Cliff Erosion and Coastal Change, mid Canterbury

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Michael R. Flatman

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Frontispiece: Looking north across the Ashburton River mouth Hapua. Hakatere Huts are to the left. The unconsolidated gravel cliffs are in the middle ground with Banks Peninsula in the background

Abstract

The mid Canterbury coast has been largely neglected in the coastal research of the South Island's East Coast. This thesis investigates cliff erosion and coastal change in mid Canterbury.

The mid Canterbury coast is comprised of mixed sand and gravel beaches with unconsolidated alluvium cliffs landward of the beaches. The average erosion rate of the cliffs is $0.43 m.yr^{-1}$. This rate masks spatial and temporal variations in cliff erosion rates. Erosion at the northern section of the study area is $0.7 m.yr^{-1}$ faster than erosion at the southern end. In the long-term (15 years) cliff height is the major controlling factor on the spatial variations of cliff erosion ($r = 0.733$). Beach volume controls short-term (1 year) spatial variations of cliff erosion ($r = -0.774$). Coastal storm frequency significantly controls temporal variations of cliff erosion ($r = 0.635$). Erosion of the mid Canterbury cliffs yields $228{,}339 m^3.yr^{-1}$ to the coast.

Longshore sediment transport is predominantly in a northward direction and provides a net sediment quantity of $40{,}645 m^3.yr^{-1}$. The mid Canterbury coast is bisected by two major rivers, the Ashburton and Rangitata. Their specific sediment yields are among the largest in the world. Sediment yields of beach forming material (coarse sands and gravels) are much lower supplying 25,000 and $28{,}000 m^3.yr^{-1}$ of sediment to the coast.

The mid Canterbury coast has a sediment budget deficit of $27{,}500 m^3.yr^{-1}$. Major sources of sediment to the mid Canterbury coast are cliff erosion (70 per cent), river transport (17 per cent) and longshore sediment transport (13 per cent). Major sediment sinks include offshore transport through abrasion (76.8 per cent) and longshore sediment transport (23.2 per cent). The large amount of sediment lost through abrasion suggests that sediment, once it arrives on the coast has a short 'life span' before it is ground up. Total beach sediment volume varies significantly from year to year but is losing $27{,}500 m^3.yr^{-1}$ of sediment on average.

Acknowledgements

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Chapter One

Introduction

1.1 The Research Problem

This thesis examines coastal change along the central Canterbury Plains. Despite the presence of large rivers draining from rapidly eroding mountains in the Southern Alps, much of the coast of the Canterbury Bight is in long-term erosion. Kirk (1969) suggests that the mid Canterbury coast, in the short-term, is in a state of erosional equilibrium, but the long-term trend is towards pronounced coastal erosion. This thesis will examine the effects that various elements and processes have on the erosion of the mid Canterbury coast.

The present research examined approximately 32km of coast that forms a central portion of the Canterbury Bight coastline. The Canterbury Bight is approximately 135km from Banks Peninsula in the north to Timaru in the south. The mid Canterbury coast, for the purposes of the present study, stretches from the mouth of the Rangitata River in the south to Wakanui Creek in the north. Wakanui Creek lies approximately 5.5km north of the Ashburton River mouth (Figure 1.1).

The mid Canterbury coast has at its landward margin, for the majority of its length, unconsolidated gravel cliffs that range in height from between 9 and 21m. It is the long-term erosion of these cliffs that is the primary focus of this research.

Cliff erosion is an ongoing problem along the mid Canterbury coast. Most studies undertaken along the mid Canterbury coast refer to the continuing coastal erosion of the region (Speight, 1950; Kirk, 1969; Kelk, 1974; Gibb, 1978). However, all of the previous examinations into the cliff erosion along the mid Canterbury coast have relied on short-term data of less than one year (Kelk, 1974), or long-term data such as that from aerial photographs (Gibb, 1978). Now, much higher quality ground survey data are available for a lengthy time period. The Canterbury Regional Council collects these data. The present research will utilise a 15-year data set of yearly cliff and beach profiles for over twenty sites from the Rangitata River to Wakanui Creek (Figure 1.1). Not only will rates of cliff erosion be investigated but the different factors that affect cliff erosion will be quantified. This type of analysis has never been attempted before on the mid Canterbury coast. Therefore, the present research is in a position to be able to explain the process of coastal cliff erosion for the mid Canterbury coast using a data set of longer than 1 year.

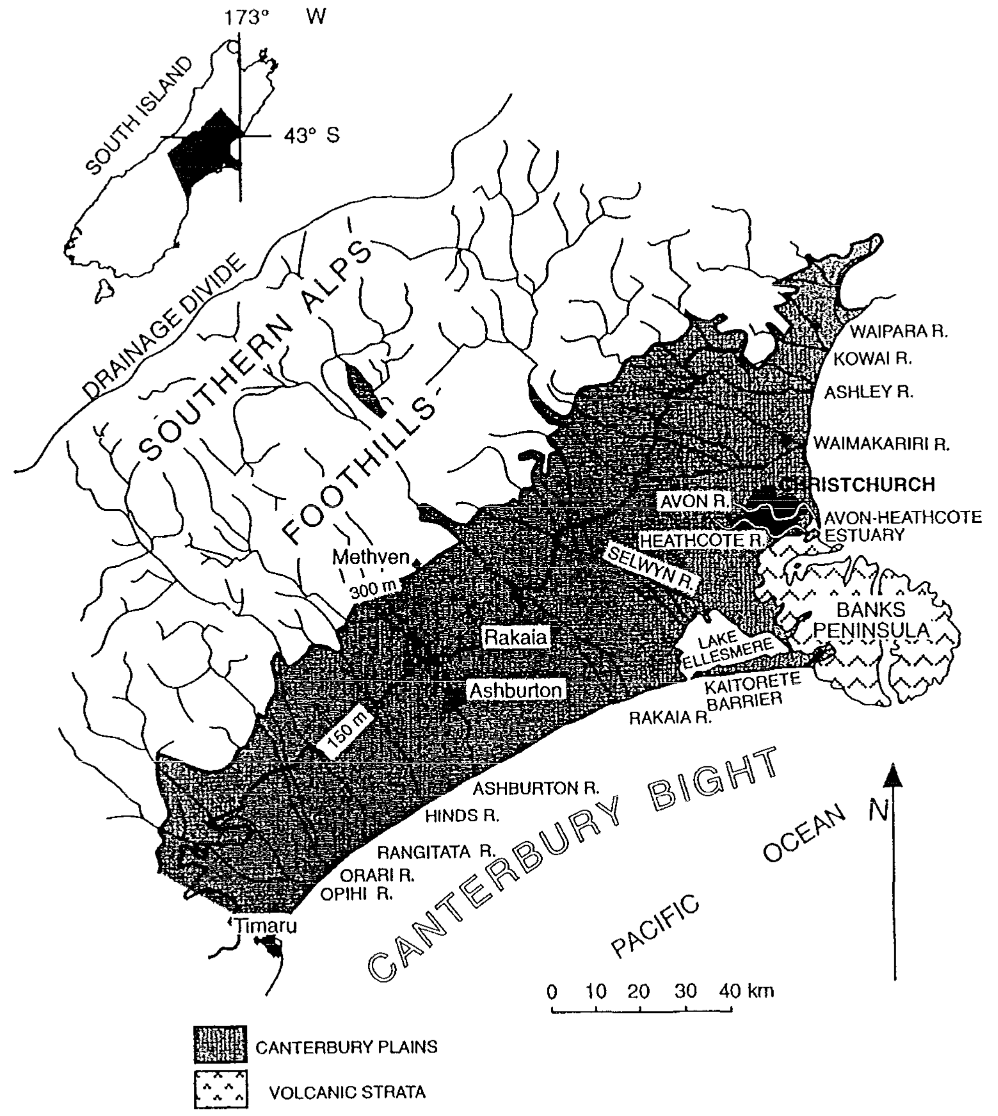

Figure 1.1: Canterbury Plains and rivers
(From Leckie, 1994 p.1241)

1.2 Research Context

"Continued study of the rates of coastal recession is necessary to more clearly determine the rates and magnitudes of change," (Kirk, 1967 p.108). Kirk was referring to the Canterbury Bight coastline, a 132km length of coast on the East Coast of New

Zealand's South Island. Kirk's statement came after he examined the sediments and morphologies of the Canterbury Bight. Speight (1950) was the first to examine the Canterbury Bight coast in any detail. However, Kirk (1967; 1969) was the first to comprehensively examine the Canterbury Bight coastline. Kelk (1974) extensively examined a 7.5km length of the mid Canterbury coast, while Kirk et al. (1977) expanded on Kelk's research. These five studies provide the bulk of the research and knowledge on the mid Canterbury coastal environment. The most recent of these studies was completed 20 years before the present research and none clarified the nature of cliff erosion or their role in the coastal sediment budget. The most comprehensive of the previous studies, Kelk (1974), was completed 23 years prior to the present study. There is a sizeable gap in research on the mid Canterbury coast. Therefore, the primary rationale for the present research is to 'fill in the gap' of knowledge for the mid Canterbury coast.

There has been a wealth of coastal research done in the Canterbury region over the last thirty years. A large proportion of this work has focussed on the South Canterbury-North Otago region. As mentioned, not a great deal of this research has focused on the mid Canterbury coast. So while this thesis will attempt to gain a greater understanding of the processes and nature of the mid Canterbury coast, it will also attempt to place the mid Canterbury coast within the context of the Canterbury coastal region as a whole.

Another focus of the thesis will be the role that the rivers have on the coastal environment of mid Canterbury. Rivers can have major effects on the coast. The amount of sediment supplied to the coast by rivers can have effects on the erosional or depositional nature of the coast. Zenkovich (1967) suggests that rivers can be classified into two groups, 'large' or 'small'. 'Large' rivers supply sufficient sediment to the coast so that river processes dominate. Accretion or stabilisation of the coast normally results. Marine processes at their mouths dominate 'small' rivers because they do not provide enough sediment to maintain the coastline against erosion. Kirk (1991) added to this concept by saying that only sediment of beach forming size is significant. The present research will examine the sediment yields for the mid Canterbury rivers in terms of their ability to affect the rate of coastal erosion through their varying sediment yields in a range of flow regimes.

Griffiths (1981) recognised the importance of floods when evaluating river sediment yields. He believed that up to 75 per cent of annual river sediment yield is transported during floods. Therefore, river derived sediment arrives at the coast in a series of 'pulses'. Neale (1987) recognised this and suggested a theory in which 'slugs of sediment' enter the coast from rivers. These river-derived slugs then migrate alongshore in the direction of the predominant longshore sediment transport. Neale's (1987) research examined the South Canterbury coast. The present study will examine the applicability of Neale's concept to the mid Canterbury coast for two reasons:

1. To see if the slugs of sediment exist on the mid Canterbury coast; and
2. To examine how slug transport may aid or hinder coastal erosion.

As suggested above, longshore sediment transport is vital for the migration of the slugs alongshore. Therefore, the process of longshore sediment transport will be examined in detail. However, a problem exists in that the vast majority of longshore sediment transport models have been developed for use on pure sand beaches. Longshore sediment transport on mixed sand and gravel beaches, (of which the mid Canterbury coast is comprised), has largely been ignored. Researchers such as Hewson (1977), Kirk (1984), and Neale (1987) have focussed on sediment transport on mixed beaches. The mixed beach transport models are derivates of the original sand based models. Therefore, the present research will examine both types of models so the longshore sediment transport along the mid Canterbury coast can be better understood. The establishment of the rates of longshore sediment transport into and out of a length of coast is vital for assessing the erosional or depositional nature of a coast.

The processes of cliff erosion and sediment transport, both alongshore and within rivers, can be examined relative to one another in a sediment budget. A sediment budget allows the quantification of sediment sources and sinks for a coastline, which in turn accounts for regions of coastal erosion or deposition (Komar, 1976). Components of a sediment budget vary between coasts. The present research will evaluate a sediment budget for the mid Canterbury coast identifying which sources and sinks are the most important for the mid Canterbury coast.

The mid Canterbury coastal environment is an interactive one where many processes and elements affect the coast. Figure 1.2 introduces this interactive nature. Many elements can be both dependent and independent of other factors. The sediment budget and morphology are dependent on the other factors of the model. Of particular interest for the present research is the interaction between coastal processes and the sediment budget and morphology of the mid Canterbury coast.

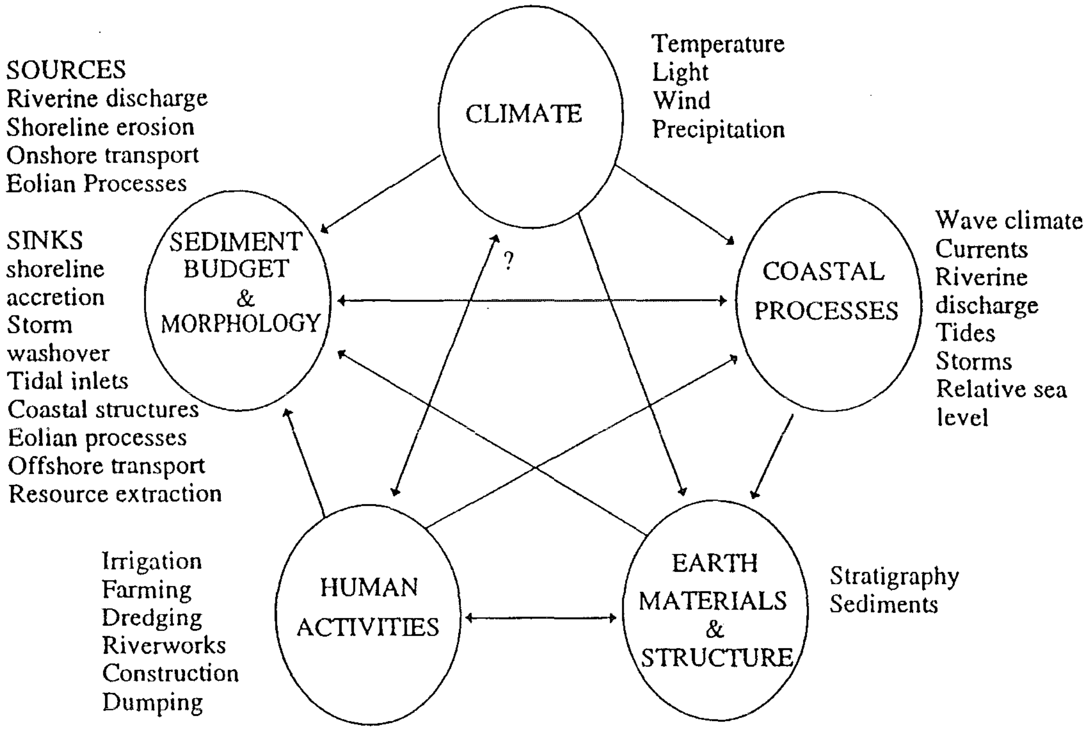

Figure 1.2: Interaction of elements affecting coastal erosion
(From Pieters, 1996 p.35 Adapted from Pilkey <u>et al</u>., 1989)

1.3 Thesis Aims

In the context of the mid Canterbury coast, the aims of this thesis are:

1. To describe coastal cliff erosion;
2. To determine the processes that cause it; and
3. To examine the role of coastal cliff retreat in the coastal sediment budget

Description of cliff erosion along the mid Canterbury coast is the first aim of the present research. Reasons for describing the cliff erosion are so that the amount and rate of cliff erosion can be identified. Also possible patterns of cliff erosion may be identified. The second aim is to identify the processes that cause and affect cliff erosion. The quantification of the factors that affect cliff erosion is the primary goal of the second aim. The third aim is to investigate the role of cliff erosion in the mid Canterbury coastal sediment budget. Komar (1976) states that sediment budget analysis is a useful tool when evaluating the relative importance of sediment sources and sinks to the beach.

1.4 Thesis Outline

Speight (1950 p.3) suggested that the mid Canterbury coastline contained, "...no outstanding features." However, a detailed examination of the study area will show that Speight was harsh in his judgement. Chapter Two will present an examination of the mid Canterbury coastal environment. The formation, as well as the nature of the mid Canterbury coastline will be examined. The cliffs of the mid Canterbury coast will be explored and the methods of their erosion will be investigated. The nature of mixed sand and gravel beaches will also be evaluated. The driving force behind much of the mid Canterbury coastal erosion is the high-energy wave environment. The wave environment will be detailed.

The quantification of factors that affect coastal cliff erosion is usually difficult to achieve. Chapter Three will quantify a number of these factors to examine their role in the erosion of the cliffs that run the length of the mid Canterbury coast. The erosion of the mid Canterbury coastal cliffs will be examined in both a spatial and temporal sense. Erosion over a short time period (1-year) and longer time period (15 years) will be investigated. Rates of coastal cliff erosion will also be determined. Once the rate of cliff erosion has been calculated, the volume of material eroded can also be calculated.

The longshore movement of sediment will be the focus of Chapter Four. Models, both sand based and those developed for mixed beaches, will be examined to calculate the rate of longshore sediment transport along the mid Canterbury coast. The movements of the 'slugs' of sediment mentioned earlier will be discussed in Chapter Four.

River derived sediment yields are examined in Chapter Five. Sediment yield depends, in part, on the discharge of rivers. Therefore, discharge and discharge variations are discussed in Chapter Five. Seasonal variations in discharge and flood events may all affect the sediment yield. Sediment yields will be examined in terms of Zenkovich's (1967) 'large' river, 'small' river concept. Kelk (1974) suggested that sediment can be stored in the river mouth lagoons. This concept, as well as lagoon morphological sequences is discussed.

Chapter Six presents a sediment budget for the mid Canterbury coastline. The significance of sediment budget analysis, in terms of determining the erosional or depositional nature is discussed in Chapter Six. As mentioned, different coasts have different sediment sources and sinks of varying significance. The important sediment sources and sinks for the mid Canterbury coast will be identified and quantified so that a sediment budget can be prepared. By identifying significant sediment sources and sinks, management of the coast may be possible and any erosion can be identified so the effects of that erosion may possibly be mitigated.

This thesis examines the mid Canterbury coastline in a number of ways. The study area is introduced in Chapter Two. Chapters Three, Four and Five examine the processes that are at work along the mid Canterbury coast. Chapter Six ties in these processes and examines them relative to one another within a sediment budget for the mid Canterbury coast. The present research is a descriptive and quantitative examination of the mid Canterbury coastal environment.

The Canterbury Plains are the largest area of continuous lowland within New Zealand (Fitzharris et al., 1982), approximately 70km wide and 185km long (Figure 1.1). These plains and the materials that comprise them, are two important aspects in the formation of the unconsolidated coastal cliffs along the mid Canterbury coastline. While the study of the Canterbury Plains and their formation may be interesting in itself, it is also vital for understanding the coastal cliff erosion that is occurring along the mid Canterbury coast.

The Pacific Ocean borders the Canterbury Plains. Along this boundary, south of Banks Peninsula lies the Canterbury Bight (Figure 1.1). This coastline has been termed 'Ninety Miles Beach' (Speight, 1950). The study area for this thesis comprises approximately 32km of this coast. Knowledge of the Canterbury Bight coast and the unconsolidated cliffs that stand above much of this coast, is useful when examining not only the nature of the environment but the processes that affect it.

Predominantly erosional processes act upon the mid Canterbury coast. Erosion has a long history along the Canterbury Bight coastline, occurring since sea level has been at its current highstand, some 5,000 years (Kirk, 1969). It is not possible to directly measure the actual amount of erosion and cliff recession that has occurred over the last approximately 5,000 years. However, it can be estimated. This erosion will be discussed in Section 2.3, but it confirms the long history of erosion along the mid Canterbury coastline.

The unconsolidated cliffs are thought to be the primary source of sediment for the beaches of the mid Canterbury coast, supplemented by bedload from the rivers. This has resulted in the beaches being comprised predominantly of mixed sand and gravel. Kirk (1969) points out that mixed sand and gravel beaches are rare on a world scale. However, they are relatively common along the East Coast of New Zealand. The lack of mixed sand and gravel beaches globally has resulted in a relatively small amount of literature specifically concerned with mixed sand and gravel beaches. Of the literature that has focussed on mixed sand and gravel beaches, a large portion has arisen from the Canterbury region (Kirk, 1975, 1980; Kelk, 1974; Neale, 1987; Single, 1992). This literature shows mixed sand and gravel beaches are morphologically and dynamically more complex than either sand or gravel beaches (Healy and Kirk, 1982). This chapter will review both mixed sand and gravel beaches and their characteristics.

The mid Canterbury coastal environment is highly erosional due largely to its exposed nature. It is highly exposed to oceanic swell, generated in the Southern Ocean and experiences storm waves with heights of 3-6m at the beach (Kirk,1980 p.194). These wave environments not only lead to direct erosion by the removal of sand and gravel but longshore currents are produced capable of transporting large amounts of sediment, in the order of 400,000 to 700,000$m^3.yr^{-1}$(Healy and Kirk, 1982 p.99). Therefore, it is necessary to closely examine the wave environment that affects the mid Canterbury coast and the longshore currents that are the product of this wave environment.

This chapter will be a morphological examination of the study area. This information will then be put in both regional and global context by means of a review of the literature that has been produced on the various components of the mid Canterbury coast.

2.1 The Canterbury Plains

2.1.1 Location

"The Plains are, in fact, a series of giant alluvial fans built by the major rivers, ..., during successive glaciations, when great quantities of gravel were poured into the river systems by the glaciers that occupied the mountain valleys" (Fitzharris et al, 1982 p.346). The Canterbury Plains are approximately 70km wide and 185km long, making them the largest area of flat land in New Zealand (Soons, 1968). They are bound on the north and west by the Southern Alps and to the east and south east by the Pacific Ocean. The major fluvial systems are the Rangitata, Ashburton, Rakaia and Waimakariri Rivers (Figure 1.1). Soons (1968) classifies the Canterbury rivers into two categories. The Rangitata, Rakaia and Waimakariri Rivers can be classified as 'Main Divide' rivers. These rivers have their sources among the peaks and glaciers of the main divide. The Ashburton River on the other hand is classified as a 'Lowland' river, and its source is among the front ranges of the Southern Alps. The 'Main Divide' rivers flood due to northwesterly rain, while the 'Lowland' rivers flood in response to southerly or northeasterly rain (Soons, 1968). The two groups rarely flood together. However, both groups are characterised by large variations in their flows. Within the study area for this thesis, only the Rangitata River is affected by northwesterly rains, while the Ashburton River floods as a consequence of rain from the easterly quarter (Chandler, 1967).

2.1.2 Formation

Historically the Canterbury Plains date from the Kaikoura Orogeny, a major mountain building episode some 3-13 million years B.P. This violent uplift was accompanied by a depression in the snow-line and a reduction of mean temperature by about 6°C. This lead to several glacial advances during the Pleistocene (Brown et al., 1968). The Kaikoura Orogeny was a major event in the history of Canterbury and New Zealand, with uplift putting most of present day New Zealand above sea level (Brown et al., 1968). The rate of uplift in the Southern Alps due to the Kaikoura Orogeny reached a maximum in the mid-Pleistocene (Soons, 1968). However, it still persists today at a rate of approximately 10mm.yr^{-1} (Leckie, 1994 p.1242). This uplift has exposed the Torlesse basement rocks of greywacke and argillite to tectonism leaving the alpine region extensively folded and faulted (Wilson, 1985).

Adams (1980) argued that rates of erosion and uplift in the Southern Alps are approximately in balance. Therefore, erosion in the Southern Alps contributes vast quantities of sediment to the fluvial systems of the South Island and specifically the Canterbury Plains. Erosion rates may produce up to $1{,}300 \pm 310 \times 10^9$ kg.yr^{-1} of sediment (Adams, 1980 p.4).

In the past there has been more erosion from the Southern Alps than in the present day. Vertical uplift within the central South Island since the onset of the Kaikoura Orogeny, has been approximately 18,000m (Brown et al, 1968). With the present day heights of the Southern Alps being on average between 2,000-3,000m there has been some 14,000-17,000m of vertical height eroded since the middle Pleistocene (Kelk, 1974). Many factors have contributed to this erosion. A drop in mean temperature of about 6°C accompanied the uplift of the Southern Alps during the Pleistocene, causing a lowering of snow-line elevation. This snow-line depression lead to a series of glaciations, as many as five (Soons, 1968). The first, the Ross Glaciation had its onset 2.5million years B.P., and the last, the Otiran Glaciation, ended approximately 15,000years B.P. Much has been written on the New Zealand glaciations of the Pleistocene with many excellent reviews (Soons, 1968; Gage, 1969; Kelk, 1974; Suggate, 1990).

The glacial and inter-glacial periods of the Pleistocene facilitated erosion of the Southern Alps. This helped form the Canterbury Plains. The erosive power of the glacial ice of successive glaciations removed massive quantities of sediment. The warming of the climate that accompanied inter-glacial periods significantly increased the volume of meltwater discharge, increasing stream competence and capacity (Leckie, 1994). The river discharge, while being a function of the meltwater discharge, is also affected by climate. The Southern Alps act as a barrier to westerly windflows. As a consequence high intensity rainfall occurs west and just east of the main divide. This creates flooding of the Rangitata, Rakaia and Waimakariri Rivers, whose catchments extend to the divide of the Southern Alps (Figure 1.1). As with an increase in meltwater discharge, flooding increased the competence and capacity of a river to transport sediment. Therefore, immense amounts of sediment provided to the fluvial systems of the Canterbury Plains resulted in, "rapid and significant aggradation and progradation of fluvial outwash fans seaward of the glacial outwash fans,"(Leckie, 1994 p.1245). The glacial outwash fans were formed by immense amounts of gravels provided to the river systems by the erosive work of the extensive mass of ice that accompanied periods of glaciation. Also during these periods of colder climate, intense erosion by freeze-thaw processes supplied large amounts of sediment (Soons, 1968; Leckie, 1994).

The rivers of the Canterbury Plains, as they emerged from the foot-hills, deposited their vast loads to form sheet deposits. Wilson (1985) suggests these sheets consisted of coalescing fans, constructed by the lateral migration of the Canterbury rivers. These fans progressively aggraded downstream to form convex fans (Wilson, 1985). These convex fans explain, in part, the varying height of the coastal cliffs to be discussed in Section 2.3.2.

Figure 2.1 shows the geomorphology of the Canterbury Plains. The formation sequence of the Canterbury Plains will not be described in full as it is discussed extensively in Fitzharris et al., (1982), Soons (1968), and Suggate (1963). However, Figure 2.1 shows the study area is formed by the fans of two major rivers, the Rangitata and Ashburton. The rivers have mountain catchment areas of approximately 1,600km^2 and 950km^2 respectively. The Hinds River, which is considerably smaller, has a catchment area of 160km^2 (Wilson, 1985 p.34). The Hinds River runs at the coalescence of the fans of the two larger rivers, within the interfan depression (Fitzharris et al., 1982).

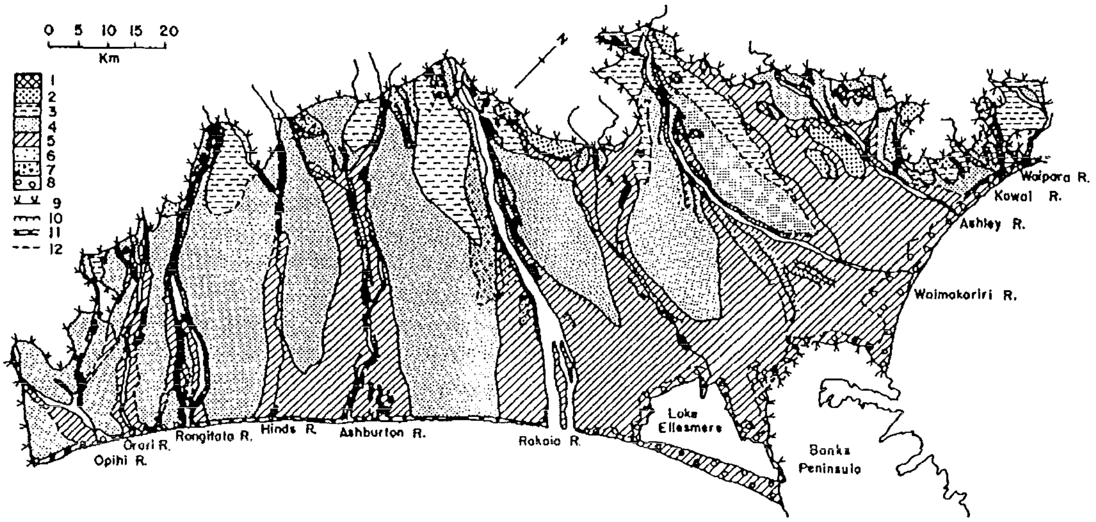

Figure 2.1: Geomorphology of the Canterbury Plains
1. Rock outcrops within the Plains
2-4. Outwash surfaces and moraines of successive ice advances: 2-Woodstock Advance and its equivalents, 3-Otarama Advance and its equivalents, 4-Blackwater Advance and its equivalents
5. Halkett Surface developed on Springston Formation
6. Areas of important aeolian deposits
7. Moraine
8. Coastal swamps and lagoons
9. Inner edge of the Plains
10. Terraces
11. Cliffs
12. Boundary uncertain
(From Fitzharris et al., 1982 p.347)

However, the geomorphological map (Figure 2.1) shows only the surface morphology. Gravel depths that constitute the Canterbury Plains are not shown. Figure 2.2 shows a probable section of the structure of the Canterbury Plains. It shows outwash gravel depths of approximately 500m. Other studies, including Walsh and Scarf (1980) and Atkins and Hicks (1979) show similar depths of gravels. The eastern extent of the

Plains is approximately 50km offshore (Kirk, 1980), beneath what is now the continental shelf.

