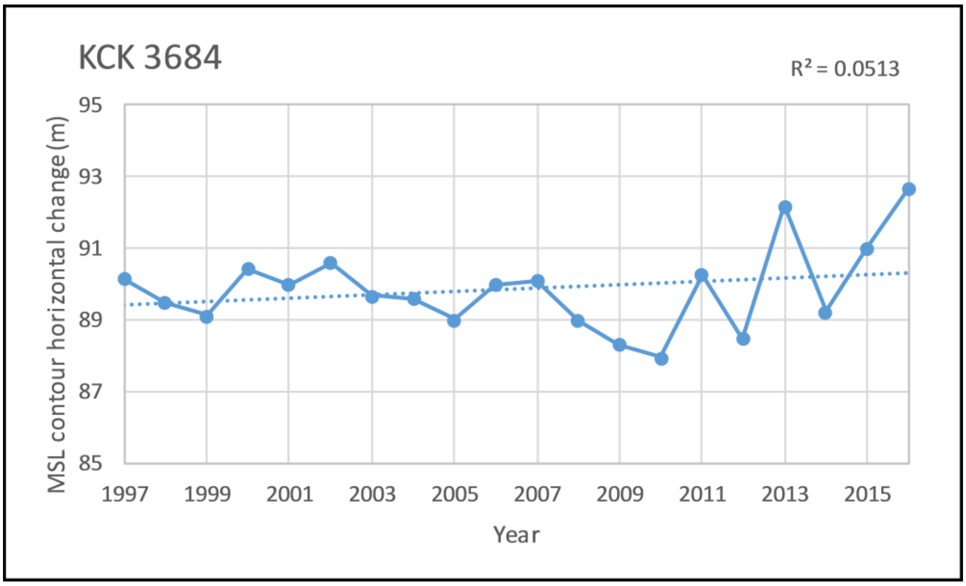

Figure 5-8: Gooch's Beach, Profile KCK 3684.

Figures 5.9 and 5.10 represent sediment volume changes over time relative to the horizontal change of the MSL contour at profile survey sites KCK 2470 and KCK 2575 in the Northern extent of South Bay. There is distinct difference in volume change over time between these two sites. KCK 2470 is showing a strong accretion trend over time compared to KCK 2575 which appears stable with very little volume changes relative to the position of the horizontal MSL contour.

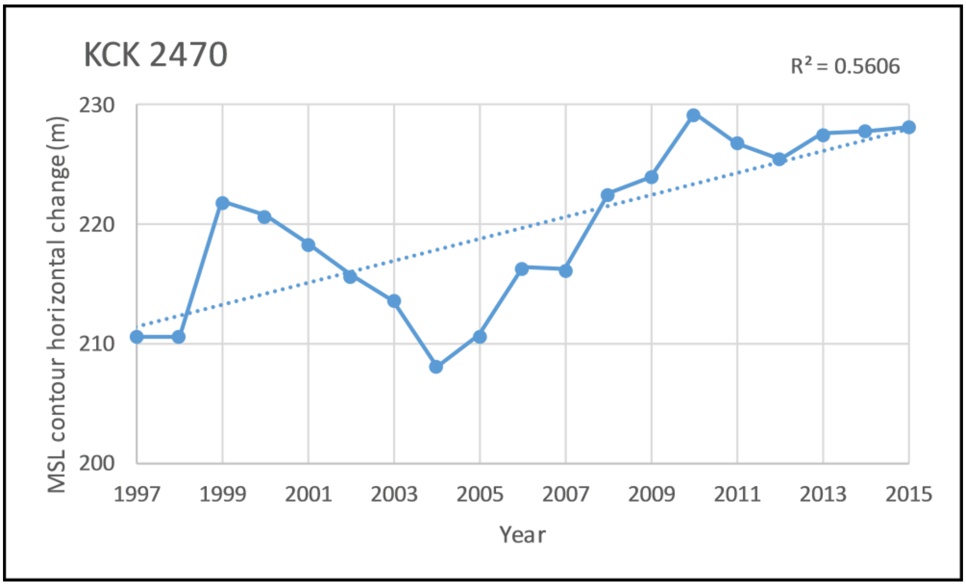

Figure 5-9: South Bay Profile, KCK 2470.

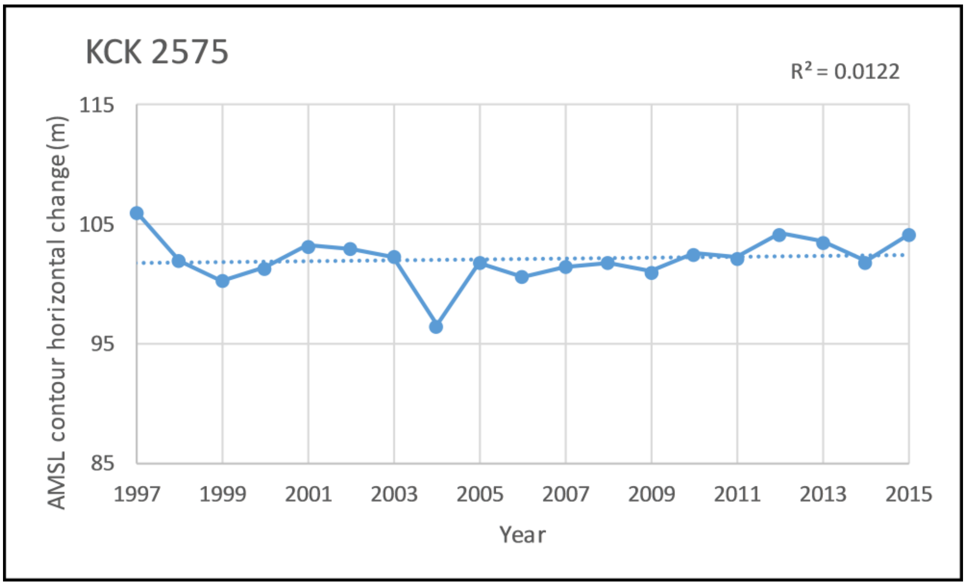

Figure 5-10: South Bay Profile, KCK 2575.

5.4.2 Alongshore variations in Foreshore Sediment Volumes

North of the Peninsula, the Hapuku River supplies the northern end of north beach with sediment, from southward drift initiated by refraction of oblique incoming north-easterly waves in the nearshore. Profiles KCK 4220 and KCK 3950 represent this section of coastline and reflect accretion over time in response to southward sediment deposition along North Beach. The extent of this transportation and deposition along the coast is limited from the Hapuku River mouth south to Lyell Creek (Dawe, 1997). The Mt Fyffe streams (Lyell Creek, Harnetts Creek, Swan Creek, Luke Creek, and Middle Creek) contribute to the sediment supply along North Beach. The sediment deposited near the Lyell Creek mouth is within the swash zone due to the orientation of the beach (Dawe, 1997). The sediment is unable to be transported further south along the beach in front of the Towns' Esplanade as it is too far from the primary sediment source. Instead, the gravels are transported up and down the length of the beach's profile. Under storm conditions the sediment is transported offshore or the gravel is captured by the intertidal rock reefs which are located parallel to the Lyell Creek mouth (Dawe, 1997). This lack of sediment deposition leaves the foreshore along Gooch's Beach vulnerable to coastal erosion and inundation evident in the two representative profiles (Figures 5.7 & 5.8).

South of the Peninsula, the Kowhai and Kahutara Rivers deposit sediment at the coast. The sediment is transported northward where it is then deposited along South Bay (Boorer, 2003; Hart et al. 2008). The Kahutara River supplies sediment alongshore as far south as Peketa north to the Kowhai River mouth. Ewelme Stream and Elms Creek also contributes sediment which is also transported alongshore. The primary sediment transport mechanism along the coast of South Bay is the Southland current (Brodie, 1960). Accretion at site KCK 2470 reflects the extent of northward sediment transport, whereas KCK 2575 is most likely affected by swash processes similar to the southern extent of North Beach.

5.5 Summary

Coastal geomorphic change along the Kaikoura coastline over the last 10,000 years has been primarily influenced by tectonic and climatic controls on fluvial sediment input and coastal deposition (Bull, 1991; Bull, 2009; McFaden & Goff, 2005). A summary of the sediment budget and controlling processes is given in Figure 5-11. These processes have driven alongshore variation in sediment deposition along the coast north and south of the peninsular, which is reflected in the excursion plots.

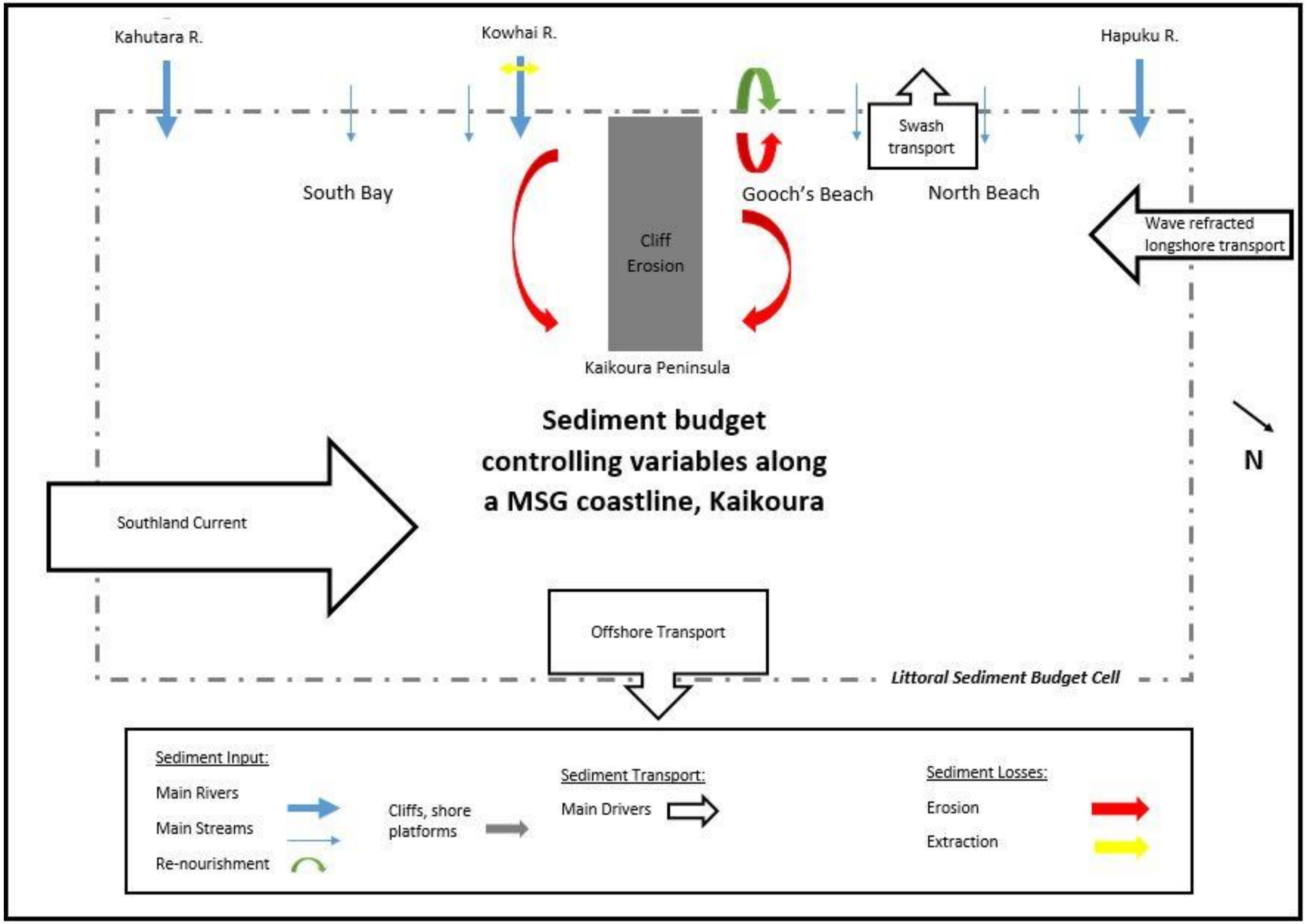

Figure 5-11: Littoral sediment budget cell and controlling processes.

Chapter 6

Hazard Management and Planning

6.1 Introduction

The Kaikoura District Zone exists within boundaries of the Conway River in the south to north of Kekerengu, the Inland Kaikoura Ranges to the north-west, and the northern Canterbury coastline to the east (Kennedy, 2005). Within this zone there are dynamic, complex, natural and societal systems that are interacting on a regular basis. To understand how vulnerable societal systems in Kaikoura are to hazards caused within the natural system, this chapter is split into three sections: (i) assessing the hazardscape, (ii) identifying risk and vulnerability in the urban environment, and (iii) reviewing national, regional, and local level policy and management frameworks.

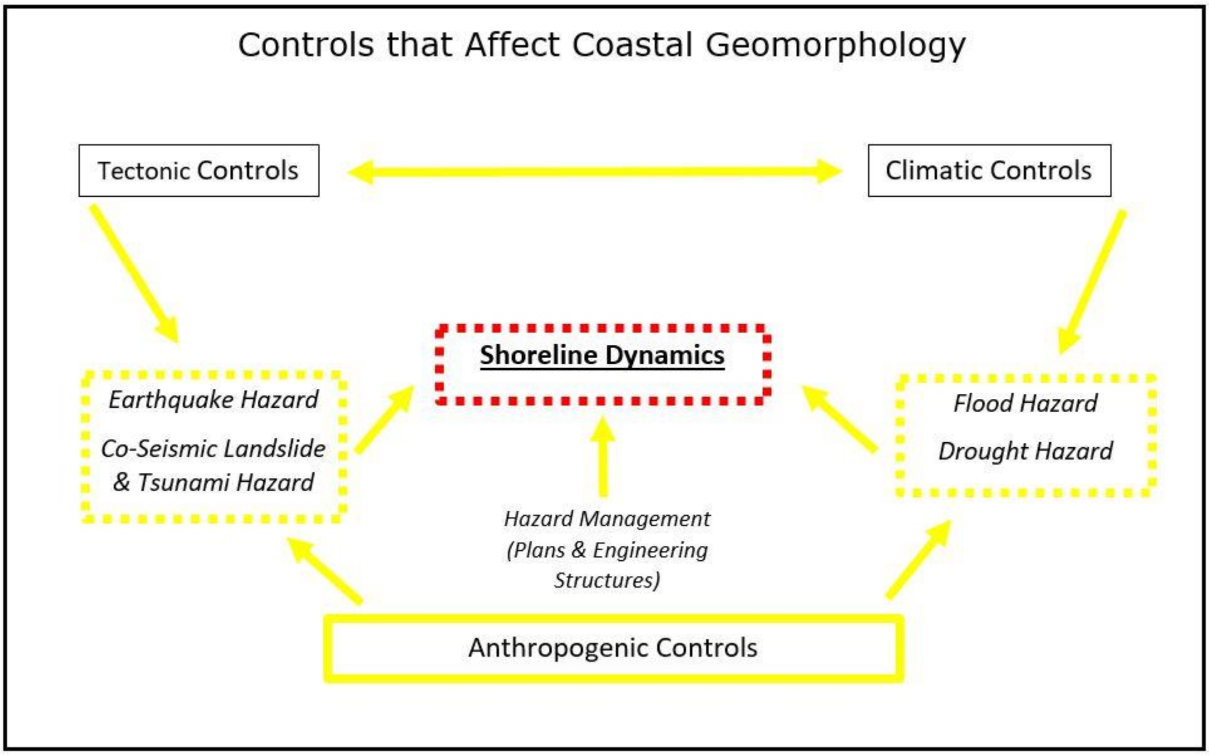

Figure 6-1: Key human controls and tectonic and climate- induced hazard factors that affect shoreline dynamics.