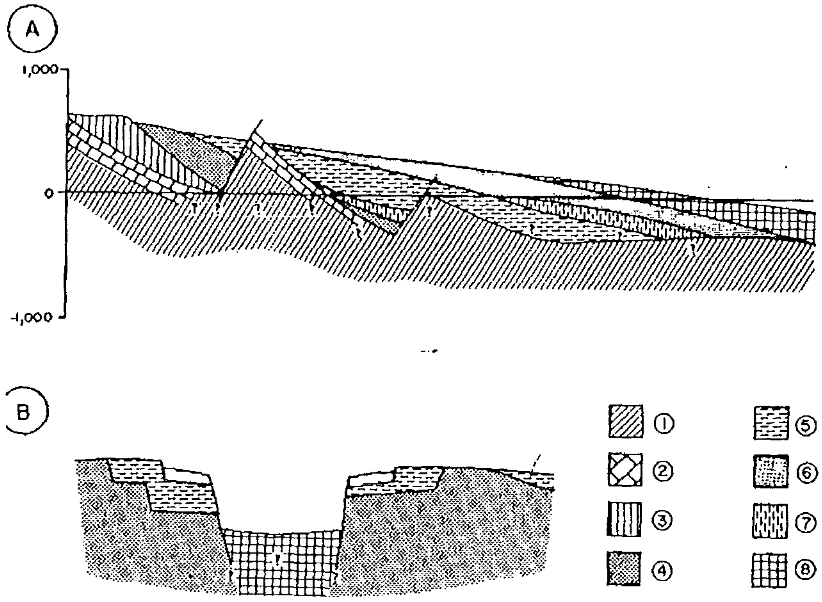

Figure 2.2: Diagrammatic section showing the probable structure of the Canterbury Plains
1. Greywacke basement
2. Cretaceous and Tertiary rocks
3-6. Glacial deposits of successive ages
7. Interglacial deposits
8. Post-glacial deposits
(From Fitzharris et al., 1982 p.347)

This section has briefly described the formation of the Canterbury Plains. They are the result of the formation of fluvio-glacial outwash fans emanating from the Southern Alps by means of four major fluvial systems, the Rangitata, Ashburton, Rakaia and Waimakariri Rivers

2.2 The mid Canterbury Coast

The coastal boundary of the southern Canterbury Plains, south of Banks Peninsula, is known as the Canterbury Bight (Figure 1.1). This coastline, often referred to as 'Ninety Miles Beach' (Speight, 1950), which is closer to 80 miles in length (Kirk, 1967), is a high energy environment, that is wave dominated, often from Antarctic storm swell (Kirk, 1980). Much of this coastline is dominated by the presence of sea cliffs that back the predominantly mixed sand and gravel beaches. This section will examine the origins and formation of these cliffs.

2.2.1 Definition

Unlike mixed sand and gravel beaches, sea cliffs are not uncommon on a world scale. For example, Emery and Kuhn (1982 p.644) estimate that 80 per cent of the Earth's ocean coast is backed by sea cliffs, and they occur at all latitudes (Figure 2.3). As defined by Zenkovich (1967), sea cliffs are subaerial scarps or steep slopes that merge near the water edge. Pethick (1984) intimates that a general, broad definition for sea cliffs is necessary in view of the wide variations and interpretations of sea cliffs in the literature.

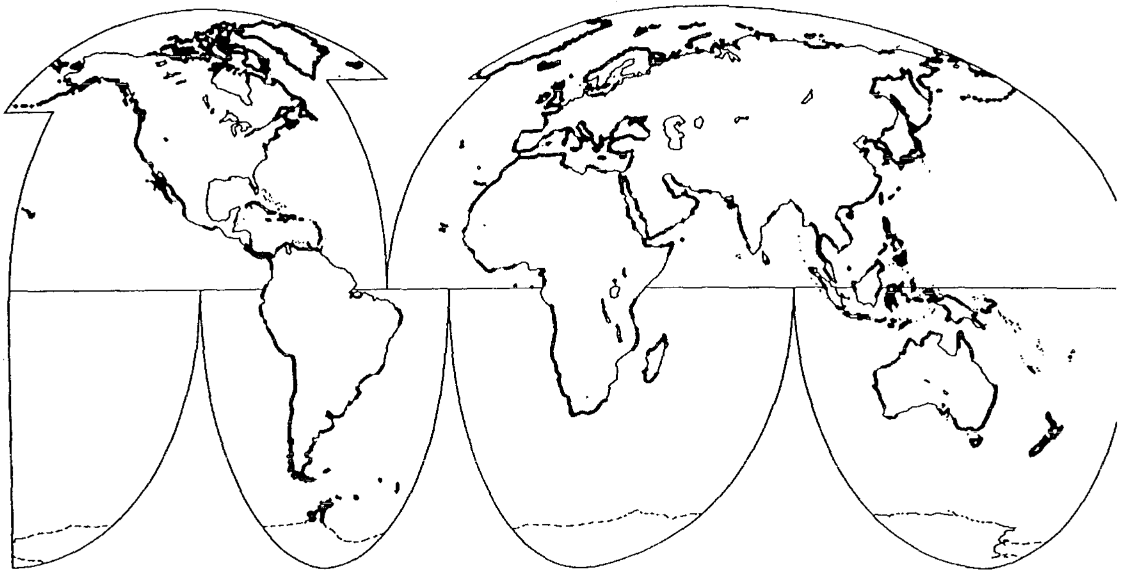

Figure 2.3: Distribution of coasts that consist mainly of sea cliffs (black), as opposed to coasts than consist mainly of beaches, mud flats, coral reefs, mangroves, and other shores unbacked by sea cliffs (From Emery and Kuhn, 1982 p.644)

There is some debate about the precise origins of various kinds of sea cliffs. Pethick (1984 p.191) goes on to say that, "The break in slope which marks the coastal cliff may be at any angle, but its position indicates that its origin is, in part at least, due to marine processes." However it is wrong to ascribe sea cliffs entirely to the action of the sea. As Zenkovich (1967) described them, sea cliffs are subaerial scarps. Therefore, they are subject to both marine and subaerial processes when it comes to their creation.

2.2.2 Morphology of the mid Canterbury Coastal Cliffs

The coastline of 'Ninety Miles Beach' is cliffed from the mouth of the Rangitata River to the mouth of the Rakaia River, a distance of approximately 60km (Figure 1.1). This thesis is concerned with only a 32km portion of these cliffs, from the Rangitata River mouth to Wakanui Creek. The 32km length of coast in question is backed by cliffs of varying heights for its entire length, except for where river mouths and dongas enter the coast. Of note are the mouths of the Ashburton and Hinds Rivers and the donga of Wakanui Creek. Plates 2.1a and 2.1b are typical of the study area.

The mid Canterbury coast, and indeed the entire Canterbury Bight coast, is geologically recent (Kirk, 1969). The cliffs themselves are comprised of Pleistocene sediments that form the Canterbury Plains (Leckie, 1994). Cliff heights vary significantly within the study area. They are at a minimum at the Rangitata River mouth with a height of approximately 9m (Plate 2.2), and rise to a maximum height of 21m about 4.5km north of the Ashburton River mouth (Plate 2.3).

2.2.3 Origins of the mid Canterbury Coastal Cliffs

Cliff heights vary due to the differing heights of the alluvial fans that make up the Canterbury Plains and to the way erosion of the coast has truncated these fans. As mentioned, the Canterbury Plains are the result of the alluvial fans deposited by the four main river systems. Primarily the Rangitata, Rakaia and Waimakariri Rivers have produced the largest fans with the Ashburton River playing a more secondary role, with its fan being much smaller than the other three. The larger fans of the Rangitata, Rakaia and Waimakariri Rivers are due to their large catchment areas that have their headwaters at the main divide of the Southern Alps. The Ashburton River on the other hand has its origins further east and has a smaller catchment as a consequence (Figure 1.1).

Kelk (1974) notes that much greater volumes of water have previously flowed through the Ashburton River. This increased discharge took place during the Pleistocene glacial and inter-glacial periods when its drainage basin received ice from

Plate 2.1a: Looking south across the Ashburton River mouth with cliffs in the background

Plate 2.1b: Unconsolidated gravel cliffs at the Ashburton River mouth. The Ashburton River mouth Hapua and the Hakatere Huts are in the background

the Rangitata and Rakaia valleys (Fitzharris et al., 1982). This enabled the Ashburton River to carry more waste and construct a large fan of its own. Therefore, the Ashburton River had a substantial influence on the building and final shape of the Canterbury Plains (Speight, 1950). While the Ashburton River fan may not be as large as the neighbouring Rangitata and Rakaia fans it is still significant within the Canterbury Plains environment.

The fans of the Canterbury Plains are approximately conical and convex upward in shape (Wilson, 1985). This, in part, explains the varying coastal cliff heights within the study area. Cliff height maximums exist where the fan height is at a maximum along the coast. Cliff height variance may also be explained by differing erosion rates. Wilson (1985) suggests that the lower cliffs at the Rangitata River mouth, as opposed to those at the Rakaia River mouth are due, in part, to a slower rate of coastal erosion. Historically this may be the case but present day erosion rates appear to be of a similar magnitude. The variations of the coastal cliffs along the mid Canterbury coast are probably due to both the differences in fan height and differences in erosion rates.

The cliffs along the mid Canterbury coast are the result of coastal processes acting through a rise in sea level that began at the end of the Otiran glaciation. Toward the end of this glaciation, approximately 20,000-16,000 years B.P., sea level was some 100-130m lower than at present (Kelk, 1974; Kirk et al., 1977; Wilson, 1985). This meant that the shoreline was about 50km seawards of the present coast (Kelk, 1974). The post-Pleistocene glaciations rise in sea level, that began approximately 16,000-15,000 years B.P., adjusted the coastal environment resulting in cliffing and erosion of the seaward edges of the fans that comprise the Canterbury Plains (Kirk, 1969). The rise in sea level continued dramatically until about 5,000 years B.P., although slowing around 7,000 years B.P. (Kelk, 1974). Over the last 5,000 years sea level has stabilised and has remained at a relatively constant level (Armon, 1974; Kirk et al., 1977).

The high energy wave environment of the Canterbury Bight and the presence of strong net littoral sediment movement has resulted in the cutting back and erosion of the fans of the Canterbury Plains, producing cliffs along the mid Canterbury coast. This cliff erosion will be discussed in Section 2.3 but, "...the long term trend is to

Plate 2.2: Unconsolidated gravel cliffs next to the Rangitata River mouth. The Rangitata River mouth Hapua is in the background

Plate 2.3: Unconsolidated gravel cliffs extending north along the mid Canterbury coast. Banks Peninsula is in the background

pronounced coastal erosion"(Kirk, 1969 p.30). This long-term erosional trend is evident when examining the amount of erosion that has occurred since sea level stabilised at its current level, 5,000 years B.P.

Kelk (1974 p.16) identifies that the slope of the Plains is approximately 8m/km in the mid Canterbury area. By using a cliff height of 20m at the coast and tracing the Plains gradient out until this line intersects the present elevation of sea level, it appears that approximately 2.5km of cliff recession may have occurred over about the last 5,000 years. Zenkovich (1967) suggests that in regions of fluvial or glacial relief, it is sometimes possible, by analysing the relief of the adjacent land area, to estimate the distance the coast has receded at a given sea level. Figure 2.4 shows the elevation contours for the Canterbury Plains. Again assuming that the coastline is at a height of 20m, there has been approximately 4-5km of cliff recession over the last 5,000 years. This erosion figure of 4-5km is similar to that found further south along the South Island's east coast at Waitaki (Hewson, 1977). The apparent long term erosion rate is also in good agreement with present day average erosion rates, which are between 0.5-1m.yr^{-1}. Given that sea level has been at its present level for about 5,000 years, there has probably been in the order of 2.5-5km of cliff retreat over that time.

Recent rates of cliff erosion along the mid Canterbury coast will be discussed in Chapter Three, but cliff recession rates show no signs of abating. Kirk (1969) suggests that a subequilibrium stage of coastal development may have been attained for the Canterbury Bight but a stable equilibrium may never actually be achieved. The cliffs of the mid Canterbury coast are erosional features and under present sea level, wave and climatic conditions this erosion may continue indefinitely.

2.3 Cliff Erosion

As Emery and Kuhn (1982) point out sea cliffs back 80 per cent of the earth's ocean coast. Much of these areas of sea cliffs are undergoing significant amounts of erosion, therefore creating a sizeable problem for many of the world's coastal areas. Large amounts of cliff erosion can lead to the destruction of property, undermining of highways and general land loss. For example Komar and Shih (1991) show that many communities along the Oregon Coast are affected by sea cliff erosion. To add to this, state lands are being lost as cliff erosion occurs at coastal parks. Also, on the Holderness Coast of England there has been some 4.8km of land lost since Roman times accounting for not only the loss of agricultural land but some thirty small towns and villages (Mason and Hansom, 1988). While this amount of land loss is extreme it does illustrate the lands vulnerability to continuing cliff erosion.

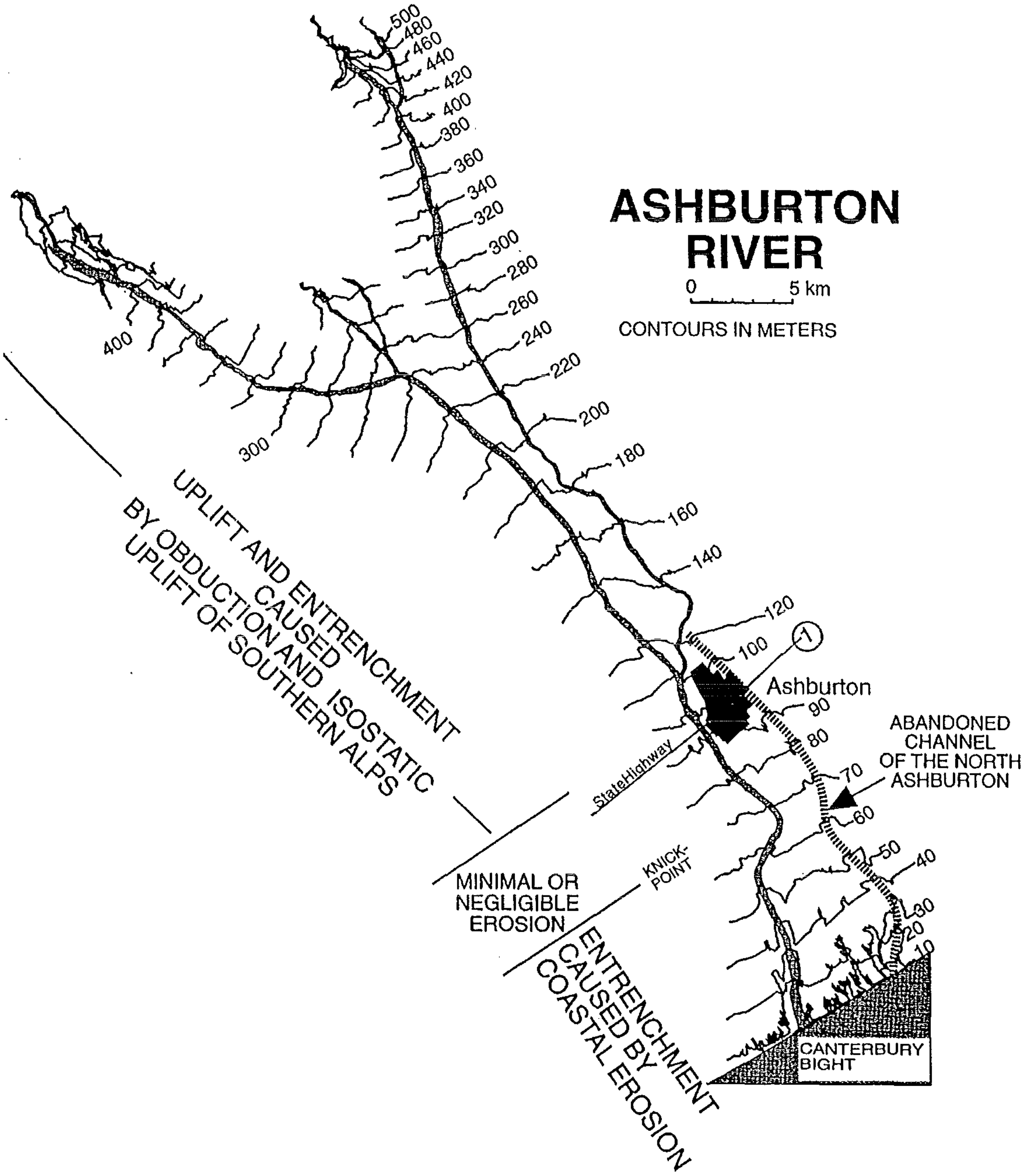

Figure 2.4: Contours of the Canterbury Plains adjacent to the Ashburton River (From Leckie, 1994 p.1251)

Komar and Shih (1993) note that in comparison with the wealth of literature on beach erosion and the associated processes, there are relatively few studies that have focussed on the problem of sea cliff erosion, even when considering the extent of the sea cliff erosion problem. They go on to say that perhaps the reason for this is the difficulty in accounting for all the variables that can affect cliff erosion.

Most of this research deals with the erosion of 'hard rock' cliffs as opposed to the 'soft' unconsolidated cliffs, like those found along the mid Canterbury coastline. Some aspects of the erosion of hard rock sea cliffs are applicable to the erosion of unconsolidated sediment cliffs. These aspects need to be addressed so that the erosion processes working on the mid Canterbury cliffs can be understood.

This section will examine and review the literature on sea cliff erosion. This will include the marine and subaerial processes involved as well as a detailed examination of the various factors that can affect these processes. Following this will be a specific examination of the processes and factors that cause erosion in cliffs of unconsolidated sediment. Another aspect of sea cliff erosion is the role that rising sea level may play. While the accuracies of the rising sea level debate will not be discussed here, it is useful to examine the effect that rising sea level may have on rates of cliff erosion.

2.3.1 Sea Cliff Erosion

Erosion can be defined as, "...the group of processes whereby earthy or rock material is loosened or dissolved and removed from any part of the earth's surface..."(Gibb, 1984 p.141). When this occurs on a subaerial scarp or steep slope that merges near the waters edge (Zenkovich, 1967), it can be said that sea cliff erosion is occurring. As mentioned, sea cliffs are the result of both marine and subaerial processes. Sunamura (1983) states that coastal cliff recession is one of the significant geomorphic events occurring at the interface of the lithosphere, hydrosphere and atmosphere. It is because of the integration of these processes that it has been difficult for geomorphologists to explain cliff erosion, due in part to a lack of quantitative studies (Pethick, 1984). This section will examine the many processes of cliff erosion and will also attempt to quantify them.

Emery and Kuhn (1982) classify sea cliffs into three categories, 1. active, 2. inactive, and 3. former. Active cliffs consist of material exposed by their continuous retreat under the influence of both marine and subaerial processes. These two processes can work separately or in conjunction with each other. Figure 2.5 displays a descriptive diagram of the cliff erosion system. The diagram indicates that toe erosion by waves or subaerial processes is essential for producing cliff erosion. What is also important to note is the importance of debris at the cliff base. The presence of debris at the cliff base impedes the ability of waves to attack the base of the cliff, which in turn undermines the cliff itself, leading to mass movement and cliff recession (Sunamura, 1983). However, cliff erosion is the direct result of two sets of processes, marine and subaerial.

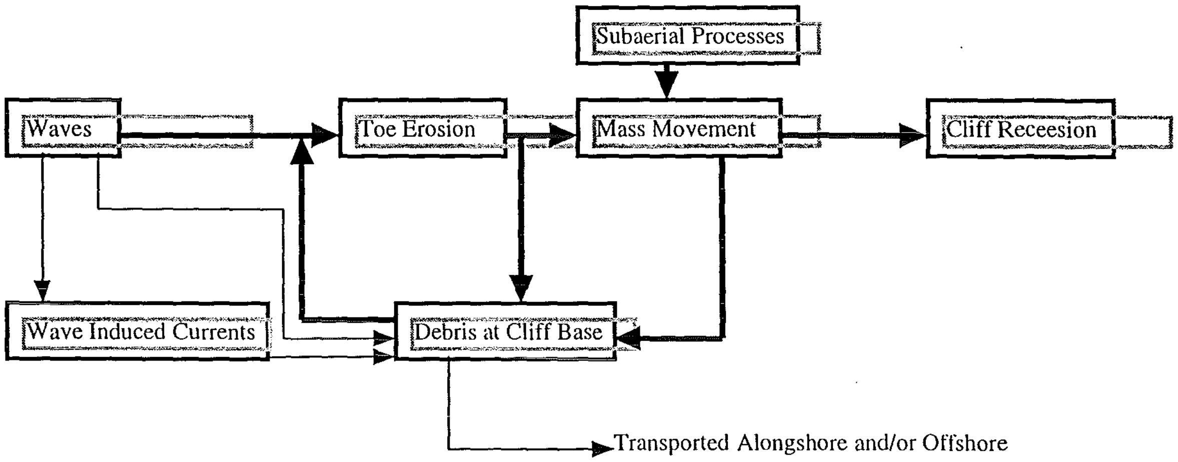

Figure 2.5: Sea cliff recession system. Toe erosion by waves is essential for continued cliff retreat. (Adapted from Sunamura, 1983 p.234)

Marine Erosion.

Emery and Kuhn (1982) suggest that marine erosion of sea cliffs at their base is achieved by abrasion, biological activity, solution by ocean water, and quarrying of blocks. Another important control on the marine erosion of cliffs, and one that is more applicable to the mid Canterbury coast, is the ability of waves to remove the debris at the cliff base (Figure 2.5). The removal of this cliff base debris is vital to the whole process of cliff erosion (Sunamura, 1983). This cliff base debris removal is usually the result of swash run-up to the cliff base (McGreal, 1979). McGreal (1979) goes on to say that erosion usually results from the smoothing action of the swash together with the erosive effect of any carried sediment. The removal of debris and any cliff toe erosion that might occur, results in the steepening of the cliff slope angle (Emery and Kuhn, 1982; Sunamura, 1983). As well as an increase in the cliff slope, toe erosion increases the stress on the slope, leading to general instability of the cliff as a whole. This instability causes slope failure in the form of mass movement of various types including slumps, rock or debris slides, mudslides, mudflows, and rock or debris falls (Sunamura, 1983).

McGreal (1979) believes that while a number of processes account for cliff line retreat, the cyclic process of wave erosion at the cliff base is of particular significance. This process includes, "slope failure - talus deposits - removal of debris by wave action - renewed wave attack at cliff base - slope failure"(McGreal, 1979 p.89).

Plate 2.4: Talus slope at the base of unconsolidated gravel cliff approximatley 600m north of the Ashburton River mouth

When the debris at the cliff base is not removed it accumulates as talus at the base (Pethick, 1984). Plate 2.4 illustrates a talus slope at the base of a cliff on the mid Canterbury coast. Accumulation of this talus has the reverse affect than the removal of it. The talus acts as a buffer between any wave attack and the cliff toe. Zenkovich (1967) believes the presence of a permanent layer of talus indicates a reduction in the erosion rate. While Emery and Kuhn (1982) classify cliffs that are mantled along the base by talus as being 'inactive.' The presence of talus may indeed indicate the slowing down or even stopping of erosion or it may simply indicate the intermittent nature of coastal cliff erosion. However, for cliff erosion to become active again any talus has to be removed.

Waves can attack a cliff by two general methods. Firstly, when a cliff is exposed to waves for at least some part of the tidal cycle the processes of abrasion, biological activity and solution become important. The second method involves the erosion of cliffs by waves during storms or high tides, so that the cliff is only intermittently exposed to wave attack. Komar (1976) believes this second method to be the most important. However, cliff erosion by storm waves is dependent on a variety of factors, as is cliff erosion as a whole. These factors include such things as beach height, tidal range and many others that will be discussed later within this section.

What is clear is that the severity and frequency of wave attack along with the degree of exposure of the cliffs to waves is fundamental when determining cliff erosion (Griggs and Trenhaile, 1994). Of equal importance is the resisting force of the cliff, whether that is the cliff material itself or the talus accumulated at the base. The other fundamental factor that influences cliff erosion by waves is time. Sunamura (1983) expressed the effect of these factors on cliff erosion (X) as:

$$X = \phi\,(f_w, f_r, t) \tag{2.1}$$

where f_w-force of waves

f_r-resisting force of the cliff

t-time

Subaerial Erosion vs. Marine Erosion

Pethick (1984) states that it is wrong to ascribe sea cliffs only to the action of the sea and marine processes, because subaerial erosional processes are of obvious importance. Kelk (1974), believes that subaerial processes are the main denudation agents, and marine processes only facilitate erosion by removing the talus accumulations at the base of the cliff.

Subaerial erosion of sea cliffs takes many forms. Pieters (1996) examines the role of infiltration and soil water movement. Emery and Kuhn (1982) believe subaerial cliff erosion takes the form of gullying and rainwash at the ground surface, while slumping and other mass movements occur due to ground water. Frost wedging may also play a part in higher latitudes, but this is not the case for the mid Canterbury coast.

Williams and Jones (1991) suggest that subaerial processes may be the dominant method of erosion for glacial sediments. Surface water wash or run-off appears to be the dominant subaerial wasting process for the unconsolidated cliffs of the West Wales Coast (Williams and Jones, 1991), which have many similarities to the mid Canterbury coast. Komar and Shih (1993) demonstrate direct impact by rainfall and groundwater seepage are the important subaerial erosion processes for the Oregon coast. Pieters (1996) indicates surface and subsurface water transport are controlling factors in the erosion process. While the role of subaerial processes in the erosion of sea cliffs will obviously vary between sites, it is clear from the literature that its role is an extremely important one.

The relative roles of subaerial and marine processes in facilitating cliff erosion vary greatly. Cliff erosion may be due to groundwater seepage and direct rain-wash while ocean waves act only to remove talus. Or on the other hand waves may directly attack a cliff at its base (Komar and Shih, 1993). Griggs and Trenhaile (1994) show convex slopes develop where subaerial weathering and erosion is dominant. Either way the processes involved in cliff erosion are complex.

Factors Influencing Cliff Erosion

Cliff erosion is difficult to both predict and explain because it is the result of a number of interacting variables (Bray and Hooke, 1997). Komar and Shih (1993) identify two 'orders' of factors that influence cliff erosion. "First order" factors act on a regional scale and include such things as relative sea level change, tectonic uplift and climate. These factors then interact with local, or "second order" factors. The role of sea level change and climate will be discussed in Section 2.3.4, but tectonic uplift will not be examined in the present research. What is of more importance are the second order factors. These factors are site specific and produce spatial and temporal variability in the processes and forms of cliff erosion (Bray and Hooke, 1997). The rate of cliff erosion is related to the interaction of the cliff-forming materials, the physical processes to which they are exposed and time (Griggs and Trenhaile, 1994). Figure 2.6 summarises the factors that influence cliff erosion.

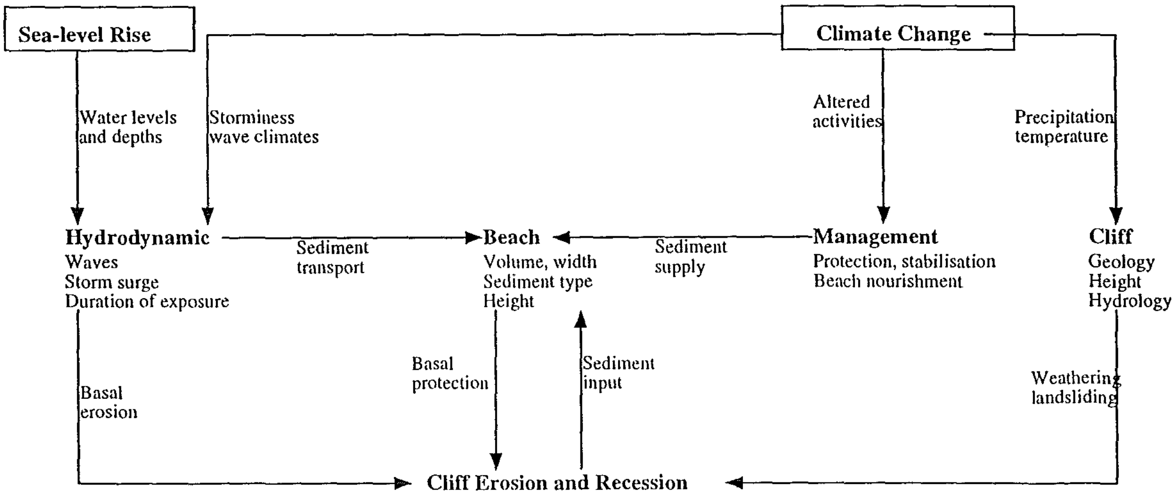

Figure 2.6: Summary of factors influencing cliff erosion
(Adapted from Bray and Hooke, 1997 p.454)

(1) Cliff Factors.