6.2 The urban environment

6.2.1 Population and Services within the Kaikoura District

The population of Kaikoura district is an estimated 3,640 people, and is projected to increase to a median population of 4,030 by 2031 (Statistics NZ, 2014). The Kaikoura Township is the largest urban settlement, within the District. The majority of the town's population resides within close proximity to the coast. Critical lifeline infrastructure such as; transport networks, power, telecommunication cables, drinking water, waste water and storm water pipelines are also located near the coast (Kaikoura District Council, 2010). The state highway and railway line infrastructure are not only important for the district, in terms of accessibility for locals, tourists, and emergency services in and out of the town, but are also nationally significant with regards to transportation and distribution of freight between main centres (Kaikoura District Council, 2010)

6.3 Kaikoura hazardscape

6.3.1 Introduction

Kaikoura Township is geographically located in a very dynamic landscape with high inland mountain ranges, rivers, alluvial fans and an eroding coastline. The area experiences active faulting, flooding, coastal erosion and inundation from increased rainfall and wind produced seasonally by anticyclones.

6.3.2 Coastal erosion

The amount of coastal erosion has varied along the Kaikoura coast. The shoreline near the Sections along the coast that are eroding are aligned with swash zones, and where there is no sediment deposition. Swash influences the beach where it reworks sediment and can transport it alongshore (Kirk, 1975). The beach in front of the township's esplanade has undergone re-nourishment using local sediment sources (Tonkin & Taylor, 1998). A sea wall has been built along Gooch's Beach to prevent further erosion (Figure 6.2). Along the majority of the Kaikoura coastline rip-rap has been placed at the base of coastal cliffs to prevent further shoreline retreat (Rattenbury et al. 2006).

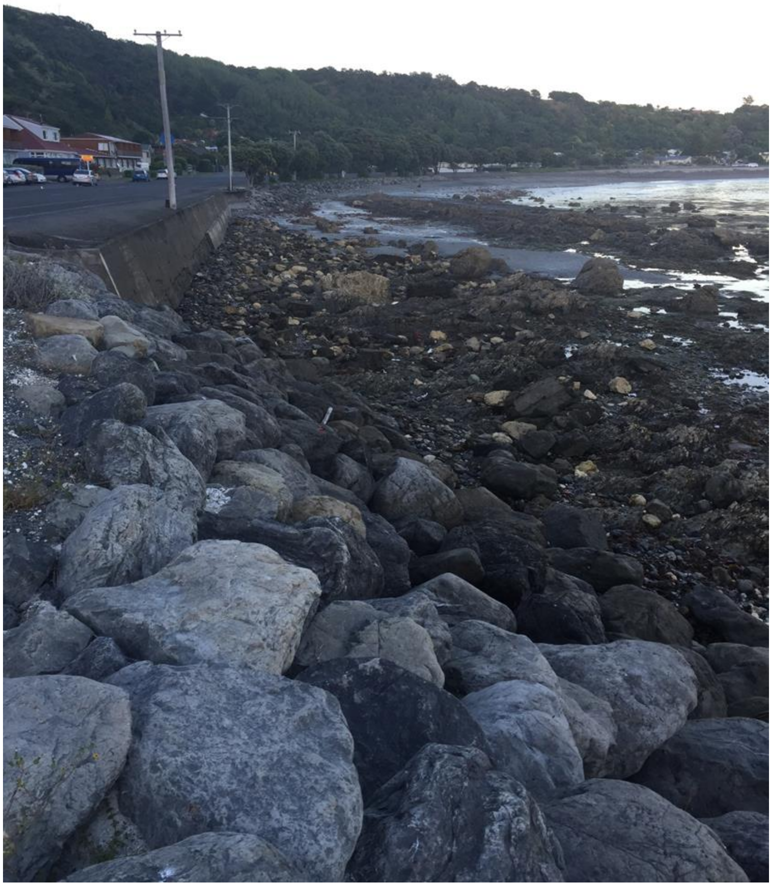

Figure 6-2: Riprap and seawall along Acova Street.

Cliffs and shore platforms of Kaikoura peninsula erode an average of 1.130 mm/yr. These sediments are so fine that they are transported offshore rather than deposited and reworked into the beaches (Stephenson and Kirk, 1998). It has been determined that the erosion of the cliffs and shore platforms is primarily due to wetting and drying processes. Rock crystals form in small fractures, expand, and slowly break apart the surface structure, leaving it exposed to sub aerial weathering (Stephenson & Kirk, 1998). The expansion of rock crystals may also cause the rock to swell, creating an area exposed to wave processes and erosion (Stephenson & Kirk, 2001).

6.3.3 Storm surge inundation

A storm event during high tide both north and south of the Peninsula, poses a high risk of wave run-up along South Bay, Gooch's Beach and the North Beach shoreline. Inundation is a likely hazard along the Esplanade and where SH1 and the railway run adjacent to the coast

(Rattenbury et al. 2006). In March 2010, a storm along the Kaikoura coastline produced waves which overtopped onto SH1 depositing debris, and causing surface flooding. Emergency services predicted it to have been worse, if it had occurred during high tide (The Marlborough Express, 2010).

6.3.4 Local Tsunami

A localised submarine landslide of unstable sediment at the head of the Kaikoura Canyon, triggered by proximal seismicity from an offshore or onshore fault displacement, could result in tsunami waves exceeding 10 metres high occurring within 1 minute at Goose Bay, and after 5-6 minutes, over 5 metre waves could occur at South Bay. This is considered to be the worst-case scenario, and is based on a potential large mass movement of material offshore from Goose Bay into the Kaikoura Canyon. Shelf edge failure above the heads of the Haumuri and/or Kaikoura canyons could also cause large tsunami waves (Mountjoy et al. 2013). Smaller mass movements within deeper sections of the canyons could cause smaller waves that may result in moderate damage to the low-lying coastline (Mountjoy et al. 2013).

6.3.5 Regional and distal tsunami

A tsunami can also be triggered by an offshore regional or distal source earthquake. The Kekerengu fault extends approximately 50 kilometres offshore north of the Clarence River, and is a potential local source of offshore seismic activity. Within 10 minutes, the Kekerengu coastline and the Clarence River mouth could be subjected to waves of over 5 metres high, and further south, the Kaikoura Township may experience 2 metre high waves. Waves are predicted to decrease further south of the Kaikoura Peninsula to heights of less than 1 metre A subduction zone triggered earthquake off the coast of Peru in South America, could trigger 6 metre high waves along the Kaikoura coast after 12 hours in a 'worst case' scenario (Lane & Arnold, 2013).

Inundation levels along the coastal strip are likely to reach 0.1 to 1.5 metres between the Kowhai River and the southwest end of South Bay, 1.0 to 1.5 metres along the township, and up to 2 metres approximately 1 kilometre south of the Hapuku River (Lane & Arnold, 2013 p.21 & 23). Inundation levels for the shore platforms southeast of the Kaikoura Peninsula are likely to reach over 2.5 metres. Platforms north and south of the Peninsula are likely to experience 1.0 to 2.5 metres of inundation (Lane & Arnold, 2013 p.21). These figures are based on tsunami arrival during a mean high water spring (MHWS) tide.

Coastal hazards such as erosion, sea water inundation and tsunami, are likely to become exacerbated by climate change impacts on relative sea level rise and climate over the next 100 years (IPCC, 2013). The frequency of coastal erosion and storm-surge inundation is likely to increase due to an increase of storm events producing large swells along the coast (IPCC, 2013).

6.4 Anthropogenic Controls

6.4.1 Fluvial environment

Human modifications along the Kowhai River is to prevent flooding of abandoned river channels. This is to manage and mitigate the flood hazard for the Kaikoura Township (Environment Canterbury (Ecan), 2000; Sutherland, 2006). Echelon stopbanks have been constructed along the Kowhai River to prevent the river from flowing across its fan to the northern side of the Peninsula in a 20-year return period flood (Ecan, 2000; Sutherland, 2006). The structure of the echelon stopbanks along a high energy river such as the Kowhai River, allows water to return into the main channel once it has been breached during floods (Sutherland, 2006). Restricting the river's flow across its fan during flood events, means that the southern end of North Beach is unable to be replenished naturally by episodic sediment delivery during major 1 in 50 year and 1 in 100 year floods. Gravel extraction from the Kowhai River is another method used to mitigate flooding for the area in terms of removing excess river bed load to create stop banks and reduce channel capacity (Environment Canterbury, 2000; Sutherland, 2006). There is are currently two active extraction consents along the Kowhai River (see Appendix D1 and D2 for extraction location and summary). The combined volume of sediment that has been extracted from these two active sites is 31,863 m^3. Between 2006 and 2016, 11,746 m^3 has been extracted from the Kowhai River (Ecan, 2016a).

Surface water and groundwater extraction from the Kowhai River and Mt Fyffe streams, are closely monitored by Environment Canterbury to ensure that flows are not negatively affected (see Appendix D3 for water resource consent activity type and location). Even though these activities are not necessarily impacting sediment delivery to the coast currently, population growth in the future and the occurrence of droughts may increase the demand of water use in Kaikoura, leading to potential adverse effects on stream discharge at the coast (Ecan, 2016c)

6.4.2 Coastal environment

Human modifications north of the Peninsula have mainly been restricted to the rocky reefs and intertidal shore platforms along Acova Street, and the beach along the town's Esplanade. This is mainly to manage chronic erosion due to lack of sediment supply to that area. Both hard and soft engineering structures have been used to mitigate erosion, such as: (i) a concrete sea wall in front of the University of Canterbury research station, (ii) a rock revetment wall along Gooch's Beach, and (iii) re-nourishment along the Esplanade between Torquay Street and Killarney Street. The concrete sea wall and the rock revetment wall are examples of hard engineering coastal management and were constructed in the last 10 years. Re-nourishment along the Esplanade's foreshore has occurred in 1997, 2002, 2009, 2012, 2016 and rock protection works in 2011 (Gabites, 2016). Approximately 18,605 m^3 of material has been deposited along the Esplanades foreshore between 1997 and 2016 and 500 m^3 of boulders in July 2011.

Figure 6-3: Beach re-nourishment comparisons Map 2012 and February 2016.

Human modifications south of the Peninsula consist of rock revetment walls along the South Bay Marina, a sea wall just south of the Kahutara River Mouth, and rip-rap boulders along the coastal section of state highway one (SH1) between the Conway and Kahutara Rivers. The coastline adjacent to SH1 is managed and modified by the New Zealand Transport Agency (NZTA). Along this section, concrete walls and rip-rap have been used to protect the road infrastructure from erosion caused by high energy waves (Rattenbury et al. 2006).

6.5 Future Management

6.5.1 Modelling coastal response: Methods and implications

Understanding how the Kaikoura coastline will respond to climate change and relative sea level rise is an important step towards future planning and policy decisions. In a report by Tonkin & Taylor (2013), the Bruun rule and passive inundation model were used to assess the effects of future sea level rise along various beaches in Christchurch and Banks Peninsula post 2010 -2011 earthquakes. The Bruun rule is primarily used to model sand beach response to sea level rise. It is a two- dimensional approach based on the assumption that a beach is in a state equilibrium. During a period of erosion, landward loss of sediment is deposited in the active seaward margin at a closure depth where sediment remains within the system and not transported further offshore, resulting in landward migration of the shoreline (Bruun, 1962). The original model was established to determine landward and sea ward shoreline movement, without taking alongshore variables into consideration. A three-dimensional component was added to the model to account for the alongshore drift within the coastal system (Bruun, 1988). For the purpose of identifying coastal zones vulnerable to future coastal erosion and inundation, in response to climate change, this model is invalid to use due to the following reasons:

- The reflective nature and composition of MSG beaches respond differently to wave erosion compared to sand beaches.
- Alongshore variation in erosion and accretion rates may vary as sediment dynamics change over time due to:
- Co-seismic hazards impacting sediment supply to the coast, and river channel morphology
- Climate change impacts on: (i) local rainfall and the impact on river flow and sediment transportation to the coast, and (ii)

- Hard and soft engineering structural effects on fluvial and coastal sediment transport.

Passive Inundation (PI) is an approach to assess shoreline retreat by using the mean high water springs (MHWS) tidal level in addition to the projected sea level rise. The position of the future shoreline is determined by the intersection of the backshore slope and the projected elevation of sea level above MHWS (Tonkin & Taylor, 2013). An assumption of the passive inundation method is the shoreline will remain stable as sea level rises and does not account for vertical land movement relative to sea level.

Figure 6.4 shows simple passive inundation modelling along the Kaikoura coast. The MHWS was increased by 1 m SLR (2115) and 2 m SLR (2300). It highlights the vulnerability of road and railway infrastructure, which run along the beach ridge parallel to the shoreline, and infrastructure along the shore platforms of the Kaikoura Peninsula. This model does not take into account storm tide levels, run-up processes, nor tectonic movement. It highlights zones around the Peninsula that are vulnerable to flooding and erosion. The spatial extent of inundation is particularly important for land use and hazard management planning on the coast.