Variations in cliff erosion can be the result of the many variables associated with the cliffs themselves. Sunamura (1983) argues the resisting force of the cliff is crucial for cliff erosion. This is illustrated in Equation 2.1. Hard rock cliffs are more resistant than soft rock cliffs, and therefore erode much slower. This differing erosion rate is due to factors such as material strength and rock mechanics (Bray and Hooke, 1997). Unconsolidated cliffs are the least resistant and can, depending on other factors, erode rapidly (Komar, 1976; Griggs and Trenhaile, 1994). Soft rock and unconsolidated cliffs are more prone to erosion because they are subject to weakening by weathering and degradation by mass movement (Bray and Hooke, 1997). The differing erosion rates between hard, soft and unconsolidated cliffs are illustrated on Table 2.1. What is clear from Table 2.1 is that erosion rates for unconsolidated cliffs, such as glacial deposits similar to the mid Canterbury cliffs, are much higher than the rates for hard rock cliffs. The resisting force of the cliff is determined by its lithology (Sunamura, 1983). The mechanical strength and geologic structure, such as jointing, faulting and stratifications are also contributing factors.

Table 2.1: Worldwide Coastal Cliff Erosion Rates
(From Sunamura, 1983 pp.235-240)

Location	Lithology	Erosion Rate(m/yr)	Interval
Point Peron near Perth	Limestone	0.0002-0.001	1953-1962
Central Part, Lake Erie, Ontario	Glacial Deposits	0.25-2.75	1810-1964
Kai-iwi Beach, Wellington	Pliocene Siltstone	1.5	1876-1893
Point Kean, Kaikoura	Tertiary Mudstone	0.24	1942-1974
Holderness, England	Glacial Deposits	0.29-1.75	1852-1952
Seven Sisters, Sussox	Chalk	0.51	1873-1961
La Jolla, California	Cretaceous-Eocene sandstone	0.0003-0.0006	-
Barrents Sea coast	Granitic rocks	0.001-0.002	-
Montara, California	Miocene Conglomerate	0.26-0.29	1912-1965
Outer Cape Cod, Mass.	Glacial Deposits	0.96	1848-1888
Fairy Dell, Dorset	Marls	0.4-0.5	1887-1969

The strength of the cliff material is of obvious importance. Cliff height is another major factor that can influence the resisting force of the cliff material. Bray and Hooke (1997) suggest that cliff retreat should be more rapid with higher cliffs because they produce higher shear stresses and suffer larger mass movement events. However, Bray and Hooke (1997) point out that higher cliffs also produce more sediment so they can maintain better protective basal deposits, such as talus and higher beach profiles. The height of the cliff base is also important. Cliff base height above sea level determines how high the tide or storm waves have to be so that they can attack the cliff base. This height is especially important when there is little or no protection afforded by the beach that is seaward of the cliffs (Jones and Williams, 1991).

Pieters (1996) links the geomorphology of the cliff to other contributing factors, particularly to porosity and permeability. Seepage and the relative strengths of different layers within the cliff can greatly affect the erosion of a cliff face. This is particularly evident when examining unconsolidated cliffs.

Sunamura (1983) identifies the assailing force of waves as being the other major factor when determining cliff erosion rates. Figure 2.7 illustrates that there are several factors that influence the force of waves. These factors include not only wave characteristics but also beach characteristics and storm surge.

(2)Beach Factors.

As McGreal (1979) points out marine erosion of the cliffline is usually the result of swash run-up to the cliff base. However, this can be affected by a number of beach factors. For example beach width can impede the erosive power of the swash run-up by dissipating the energy. Bray and Hooke (1997 p.455) suggest that a mean beach width above sea level, of 20-30m, affords significant protection for the cliff while a 60m wide beach provides complete protection for the cliff toe. The degree to which a given beach width offers protection to a cliff depends also on particle size. For example, because sands are more susceptible to cross-shore transport than coarser sediment, a beach consisting of sand would require a wider beach to offer comparable toe protection (Bray and Hooke, 1997). Griggs and Trenhaile (1994) state that the presence or absence of a protective beach, permanent or seasonal, may provide the most important buffer to the cliff from direct wave attack. As mentioned, beach width and particle size plays a part in the protection of the cliff from wave attack. Beach profile height can also play an important role. As beach profile height is increased so is the height that tides and storm waves have to be so that they can attack the cliff base.

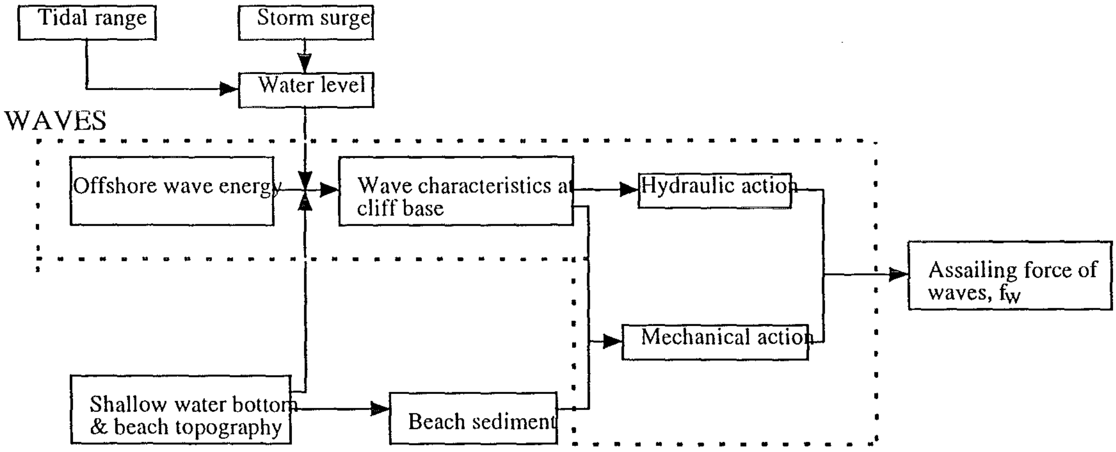

Figure 2.7: Factors influencing assailing force of waves for coastal cliff erosion (Adapted from Sunamura, 1983 p.243)

Pringle (1981) notes the presence of 'ords' along the Holderness coast of England. Ords are sections of beach that are locally extremely low. Ords occur on a section of beach where the normal upper-lower beach form breaks down. The result is the beach becomes either very low or is completely absent. The average length of an ord appears to be between 1-2km (Pringle, 1981 p.196). In between ords, where beach heights are greater than at an ord, extreme high water spring tides are necessary for waves to reach the cliff foot. For lengths of beach where an ord is present, high water spring and neap tides enable waves to reach the cliff foot, thus increasing the wave energy exerted there by 600 percent (Pringle, 1981 p.196). Therefore, due to a variety of factors, beaches can drastically influence cliff erosion, so much so that beaches can act as an extremely effective buffer between the cliff and the erosive forces of waves (Komar and Shih, 1993).

(3) Wave Factors

While it has been shown that cliff erosion is the result of both marine and subaerial processes, marine erosion is significant and is dependent on waves. Whether erosion is caused by the abrasive action of waves or simply by the removal of toe debris by swash run-up, the waves have to be of a size so that they overtop any beach offering protection to the cliff. In some instances this may happen every tidal cycle but generally this is not the case. Komar (1976) states that wave erosion of cliffs occurs chiefly during storms. The mid Canterbury coast, for example, has an average wave height of approximately 1.5m but during storm events this wave height can be between 3-6m (Kirk, 1980). This greatly enhances the waves ability to overtop the beach and attack the cliff base.

Associated with storm wave heights is water level. Often coastal storms are accompanied by a storm surge. Storm surges are caused by the adjustment of the sea surface to atmospheric pressure, alongshore wind transporting water onto or away from the coast and the wind and wave set-up (Heath, 1979; Kirk, 1979). Heath (1979 p.259) believes that storm surges of between 0.3-0.8m can occur on the New Zealand coast. However, this figure is contested as being under-estimated (Kirk, 1979). Whatever the case, storm surges have the ability to increase water level locally, allowing beach overtopping to occur. Increases in water level such as tides, particularly spring and neap tides, can also aid in the overtopping of beaches. Severe erosion may result when high tides are combined with storm waves and storm surges. McGreal (1979) states that for the Kilkeel coast in Northern Ireland, erosion only occurs when there is wave action combined with a tidal level that corresponds to the predicted mean high water springs. Surges, when coupled with already high predicted tides, may lead to catastrophic erosion events on the Kilkeel coast. Conditions for erosion were only met approximately twenty times per year in McGreal's (1979) study. This highlights the need for a number of corresponding factors to be present for cliff erosion to occur.

As has been shown there a number of variables that can influence coastal cliff erosion and the extent to which it occurs. A great many of these are localised and only occur at specific locations. For example, Komar and Shih (1993) discuss the possibility that drift logs may provide some influence. Other factors mentioned elsewhere (Komar and Shih, 1993; Pieters, 1996) but not examined in this thesis include precipitation and water throughflow. It is because of these variables that it has been difficult for researchers to quantify cliff erosion. Jones and Williams (1991) attempted a statistical analysis of ten factors influencing cliff erosion on the West Wales coast. These factors included beach face volume, tidal coverage, total beach volume, beach face width, beach face slope, beach terrace height, height of beach, aspect, beach terrace slope and strength of cliff material. Firstly, Jones and Williams (1991 p.107) did a multiple regression for the ten variables over a long-term period from 1880-1970. For this period the ten factors accounted for only 27 percent of the total variations in erosion rates. However, the multiple regression for a shorter time period (2 years) explained 92 percent of the variance (Jones and Williams, 1991). This demonstrates the difficulty in quantifying cliff erosion over long time periods, but suggests that explaining cliff erosion over the short-term is perhaps possible.

This section has highlighted that numerous factors exist that influence coastal cliff erosion. While these have been too many to discuss here, what has been shown are some of the major, more common variables. There have been attempts to quantify cliff erosion (Jones and Williams, 1991), but this is difficult and may only be possible over a short time period on spatially limited cliffs.

2.3.2 Erosion of Unconsolidated Cliffs

The sea cliffs that back the mid Canterbury coast are constructed of unconsolidated sediment. The cliffs examined by Pieters (1996) along the Morven-Glenavy coast of the South Island's East Coast, are similar to the mid Canterbury cliffs.

They are both matrix dominated with a mixture of fine and coarse sediments. Lenses of sands are also present within the cliff face (Plate 2.5). Due to the characteristics of unconsolidated cliffs they are the least resistant to erosion (Griggs and Trenhaile, 1994). This section will examine the erosion processes, and the types of erosion that are common for unconsolidated cliffs.

Plate 2.5: Sand lens within the unconsolidated sediment cliff matrix along the mid Canterbury coast

As with the erosion of most sea cliffs, the erosion of unconsolidated cliffs is dependent on a number of factors and a combination of processes. Kelk (1974) points out that the erosion of the mid Canterbury cliffs is the result of both marine and subaerial processes. He states that cliff erosion is predominantly subaerial and the sea only facilitates erosion by removing slumped material away from the base of the cliff. This steepens the cliff, enabling erosion to continue. The relationship between the two processes is undeniable. Kelk (1974) showed that unless the basal debris was removed, little erosion occurred. This is consistent with the views of Zenkovich (1967) who believes that the presence of a layer of talus suggests the slowing down of erosion. However, if this material is removed then erosion can continue.

For marine erosion to occur, waves must be able to attack the base of the cliff, in the case of mid Canterbury to remove slumped debris. For this to occur, two major factors have to be met. Firstly, lower beach crests allow beach overtopping. Pringle (1981),and Mason and Hansom (1988), both identified the role of lower beach crests for the erosion of the unconsolidated cliffs of the Holderness Coast, England. Mason and Hansom (1988 p.34) discovered a strong correlation (r=-0.827) between beach elevation and cliff retreat rate. This explains the spatial variance of erosion for a given length of coast. As storm waves attack, access to the entire cliffline is limited, leading to differential erosion. Mason and Hansom (1988) go on to say that these differential beach crest heights migrate alongshore, enabling the entire length of coast to be eroded in the long term. A related theory in which 'slugs of sediment' are envisaged to be migrating alongshore has been examined by Neale (1987). How these slugs may impede erosion will be the focus of Chapter Four. The second major factor is the need for sufficiently high waves to overtop the beach crest. The mid Canterbury coast is a high energy environment with storm waves being between 3-6m (Kirk, 1980). In the present study storm wave heights were observed to be consistent with those estimated by Kirk (1980) and they are summarised in Section 2.5. As will be shown, waves of this magnitude occur for approximately 3 per cent of the time. When these two factors are met, low beach crest height and sufficient wave heights, this facilitates marine erosion and the removal of basal debris.

Even though it has been shown that marine erosion of the basal debris is crucial for the continued erosion of the unconsolidated cliffs of the mid Canterbury coast, subaerial processes appear to cause most of the erosion. Kelk (1974 p.37) showed that slumping is by far the most significant type of erosion along the cliff-face, accounting for approximately 95 per cent of the total erosion. While this figure may appear large, slumping is also a significant wasting process for many of the world's coastal cliffs (Emery and Kuhn, 1982; Bray and Hooke, 1997). Slumping is characterised by the sliding of cliff material along well defined shear planes (Kelk, 1974). Failure by slumping is due to a loss of strength of the particles that form the cliffs. This loss of strength is facilitated by the presence of moisture. Kelk (1974) suggests that moisture affects the forces that bind the cliff particles together. This influences the arrangement of particles so that porosity, shear strength, consolidation and permeability are affected. Moisture can enter the cliff system by precipitation and irrigation and is dependent on infiltration and soil water transport rates (Pieters, 1996).

Shear strength depends on the density of the deposit and the ability of water to migrate as stress is applied. Water migration is dependent on permeability. When moisture is applied this migration may be affected causing an increase in the pore water pressure. Sand lenses (Plate 2.5) when saturated may develop high pore water pressure. Kelk (1974) states that these beds have no cohesion and their shear strength (S) is determined by:

$$S = (p - U_w) \tan \theta \tag{2.2}$$

where p is pressure, U_w is the pore water pressure and θ is the angle of shearing resistance. This relationship shows that as pore water pressure increases, the shear strength decreases until a point when the bed can no longer support the overlying mass and failure occurs (Kelk, 1974). Moisture can also contribute to erosion by other means. Particle dislodgement can be caused by direct rain-wash (Kelk, 1974; Komar and Shih, 1993), and moisture trickling down the cliff face (Kelk, 1974).

2.3.3 Erosion as an Intermittent and Multi-facetted Process

Figures 2.5 and 2.6 clearly demonstrate the multi-facetted nature of coastal cliff erosion. What is also clear is that sea cliff erosion is an intermittent and localised process. Long term erosion rates often mask shorter term variations in the erosion rates. For example, this research will show that in one case the average annual erosion rate was about 0.6m.yr^{-1} for a sixteen year period, while over 2m was eroded in the space of approximately 11 months. Mason and Hansom (1988 p.34) also report a large variation in the erosion of the Holderness Coast, England. They discovered that some cliffs remained stationary for months, while others reported recession of over 3m in 2 weeks. Figure 2.8 demonstrates temporal change of cliff recession. It shows that short term erosion events differ significantly from the long term average value.

Cliff erosion can be a localised process due to spatial variations in erosion of the cliffline. The most common cause of this are differences in beach crest elevation. These differences create spatial variations along the coast and explain why some lengths of coast erode while neighbouring cliffs do not (McGreal, 1979; Pringle, 1981; Mason and

Hansom, 1988; Bray and Hooke, 1997). Another cause of variation in the spatial distribution of erosion are variations in the resistance of the cliff forming material (Sunamura, 1983). However, the mid Canterbury cliffline is fairly uniform. Any spatial variations in the erosion of these cliffs are due more to differences in beach crest elevation than to differences in cliff forming material resistance.

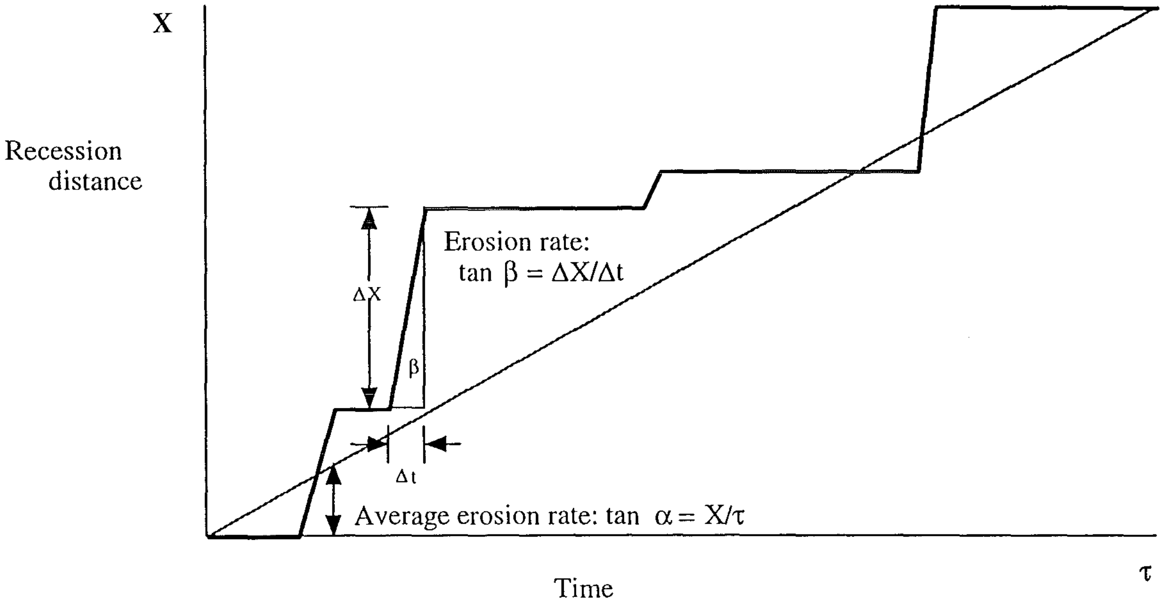

Figure 2.8: Representation of temporal change of cliff recession distance. A very short-term erosion rate, ΔW/Δt, is quite different from the long-term average, X/τ
(From Sunamura, 1983 p.241)

Figure 2.8 also illustrates temporal variations in erosion rates. McGreal (1979) suggests that temporal variations in erosion are explained by tidal and meteorological variations, such as storms, and changes in beach profiles. As mentioned only storm waves of given values are big enough to cause erosion. The more frequently that these waves attack a coast during a certain time period, the faster the cliff will recede (Sunamura, 1983). Wave conditions also exert some control on the beach elevation. Mason and Hansom (1988) believe that the frequency of high energy waves affects sediment movement, which affects the level of the beach and cliff erosion. This is an issue for the mid Canterbury coast. The wave regime of the coast is vital for the migration of 'slugs of sediment' alongshore. These slugs have the effect of raising the beach crest elevation, therefore impeding the storm waves ability to erode. This creates both temporal and spatial variations in the erosion of the mid Canterbury cliffs. Mason and Hansom (1988) also show temporal variations are caused by the dramatic erosion that accompanies heavy rain that follows a prolonged dry spell.

In the long term, coasts, especially those similar to the mid Canterbury coast, exhibit uniform coastal retreat. However, when shorter term erosion is examined there is a general pattern of spatial and temporal variation in the rates and placing of erosion. This is due partly to the multi-facetted nature of the cliff erosion process. There are many factors that contribute to or impede cliff erosion. This leads to many variations that occur in sea cliff erosion.

2.3.4 The Role of Sea Level Rise

A lot of research has focussed on the possible rise in global mean sea level that is thought to be associated with climate change projections. Rises may be due to the melting of the polar ice caps or by the thermal expansion of sea water. However, there has been as much disagreement about the sea level rise debate as there has been written on it. This thesis does not wish to enter that debate, but rather wants to examine the impact that any long term sea level rise, both eustatic or isostatic, may have on cliff erosion, particularly on the mid Canterbury cliffs.

Zenkovich (1967) states that a coast will not recede very far when sea level remains constant. Sea level has been at its current level for the past 5,000 years. However, it has been shown that for the mid Canterbury coast there has been 4-5km of recession with sea level at its current position. Therefore, a large amount of erosion is occurring while sea level is constant.

The best known model examining the relationship between sea level rise and coastal erosion is the 'Bruun Rule.' The Bruun Rule states that a given rise in sea level would result in

> *"...(a) a shoreward displacement of the beach profile as the upper beach is eroded; (b) movement of the material eroded from the upper beach would be equal in volume to the material deposited on the near offshore bottom; and (c) a rise of the near offshore bottom as a result of this deposition, equal to the rise in sea level, thus maintaining a constant water depth in that area."*
>
> (Bruun, 1988 p.631)

This 'rule' has many limitations as discussed by Bruun (1988). It was written for use when examining sea level rise on sand beaches with no longshore transport of sediment. It was not written for application on mixed sand and gravel beaches, which are backed by unconsolidated sea cliffs. Also the wave environment of the mid Canterbury coast has a very strong net longshore sediment transport component. This effectively washes away the material deposited on the near offshore bottom. Because the Bruun Rule is essentially a two-dimensional model as opposed to a three-dimensional one (Bruun, 1988), it is not applicable for use when examining the cliff erosion of the mid Canterbury coast.

Putting the Bruun Rule aside, the general belief is that there will be erosion with a rise in sea level. Bray and Hooke (1997) suggest that with a rise in sea level, nearshore water depths will increase allowing waves to break further in shore. However, this also is not an issue for the mid Canterbury coast where is the presence of a nearshore step enables waves to reach the shore largely unaffected by shoaling. Therefore, due to the high present rate of coastal erosion and the high energy wave environment that is working on the mid Canterbury coast, sea level rise and its effects may be negligible.

2.4 Mixed Sand and Gravel Beaches

Mixed sand and gravel beaches are rare on a world scale. They are also complex in nature. Zenkovich (1967) recognises that mixed beaches are complex systems. However, there are common features present on all mixed beaches. Single (1992 p.26) reviews these features.

1. They contain a wide range of sediment sizes (sand to boulders).
2. They are derived from the same dominant rock type (greywacke).
3. They are backed by Pleistocene and Holocene alluvial plains and fans often crossed by major rivers.
4. They are exposed to high-energy waves.

It has been shown that the Canterbury Plains are alluvial fans crossed by major rivers. The greywacke that is present on all mixed beaches, including the mid Canterbury beaches, comes from a number of sources. McLean (1969) reviews the supply of greywacke to the mixed beaches of New Zealand. Ultimately, the source of the greywacke is the mountain axis. Huge quantities of gravel were transported during the Quaternary glaciations by the major rivers and glaciers. However, McLean (1969) believes that the present day source of gravel is not fluvial for many reasons, including: (1) a lack of contemporary deltas at river mouths; (2) the lower reaches of some rivers are devoid of gravel; and (3) rivers are incapable of transporting the gravel bed load during normal flows. The absence of deltas can be explained by the existence of a strong net longshore sediment movement. This would remove any delta that may form. It is true that at normal flows the rivers of the Canterbury Plains are incapable of transporting gravels. However, during floods these rivers are more than capable of transporting large amounts of bedload. Chapter Four will examine the role that slugs of sediment, input by rivers, have on the coastal system. While the primary source of greywacke to mixed beaches, particularly mid Canterbury beaches, may not be fluvial, rivers do input significant and important quantities of sediment. The major source of greywacke is cliff erosion, particularly when those cliffs are cut into Pleistocene sediments (McLean, 1969). However, McLean (1969) believes that the quantity of gravel on the mixed beaches of New Zealand is too great to have been provided under present conditions. Therefore it appears that some of the gravel is relict, although Single (1992) points out that Canterbury Bight beaches are potentially well supplied from rivers and cliff erosion.

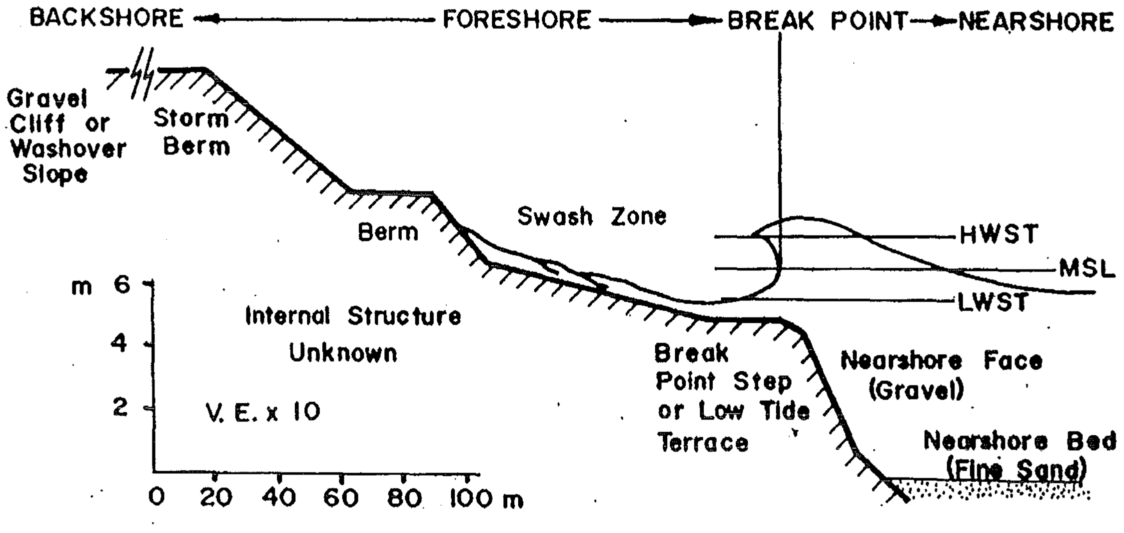

Figure 2.9: Typical morphology and zonation of mixed sand and gravel beach profiles (From Kirk, 1980 p.193)

Perhaps the most widely recognised review of the morphologies and processes of mixed sand and gravel beaches was made by Kirk (1980). Figure 2.9 illustrates the typical morphology of a mixed sand and gravel beach profile. The beach is typically 100-200m wide and rises between 4-6m above mean sea level. The backshore is usually typified by a storm berm. In the case of the mid Canterbury coast, where cliffs are present, there are no storm berms and the upper foreshore is broadly planar (Kirk, 1980). The foreshore extends from the wave break point to the base of the cliff and is steep (Single, 1992). It is here that most change occurs and Kirk (1980 p.193) described this zone as the 'engine-room' of the beach. Neale (1987) recognised the importance of the foreshore and he separated it into different facets, shown on Figure 2.10.

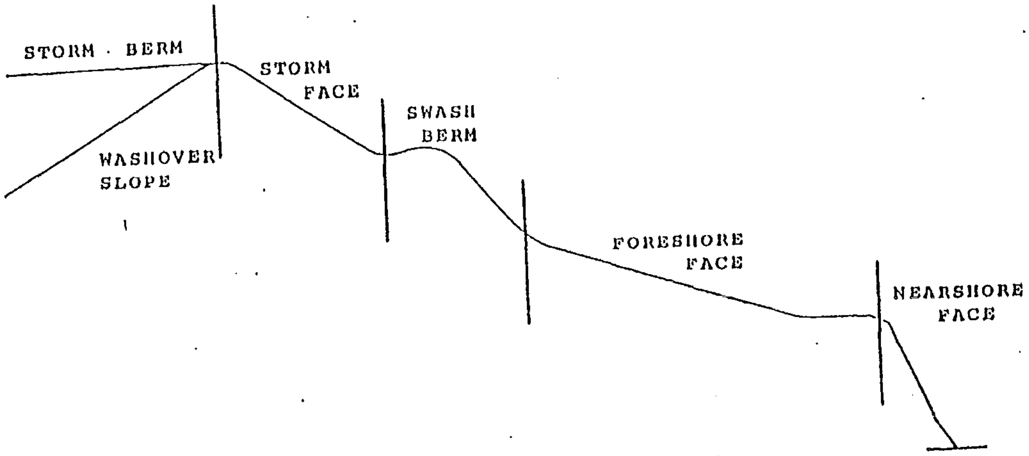

Figure 2.10: Slope facets of a mixed sand and gravel foreshore
(From Neale, 1987 p.67)

The nearshore face consists of coarse gravels and cobbles that lie at or near their angle of repose (Kirk, 1980). McLean (1969) suggests this face drops some 3-4m over a horizontal distance of only 2-3m. The nearshore face is also continuous alongshore (Kirk, 1980). Therefore, it exerts a significant control on the location of the breaking zone. Due to this nearshore face and a moderate tidal range, mixed beaches have only one line of breakers that either plunge or collapse (Kirk, 1980). This combined with the steepness of the foreshore means that there are high flow energies per unit area of beach (Single, 1992). The result is that a mixed beach has the ability to erode and transport large quantities of sediment, especially longshore. The nearshore face also creates a situation where there is little on-shore movement of sediment (McLean, 1969). Neale (1987) also discusses that the transport of sediment in this zone is complex and is determined by the initial wave shape and the beach slope.