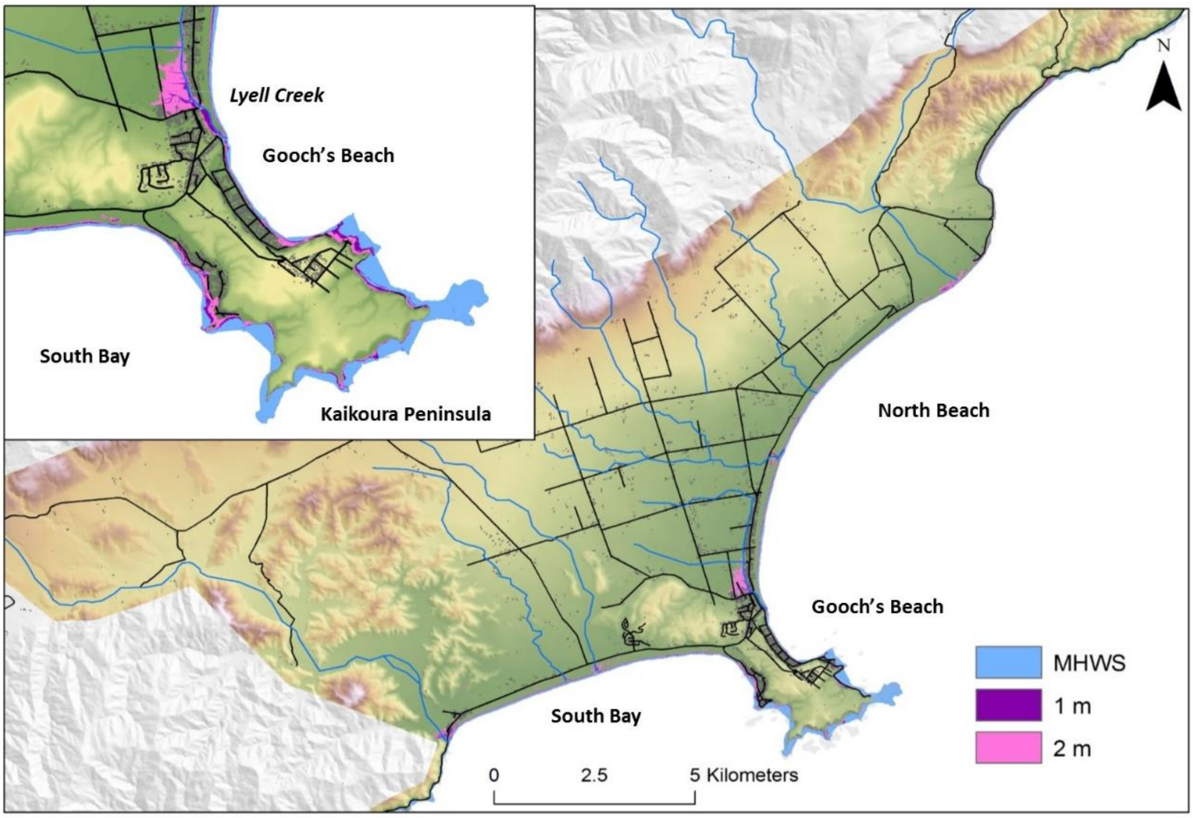

Figure 6-4: Passive Inundation Model to represent 1 m sea level rise by 2115 and 2 m sea level rise. This model does not take into account storm tide and tectonic variability. This model was developed pre November 14 2016 Kaikoura Equarthquake.

6.5.2 Identifying Hazards and Planning Responses

Since the risks posed by coastal hazards are likely to become exacerbated with climate change effects and sea level rise over the next 100 years, it is important that the areas at risk are managed, in order to plan for future land use and development on the coast (NZCPS, 2010; Ecan, 2013).

The New Zealand Coastal Policy Statement 2010 (NZCPS) is the national guide which regional and local councils use for coastal hazard management and planning on the coast. Policies 24 to 27 acknowledge the following (NZCPS, 2010):

- Policy 24 - Identification of coastal hazards
- Policy 25 - Subdivision, use, and development in areas of coastal hazard risk
- Policy 26 - Natural defences against coastal hazards
- Policy 27 - Strategies for protecting significant existing development from coastal hazard risk

Each policy is recognised under the Canterbury Regional Policy Statement (CRPS) 2013. The objectives and policies for coastal hazards under the CRPS are to achieve the policies set out by the NZCPS, and to guide local councils in the Canterbury region (Ecan, 2013).

The Kaikoura District Council identifies erosion, storm surge inundation and tsunami as coastal hazards in their operative District Plan (Kaikoura District Council, 2010). The plan recognises the likelihood of sea level rise and monitors any relevant research on sea level rise. The plan does not acknowledge how local sediment dynamics will change as a result of increased seismicity, rainfall, storm intensity and frequency predicted for the next 50 to 100 years. Based on local preliminary assessments explored in Chapters 3 to 6, fluvial and coastal sediment dynamics are affected by active faults and interannual to interdecadal climate variability. Further assessment and monitoring is required to quantify changes in sediment budget over time based on the likelihood on future co-seismic sediment input and increased aggradation during frequent flood events.

6.6 Summary

Coastal erosion and flooding management is confined to Gooch's Beach and around South Bay marina. The local coastal area is subject to significant tsunami hazard from local and remote sources and this is important to consider for future shoreline modelling to better understand the risk. Human modification to the fluvial environment, particularly the Kowhai River has restricted episodic sediment delivery to the coastline north of the peninsular which has resulted in sediment deficit and erosion. The passive inundation model was used as a baseline approach to determine the extent of sea level rise on the coast, however, this model does not account for tectonic variations, wave run-up processes and storm tides which could impact the extent of inundation.

Chapter Seven

Discussion & Conclusions

7.1 Discussion of Main Findings

Future Coastal Geormorphic Reponses to:

Tectonic Controls

Based on assessments in Chapter 3 and 5, it is expected that there will be an increase in fluvial aggradation and river channel migration in response to horizontal fault displacements in active catchment systems and increased sediment supply from seismic-induced landsliding. Uplift of the intertidal platforms and reefs around the Peninsula, caused by the November 2016 Kaikoura Earthquakes has resulted in relative sea-level fall. Wave energies are likely to decrease around the peninsula as a result and beach sediments will take longer to erode in sections confined by uplifted reefs in the nearshore environment along Gooch's Beach.

Climate Controls

Based on assessments in Chapter 4 and 5, it is expected that there will be an increase in fluvial aggradation and sediment transport to the coast in response to an increase in mean annual rainfall predicted in the Seaward Kaikoura Range. Southerly and northerly storms are expected to intensify along the coast resulting in short term erosion. Local wind flow will become more prevalent from the northeast and southward drift along North Beach is likely to extend further along the coast. As a result, coastal sediment volumes are likely increase in the long term in sections further south along North Beach.

Anthropogenic Controls

Based on assessments in Chapter 4 and 5 Flood management is likely to increase along the Hapuku, Kowhai, and Kahutara Rivers due to the likelihood of increased flood flows and aggradation. Droughts are likely to become frequent during summer as temperatures are expected to rise along the Canterbury Plains, creating pressure on water resources. Recent relative sea-level along the coastline will likely reduce the effects of coastal erosion and inundation along Gooch's Beach and Kaikoura Peninsula, taking less pressure off engineering structures.

7.2 Thesis Aims Revisited

The purpose of this chapter is to summarise the main findings of this study. The main research objective presented in Chapter One was: To predict how coastal geomorphology in Kaikoura is likely to respond to local tectonic and climate change- induced adjustments in landscape and sea level dynamics over the next 100+ years.

The objectives were achieved and the following findings have been presented:

1. The potential impacts of local tectonic activity were identified based on assessing co-seismic impacts and active fault configurations based on previous studies conducted in the region.
2. Measured regional-scale and predicated climate change data are used to show local climate variability in order to predict local changes relative to regional projections of relative sea level.
3. Future changes in the shore line were assumed based on future tectonic activity and predicted climate variations, based on which hazard management approaches can be implemented to mitigate against dynamic responses to climate change.

The motivation for this research was developed from some previous site assessments on the hazard environment by the author in 2014. The coastal environment is controlled by a combination of large scale active tectonics, variable climate, and high energy fluvial and coastal processes within such a small spatial scale. There are national and regional guidelines for climate change adaption to mitigate the effects of future sea-level rise in New Zealand. In terms of taking into account all these variables for local coastal management, the author agreed with Dawe's (1997) opinion that:

"…*beach systems cannot be collectively explained on the basis of a universal model. Beaches are individual systems, and care must be taken to examine all the local environment factors, in order to make accurate judgments about its development, morphology and textural characteristics*."

This research examined tectonic, climactic and anthropogenic controls on the local fluvial and coastal environment.

7.3 Further Research

Determining how each control influences sediment dynamics proved challenging in a relatively sparse data context; however, digital elevation models were useful in analysing watersheds and topographical variations, and along with rainfall, river gauge, and beach profile data. These combined analyses provide sufficient information to construct a conceptual model for the preliminary assessment of local sediment dynamics, how climate change could affect sediment supply, and how future relative sea level may manifest in the Kaikoura region.

Areas of further research that are required are:

i. Research to determine co-seismic landslide potential based on a potential Hope Fault rupture in the Hapuku, Kowhai, and Kahutara River catchments.
ii. Sediment budgets assessments for the three main rivers.
iii. Consistent river flow monitoring to allow for improved application of the models reviewed in Chapter 5.
iv. The research contained in this thesis was predominantly carried out prior to the 2016 earthquakes, from which further information is available and significant variations in the local environment have occurred. Post 2016 EQ beach profile monitoring would be beneficial to assess the effects on the beaches from uplifted reef and platforms and landslide dams in the upper catchments.

7.4 Concluding Remarks

This investigation has taken a multidisciplinary approach, by assessing regional to local scale tectonic, climate, and anthropogenic controls on local sediment dynamics, to determine future shoreline response to climate change.

Determining how each control influences local sediment dynamics proved challenging in a relatively sparse data context. Conceptual frameworks were developed in relation to temporal and spatial scales in order to identify key processes and interactions between each control and the coastal environment. Assumptions were made on likely coastal geomorphology changes in response to active fault displacements, co-seismic sediment delivery, relative sea level fall, ENSO and IPO effects on local atmospheric and ocean climate variability and hazard management along the coastline.

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- Storm timeline and datasets
- Beach Profile Survey datasets
- Beach Profile Survey locations (shapefiles)

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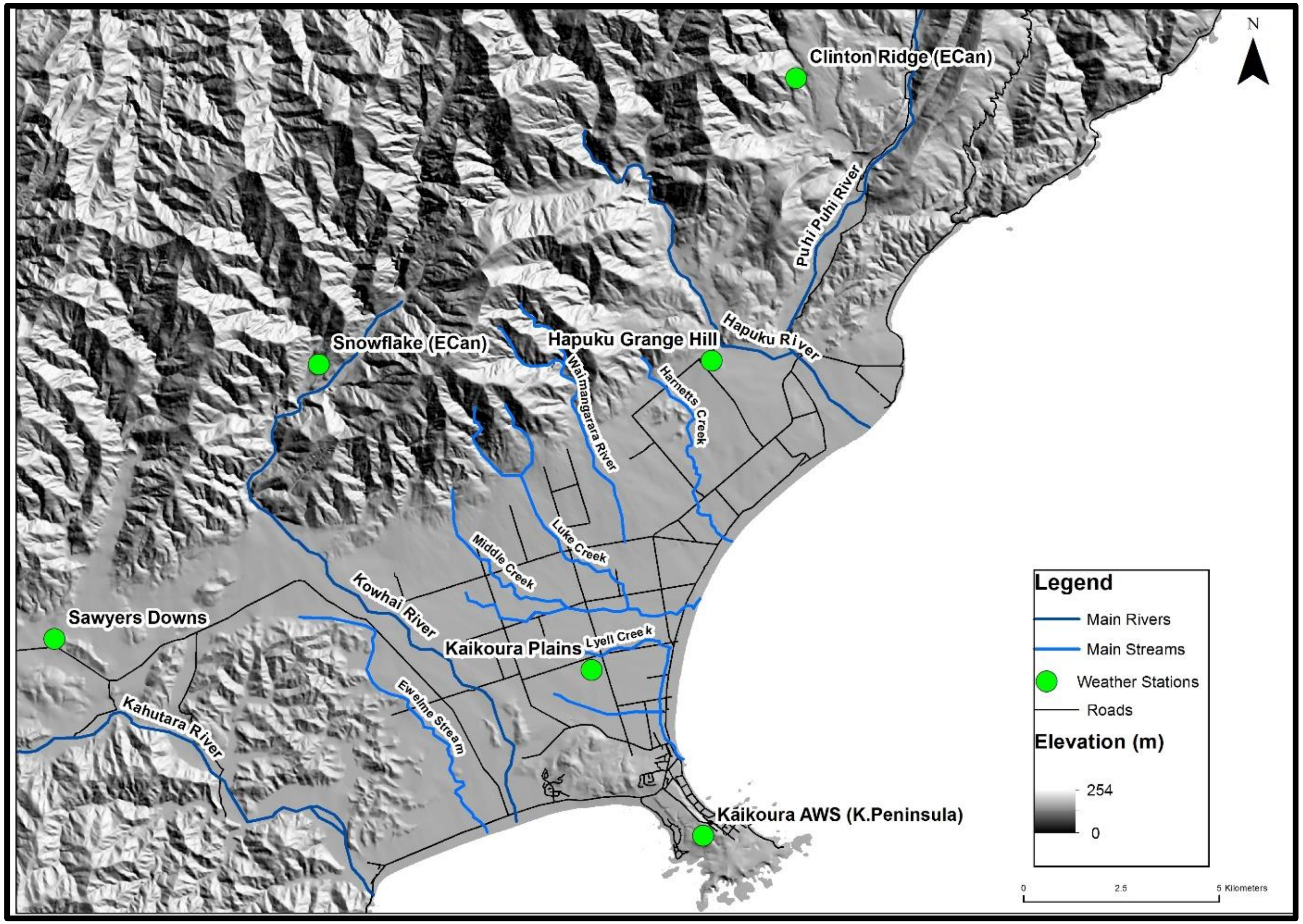
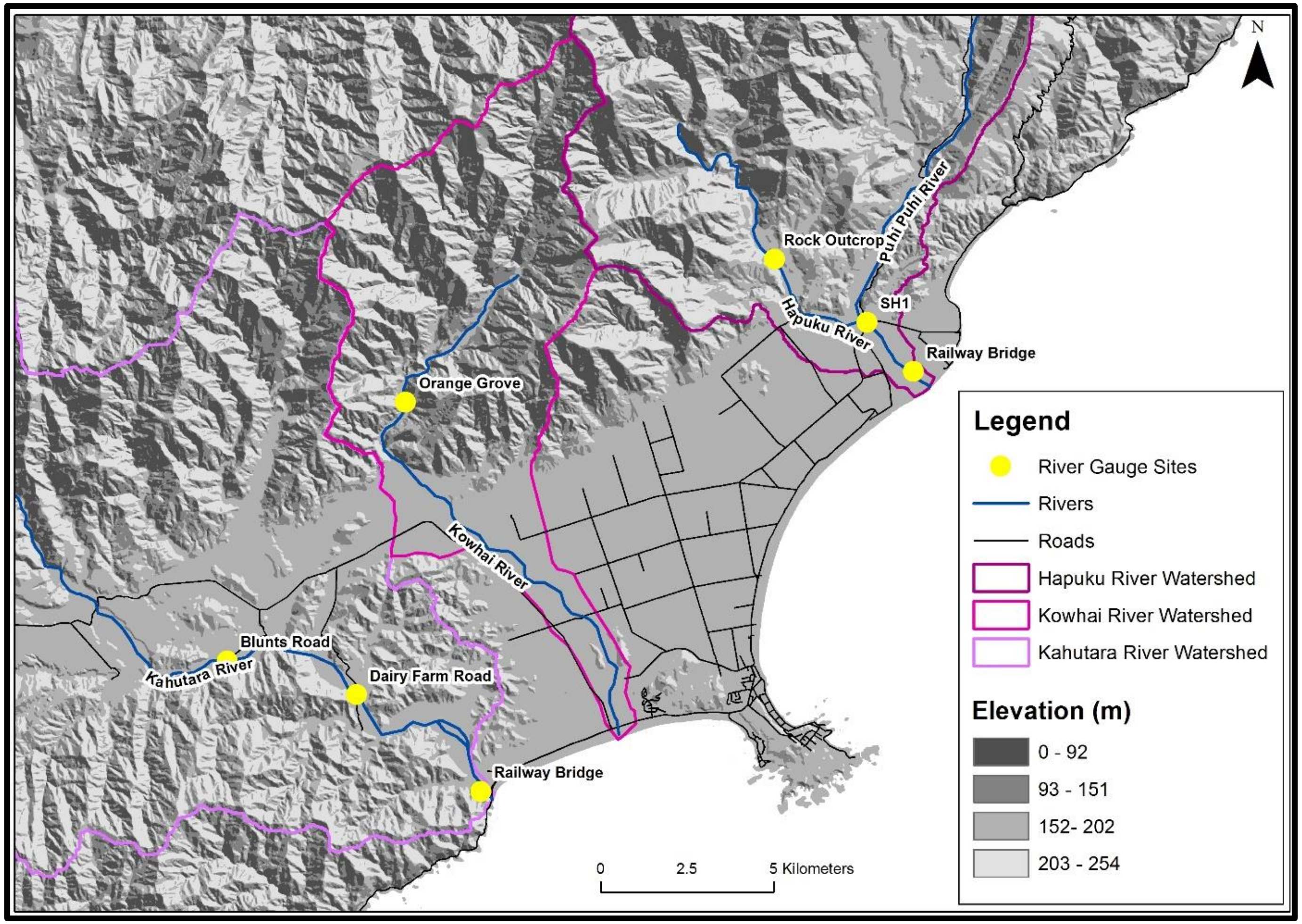
Appendix A