The foreshore face is immediately landward of the breaker zone. It is in this engine-room that the unspent wave energy from the breakers, forms the swash (Neale, 1987). Neale (1987pp.70-72) also found that the width of the foreshore face is determined by swash length, which in turn is the direct result of breaker height. Kirk (1980 p.196) demonstrates swash velocities average that 1.68m.sec^{-1} and can be as high as 2.5m.sec^{-1}. These velocities are more than enough to transport any sediment that is present on the foreshore. The longshore sediment transport capabilities of the swash and backwash of the foreshore will be discussed in Chapter Four.

The swash berm exists at the upper limit of the swash. Its position is variable depending on the length and run-up height of the foreshore swash (Neale, 1987). The berm is created by the rapid drop in swash velocities (Kirk, 1980) at its landward extent. Neale (1987) also suggests that beach cusps may form which are largely confined to the swash berm.

In the presence of larger storm waves, swash lengths increase so that previously unaffected parts of the foreshore become subject to swash processes. Because this storm face is only acted upon intermittently its gradient is lower than the foreshore (Neale, 1987). The landward limit of the storm face, in the case of the mid Canterbury coast, is the base of the cliff. In fact the cliff base position may be a function of the landward extent of the storm wave swash length.

Swash zone processes drive mixed beaches. The length of the swash and therefore the elevation up the foreshore to where the swash will affect, is determined by wave height. As stated the swash zone is the engine-room of the beach system, particularly when dealing with longshore sediment transport. Also of importance is the wave and swash period ratio when determining whether there is erosion or accretion. Kemp (1960) points out that wave steepness is not as important (Single, 1992). High phase differences in the wave and swash period ratio occur when there is continual interference between the incoming wave and the outgoing swash (Kemp, 1960). That is, the outgoing swash does not have time to clear before the arrival of the next incoming wave. This results in enhanced erosion (Single, 1992). While longshore sediment transport will be considered in subsequent chapters, it is useful to note the presence of two separate transport systems. One operates seaward of the nearshore step (Figure 2.9) and causes the transport of fine and medium sands in the nearshore (Single, 1992). The second process, and most important, is beach drift which occurs in the swash zone. Because mixed beaches have only a single line of breakers under all wave conditions, longshore transport rates are related to the angle of wave approach and the wave power.

Mixed sand and gravel beaches are a common morphological feature of the East Coast of New Zealand. The entire length of the mid Canterbury coast is dominated by mixed beaches. They are morphologically different from sandy or pure gravel beaches, as are the process regimes that act upon them. This section has only briefly examined mixed beaches, their morphologies and processes. Kirk (1980), Neale (1987) and Single (1992) give more indepth reviews of these very complex beaches.

2.5 Wave Environment

The mid Canterbury coast is subject to a high-energy wave environment. Previous research has shown that average wave heights are in the range of 1-2m at breaking. Figure 2.11 shows the average wave heights for the coast extending from the Waitaki River to the Rakaia River. Clearly the predominant wave height is between 1-2m, a finding comparable to other research (Kelk, 1974; Kirk, 1980). Figure 2.11 also shows that storm waves, those with a height greater than 3m, occur for approximately 3 per cent of the time. This being between 8-10 times per year. Again this is consistent with other studies (Kirk, 1980).

Figure 2.12 illustrates the direction of wave attack. Waves from a southerly direction clearly dominate, occurring 61 per cent of the time. Of this 61 per cent, waves from the south east quadrant, from south to east south east, make up the greater proportion. Of the waves from the north, virtually all of them emanate from the north east quadrant. Kelk (1974) believe southerly waves were more common in winter conditions and northerly and easterly waves were more frequent in summer conditions. This greater proportion of waves from a southerly direction leads to a net longshore sediment movement in the north direction. Komar and Shih (1993) on the Washington coast of the U.S.A. state the majority of erosion occurs during storms. Therefore, one can assume that the majority of work on the mid Canterbury coast would be done during storm events. Storm events also come predominantly from the south (82 per cent). The present study has found there to be between 8-10 storm events per year on average. This masks variations in the year to year occurrences. The number of storm events per year ranged from as low as 3 to as high as 18 in the present research. This suggests that some years are stormier than others, therefore producing more work on the coast. This concept will be examined in more detail further on. However, any findings should be approached with caution because of the relatively short length of the data set, 1983-1995. Kirk (1980) suggests that there is no apparent seasonality of the storms. However, Kelk (1974) believes there to be added storminess during the winter. The present study shows that indeed there appears to be more storm waves (waves with a height of greater than 3m) from April to September. Approximately 69 per cent of all storm waves occur from April to September. Again any findings have to be taken with caution due to the short nature of the data set.

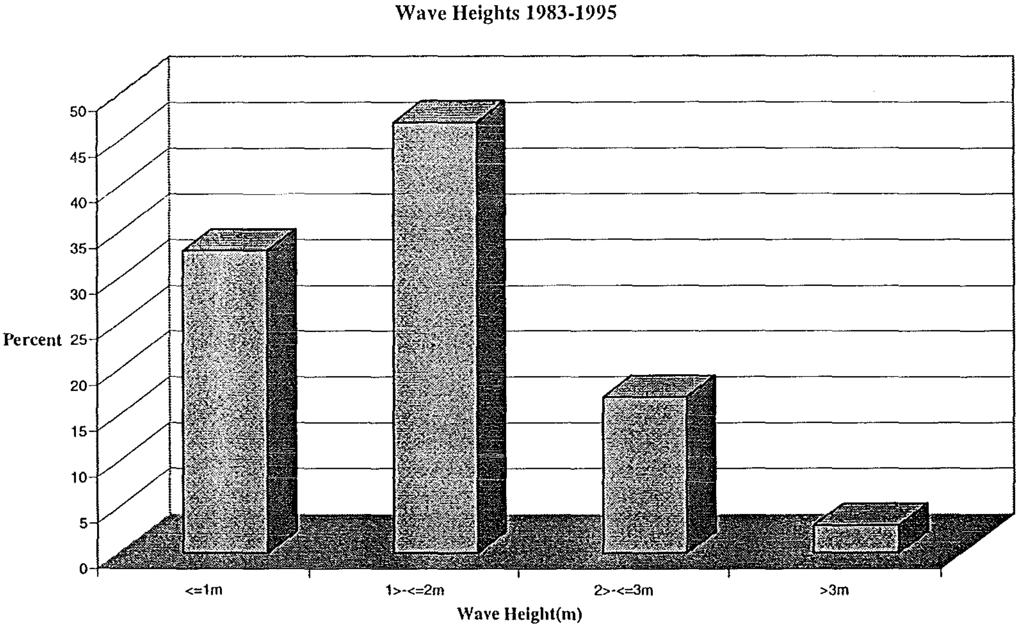

Figure 2.11: Average wave heights 1983-1995 for the Waitaki to Rakaia coast from marine forecasts

The predominance of both swell and storm waves from the south is due to the virtually unlimited fetch in the south easterly direction. Waves from this direction are generated in the Southern Ocean with the dominant and most powerful waves originating from cyclonic weather systems (Neale, 1987). The bathymetry of the continental shelf that extends east from the coast of mid Canterbury has a gentle gradient of 1:500 to a depth of 200m (Neale, 1987 p.55). Because of the depth and low gradient of the continental shelf, the effect of the seabed on the waves is low, therefore wave propagation is largely unaffected. This coupled with the nearshore face, large and highly erosive waves, predominantly plunging (Kelk, 1974), attack the mid Canterbury coast. Because of the nearshore face, the pattern of wave breaking is concentrated on a small area of the beach profile. When combined with the steep foreshore and high energy waves, high flow energies per unit area of beach result (Single, 1992), creating a highly erosional system. Waves from the north east quadrant, while being fairly common, tend to be smaller and less powerful due to their more localised origins.

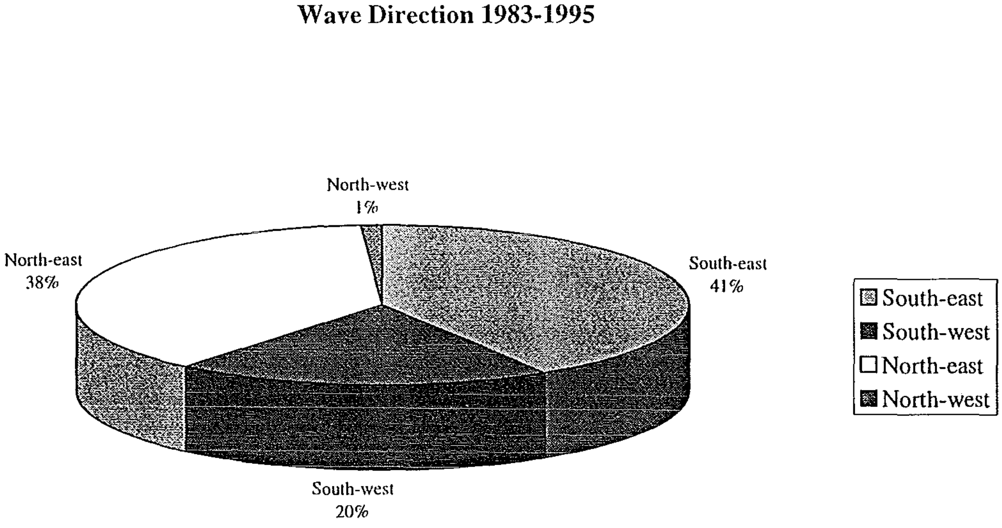

Figure 2.12: Wave direction 1983-1995 for Waitaki to Rakaia coast from marine forecasts.

2.6 Summary

Speight (1950) describes the mid Canterbury coastline as being a relatively featureless one. He failed to recognise the morphologically diverse landscape that exists along the mid Canterbury coast. Indeed the features found along the mid Canterbury coastline are not only varied but are rare on a world scale. Mixed sand and gravel beaches and the mouths of the Canterbury Plains rivers, or Hapua (to be reviewed in Chapter Five), while being common along the East Coast of the South Island are relatively rare throughout the world.

The mid Canterbury coast is erosional in origin and is geologically recent. The entire landscape having been formed since the Pleistocene, with the beaches and cliffs having only been produced in the last 5,000 years. The sea cliffs of the Canterbury Bight are the result of the cutting back of the alluvial fans that make up the Canterbury Plains. These cliffs erode predominantly due to subaerial weathering, while marine processes facilitate the erosion by removing any slumped material from the base of the cliff. However many factors affect the erosion of the sea cliffs. These factors include cliff material resistance, beach width, wave height and numerous others. Cliff erosion has been shown to be a multi-facetted process (Figure 2.6) dependent on a number of variables.

Mixed sand and gravel beaches are both rare on a world scale and more complex than either sand or gravel beaches. Their morphologies and process regimes are complicated and are vastly different than those of pure sand or gravel beaches. The presence of a nearshore face resulting in a single line of breakers leads to mixed beaches being in a high wave energy environment. This has resulted in a long history of erosion and longshore sediment transport, both of which will be discussed in Chapters Three and Four.

Knowledge of the various components of the mid Canterbury coast has been given in this chapter. This knowledge is important in the context of what this thesis will be examining. Chapter Three will examine rates and patterns of coastal change, particularly looking at cliff erosion. Therefore, the knowledge of cliff erosion given by this chapter is crucial for understanding the coastal change that occurs along the mid Canterbury coast. Chapter Four examines longshore sediment transport. Because the beaches of mid Canterbury are comprised of mixed sand and gravel, this is the material that will be transported. Knowledge of mixed beaches helps in the understanding of longshore sediment transport along the mid Canterbury coast. This chapter has given information that is required for the understanding of the change and processes that occur along the mid Canterbury coast.

Chapter Three

Rates and Patterns of Coastal Change

Coastal erosion has a long history on the Mid Canterbury coast. Approximately 4-5km of land has been eroded over the last 5,000 years. This erosion continues in the present day and has been reported on numerous occasions (Speight, 1950; Kirk, 1969; Kelk, 1974; Gibb, 1978). However, previous research has relied on aerial photographs, which only give total erosion over a long time period, and short-term monitoring. These studies are useful when examining long-term average erosion trends or when looking at changes that occur within the space of a year. Unfortunately they are unable to examine coastal change on an annual basis. This chapter will review and examine cliff and beach profile data that has been measured annually over a fifteen-year period.

By focussing on a fifteen-year data set, this thesis will be able to extract coastal change patterns that previously have been difficult to find. By examining annual data, analysis of the times when major erosion events may have occurred becomes possible. Variations in the effects of year to year storminess can be examined, as can the effects of the El Nino Southern Oscillation phenomena. This type of evaluation has not been possible in previous research because of the limited nature of the available data. Therefore, this thesis presents new research in that it examines rates and patterns of coastal change previously not attempted in the literature.

The present chapter will firstly summarise previous research that has examined erosion and coastal change along the mid Canterbury coast. This work is limited not only in the nature of the data but in the actual number of studies that have concentrated on the mid Canterbury coast. However, it is useful to compare the findings of past research with the findings of this thesis. As mentioned, the ground survey data used for this thesis is of a longer-term nature than has been available in previous studies. A description of the nature of the data will be given.

The recession of the coast will be investigated in detail. This will include the recession of the cliff top. It will not simply be an investigation into the rate of recession. Rather, both spatial and temporal patterns in the recession of the mid Canterbury coast are investigated. Explanations for the recession will then be sought through marine forecast wave data. Chapter Two outlined the importance of beach width and volume in cliff erosion. Of equal importance in the mid Canterbury context is talus volume.

Therefore, it is necessary to examine changes in the beach and talus volumes as well as changes to beach width.

Chapter Six will outline a coastal sediment budget and its significance. A vital part of the budget for the mid Canterbury coast is the contribution that is made by the erosion of the cliffs. This chapter will examine the volume of sediment that is supplied to the mid Canterbury coast by cliff erosion. However, more than just a total volume will be given. Spatial and temporal variations in cliff erosion also enable annual cliff erosion volumes for different sections of the coast to be given.

The periodicity of coastal storms may produce intermittency in the erosion of the coastal cliffs of mid Canterbury. This periodicity may include variations in storminess from year to year as well as long term patterns storminess. New Zealand is affected by a Southern Oscillation producing two distinct weather regimes, El Nino and La Nina. These two patterns have different effects on different parts of the country. This chapter will examine possible links between the Southern Oscillation and erosion on the mid Canterbury coast as well as other variations that may affect cliff erosion.

This chapter will largely be a descriptive account of coastal change along the mid Canterbury coast since 1981. This will include an examination of the recession of the coast, the role of beaches and talus on erosion, the volume contributed to the sediment budget by cliff erosion, and the possible effects of periodicity. Attempts to quantify the coastal erosion will also be done.

3.1 Previous Research on mid Canterbury

Speight (1950) was one of the first to concentrate on the Canterbury Bight coastline. His study involved the geomorphological description of coastal features from north of the Rakaia River mouth to the Rangitata River mouth. He also estimated rates of erosion. Speight's (1950) findings demonstrate the localised nature of cliff erosion as discussed in Chapter Two. He noted that some farmers experienced sea-frontage losses of approximately two feet per year (about 0.6m), while other farmers had little coastal erosion (Speight, 1950 p.11). Speight also discussed the erosion and cutting back of the coast which necessitated that roads had to be moved. The Rakaia Mouth Settlement road, for example, had to be moved back about a chain (approximately 20m) since the place was first inhabited (Speight, 1950 p.11). However, he did not specify on what side of the river the road was. Speight not only discusses contemporary erosion of the Canterbury Bight, he goes on to examine past erosion. He discovered that if the slope of the surface of the plain continued seaward at the same angle as that between Chertsey and Wakanui, then the plain would have intersected the surface of the sea 2.5 miles (about 4km) from the present shore (Speight, 1950 pp.11-12). This is consistent with the findings in this study as discussed in Chapter Two. Speight also identified the role that river mouths play in the erosion of the coast, in particular the erosion of the cliffs. He suggested that the cliffs on the northern side of the river mouths have eroded further than their southern counterparts. This is due to the direct erosion of the cliffs by the rivers. This phenomenon has also been examined by Kirk et al. (1977) and will be discussed in more detail later. Speight recognised present day and long-term erosion has been taking place along the Canterbury Bight coastline at a rate of approximately 0.5m per year.

Kirk (1967, 1969) was the next to comprehensively examine the Canterbury Bight coast. He mainly focussed on beach morphology and erosion. However, he noted that retrogression of the cliff line was approximately three feet per year (about 0.9m) and that it occurs everywhere along the Bight, except for the northern and southern termini (Kirk, 1967 p.24). This erosion is also likely to occur at any time throughout the year (Kirk, 1967). Kirk (1969 p.31) also illustrates the intermittent nature of coastal erosion. For one site erosion rates varied markedly over time. From 1931-1945 erosion averaged 0.15 (0.05m) feet per year. This figure increased to 3 (0.9m) feet per year for the period 1945-1962. 1962-1965 produced erosion of 1.67 (0.5m) feet per year while from 1965-1967 erosion was 5 (1.5m) feet per year. These figures are for the coastline north of the Rakaia River mouth, which is not cliffed. However, they clearly show how long-term averages can mask and distort erosion rates. It also shows the intermittent, event orientated nature of coastal erosion, as discussed in Chapter Two.

Kelk (1974) produced the most comprehensive study of the mid Canterbury coast to date. His examination concerned morphologies and processes. He studied the three major morhphological components of the mid Canterbury coast: the cliff line, the beaches, and the river mouth lagoon. As part of his study, Kelk (1974) examined the erosion of the cliff line comprehensively. This included types and causes of erosion, as well as rates of cliff recession. The types and causes of erosion have been summarised earlier in Chapter Two. Kelk (1974) discovered that cliff erosion can occur without registering any summit retreat. This occurs by slumping that severs at the loess shingle interface, leaving remnants. While Kirk (1967) believes that cliff erosion can occur at any time throughout the year, Kelk (1974) showed that 90% of the cliff erosion during his study occurred from July to October. However, his results are for a nine-month period only so caution has to be used when interpreting his results. Kelk (1974) believed that moisture was paramount to any seasonal variations in cliff recession. The increased moisture in winter due to the cliff line lying in shadow, sea spray and heavy rain allows more erosion to occur during this time of year.

Kelk (1974) found an average cliff recession of 1.53m during his nine-month study period. This corresponds to an equivalent annual rate of retreat of approximately $2m.yr^{-1}$. Erosion rates for cliffs north and south of the Ashburton River mouth were both approximately 1.5m (approximately $2m.yr^{-1}$). However, erosion of the cliffs landward of the river mouth lagoon was at a much slower rate, $0.32m.yr^{-1}$. Therefore, Kelk (1974) suggests that the sea seems to play a significant role in cliff retreat while those cliffs protected by the lagoon exhibit little recession. Kelk's recession results appear to be much larger than the other studies reviewed in this section. Kelk noted that during his study period, Canterbury experienced a year with extremely high precipitation and a number of exceptionally high tides, such as occur only every few hundred years. Both phenomena enhanced cliff erosion. However, this again illustrates the periodic nature of cliff erosion.

Kirk et al. (1977) focussed more on the role the Ashburton River mouth has on coastal cliff erosion. They state that some of the most rapid erosion rates occur on the northern margins of the river mouths. This is related to the flow of the river. In times of prolonged low flow the river mouth can close. This closure is inevitably followed by high river flows. When this occurs, flows and turbulence within the lagoon increase so erosion of the cliffs takes place. This continues until either the flow begins to subside or the barrier is breached.

Table 3.1: Erosion rates for the mid Canterbury coast from previous studies

Location	Erosion Rate ($m.yr^{-1}$)	Source
Canterbury Bight	0.60	Speight (1950)
Canterbury Bight	0.90	Kirk (1967)
Canterbury Bight	0.04 (1931-1945)	Kirk (1969)
Canterbury Bight	0.90 (1945-1962)	Kirk (1969)
Canterbury Bight	0.50 (1962-1965)	Kirk (1969)
Canterbury Bight	1.50 (1965-1967)	Kirk (1969)
North and South of Ashburton River mouth	1.50m (for 9 months)	Kelk (1974)
Cliffs landward of Ashburton River mouth lagoon	0.24m (for 9 months)	Kelk (1974)
North Rangitata Riv. mouth	0.27 (1939-1961)	Gibb (1978)
Beach Road	0.73 (1939-1965)	Gibb (1978)
Twentyone Road	0.91 (1939-1965)	Gibb (1978)
North Hinds Riv. mouth	0.23 (1939-1965)	Gibb (1978)
Tansey's Road	0.55 (1941-1965)	Gibb (1978)
South Ashburton River	0.38 (1941-1965)	Gibb (1978)
North Ashburton River	0.68 (1941-1976)	Gibb (1978)
Wakanui	0.84 (1942-1976)	Gibb (1978)
450m south of southern Ashburton River bank	0.51 (1941-1990)	CRC (1993)
150m south of southern Ashburton River bank	0.50 (1941-1990)	CRC (1993)
Hakatere Settlement Road	0.17 (1941-1991)	CRC (1993)
200m north of northern Ashburton River bank	0.33 (1941-1990)	CRC (1993)
500m north of northern Ashburton River bank	0.25 (1941-1990)	CRC (1993)
900m north of northern Ashburton River bank	0.29 (1941-1991)	CRC (1993)
1,500m north of northern Ashburton River bank	0.53 (1941-1990)	CRC (1993)

Note: CRC = Canterbury Regional Council

Gibb (1978) examined rates of coastal erosion and accretion for New Zealand. His study used aerial photographs, cadastral plans and field measurements to examine 471 sites around New Zealand. Gibb (1978) had 8 sites within the study area of the present research, from the Rangitata River mouth to Wakanui Creek. He discovered erosion rates that are comparable to those of the other studies already mentioned in this section. Erosion rates varied from 0.23 to $0.91 m.yr^{-1}$.

The Canterbury Regional Council (CRC Report, 1993) evaluated coastal erosion adjacent to the Ashburton River mouth from aerial photographs from 1941 to 1991. Their study examined seven sites starting at 450m south of the southern river bank to 1,500m north of the northern river bank. Erosion rates were at a maximum at the northern and southern extremes of the study area, approximately $0.5m.yr^{-1}$. They were at a minimum where the cliffs are protected by the lagoon, about $0.2m.yr^{-1}$-$0.3m.yr^{-1}$.

There is not a void in research on erosion for the mid Canterbury coast. Table 3.1 summarises the erosion rates for the present study area from previous research. This table shows the mid Canterbury coast is erosional in nature. Erosion varies between different studies and different sites. With the exception of Kelk (1974), erosion has been determined by examining historical records such as aerial photographs and cadastral plans. A lack of actual field measurements over a time period of more than one year is evident for the mid Canterbury coast. Kelk (1974) notes that figures derived from maps and aerial photographs are lower than erosion measured by ground survey. Therefore, erosion data for the mid Canterbury coast to date may not give a true indication of the extent and rates of erosion. This thesis, using cliff and beach profile data measured yearly for fifteen years, will give a better indication of erosion rates and patterns for the mid Canterbury coast.

3.2 Coastal Monitoring Network

The main focus of this thesis is the change to the mid Canterbury coastal environment. Monitoring and identifying this change has been done by analysing a number of cliff and beach profiles. Figure 3.1 shows the sites of the twenty-five profiles used for the present research. The Canterbury Regional Council maintains the profile sites. The profile sites are roughly evenly spaced along the coastline from the northern banks of the Rangitata River to Wakanui Creek, approximately 5km north of the Ashburton River mouth. The entire length of the study area is about 32km. Profile sites are named either Ashburton or Rangitata, depending on their proximity to either river. Profile names are also accompanied with a number, signifying the distance from the Opihi River mouth to the profile site in kilometres. The majority of the profiles were established in 1981 and continue through to 1996. Some profiles are of a shorter duration. Due to the varying widths of beaches and heights of cliffs between every profile, graphing all the profiles on the same axis parameters is impractical. Therefore, different sets of graph parameters have been used. Direct comparisons between profiles therefore, have to be done with caution.

To aid in the identification of erosion patterns a number of other data sets have been used. Marine forecasts for the Waitaki-Rakaia coastal region from 1983-1996 have been utilised. These data include average wave heights and direction. Mean daily discharge data for the Ashburton and Rangitata Rivers have also been used. These data run from 1982 to March, 1997. However, the river discharge data is measured at upstream locations. Goring and Valentine (1995) noted that the use of upstream data sources for use at the mouth of the Rakaia River is problematical. Problems arise because of the interaction with groundwater as the braided river flows over beds of porous gravels. However, measurement of river discharge on braided rivers such as the Rakaia, Ashburton and Rangitata is only practical at a point where all channels combine, for example in a gorge (Goring and Valentine, 1995). Goring and Valentine (1995 p.9) discovered that only approximately 10 per cent of flow was lost between the gorge and the mouth on the Rakaia River. A small amount considering the distance between the two measuring points, about 64km. They also discovered that the groundwater effect during medium and high floods was insignificant. Therefore, while the use of upstream flow data on the Ashburton and Rangitata Rivers may be problematical, it is still useful in the context of this study. The main role of the discharge data is to enable examination of the effect that floods may have on the coastal erosion of the mid Canterbury coast. Another aspect to be considered by this thesis is the role of the El Nino Southern Oscillation. Therefore, data from 1981-1996 on the Southern Oscillation has been obtained.

This chapter thus presents analysis of a wide range of data to examine the rates and patterns of coastal change along the mid Canterbury coast. Such an examination has not been attempted before on the mid Canterbury coast. Also of note is that no significant research has occurred on the mid Canterbury coast since Kelk (1974), 23 years ago. Significant time has elapsed and sufficient data have been collected that longer-term studies of cliff erosion based on ground surveyed data are now possible.

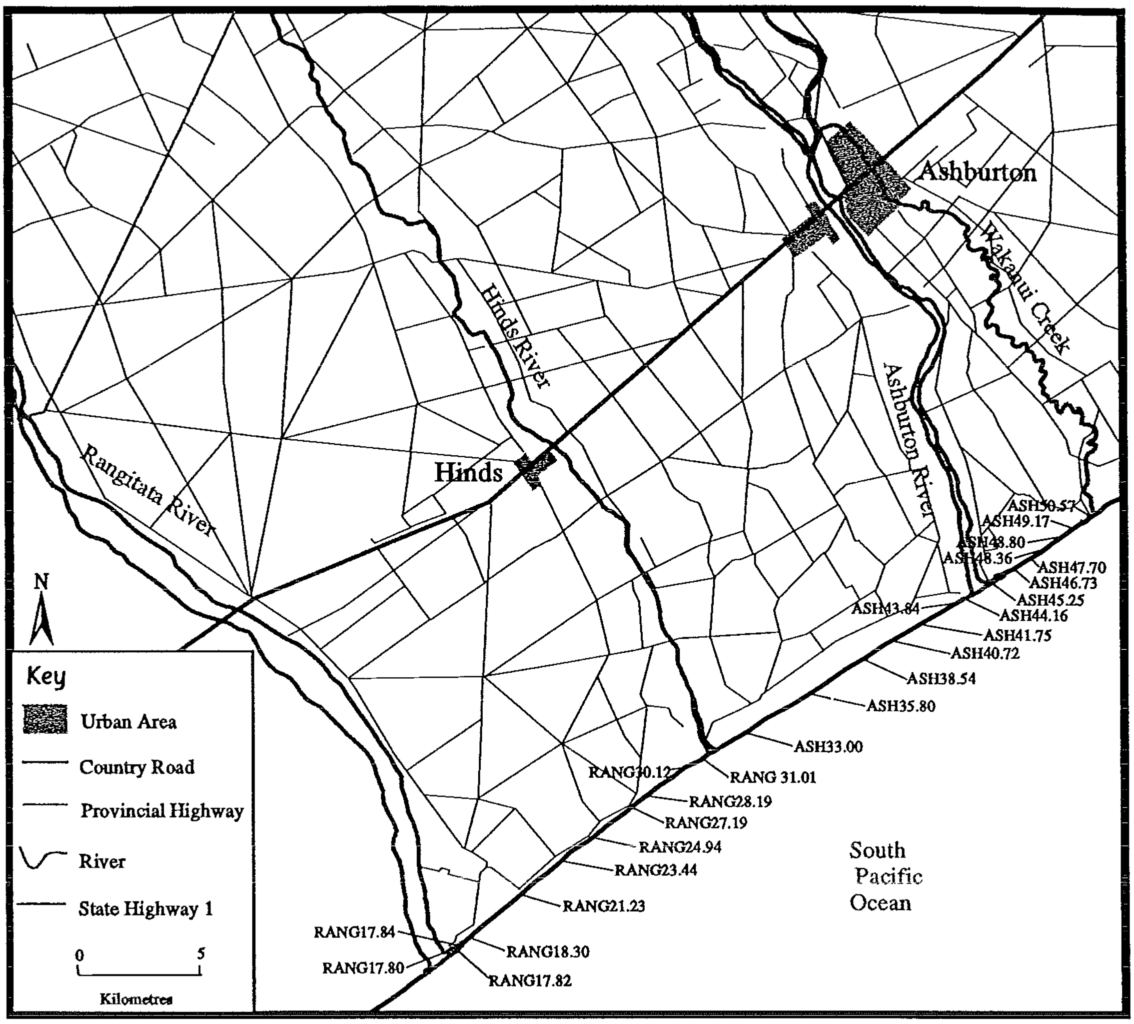

Figure 3.1: The mid Canterbury coastline showing cliff profile survey sites. (Data from the Canterbury Regional Council)

3.3 Coastal Recession

3.3.1 Spatial Patterns of Erosion

Clearly due to its linear nature, the mid Canterbury coastline has eroded in a roughly uniform fashion over its length during the last 5,000 years. However, as discussed in Chapter Two, erosion is not spatially uniform at relatively shorter time periods. This is evident when examining cliff recession rates over the last approximately fifteen years. Figure 3.2 summarises the average cliff top recession rates for 21 of the profile sites from 1981-1996. As can be seen there are large variations from the mean recession rate for the entire coast, which is 0.43m.yr^{-1}. Erosion rates are as high as 1.09m.yr^{-1}, and are as low as 0.03m.yr^{-1}. This mean rate of cliff top recession is much lower than other values reported in the literature (Table 3.1). This is surprising considering that the data used in the present research is from ground survey. According to Kelk (1974) measured rates of recession should be higher than rates deduced from aerial photographs.

Cliff top recession is clearly not spatially uniform, as shown in Figure 3.2. There are large fluctuations around the mean that appear to be random. Erosion rates vary from 0.03 to 1.09m.yr^{-1}. However, erosion appears to increase as you move northward through the study area. This trend occurs for both the maximum and minimum erosion rates. Also on Figure 3.2 is the trendline for the erosion rate. This line shows that for every kilometre northward along the coast, there is a subsequent increase in the erosion rate of approximately 0.02m.yr^{-1}. This is significant because erosion rates at the extreme northern end of the study area are about 0.7m.yr^{-1} greater than those at the southern extreme. The disparity in erosion rates may be due to the proximity of the various parts of the coast to major sediment sources. The lowest erosion values are on the cliffs just north of the northern banks of the Rangitata River mouth. Suggesting that the Rangitata River may provide sediment to the beaches which slows down erosion. Erosion increases until Wakanui Creek, at the northern end of the study area, is reached. The Ashburton River appears to have only a slight, if any, impact on the erosion rate. This suggests that the Ashburton River may not be a major contributor of sediment to the coastal environment. Therefore, the Rangitata River appears to be a more important sediment contributor to the coastal environment than the Ashburton River and the further away from the major sediment source, more erosion occurs.

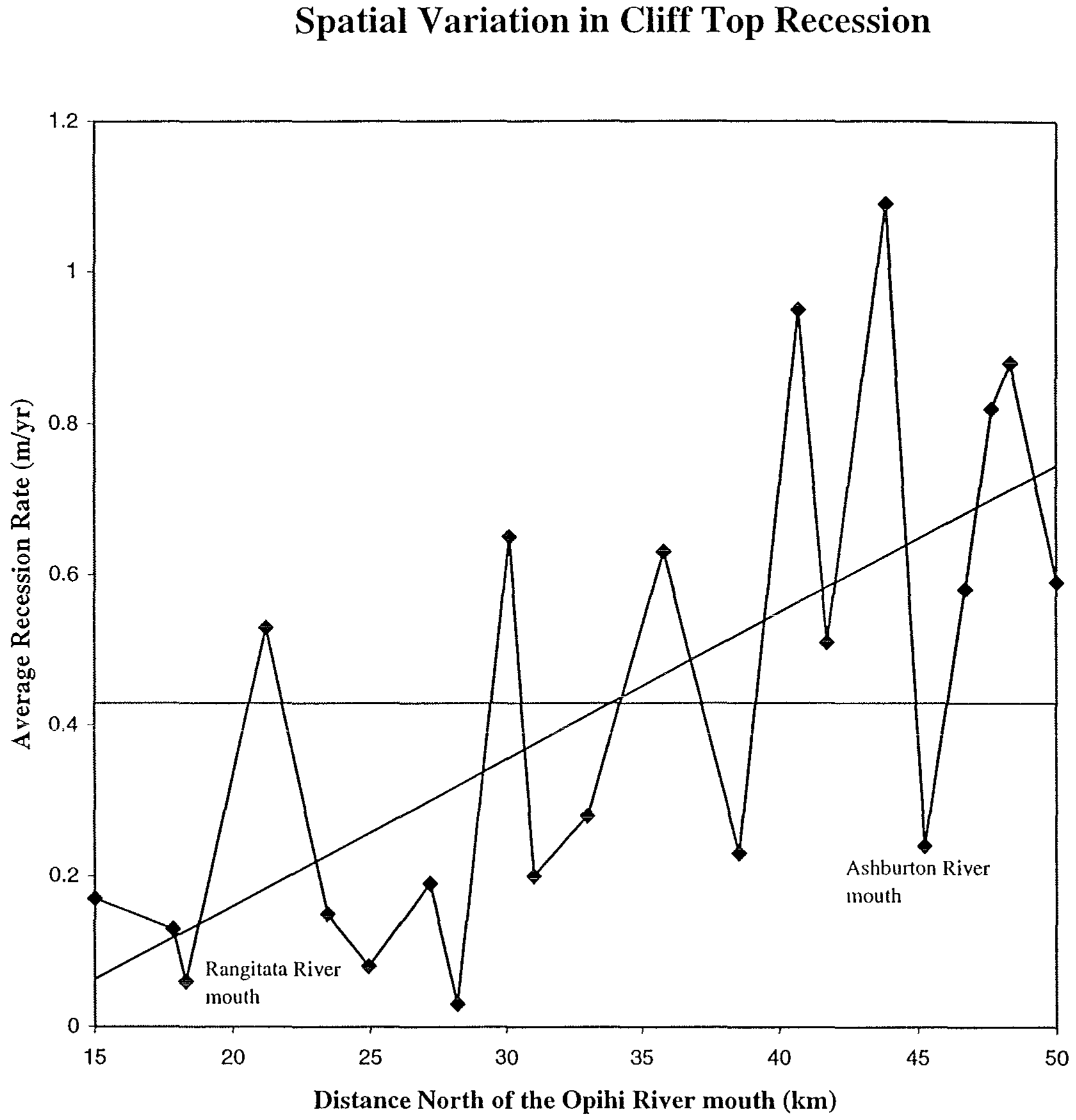

Figure 3.2: Average cliff top recession rates for the mid Canterbury coast, 1981-1996
(Data from the Canterbury Regional Council)
(Nb. Mean recession rate for entire coast = 0.43m.yr^{-1})

Cliff height may also be a factor in the variation of the erosion rate. Bray and Hooke (1997) suggest that higher cliffs retreat at faster rates. This occurs because they generate higher shear stresses, so they suffer larger landslides. The cliffs at the northern end of the study area are about twice as high as the cliffs at the southern end. The cliff

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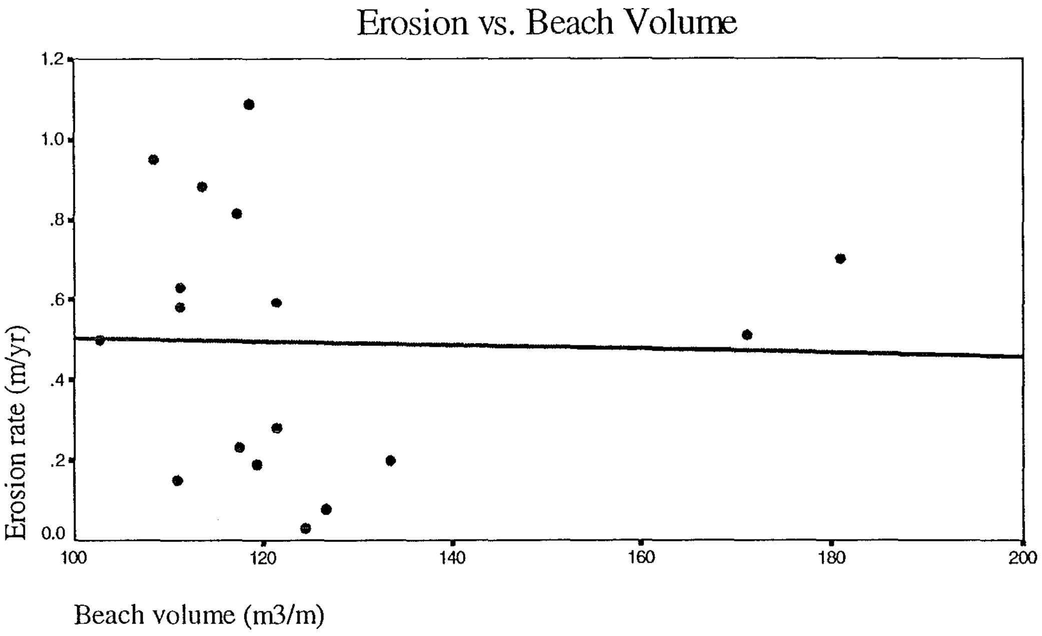

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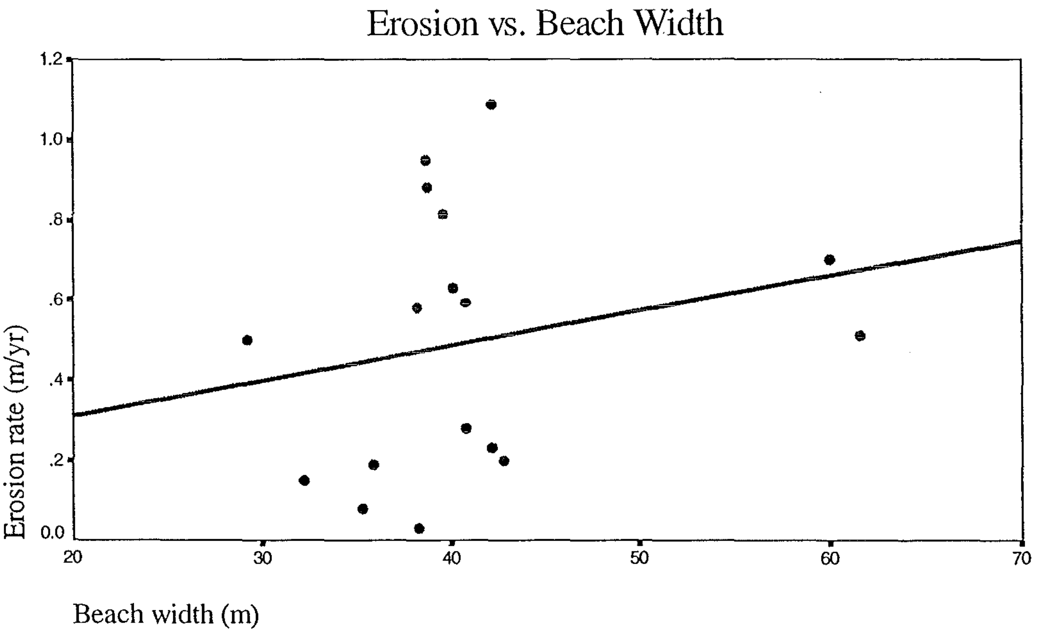

Figure 3.3: Relationship between spatial variations in erosion rate and beach and cliff factors (1981-1996) for the mid Canterbury coast

A. Beach Volume (r = -0.029 where p=0.913)
B. Beach Width (r = 0.222 where p=0.392)

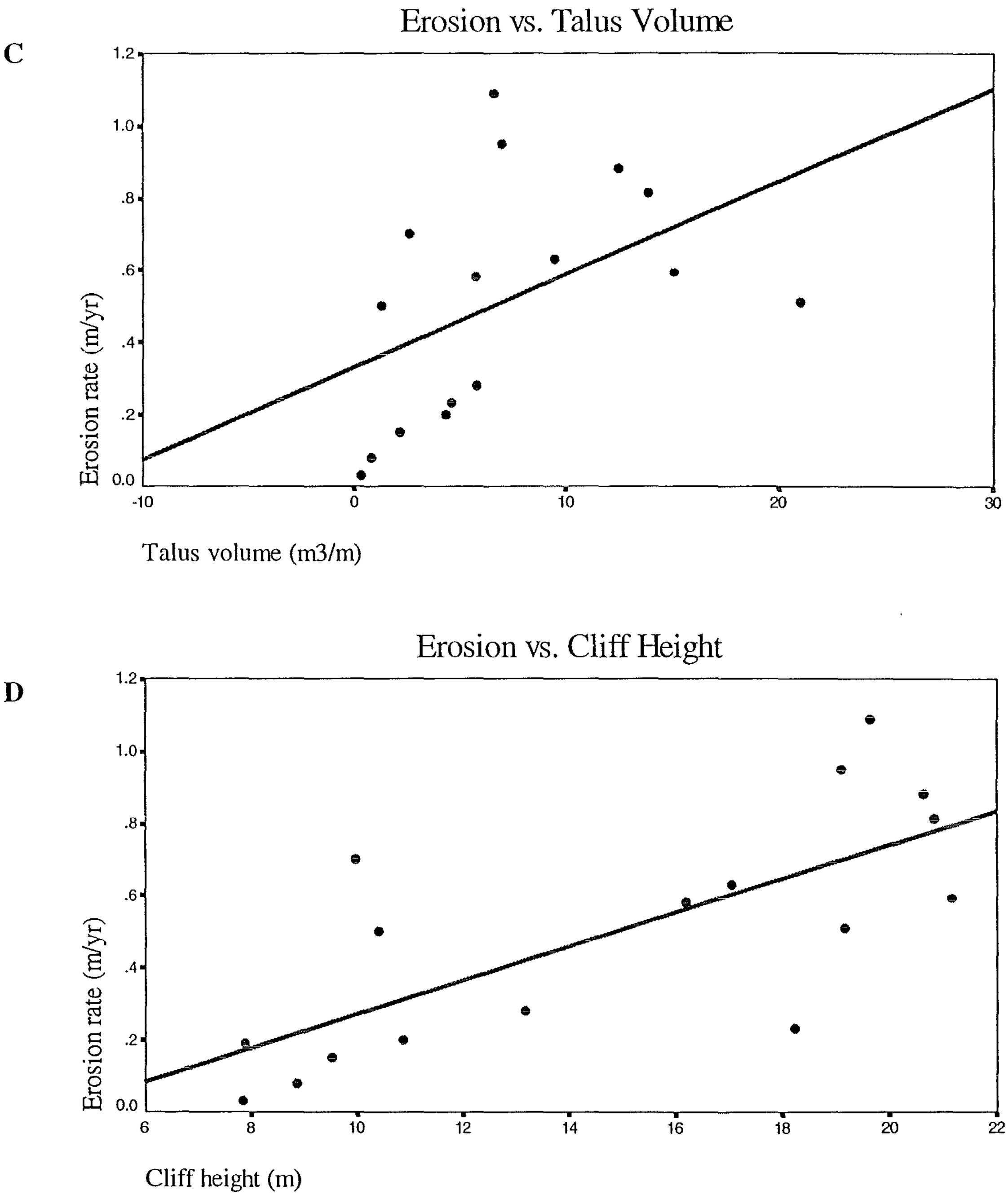

Figure 3.3: Relationship between spatial variations in erosion rate and beach and cliff factors (1981-1996) for the mid Canterbury coast

C. Talus Volume ($r = 0.501$ where $p=0.040$)

D. Cliff Height ($r = 0.733$ where $p=0.001$)

heights increase in a regular fashion with distance from south to north. Bray and Hooke (1997) also point out that higher cliffs also produce more sediment per unit of recession, so they should be able to maintain better protective basal debris stores. However, the strong net longshore sediment movement along the mid Canterbury coast (as discussed in Chapter Four) transports this debris away. Therefore, cliff height appears to be a major factor in the cliff erosion of the mid Canterbury coast.

Other factors such as beach volume, beach width and talus volume may also affect cliff erosion. The relationships between the four mentioned factors and cliff erosion over the fifteen year study period, from 1981-1996, are set out on Figure 3.3. From the correlation coefficients of the four graphs, cliff height is the major controlling factor on cliff erosion. The correlations are shown by r, displayed on Table 3.2. There is a strong positive correlation between cliff height and cliff erosion, where r = 0.733. As cliff height increases so does the erosion rate. Basal debris is thought to impede cliff erosion. However, talus volume has a positive correlation with erosion (r = 0.501). This suggests that with greater erosion rates talus volumes are larger. Therefore, the presence of a talus slope suggests erosion is occurring. This is contrary to the belief that talus indicates a slowing of erosion, as expressed by Zenkovich (1967). This apparent contradiction may be explained by the unconsolidated nature of the mid Canterbury cliffs and the strong net longshore sediment movement. This facilitates continued erosion, allowing talus slopes to form. The other two factors explored, beach volume and beach width (r values of –0.029 and 0.222 respectively), show little correlation with cliff erosion rates. However, the two outliers on these graphs (Figures 3.3A and 3.3B) distort the correlation. It would be misleading to remove these sites but it would be useful to examine the two sites. One site (ASH41.75) is situated between two dongas. The other site (RANG30.12) outlier has a drain outlet discharging to the south of it. This has caused a lagoon type structure to form near the base of the cliff. The beach width, and hence its volume, are much greater. The survey histories of these two profiles, and the other profiles shown on Figure 3.1, are displayed in Appendix 1.

While there is a strong correlation between erosion and cliff height from 1981-1996, this does not fully explain the cliff erosion. Regression analysis was carried out using beach width, beach volume, talus volume and cliff height as variables. The results of the regressions are shown on Table 3.2. This establishes cliff height to be the most important factor affecting spatial variations of long term cliff erosion, with a r^2 value of 0.537. The relationship between cliff height and cliff erosion is significant to SigF=0.001. SigF is an evaluation of the significance of the statistic F, and is expressed in terms of a percentage. Statistic F is the ratio of the greater to the lesser variance of the relationship (Shaw and Wheeler, 1985). SigF values of less than 5 per cent (0.05) represent a significant relationship. The importance of cliff height is also illustrated by the correlation coefficients shown on Figure 3.3. Again only cliff height (P=0.001) is significant in effecting cliff erosion. P measures the significance of the correlation between two variables, r. Table 3.2 also shows that beach volume and beach width are not significant in explaining cliff erosion on the mid Canterbury coast over a long-term period (with SigF values of 0.913 and 0.392 respectively). Multiple regression analysis was done using the four above factors in an attempt to explain cliff erosion was also calculated (Table 3.2). The multiple regression explained 61 per cent ($r^2 = 0.612$) of cliff erosion and was significant to less than 2 per cent (SIGF=0.016). Therefore, 61 per cent of the long-term spatial variations in cliff erosion on the mid Canterbury coast can be explained by the variables: beach volume; beach width; talus volume; and cliff height. However, only talus volume (SigF=0.040) and cliff height (SigF=0.001) are significant to less than 5 per cent. Quantifying long-term spatial variations in cliff erosion is difficult to achieve. Jones and Williams (1997 pp.107-108) could only explain 27 per cent of the spatial variations in cliff erosion on the West Wales coast using factors outlined in Section 2.3.1. Therefore, the 61 per cent explained in the present research is significant.

Another major feature of Figure 3.2 is the massive variability in erosion rates between profile sites. Seven of the sites show erosion rates much greater (between 0.4-0.6m.yr^{-1}) than the sites on either side of them. The land near two sites (ASH48.36 and ASH47.70) has extensive irrigation. The amount, extent and timing of this irrigation is unknown. However, it has been shown that moisture, either from irrigation or other sources, has an effect on the erosion of unconsolidated coastal cliffs (Kelk, 1974; Pieters, 1996). Sites ASH43.84 and ASH40.72 both have dongas on their northern side. ASH40.72 is a site for gravel extraction and this would clearly exert an influence on the erosion of the coast. RANG30.12 is the site with a drain outlet to the south, mentioned earlier. This increases cliff erosion as discussed by Pieters (1996).

Table 3.2: Regression analysis of factors influencing spatial variations in coastal cliff erosion, mid Canterbury, 1981-1996.

x	y	r	r^2	F	SigF	P	Signif. Y/N
Beach Volume	Erosion	-0.029	0.001	0.012	0.913	0.913	N
Beach Width	Erosion	0.222	0.049	0.776	0.392	0.392	N
Talus Volume	Erosion	0.501	0.251	5.032	0.040	0.040	Y
Cliff Height	Erosion	0.733	0.537	17.389	0.001	0.001	Y
Multiple Regression	Erosion	0.783	0.612	4.737	0.016	0.016	Y

Figure 3.2 also shows several sites with low erosion rates. The mouths of the Rangitata, Hinds and Ashburton Rivers clearly control the erosion on the sites in close proximity to the river mouths. Sites RANG28.19 and RANG24.94 (refer Figure 3.1) also have extremely low erosion rates. However, reasons for this are not clear. Particularly so for RANG28.19 which has a gravel extraction pit behind the beach. These sites appear to be anomalies. That is, there appears to be no explanation for their low erosion rates.

There appears to be a pattern to the variability in the longshore cliff erosion of the mid Canterbury coast from 1981-1996. Figure 3.2 illustrates peaks of erosion are followed by one or two low troughs of erosion, which in turn are followed by another high peak. However, most of the variability appears to be site specific. Different factors and conditions control the erosion at the various sites creating a pattern of spatial variation in cliff erosion along the mid Canterbury coast that may be misleading.

Jones and Williams (1991) noted the difficulty of quantifying cliff erosion in the long term. However, they had more success when they examined short term data. Therefore, two different years of data, both exhibiting greater than average erosion, will be examined in this research. April 1992 to April 1993 was a period that exhibited higher than average erosion, (three to five times higher for the majority of the profile

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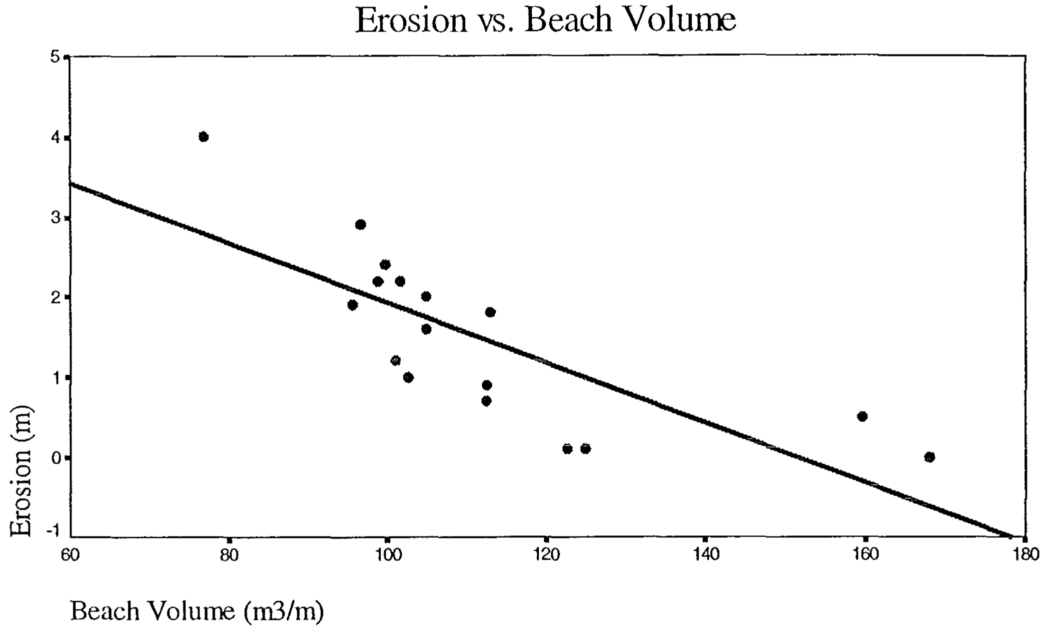

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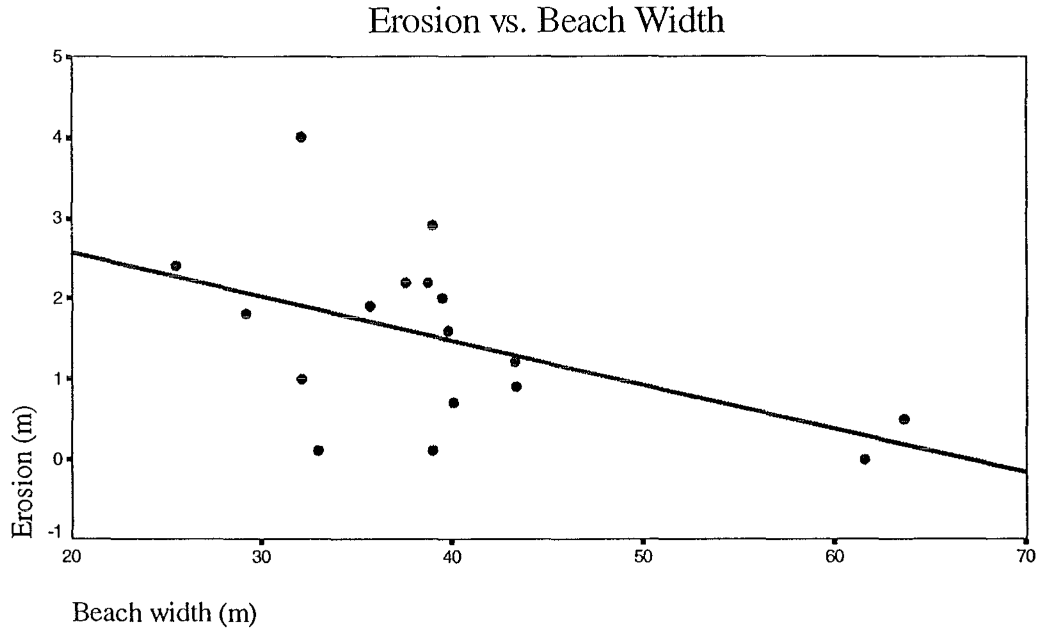

Figure 3.4: Relationship between spatial variations in erosion and beach and cliff factors (April 1992-April 1993) for the mid Canterbury coast

A. Beach Volume (r = -0.774 where p=0.000)
B. Beach Width (r = -0.497 where p=0.042)

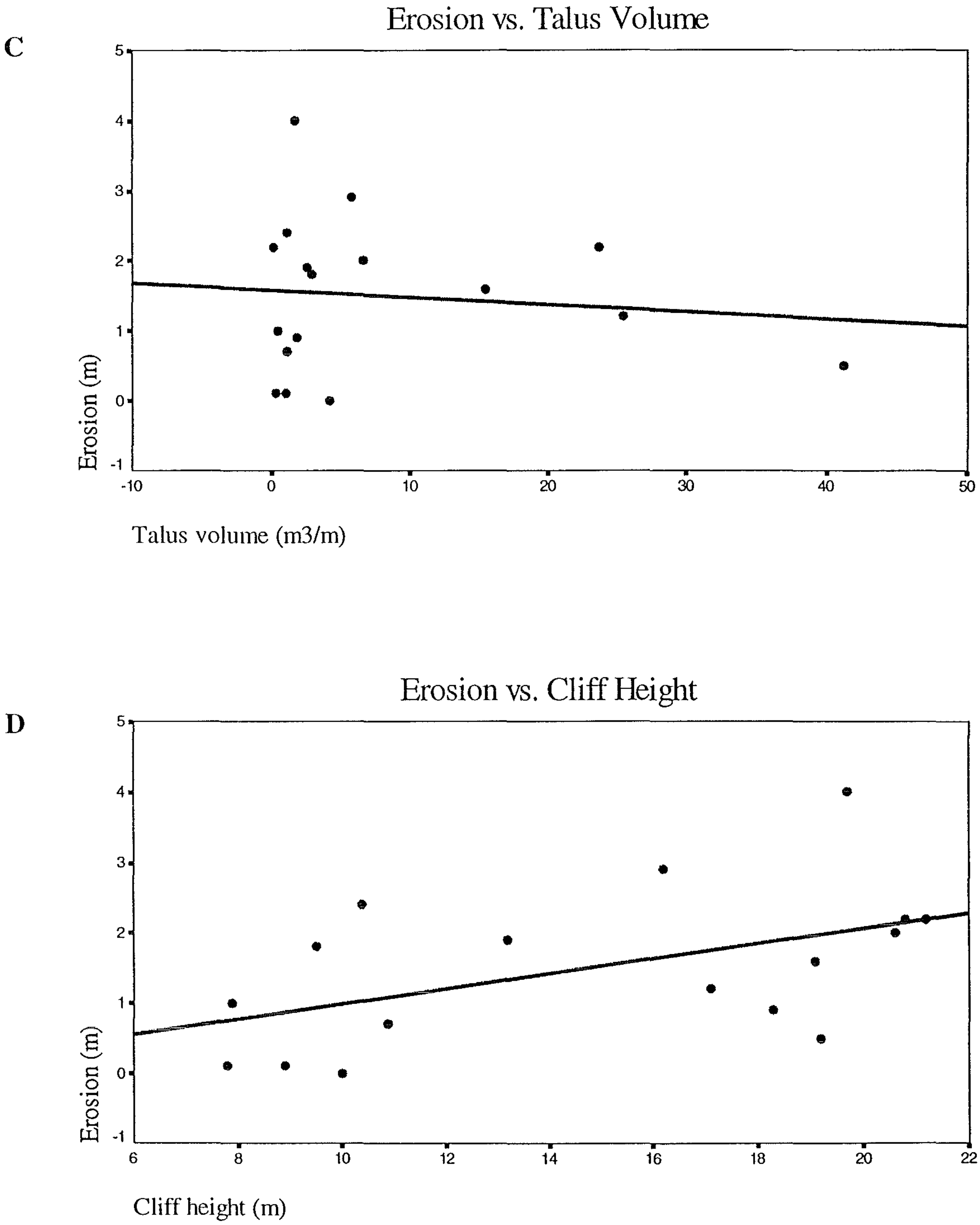

Figure 3.4: Relationship between spatial variations in erosion and beach and cliff factors (April 1992-April 1993) for the mid Canterbury coast

C. Talus Volume ($r = -0.111$ where $p=0.673$)
D. Cliff Height ($r = 0.506$ where $p=0.038$)

sites). Figure 3.4 shows a series of relationships between erosion and beach volume, beach width, talus volume and cliff height for this time period. Regressions between cliff erosion and the four factors were performed, and the results are shown on Table 3.3. Beach volume has a strong negative correlation, r = -0.774, with erosion. The relationship was significant to p=0.000. Therefore, as beach volume increases there is less erosion. The increase in beach volume probably corresponded with an increase in beach width and height. Thus storm waves have to be larger to be able to attack the cliff. Beach width (r = -0.497) and cliff height (r = 0.506) also show significant correlation (where p=0.04 and p=0.03 respectively) with erosion. Bray and Hooke (1997 p.455) suggest that beach widths of 20-30m offer significant protection to cliffs while beaches 60m wide give complete protection to the cliffs. While the dimensions are incorrect for the mid Canterbury coast, the concept is still applicable. Clearly from Figure 3.4B erosion decreases as beach width increases. Unlike the long term data from 1981-1996, the effect of talus appears to be negligible. To quantify the erosion, multiple regression analysis was undertaken using beach volume, beach width, talus volume and cliff height as variables. Table 3.3 shows a r^2 of 0.694. From the correlation coefficients, r, (refer Table 3.3) between erosion and the four beach and cliff factors, beach volume (r = -0.774 where p=0.000), beach width (r = -0.497 where p=0.042) and cliff height (r = 0.506 where p=0.038) are all significant factors to less than 5 per cent in cliff erosion.