A1: Map showing weather station locations local rainfall and temperature were recorded between 1984 and 2014.



Appendix B

B1: River Gauge Locations



B2: River Gauge Summary Table for sites in B1. Flow is given a range value due to inconsistent monitoring.

Year	Mean Flow (m³/s) Hapuku River at Rock Outcrop	Mean Flow (m³/s) Hapuku River at SH1	Mean Flow (m³/s) Hapuku River at Railway Bridge	Mean Flow (m³/s) Kahutara River at Blunts Road	Mean Flow (m³/s) Kahutara River at Dairy Farm Road	Mean Flow (m³/s) Kahutara River at Railway Bridge	Mean Flow (m³/s) Kowhai River at Orange Grove
2004	-	1.9 – 3.9*[6]	-	0.4 – 0.6*[6]	-	1.7 – 6.7*[5]	-
2005	-	1.5 – 2.1*[2]	-	0.2 – 0.6*[2]	-	0.4 – 3.4*[9]	-
2006	-	3.3*	-	0.6*	2.6*	0.4 – 6.0*[7]	-
2007	-	1.3*	-	0.1 – 0.3*[2]	0.6 – 1.0*[2]	0.5 – 0.7*[3]	-
2008	1.1 – 1.3*[2]	3.3*	1.7 – 2.4*[2]	0.2 – 0.4*[2]	1.0 – 1.4*[2]	0.4 – 4.2*[5]	-
2009	1.0 – 1.9*[3]	1.9*	1.6 – 3.9	0.1 – 1.0*[3]	0.4 – 2.4*[3]	0.3 – 2.6*[3]	-
2010	0.5 – 2.3*[4]	-	0.9 – 3.7*[4]	0.2 – 2.7*[4]	0.8 – 5.3*[4]	0.6 – 6.0*[4]	-
2011	0.9 – 1.9*[4]	-	1.7 – 4.0*[4]	0.7 – 1.6*[4]	1.7 – 3.3*[4]	1.6 – 3.3*[4]	2.4
2012	1.2 – 1.5*[2]	-	2.2 – 3.4*[2]	0.4 – 1.3*[2]	1.4 – 3.5*[2]	1.2 – 3.6*[2]	2.1
2013	1.1*	-	1.9	0.4*	1.0*	1.0*	3.4
2014	-	-	-	-	-	-	1.3
2015	0.6*	-	1.1	-	-	0.6*	1.0
Spatial and Topographical context (Fig.)	Valley – upper catchment	Fan – confluence with Puhi Puhi River	Coastal – near river mouth	Valley – middle catchment	Valley – middle catchment	Coastal – near river mouth	Valley – upper catchment

*[number] refers to the total number of recordings taken that year that the ranges are based on.

Appendix C

C1: North Beach

Year	MSL contour horizontal change (m)						
	K3855	**K3950**	**K4220**	**K4700**	**K5025**	**K5165**	**K5210**
1997		185.95	214.00	188.80	133.83	47.57	103.40
1998		185.01	215.00	185.30	132.00	49.24	98.70
1999		190.94	206.78	170.60	125.20	42.36	97.86
2000		193.93	216.00	176.50	128.80	47.48	87.78
2001		189.27	211.10	183.20	132.20	52.10	90.50
2002		171.99	203.90	172.40	128.50	45.10	90.10
2003		185.69	215.50	168.20	129.10	50.20	79.60
2004		176.18	212.69	183.95	130.44	45.86	95.60
2005		179.20	213.15	177.27	129.35	51.13	83.97
2006		182.92	218.23	143.36	130.18	47.93	95.88
2007		182.45	214.06	183.34	130.44	47.37	83.88
2008		181.89	210.22	198.37	131.84	48.82	80.02
2009	109.84	176.57	217.82	166.37	128.64	48.32	90.14
2010	110.93	185.68	221.86	159.97	129.74	49.34	92.07
2011	112.01	191.10	224.30	161.35	130.36	48.57	97.65
2012	119.45	194.78	215.90	152.96	128.91	48.19	89.81
2013	119.26	200.38	214.10	172.75	129.60	52.29	88.71
2014	122.11	193.53	212.30	163.54	127.46	49.84	94.52
2015	124.38	195.42	214.57	194.37	129.80	52.66	87.94

C2: Gooch's Beach

Year	MSL contour horizontal change (m)							
	K3604	**K3619**	**K3634**	**K3659**	**K3684**	**K3712**	**K3737**	**K3800**
1997	45.91	41.48	58.10	59.13	90.17	57.79	54.55	113.30
1998	46.54	42.83	60.09	58.58	89.50	55.64	49.37	120.61
1999	46.30	42.38	59.20	56.47	89.12	57.20	52.54	123.24
2000	46.30	42.80	57.60	59.86	90.44	57.83	54.15	125.72
2001	46.64	43.00	59.20	61.20	90.00	55.88	53.60	128.74
2002	47.70	42.12	58.41	58.90	90.60	59.90	55.30	123.55
2003	46.01	42.90	57.00	55.40	89.70	56.50	52.10	121.20
2004	46.85	44.15	60.87	56.32	89.60	57.58	52.85	123.91
2005	45.97	45.03	58.01	57.45	89.03	57.60	53.32	129.23
2006	49.89	44.10	60.34	55.35	89.98	59.41	56.05	127.43
2007	48.65	44.03	59.08	53.79	90.10	59.07	56.17	125.35
2008	48.08	44.09	60.63	54.75	88.99	57.43	54.74	127.96
2009	47.42	43.83	60.07	56.92	88.31	60.73	58.31	127.12
2010	45.34	44.40	58.31	54.97	87.96	62.16	58.09	125.77
2011	44.51	42.46	59.69	57.98	90.28	61.08	57.56	124.23
2012	46.29	40.69	62.09	56.56	88.50	60.90	57.25	129.76
2013	45.02	43.13	58.72	58.57	92.19	62.58	56.17	132.84
2014	45.16	41.20	57.60	56.05	89.25	61.50	58.63	129.14
2015	46.43	42.64	56.73	58.95	91.01	64.32	59.32	131.23
2016		41.57	57.25	54.94	92.68			

C3: Kaikoura Peninsula

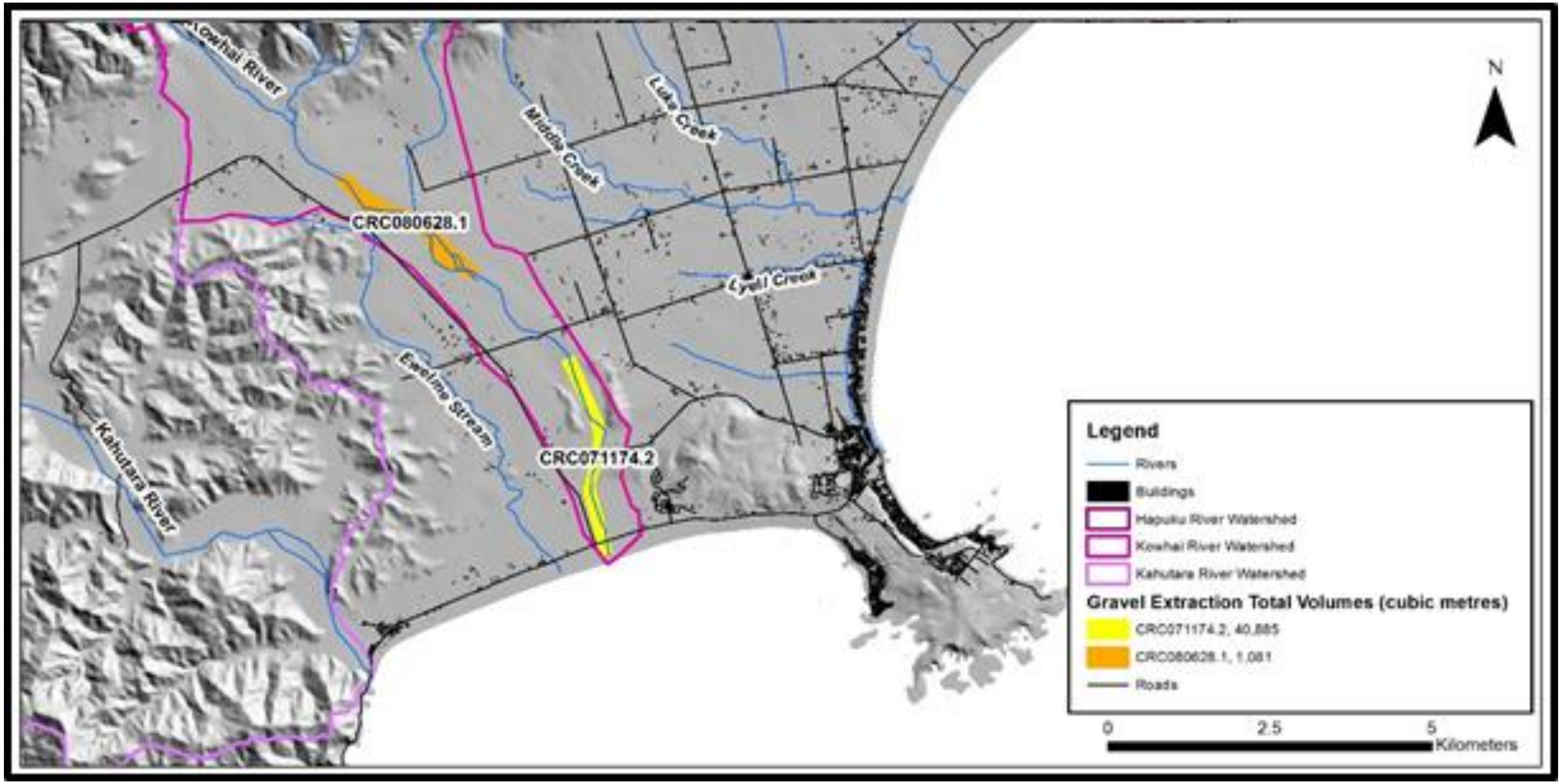
Year	MSL contour horizontal change (m)	
	K3405	K3425
1997	48.63	65.02
1998	53.55	61.45
1999	51.27	62.04
2000	50.80	62.85
2001	49.80	64.00
2002	61.00	67.40
2003	53.70	65.90
2004	53.17	62.27
2005	52.46	62.96
2006	50.34	63.50
2007	58.62	59.11
2008	61.15	60.81
2009	63.58	62.59
2010	61.41	66.02
2011	58.54	66.68
2012	54.70	64.40
2013	60.92	62.92
2014	62.81	61.56
2015	62.56	65.22

C4: South Bay

Year	MSL contour horizontal change (m)						
	K1870	**K2200**	**K2470**	**K2510**	**K2550**	**K2575**	**K2645**
1997	155.21	324.48	210.67	147.46	72.50	106.06	141.82
1998	136.48	305.40	210.66	145.33	73.21	101.96	142.50
1999	132.66	316.92	221.91	148.03	73.90	100.35	141.87
2000	133.31	320.48	220.78	151.79	75.43	101.37	151.34
2001	141.70	315.30	218.40	143.50	73.90	103.20	143.08
2002	145.07	318.30	215.70	157.70	75.66	103.00	142.65
2003	127.00	310.50	213.60	152.10	78.00	102.30	143.34
2004	138.26	322.46	208.12	150.75	72.55	96.57	143.71
2005	129.49	327.59	210.74	154.68	78.01	101.84	144.49
2006	127.42	314.85	216.44	153.91	79.66	100.65	143.15
2007	124.70	316.87	216.27	157.75	81.39	101.45	143.26
2008	110.25	306.17	222.59	158.03	82.17	101.83	141.99
2009	137.75	331.25	224.04	159.93	82.00	101.10	143.47
2010	131.59	316.39	229.31	160.35	85.63	102.57	142.37
2011	148.09	320.93	226.87	162.29	84.37	102.21	141.70
2012	126.74	318.33	225.55	164.03	85.71	104.22	142.69
2013	131.55	313.58	227.58	163.64	86.58	103.57	141.95
2014	146.59	300.32	227.86	166.52	87.94	101.88	141.20
2015	145.52	322.65	228.23	164.04	88.88	104.13	140.11

Appendix D

D1: Active Gravel Extraction in Kaikoura.



D2: Gravel Extraction Volume Summary 2007 – 2015.

Year	**Total volume extracted per year (m^3)** **Consent number: CRC071174 (CRC071174.1, CRC071174.2)**
2007	7,717
2008	2,204
2009	1,736
2010	16,335
2011	7,836
2012	1,552
2013	0
2014	910
2015	2,595
Total Volume (m^3)	**40,885**
Total Mass (t)	**107,528**
Average Volume (m^3)	**4,543**
Average Mass (t)	**11,948**

D3: Water Resource Consent Locations and Summary of Activity Type in Kaikoura.