Table 3.3: Regression analysis of factors influencing spatial variations in coastal cliff erosion, mid Canterbury, April 1992-April 1993.

x	y	r	r^2	F	SigF	P	Signif. Y/N
Beach Volume	Erosion	-0.774	0.599	22.370	0.000	0.000	Y
Beach Width	Erosion	-0.497	0.247	4.926	0.042	0.042	Y
Talus Volume	Erosion	-0.111	0.012	0.186	0.673	0.673	N
Cliff Height	Erosion	0.506	0.256	5.161	0.038	0.038	Y
Multiple Regression	Erosion	0.833	0.694	6.804	0.004	0.004	Y

A second year of data showing higher than average erosion was also examined, May 1994 to June 1995. As with the data from 1992-1993, correlations were done between erosion and beach volume, beach width, talus volume and cliff height, shown on Figure 3.5. Cliff height is the most important factor (r = 0.569 significant to p=0.017). Talus volume (r = -0.145 significant to p=0.578), beach volume (r = -0.403 significant to p=0.109) and beach width (r = -0.159 significant to p=0.543) have little

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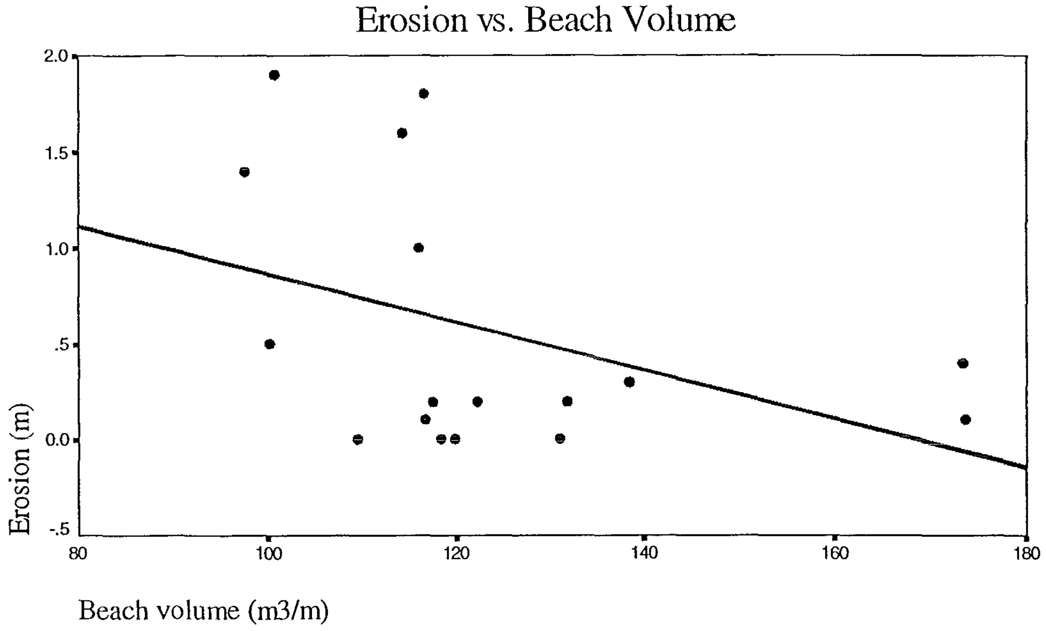

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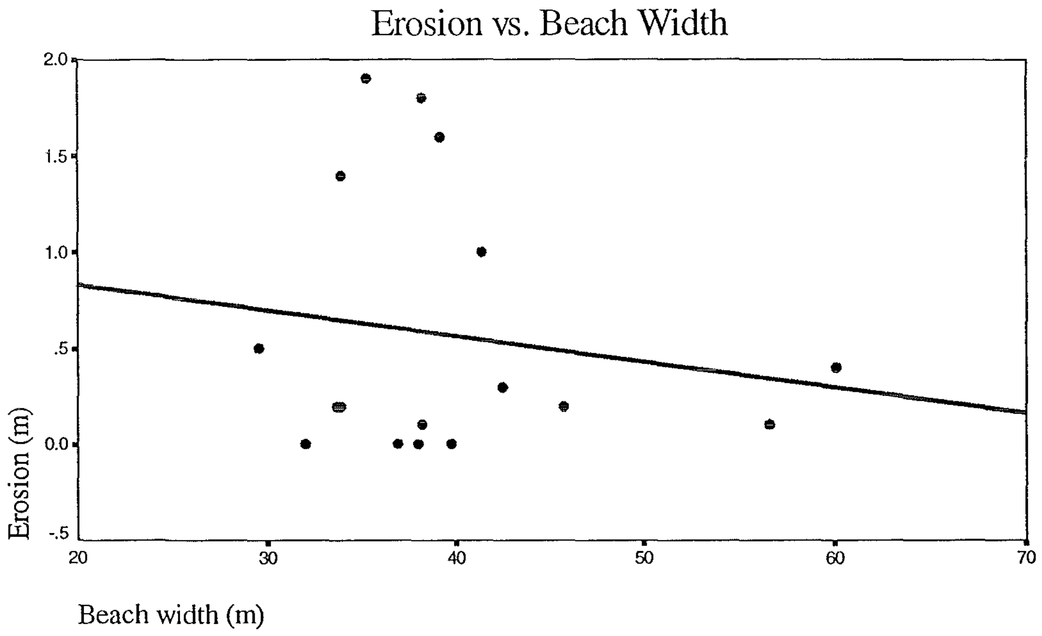

Figure 3.5: Relationship between spatial variations in erosion and beach and cliff factors (May 1994-June 1995) for the mid Canterbury coast

A. Beach Volume ($r = -0.403$ where $p=0.109$)
B. Beach Width ($r = -0.159$ where $p=0.543$)

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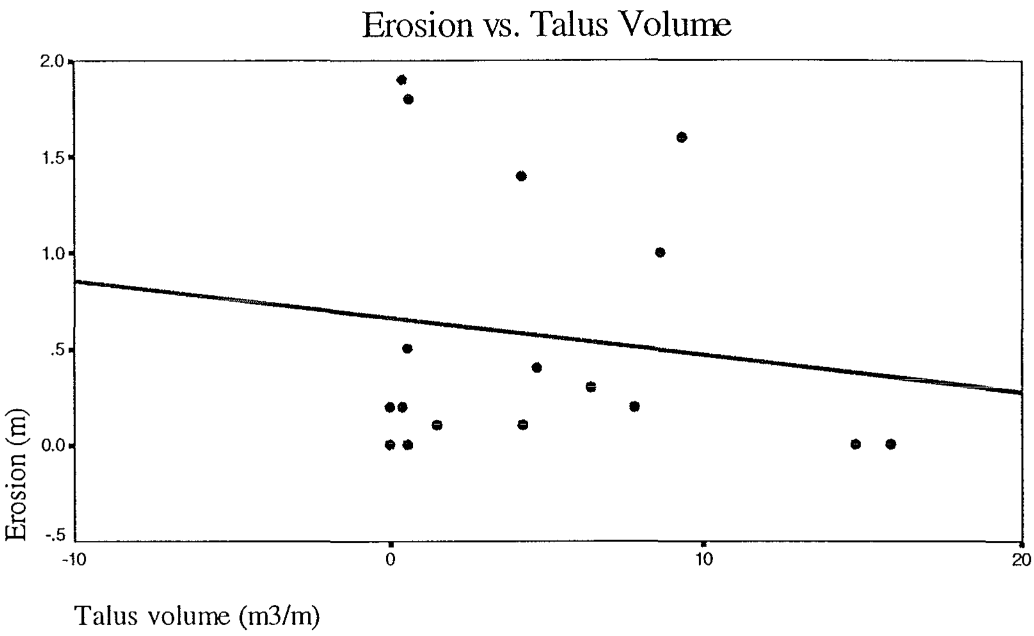

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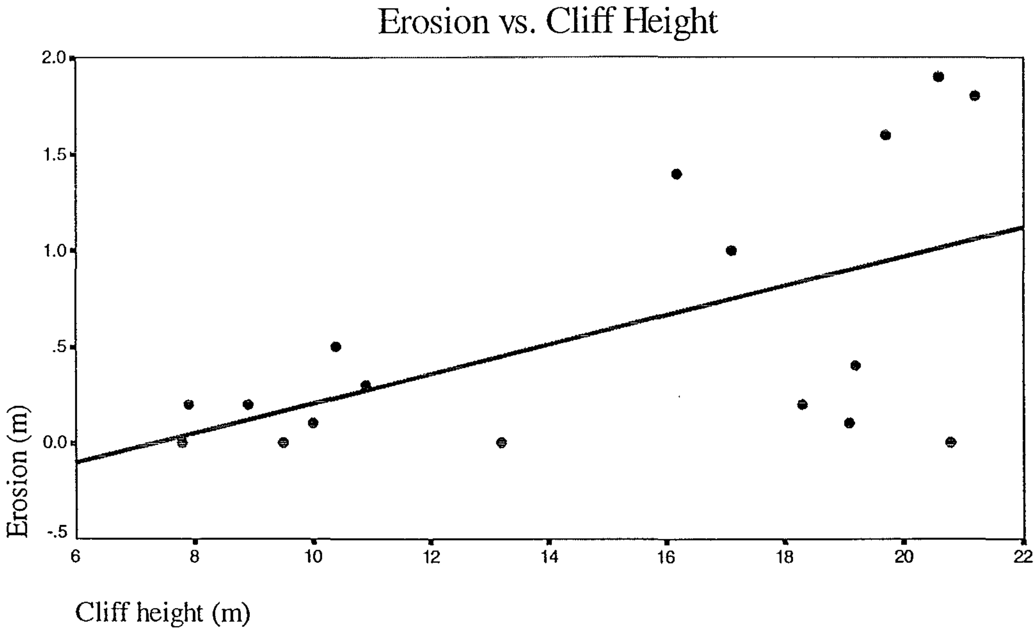

Figure 3.5: Relationship between spatial variations in erosion and beach and cliff factors (May 1994-June 1995) for the mid Canterbury coast

C. Talus Volume (r = -0.145 where p=0.578)
D. Cliff Height (r = 0.569 where p=0.017)

control on erosion. A multiple regression was also done using the same parameters as those used for the 1981-1996 and 1992-1993 data. Results of the regression are displayed on Table 3.4. The multiple regression model produced a r^2 of 0.625 (F=4.994 significant at 0.013). For 1994-1995 approximately 63 per cent of the cliff erosion can be explained by beach volume, beach width, talus volume and cliff height.

The multiple regression analysis of the 1992-1993 data produced statistically a higher level of significance (SigF=0.004) than the data from the 1994-1995 period (SigF=0.013). The analysis of the 1992-1993 data showed that beach volume, with a r value of –0.774 significant to p=0.000, was the most significant factor influencing cliff erosion spatially in the short-term on the mid Canterbury coast. Therefore, cliff height and beach volume, in the long-term and short-term respectively, are the two most significant controlling factors influencing spatial variations in cliff erosion along the mid Canterbury coast.

Table 3.4: Regression analysis of factors influencing spatial variations in coastal cliff erosion, mid Canterbury, May 1994-June 1995.

x	y	r	r^2	F	SigF	P	Signif. Y/N
Beach Volume	Erosion	-0.403	0.163	2.91	0.109	0.109	N
Beach Width	Erosion	-0.159	0.025	0.387	0.543	0.543	N
Talus Volume	Erosion	-0.145	0.021	0.324	0.578	0.578	N
Cliff Height	Erosion	0.569	0.324	7.191	0.017	0.017	Y
Multiple Regression	Erosion	0.790	0.625	4.994	0.013	0.013	Y

While some cliff and beach factors have been examined in an attempt to quantify spatial variations in cliff erosion, other factors may contribute. As mentioned above, the presence of dongas, drain outlets, irrigation and gravel extraction pits may all effect cliff erosion spatially. River mouths also have an influence (Figure 3.2). Kirk et al. (1977) suggest that river mouths, particularly when they are closed, contribute to accelerated cliff erosion of the adjacent cliffs. This is perhaps the case in specific flood events but it is not the case in the longer term, 1981-1996, for the mid Canterbury coast. Figure 3.2 shows that profile sites adjacent to river mouths, have erosion lower than the profile sites away from river mouths.

3.3.2 Temporal Patterns of Erosion

Cliff recession also varies over time. Many of the factors that influence the spatial distribution of erosion are also responsible for temporal variations in erosion. These factors include wave conditions, beach volume, beach width, talus volume and moisture content of the cliffs themselves. A higher frequency of high energy waves results in higher rates of cliff erosion. Changes over time to beach volume, beach width and talus volume at specific sites effect the erosion that occurs over time. These factors will be explored shortly. Moisture content is a major contributor to the cliff erosion of the mid Canterbury coast. Kelk (1974) showed with greater moisture within the cliff, shear strength is reduced, leading to failure. Kirk (1967) believed that cliff erosion could occur at any time. While acknowledging this, Kelk (1974) believed there to be a greater chance of erosion during the winter months. The aspect of the mid Canterbury cliffs means they are in the shade for much of the winter. Rainfall also tends to be greater in the winter months. Therefore, cliff erosion has a higher probability of occurring in winter.

Figure 3.6 illustrates the change in mean erosion rates for the entire mid Canterbury coast from 1981-1996. The data set is not long enough to establish any temporal patterns in erosion. However, what is clear is that cliff erosion is intermittent. High peaks in erosion for a year were followed by a series of years where relatively little erosion occurred. The explanation for this pattern of temporal variation in coastal recession is shown on Figure 3.7. The erosion rates from Figure 3.6 are compared to the frequency of coastal storms (where wave height >3m). This relationship exhibits a strong positive correlation, where $r = 0.764$ significant to $p=0.002$). The two peaks in coastal storm frequency shown in Figure 3.7 correspond with the two peaks in erosion shown on Figure 3.6. Storm waves appear to have a major influence on temporal variations in cliff recession.

To further examine temporal variations in cliff erosion rates, a closer examination of two specific profile sites has been undertaken. Note, the two profile sites examined (Figures 3.8 and 3.10) have different scales, so direct comparisons between

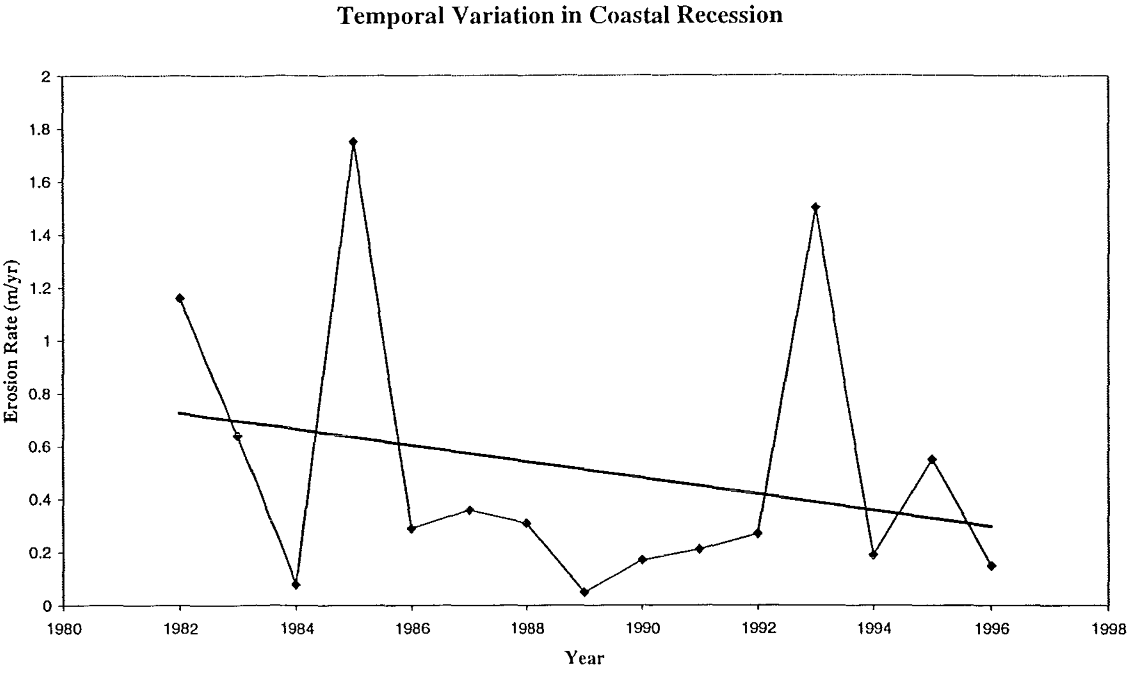

Figure 3.6: Temporal variation in coastal erosion, mid Canterbury (1981-1996)

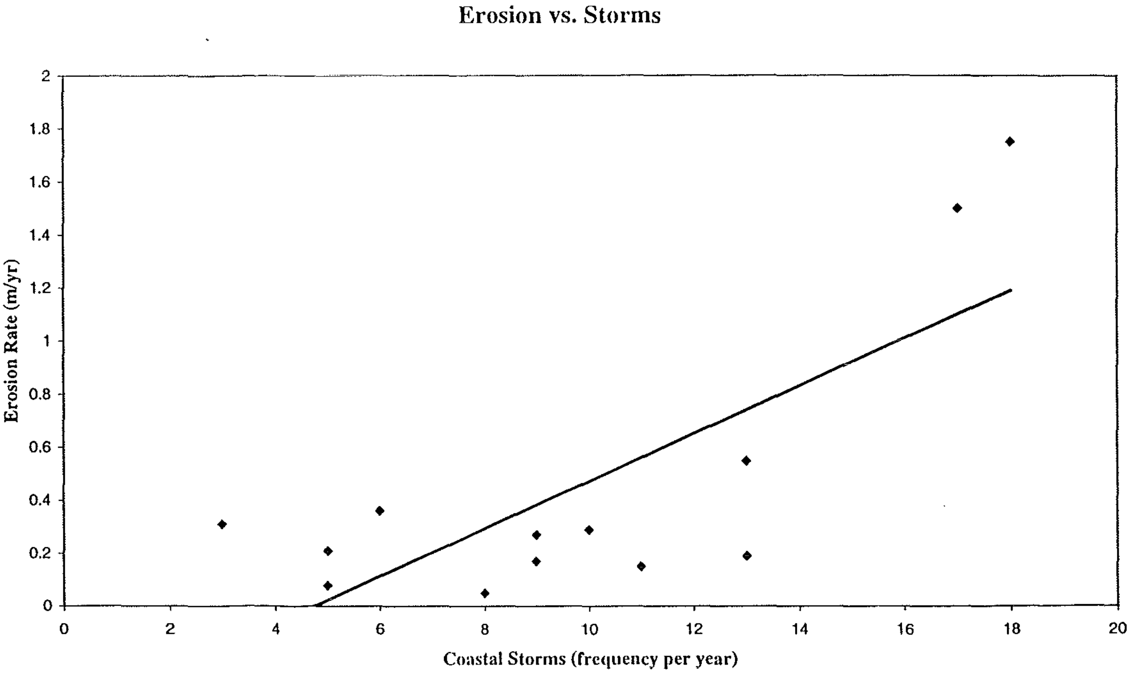

Figure 3.7: Relationship between erosion rate and coastal storms, mid Canterbury 1981-1996. (correlation coefficient = 0.763759 where p=0.002)

them should be made with caution. Multiple regression between erosion rate and beach volume, beach width, coastal storm frequency and talus volume were performed.

Figure 3.8 shows the cliff and beach profiles for site ASH49.17, situated 49.17km north of the Opihi River mouth, from 1986-1996. Evident from these profiles is the intermittent nature of the cliff retreat. Relatively little cliff retreat occurred from 1986-1992. However, in 1992 and 1993 there was significant retreat of the cliff top. There were large amounts of erosion occurring along the entire mid Canterbury during that year (refer Figure 3.6), most probably due to the high number of coastal storms encountered during that time. Figure 3.9 examines the correlations between cliff erosion rates for site ASH49.17 and the factors mentioned above. The results of the correlations and regressions are displayed on Table 3.5. Of the factors examined, only coastal storm frequency ($r = 0.635$ significant to $p=0.048$) is a significant factor contributing to cliff erosion. Multiple regression analysing the significance of the above factors on cliff erosion produced a r^2 of 0.626. However, the multiple regression only has a significance of $p=0.219$. Therefore the relationship has a 22 per cent probability that it is by chance, so the multiple regression is not significant.

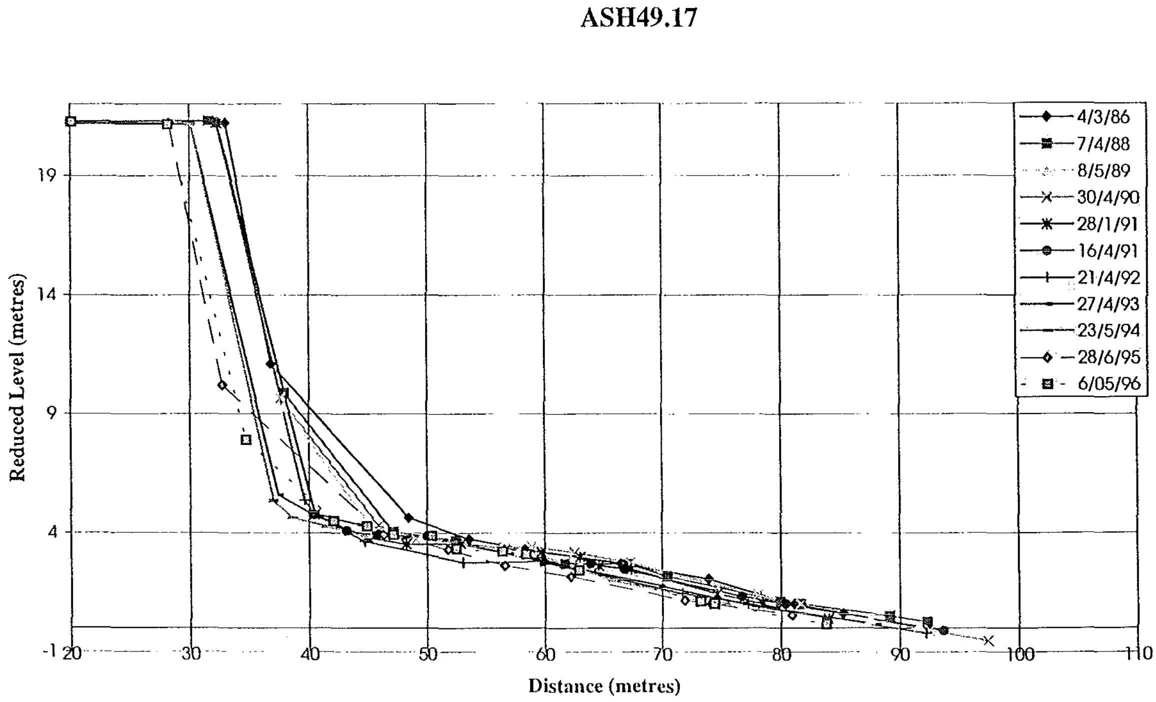

Figure 3.8: Cliff and beach profiles for site ASH49.17 (49.17km north of the Opihi River), 1986-1996. V.E.=1.75
(Data from the Canterbury Regional Council)

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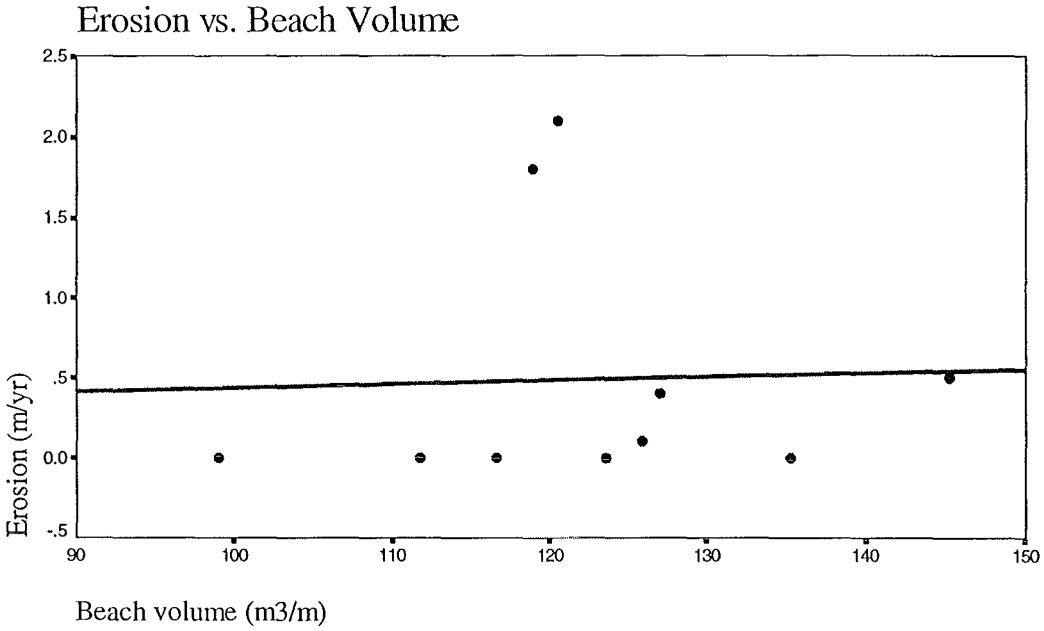

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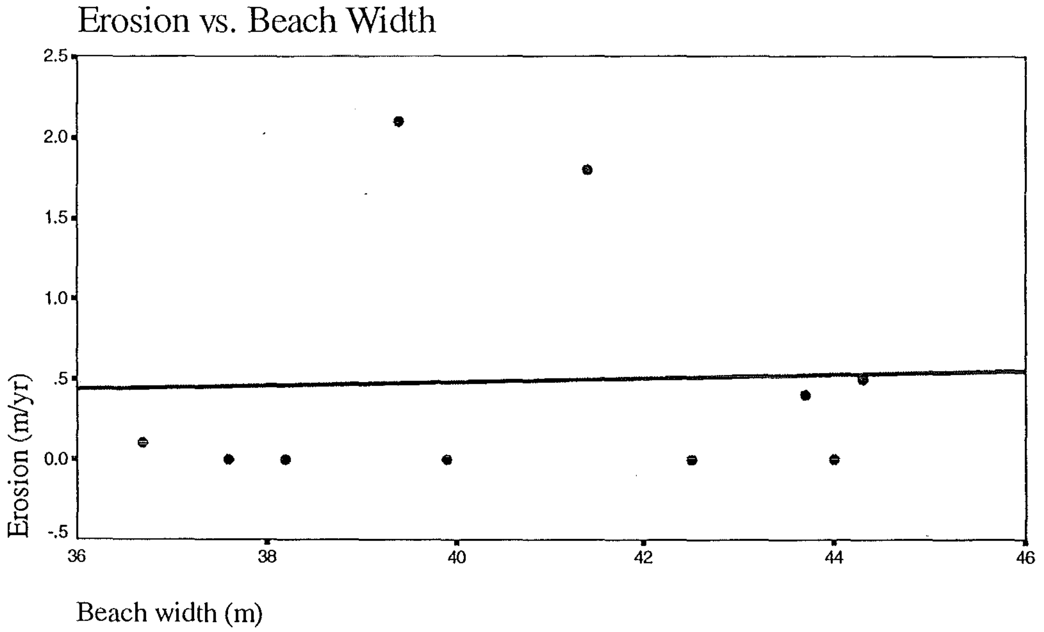


Figure 3.9: Relationships between temporal variations in erosion rate and beach, cliff and wave factors for profile ASH49.17 (1986-1996)

A. Beach Volume (r = 0.038 where p=0.918)
B. Beach Width (r = 0.039 where p=0.914)

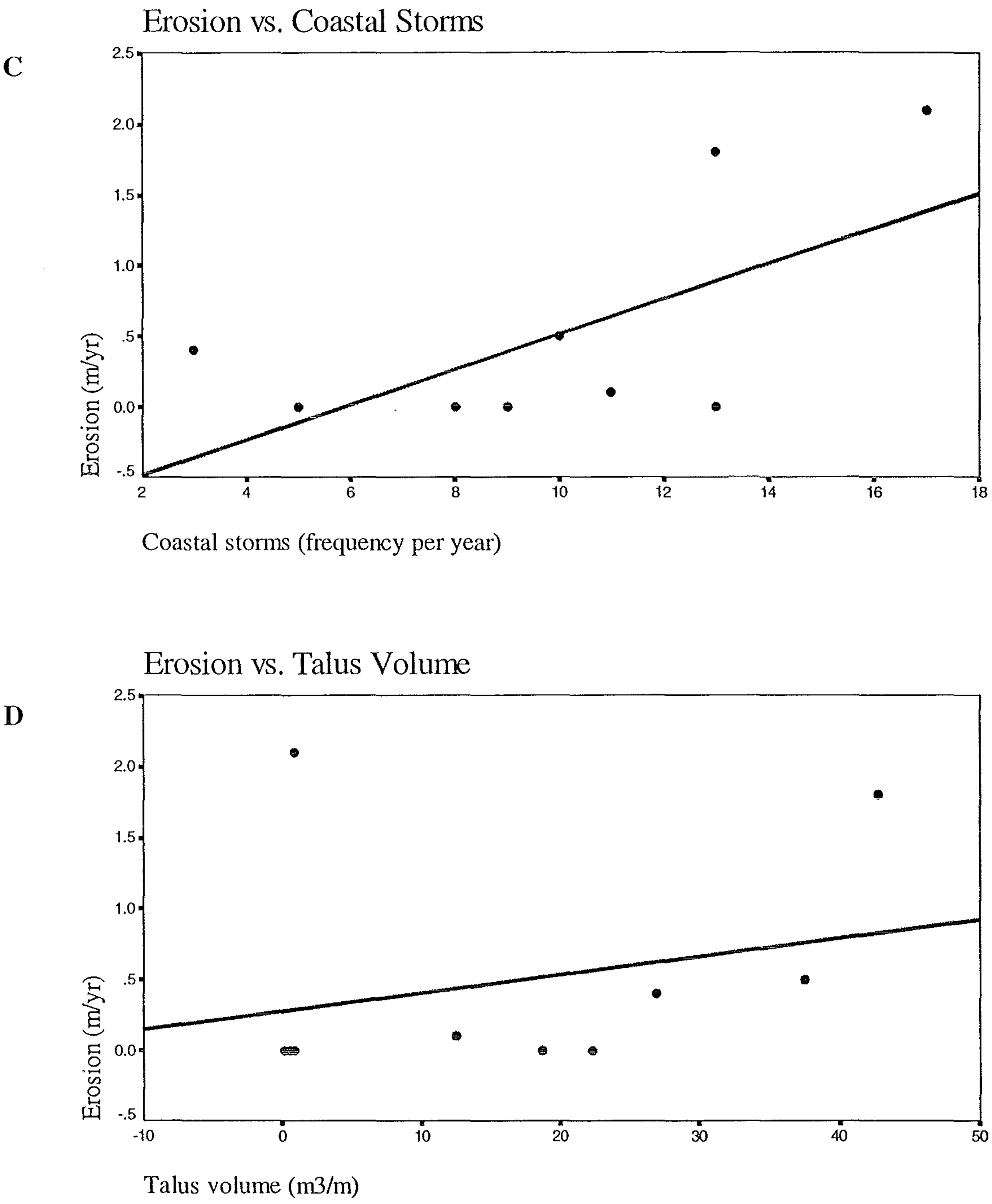


Figure 3.9: Relationships between temporal variations in erosion rate and beach, cliff and wave factors for profile ASH49.17 (1986-1996)

C. Storm Frequency (r = 0.635 where p=0.048)
D. Talus Volume (r = 0.260 where p=0.468)

Table 3.5: Regression analysis of factors influencing temporal variations in coastal cliff erosion, Profile site ASH49.17 (km north of Opihi River), mid Canterbury, 1986-1996.

x	y	r	r^2	F	SigF	P	Signif. Y/N
Beach Volume	Erosion	0.038	0.001	0.011	0.918	0.918	N
Beach Width	Erosion	0.039	0.002	0.012	0.914	0.914	N
Talus Volume	Erosion	0.260	0.068	0.579	0.468	0.468	N
Storm Frequency	Erosion	0.635	0.404	5.417	0.048	0.048	Y
Multiple Regression	Erosion	0.791	0.626	2.095	0.219	0.219	N

The second profile site examined was RANG21.23 (located 21.23km north of the Opihi River mouth), and is shown on Figure 3.10. Similar to ASH49.17, relatively little erosion occurred until between 1992 and 1993. RANG21.23 does show marked variability in beach and talus volume from year to year. Figure 3.11 shows the correlations between cliff erosion for RANG21.23 and beach volume (r = -0.246), beach width (r = 0.161), coastal storm frequency (r = 0.684) and talus volume (r = 0.637). Coastal storm frequency is again significant (p=0.029). However, so is talus volume (p=0.048). A multiple regression analysing all four variables produced r^2 of 0.761 (F=3.97 significant at 0.081). The regression therefore, is significant to only 8 per cent (Table 3.6).

Table 3.6: Regression analysis of factors influencing temporal variations in coastal cliff erosion, Profile RANG21.23 (km north of Opihi River), mid Canterbury, 1986-1996.

x	y	r	r^2	F	SigF	P	Signif. Y/N
Beach Volume	Erosion	-0.246	0.061	0.516	0.493	0.493	N
Beach Width	Erosion	0.161	0.026	0.213	0.657	0.657	N
Talus Volume	Erosion	0.637	0.406	5.456	0.048	0.048	Y
Storm Frequency	Erosion	0.684	0.468	7.040	0.029	0.029	Y
Multiple Regression	Erosion	0.872	0.761	3.974	0.081	0.081	N

Storm waves also play an important role in cliff erosion, as discussed in Chapter Two. The average number of days when storm waves (waves with heights of >3m) attacked the mid Canterbury coast per year from 1981-1996 was between 8-10. However, some years are stormier than others. When this occurs, the frequency of wave attack at the cliff base is increased, resulting most probably in more erosion. Erosion data from 1992-1993 and 1994-1995 were examined because both sets exhibited higher than usual erosion. The most probable cause of this was the number of days when storm waves assailed on the coast. From April 1992 to April 1993 there were 17 days when storm waves struck the coast, almost twice the average. This resulted in erosion that was 3-5 times larger than normal. May 1994 to June 1995 was not as stormy as 1992-1993 but there were still 13 storm days. This again resulted in increased erosion. Similarly, years characterised by less storms have less erosion than normal. For example, 1984 only had 5 coastal storms throughout the year. This resulted in erosion of only 0.08m. Also 1991 only had 5 coastal storms which resulted in only 0.21m being eroded in that year. Both of these years have erosion much lower than the mean (0.43m.yr^{-1}). Kirk (1969) mentions the acceleration and deceleration of erosion rates for the Canterbury Bight. This may be the result of fluctuations in storminess from year to year. This study cannot verify such interpretations because of the relatively short-term nature of the wave data used (1983-1996). Wave observations of a much longer time scale would be required.

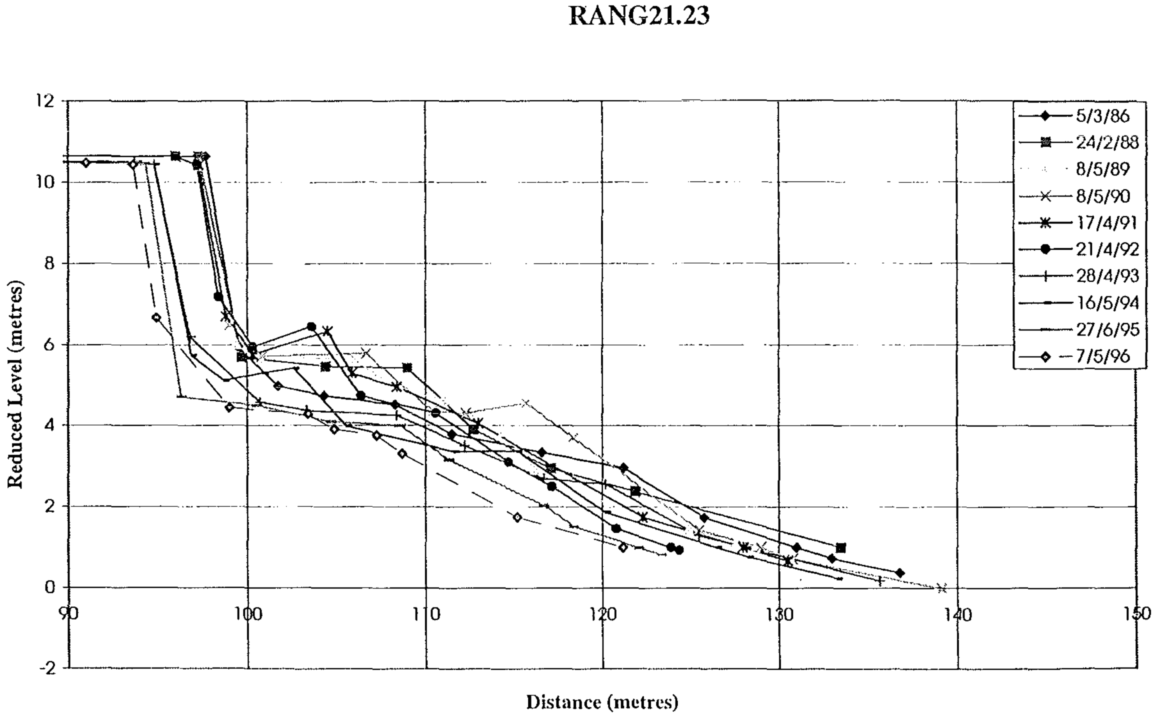
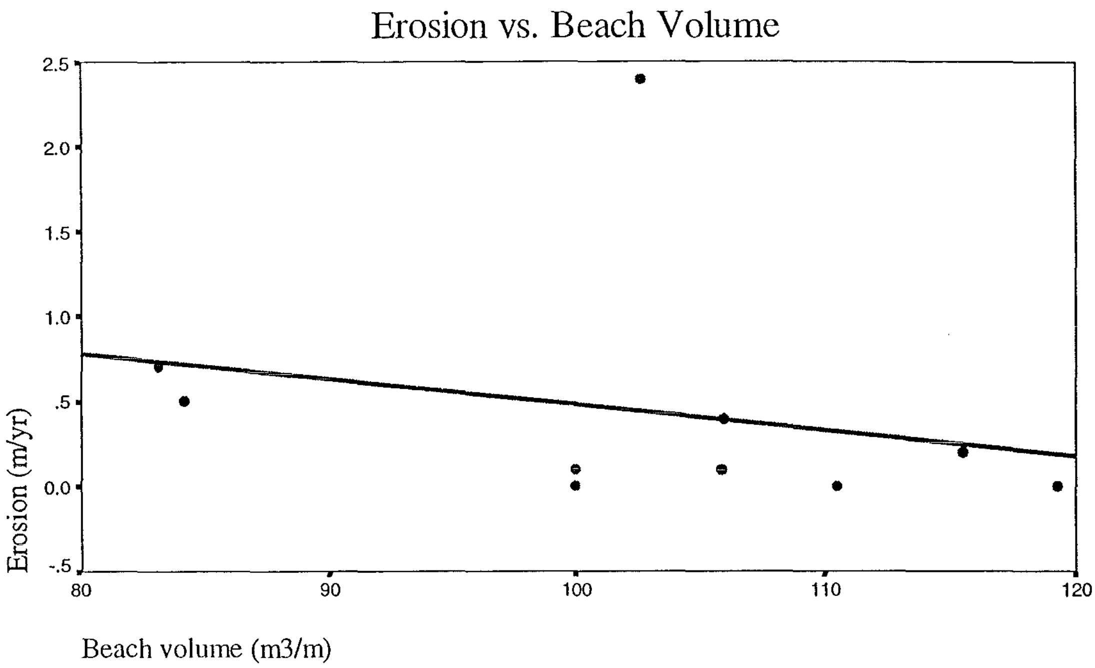


Figure 3.10: Cliff and beach profiles for site RANG21.23 (21.23km north of the Opihi River), 1986-1996. V.E.=2.4
(Data from the Canterbury Regional Council)

Temporal variations in cliff erosion for the mid Canterbury coast appear to be more difficult to explain than spatial variations. Beach volume, beach width and talus

A



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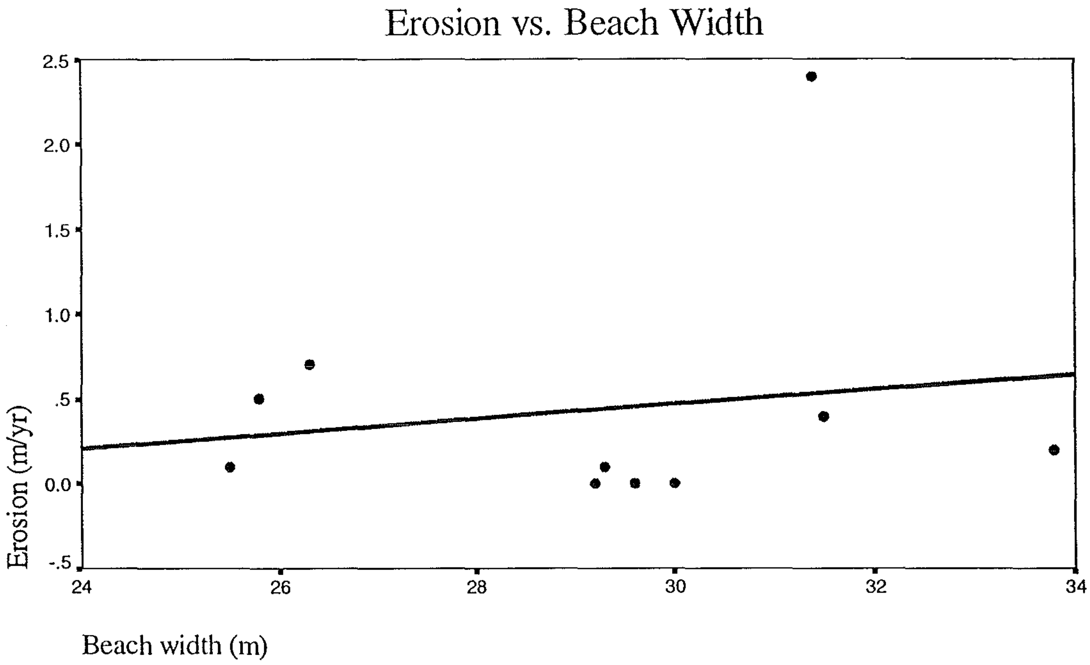
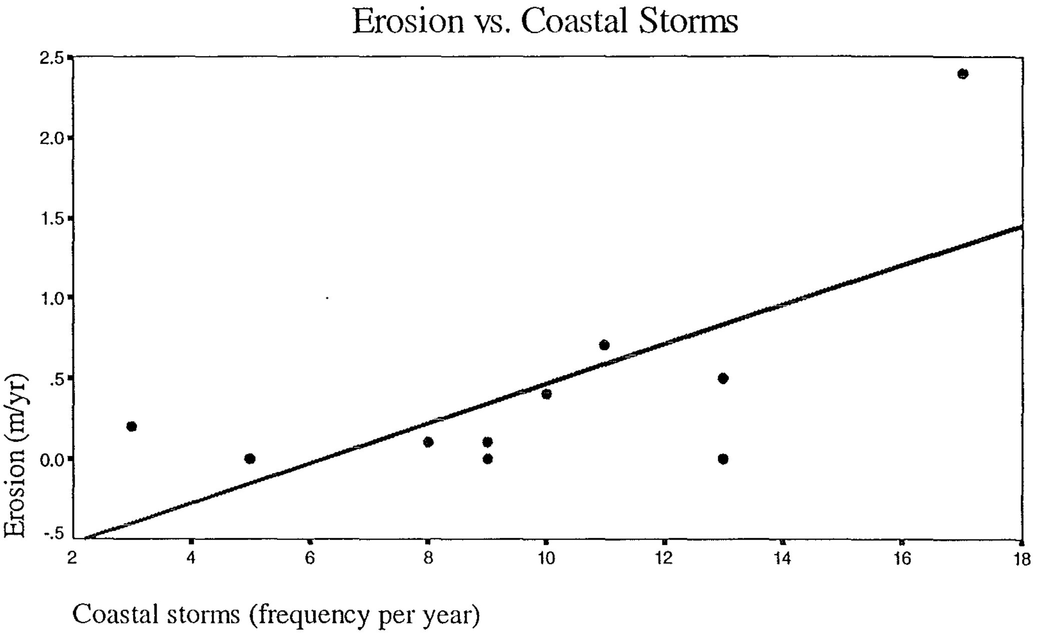


Figure 3.11: Relationships between temporal variations in erosion rate and beach, cliff and wave factors for profile RANG21.23 (1986-1996)

A. Beach Volume (r = -0.246 where p=0.493)
B. Beach Width (r = 0.161 where p=0.657)

C



D

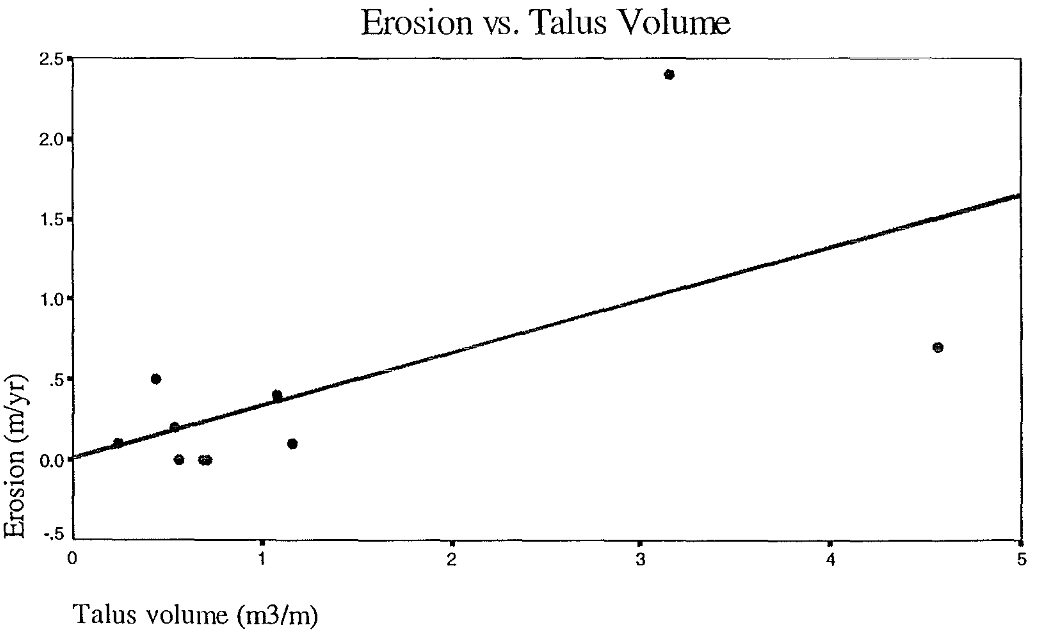


Figure 3.11: Relationships between temporal variations in erosion rate and beach, cliff and wave factors for profile RANG21.23 (1986-1996)

C. Storm Frequency (r = 0.684 where p=0.029)

D. Talus Volume (r = 0.637 where p=.048) volume are all poor indicators of cliff erosion. However, coastal storm frequency is significant in explaining variations in cliff erosion for the mid Canterbury coast over time.

3.4 Volume of Cliff Erosion

The sediment budget to be examined in Chapter Six will highlight the importance, for the mid Canterbury coast, of the sediment contributed by cliff erosion. This sediment is the primary source for the mixed sand and gravel beaches of the mid Canterbury coast. Therefore, it is necessary to know the actual volume of sediment contributed by cliff erosion. This section will examine the volumetric aspects of cliff erosion on the mid Canterbury coast. A total amount from 1981-1996 will be calculated. However, because cliff erosion has considerable temporal variations, the volume of cliff erosion from year to year will be calculated.

As previously discussed, the cliffs along the mid Canterbury coast vary greatly in height. The range in height of the cliffs is approximately 8-21m. This variation in height leads to spatial variations in the amount of sediment supplied by cliff erosion along the coast. For the purposes of calculating the total and yearly volume of cliff erosion for the entire mid Canterbury coast, the coastline has been divided into a number of 'cells'. Each cell is centred on a profile site (Figure 3.1). The length of the cell is dependent on the distance between the adjacent profile sites. Local erosion rates have been calculated for each cell. Cliff heights also vary between cells. Table 3.7 displays the cliff length, cliff height, erosion rate and erosion volume for each cell along the mid Canterbury coast. Erosion rates displayed are the mean annual rates for the cell. The volume of sediment, s, contributed by a length of cliff is represented by Equation 3.1 from Mason and Hansom (1988 p.35):

$$s = [(H \times r) + p] \times l \qquad (3.1)$$

where H is cliff height (m), r is retreat rate ($m.yr^{-1}$), p is the contribution from the retreat of the shore platform, and l is the length of eroded cliff (m). However, there is no shore platform present along the mid Canterbury coast, so p can be discarded.

Table 3.7 shows an average of 228,339m^3 of sediment is supplied annually by the erosion of the mid Canterbury coastal cliffs. A total of 3,653,424m^3 of sediment has been supplied from 1981-1996. Therefore, a significant amount of sediment is supplied to the coastal environment of mid Canterbury by the erosion of the coastal cliffs of the region. However, not all of the sediment yielded will be useful to the beaches. Only the proportion of gravels and coarse sands will remain on the beach profile. Finer sands will be removed by wave action offshore.

Table 3.7: Cliff erosion rates for the mid Canterbury coast, 1981-1996
(Data from the Canterbury Regional Council)

Profile Cell (km north of Opihi River mouth)	Cliff length (m)	Erosion (m.yr^{-1})	Cliff Height (m)	Erosion Volume (m^3.yr^{-1})	Standardised Erosion Volume (m^3.km^{-1})
ASH49.17	1,810	0.59	21.16	22,794	12,544
ASH48.36	740	0.88	20.63	13,434	18,154
ASH47.70	815	0.82	20.83	14,006	17,185
ASH46.73	1,230	0.59	16.21	11,764	9,564
ASH45.25	1,010	0.26	6.60	1,733	1,716
ASH43.84	1,840	1.09	19.65	39,410	21,419
ASH41.75	1,560	0.51	19.18	15,260	9,782
ASH40.72	1,610	0.89	19.11	27,383	17,008
ASH38.54	2,460	0.23	18.25	10,326	4,198
ASH35.80	2,770	0.63	17.06	29,771	10,748
ASH33.00	2,725	0.28	13.19	10,082	3,700
RANG31.01	710	0.20	10.88	1,545	2,176
RANG30.12	1,410	0.65	9.97	9,138	6,481
RANG28.19	1,470	0.03	7.84	346	235
RANG27.19	1,630	0.15	7.89	1,929	1,183
RANG24.94	1,880	0.08	8.86	1,333	709
RANG23.44	1,860	0.15	9.53	2,659	1,430
RANG21.23	2,570	0.53	10.42	14,193	5,523
RANG18.30	1,970	0.06	11.19	1,323	672
Totals	32,080			228,339	

The considerable spatial variation in cliff erosion (Figure 3.2) is also evident in the cliff erosion volume. Table 3.7 also displays a standardised erosion volume for each cell along the mid Canterbury coast. This allows volumes of cliff erosion from different cells to be directly compared to one another. The standardised erosion volumes show that erosion is generally greater on the northern sections of the mid Canterbury coast. Cliff height is the most probable cause of this. Table 3.2 demonstrates the significance of cliff height on erosion rates. Erosion rate is a vital component of Equation 3.1. Therefore, cliff height has a direct effect on the cliff erosion volume on the mid Canterbury coast.

Table 3.7 does not show temporal variations in cliff erosion volume. Figure 3.6 demonstrates the variations in erosion rates from year to year. As mentioned erosion rate is one of the parameters used when calculating cliff erosion volume. Therefore, the mid Canterbury coast would exhibit considerable temporal variation in cliff erosion volume. Figure 3.7 suggests that the frequency of coastal storms control cliff erosion. Therefore, it can be assumed that coastal storms would also affect cliff erosion volume on the mid Canterbury coast.

This section has displayed the volume of sediment contributed to the mid Canterbury coast by cliff erosion. Chapter Six will compare the erosion volume with other sediment inputs, when a sediment budget for the mid Canterbury coast will be examined. Chapter Four will focus on longshore sediment transport and the sediment supplied by that process. Chapter Five will concentrate on the rivers within the study area (Figure 3.1), and their contribution to the sediment budget.

3.5 Periodicity and ENSO

Kirk (1969) suggests that there may be acceleration and deceleration of erosion rates over time. Erosion rates for the Canterbury Bight from Kirk (1969), displayed on Table 3.1, illustrates this. Due to the relatively short duration of the data used in the present research, assumptions on patterns of change in erosion rates over time on the mid Canterbury coast are difficult to make. However, Figure 3.6 clearly shows temporal variations in erosion rates for the mid Canterbury coast, during the course of the study period. The frequency of coastal storms has also been shown to be a factor that contributes most to the variation. El Nino-Southern Oscillation (ENSO) may be another cause.

Fluctuations in the intensity of the Walker circulation result in the phenomenon called Southern Oscillation (Sturman and Tapper, 1996). The Walker circulation is a major circulation cell moving air between eastern and western sides of the South Pacific and is orientated north west to south east. The strength of the Southern Oscillation is proportional to the difference in pressure between Indonesia and the eastern South Pacific (Sturman and Tapper, 1996). The measure of strength of the Walker circulation is known as the Southern Oscillation Index (SOI). The SOI from 1981-1996 is displayed on Figure 3.12. Sturman and Tapper (1996) discuss that the SOI is high when pressure over Indonesia is at its lowest.

> *"When the SOI becomes anomalously low (negative) it is associated with the well-known El Nino phenomenon; a strong positive anomaly is called La Nina."*
>
> (Sturman and Tapper, 1996 p.371)

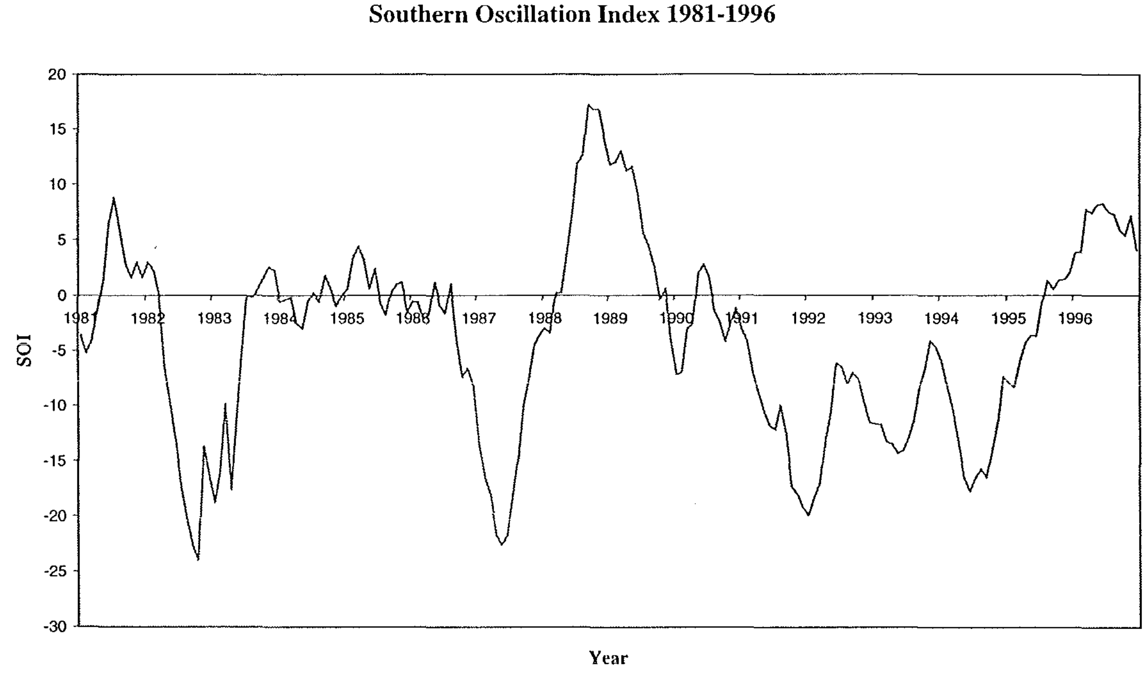


Figure 3.12: Five month moving average of the southern oscillation index from 1981-1996 (Source: Bureau of Meteorology, Climate Monitoring Bulletin Australia)

Sturman and Tapper (1996) go on to say that negative SOI values in New Zealand give anomalous south-westerly airflow, while positive values produce anomalous north easterlies. Negative SOI values, or El Nino, results in more rainfall for the southern and western parts of New Zealand, and less for the north and east. For example, during an El Nino event from January to March 1983, Canterbury received only 51-72 per cent of its normal rainfall, while Southland received 155 per cent of normal rainfall (Sturman and Tapper, 1996 p.374). Positive SOI values, or La Nina, produces the opposite effect of El Nino. During La Nina events, Canterbury can expect higher than usual rainfall. Because there is a relationship between moisture and cliff erosion as discussed in Chapter Two, it is reasonable to assume that more cliff erosion would occur along the mid Canterbury coast during La Nina events.

However, when examining Figures 3.6 and 3.12, there appears to be no relationship between coastal erosion rates and the Southern Oscillation. The two years with the largest erosion rates exhibit a very low positive or negative SOI. 1988 and 1989 have the strongest positive SOI, or La Nina, of the study period. However this corresponds with the years that have the lowest erosion rate. Therefore, there is no relationship between temporal variations in cliff erosion along the mid Canterbury coast and the Southern Oscillation.

3.6 Summary

It has been shown that the mid Canterbury coast is eroding at rates that vary both in space and time. An extensive monitoring system along the coast has provided the means to test this. Past researchers have found considerable variations in erosion rates. The present research has confirmed and extended knowledge of this. Firstly, spatial variations in cliff erosion were examined. In the long term, 1981-1996, spatial erosion rate variation is primarily a function of cliff height. So much so that cliff height explains 61 per cent of the variance. This is significant, particularly when comparing the result with other quantitative studies of cliff erosion. However, for the short term, April 1992 to April 1993, beach volume was the major controlling factor. Beach volume explains 59 per cent of the cliff erosion variance in the short term.

Secondly, temporal variations in cliff erosion on the mid Canterbury coast were examined. It appears that variations in cliff erosion over time are harder to explain than spatial variations. However, the frequency of coastal storms is the controlling factor on variations in cliff erosion over time. Two case studies of two profile sites along the mid Canterbury coast from 1986-1996 confirmed the importance of coastal storm frequency.

Multiple regressions showed that between 40 and 46 per cent of the temporal variations are explained by coastal storm frequency.

The primary source of sediment to the coastal environment of mid Canterbury is thought to be the cliffs. Therefore, knowing the amount of sediment contributed to the coast is important. Between 1981 and 1996 approximately 3,653,000m^3 of sediment has been supplied by the mid Canterbury coastal cliffs. Comparisons between cliff erosion volumes and sediment contributed to the coast by longshore sediment transport and river output will be made in Chapter Six. However, as with erosion rates, sediment yield varies significantly over space. This is also a function of cliff height. The northern section of the mid Canterbury coast, which has the highest cliffs within the study area, yields the most sediment. The significance of the sediment supplied by the mid Canterbury coastal cliffs within an entire sediment budget will be examined in Chapter Six.

Variations in cliff erosion over time may be the result of atmospheric pressure circulation changes. Walker circulation cell of the South Pacific effects the weather patterns in New Zealand. La Nina produces higher than average rainfalls within Canterbury, therefore increasing the probability of cliff erosion. However, no relationship was found between the SOI and erosion rates. Other factors may contribute to the lack of correlation.

Chapter Four

Longshore Sediment Transport

Longshore sediment transport is a vital component of any sediment budget. The state of a beach, whether it be erosional, depositional or stable is controlled by the difference between the inputs and outputs of sediment.

> *"The major role of longshore sediment transport in the balancing of inputs and outputs of open-ended beach systems lays a great importance on the need for some knowledge of the rate at which the transport occurs."*
>
> (Neale, 1987 p.22)

This chapter will examine longshore sediment transport on the mid Canterbury coast.

Because of the importance of longshore sediment transport within the coastal environment, a sizeable amount of literature has built up on the topic. This chapter will spend some time examining selected parts of it. Of note is the work of Komar (1976). He gives an excellent review of the literature on longshore currents and sediment transport. However, a problem exists when comparing characteristics of the mid Canterbury coast with most of the literature. Most research has focussed on longshore transport on sandy foreshores. There has been comparative neglect of longshore transport on mixed sand and gravel beaches. A mixed beach presents an entirely different process situation than that of a pure sand or pure gravel beach. Owing to the differences between mixed and pure beaches, as detailed by Kirk (1980), this chapter will specifically examine the longshore transport of sediment on a mixed sand and gravel foreshore.

Once the literature and relevant models of longshore sediment transport have been reviewed they will be put into the mid Canterbury context. The amount of transport along the mid Canterbury coast will be determined. Models based on transport on sand beaches will be used for the mid Canterbury coast, as will models specifically formulated for mixed beaches. This will be done so that comparisons between models can be achieved.

Chapter Three showed the considerable temporal variation in cliff erosion on the mid Canterbury coast. This is also the case for rates of longshore sediment transport. Considerable amounts of transport can occur during single events. Therefore, average and single event rates of longshore sediment transport will be examined.

Neale (1987) determined the presence of 'slugs' of sediment, migrating alongshore, in the direction of the predominant longshore transport direction in South Canterbury. The slugs are the result of large pulses of sediment input to the coast by rivers, and in the case of Neale (1987), the Waitaki River and by cliff erosion. This thesis will examine Neale's theory. It has been an important part of the present study to determine whether slug transport is present on the mid Canterbury coast. The influence of them on cliff erosion has also been examined. As the slugs migrate alongshore, it is possible that they increase the local beach height and volume, therefore, impeding cliff erosion. This would also lead to spatial variations in cliff erosion, as outlined in Chapter Three.

This chapter has a dual role. Firstly, the rates and amounts of longshore sediment transport on the mid Canterbury coast is to be determined. This longshore transport will also form a vital part of the sediment budget that will be examined in Chapter Six. Secondly, the role of longshore sediment transport on cliff erosion will be looked at in detail.

4.1 Longshore Sediment Transport: A Review

Longshore and nearshore sediment transport has been a central research theme in coastal science (Allen, 1988). Bodge and Kraus (1991) also point out that prediction of the rate of longshore sediment transport is central to many, if not most, coastal engineering studies. Therefore, a large amount of literature and research exists on the topic. A comprehensive review of this research is neither possible, because of the size of the literature available, nor is it the aim of this thesis. However, a brief review of longshore sediment transport, based on the work of the Coastal Engineering Research Centre (C.E.R.C.), will be given. Also examined will be the distribution of longshore sediment transport across the surf zone (Bodge, 1989). The majority of the models to be reviewed have been developed on sand beaches. These are being examined because mixed sand and gravel longshore transport models, to be reviewed in Section 4.1.4, are simply modified versions of the original pure sand models. Therefore, knowledge of the structure of the sand based longshore sediment transport models is necessary when determining longshore sediment transport on a mixed sand and gravel foreshore.

Longshore sediment transport is dependent upon two factors. Firstly, the sediment particles have to be set in motion. Secondly, a longshore current has to be present so the particle can migrate alongshore.

4.1.1 Thresholds of Sediment Motion

Soulsby and Whitehouse (1997) suggest that the threshold of sediment motion plays an important role in a number of applications, of which sediment transport rates is one. The threshold of sediment motion also governs the size of sediment that is transported on a beach, under certain wave conditions (Komar, 1976).

Komar (1976) reports that the threshold of sediment movement is reached, when the orbital velocity of water flow over a bed of sediment is increased to a point where the water exerts a force on the sediment particles sufficient to move them from the bed. Komar and Miller (1973) showed that for sediment grain sizes of less than 0.5mm (medium sands and finer), the threshold for sediment motion is best related by:

$$\frac{\rho u_t^2}{(\rho_s - \rho)gD} = 0.21\left(\frac{d_o}{D}\right)^{1/2} \qquad (4.1)$$

where ρ is the density of seawater; u_t is the near-bottom threshold velocity; ρ_s is the density of the sediment; D is the diameter of sediment grains; and d_o is the orbital diameter of wave motion. For grain diameters of greater than 0.5mm (coarse sands and coarser), the threshold for sediment motion is similar to Equation 4.1 and is expressed by:

$$\frac{\rho u_t^2}{(\rho_s - \rho)gD} = 0.46\pi\left(\frac{d_o}{D}\right)^{1/4} \qquad (4.2)$$

The near-bottom threshold velocity and the orbital diameter of wave motion are related to wave height H, water depth h, wave length L, and period T (Komar, 1976) by:

$$u_t = \frac{\pi d_o}{T} = \frac{\pi H}{T \sinh(2\pi h / L)} \tag{4.3}$$

Komar (1976) intimates that for a given grain density and diameter, the threshold for sediment motion under waves can be established by a certain wave period T and orbital velocity u_t or diameter d_o. Since $u_t = \pi d_o / T$, only two of the three parameters need to be established when defining the threshold. Komar and Miller (1975) produced a graph for the threshold values of T and u_t (Figure 4.1). The higher the wave period the greater the orbital velocity has to be for sediment to be set in motion. Also, as sediment diameter increases so does the orbital velocity required to move that sediment. However, the above equations are for sinusoidal wave motion (Komar, 1976). Because orbital motions are generally irregular, and when waves enter shallow water the orbital motions have a net on-shore movement, the use of Equations 4.1 and 4.2 may be inadequate. However, they may be useful if a rough estimate of the threshold is required (Komar, 1976).

4.1.2 Nearshore Currents

Nearshore currents that travel in the longshore direction are vital to the process of longshore sediment transport. Komar (1976) presents an extensive review of currents in the nearshore. His investigation examines currents that are the result of nearshore cell circulation, oblique wave approach and longshore variations in wave height. However, (Kirk, 1980) notes that because of the nearshore face and reflective nature of mixed sand and gravel beaches, return circulation of the water occurs through the base of the breaker so cell circulation, and associated rip currents, do not form. For this reason the present study does not examine longshore currents that are the result of nearshore cell circulation.

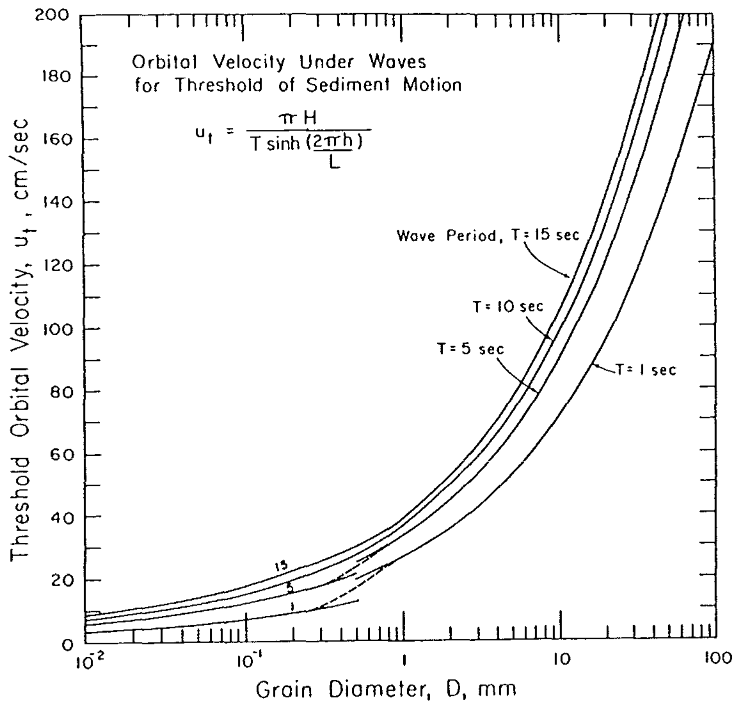


Figure 4.1: The wave period and near-bottom orbital velocity required for threshold of motion of sediment of a particular grain size and density 2650kg/m^3 (quartz).
(From Komar and Miller, 1975)

The current that is generally confined between the first breaker and the shoreline, is wave induced and flows alongshore, can be termed the longshore current (C.E.R.C., 1982). These currents are most commonly created by waves breaking at some angle to the shoreline (C.E.R.C., 1984). Figure 4.2 illustrates the angle of wave approach. Sherman (1988) evaluates three commonly used models for predicting longshore currents that are the result of oblique wave approach. Firstly Longuet-Higgins' (1970) model predicts the average longshore current velocity at the breaker zone using the concept of radiation stress. Komar (1976) discusses that the radiation stress is an energy flux, toward the shoreline, of momentum directed parallel to the shoreline and is described by:

$$S_{xy} = E \sin\alpha \cos\alpha \qquad (4.4)$$

where S_{xy} is the component of the onshore flux, E is the wave energy, and α is the angle of wave approach (Sherman, 1988 p.159). Sherman (1988) states that Equation

4.4 provides the physical basis for the widely used longshore current models, to be described in the present research. Longuet-Higgins' (1970) model is described by the formula:

$$\bar{V}=\frac{5}{8}\pi\frac{s}{C}\gamma(gh_b)^{1/2}(\sin\alpha\cos\alpha) \tag{4.5}$$

where s is nearshore slope, C is a friction coefficient, and γ is the ratio of wave amplitude to water depth at breaking h_b. The U.S. Army Corps of Engineers in the Shore Protection Manual, SPM, (C.E.R.C., 1984) modified the Longuet-Higgins model to produce a model that they propose is the best method for predicting longshore current velocity (Sherman, 1988). The modified model is expressed by:

$$\bar{V}=20.7s(gH_b)^{1/2}\sin\alpha\cos\alpha \tag{4.6}$$

where H_b is the wave height at breaking. The third commonly used model is from Komar and Inman (1970), and is also based on the concept of radiation stress (Sherman, 1988), is expressed by:

$$\bar{V}=2.7u_m\sin\alpha\cos\alpha \tag{4.7}$$

where u_m is the maximum orbital velocity of the water particles under the wave. The major controlling factor on the models that predict longshore current velocities, expressed on Equations 4.5, 4.6 and 4.7 is the angle of wave approach α.

Sherman (1988) evaluated the three predictive models expressed in Equations 4.5, 4.6 and 4.7. He tested the models by directly measuring longshore currents and then examined how accurate the models were in predicting longshore current velocities. Field measurements of longshore current velocities were taken at three sites. The most successful model was the modified Longuet-Higgins model from the SPM, Equation 4.6, (C.E.R.C., 1984). Sherman (1988 p.163) showed that for the three sites he studied the C.E.R.C. (1984) model had an error of 35 per cent when comparing its results with field measurements. The original Longuet-Higgins (1970) model, (Equation 4.5), had an error of 300 per cent while the Komar and Inman (1970) model, (Equation 4.7), gave an error of 65 per cent.

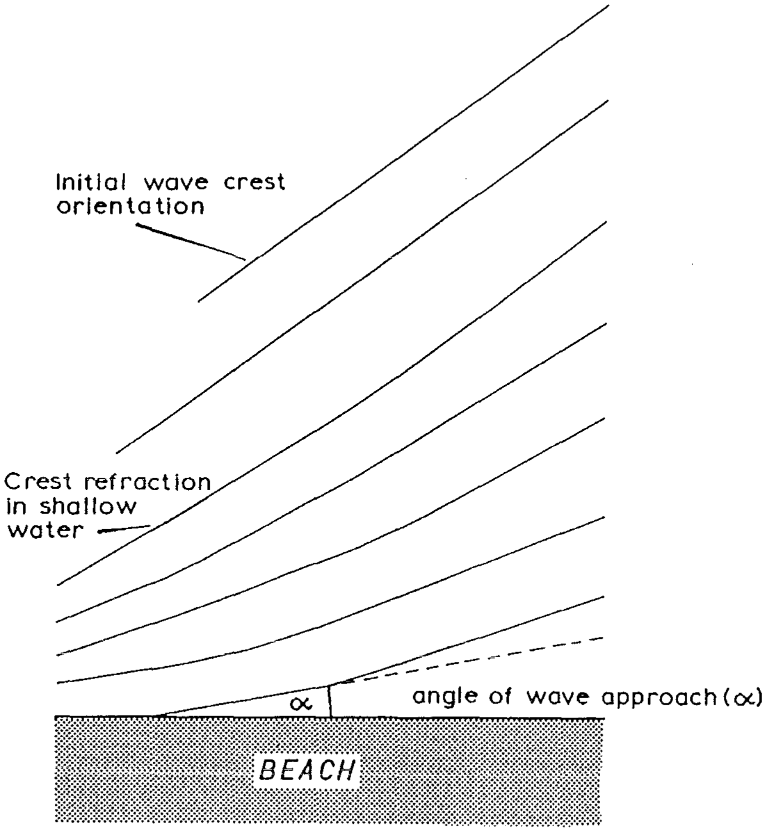


Figure 4.2: The angle between wave crest and shoreline is the wave approach angle (From Pethick, 1984 p.34)

The predictive models of longshore current velocity examined above do not appear to be accurate. However, whatever model is used, the angle of wave approach (Figure 4.2) is the main influence on the velocity of longshore currents. Sherman (1988) notes that the accurate measurement of the wave approach angle is difficult to achieve. This is problematical when examining quantities of longshore sediment transport, which will be discussed in more detail further on.

4.1.3 Measurement of Longshore Sediment Transport

Knowledge of the quantity of longshore sediment transport is needed to determine whether a beach is stabilised, eroding or accreting (Allen, 1988). Estimating the longshore transport rate comes from a knowledge of wave and current parameters, that cause the transport (Komar, 1976), that were discussed in Sections 4.1.1 and 4.1.2. Wave induced longshore currents are the main cause of sediment movement (Komar, 1976). Komar (1976) reviews longshore transport of sediment on beaches. However, as with the bulk of research on the topic, he focuses on sand transport. Therefore, Komar's review will not be discussed in the present research.

C.E.R.C. (1980) presents four methods for calculating longshore sediment transport quantities. However, only one of these methods will be examined in the present research. The method to be discussed is based on the relationship between the longshore component of wave energy flux entering the surf zone and the immersed weight of sand moved (C.E.R.C., 1980). Both parameters have units of force per unit time, and the relationship is expressed as:

$$I_l = KP_l \tag{4.8}$$

where I_l is the immersed weight transport rate, K a dimensionless coefficient, and P_l the longshore component of wave energy flux. C.E.R.C. (1980) then define P_l as:

$$P_l = \frac{\rho g}{16} H^2 C_g \sin 2\alpha \tag{4.9}$$

where C_g is the wave group velocity. When the breaker values of the wave characteristics (H_b, C_{gb}, α_b) and the significant wave height (H_s), which is the average height of the highest one-third of waves in given wave conditions, are added into Equation 4.9, the energy flux factor results:

$$P_{ls} = \frac{\rho g}{16} H_{sb}^2 C_{gb} \sin 2\alpha_b \qquad (4.10)$$

C.E.R.C. (1980) report that the empirical relationship between longshore transport rate and P_{ls} is based on field measurements. The immersed weight of sand moved (Equation 4.8) cannot be measured directly, therefore, the volume of sand moved is usually determined. C.E.R.C. (1980) show that by substituting Q for I_l into Equation 4.8, the volume of sand moved is found by:

$$Q = \frac{K}{(\rho_s - \rho) g a'} P_{ls} \qquad (4.11)$$

where a' equals the ratio of the volume of solids to total volume (for sand a' =0.6). Therefore, wave height at breaking and the angle of wave approach are required to calculate the quantity of sediment transported alongshore. However, as previously mentioned, Sherman (1988) discussed the difficulty in measuring the angle of wave approach and wave height. This difficulty in measuring these parameters and the possible inaccuracies that may result is significant when calculating the volume of longshore sediment transport. C.E.R.C. (1991) report that a 15 per cent accuracy in wave height and 15 per cent accuracy in wave angle result in 37.5 and 15 per cent uncertainty in the contributions of height and angle. This totals a 52.5 per cent uncertainty when calculating Q. Therefore, extreme care and caution have to be used when calculating the volume of longshore sediment transport.

4.1.4 Longshore Sediment Transport on a Mixed Sand and Gravel Beach

As mentioned, the majority of models that examine longshore sediment transport were designed for use on sand beaches. This section will examine models of longshore sediment transport on mixed sand and gravel beaches.

Kirk (1980) reports that mixed beach profiles are dominated by processes of swash and backwash. The morphologies and processes of mixed beaches were discussed in Chapter Two. That discussion reported that swash and backwash velocities are more than enough to transport any sediment alongshore. Mixed beach profiles are also characterised by having only one line of breakers. When this is coupled with the high swash and backwash velocities, it is not surprising that longshore transport occurs principally by beach drifting in the swash zone (Kirk, 1980). Beach drifting is illustrated on Figure 4.3.

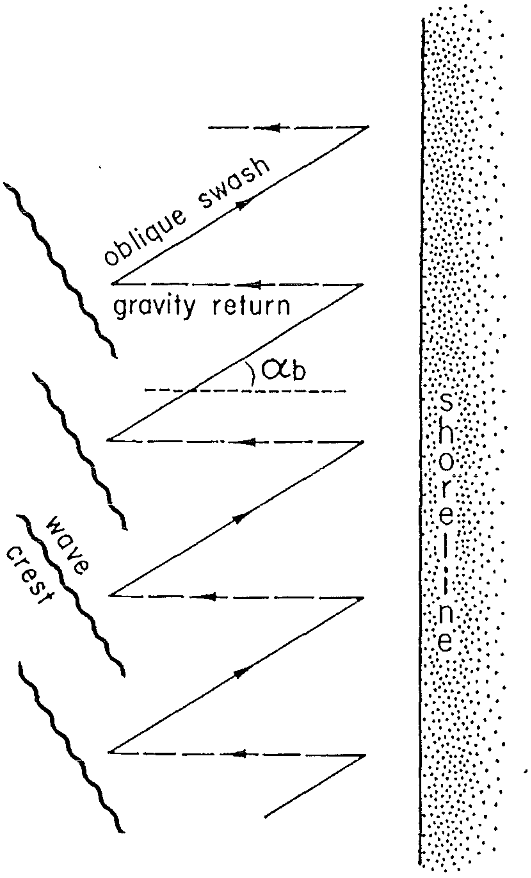


Figure 4.3: Zigzag motion of sediment motion along a mixed sand and gravel foreshore, known as beach drift. The incoming wave swash drives sediment up the beach at an oblique wave angle and gravity flow washes it back.
(From Komar, 1976 p.212)

Neale (1987) examined the longshore sediment transport in a mixed sand and gravel foreshore, on the South Canterbury coast. Neale measured the longshore sediment transport by calculating the accumulation of coarse material against the harbour breakwater of the Port of Timaru. He calculated transport rates to be 51,288 $m^3.yr^{-1}$ (Neale, 1987 p.173). Having measured the longshore transport rate, Neale applied the South Canterbury coast to the existing models of longshore sediment transport that were created for use on sand beaches. Using a similar method to Equation 4.11, longshore transport rates were calculated using:

$$Q = KP_{ls} \tag{4.12}$$

For sand beaches C.E.R.C. calculate K to be 1290. However, Neale (1987 p.191) found this figure to be too high and recalculated K for the South Canterbury coast and mixed beaches to be 13.8-14.9, two orders of magnitude less than the C.E.R.C. value. The longshore energy flux, P_{ls}, is calculated from a number of variables such as wave heights, velocities and approach angles. These variables are independent of the foreshore, therefore, the calculation of the longshore energy flux is the same for both types of beaches, sand and mixed (Neale, 1987).

Neale's (1987) investigation shows that pure sand and mixed sand and gravel beaches are vastly different. Therefore, a different approach has to be taken when calculating longshore sediment transport volumes on mixed foreshores. Section 4.2 will examine the longshore sediment transport on the mid Canterbury coast, which is a mixed sand and gravel coastline.

4.1.5 Distribution of Longshore Sediment Transport across the Surf Zone

Bodge (1989) presented a summary of research that concentrated on the distribution of longshore sediment transport across the surf zone. He reports that interest in the distribution of transport has grown, because it is thought that improved knowledge of the distribution may enhance the understanding of the total longshore transport. From Bodge (1989) it can be reported that the majority of models examining the distribution of longshore sediment transport across the surf zone predict transport to be at a maximum at the outer-mid surf zone, and decreases to zero at the shoreline. Bodge also reports that total longshore transport is greater with plunging and collapsing breakers rather than spilling breakers.

Bodge (1989) concludes that many of the models that predict the distribution of longshore sediment transport across the surf zone are inadequate. He points out that significant levels of transport can occur in the swash zone. He also suggests that the contribution of swash zone transport increases as waves break near or upon the foreshore. These last two points are particularly relevant for mixed sand and gravel beaches. Kirk (1980) has shown that the majority of longshore sediment transport on a mixed sand and gravel foreshore occurs within the swash zone. Also, because of the single line of breakers on mixed beaches, waves break on or very near the foreshore. Therefore, the contribution of swash zone longshore sediment transport is significant on a mixed sand and gravel foreshore.

4.2 Longshore Sediment Transport on the mid Canterbury Coast

Unlike the Port of Timaru, used in Neale's (1987) study, there are no breakwaters for sediment to be accumulated against along the mid Canterbury coast. Therefore, longshore transport of sediment has to be found by using empirical models, such as the ones described in Sections 4.1.3 and 4.1.4. However, these models provide only potential longshore sediment transport. Actual rates depend on factors that are not accounted for in the models, such as sediment supply and tend to be lower than potential transport rates.

Sea condition observations were taken by the Canterbury Regional Council, at the Ashburton River mouth, from October 1991 to February 1992. Observations were made daily and recorded among other things, wave height and approach angle. Equation 4.10 shows that wave group velocity is also required when determining longshore energy flux, and thus is required to determine the longshore sediment transport rate. Wave group velocity in shallow water is determined by:

$$C_{gb} = \sqrt{g(d + H_b)} \tag{4.13}$$

where d is the water depth. Water depth has not been measured. When water depth is not measured, it can be calculated using the reciprocal of H/d. H/d is generally regarded as being 0.78. The reciprocal of this is 1.28. To calculate water depth, d_b, the reciprocal of H/d is multiplied by the wave height at breaking, H_b. Therefore, water depth for use in Equation 4.13 is taken as: $d_b = H_b \times 1/0.78$.

Table 4.1: Potential longshore sediment transport rates for the mid Canterbury coast, October, 1991 to February, 1992.

Wave Height H_{sb} (m)	Wave Approach Angle α_b (°)	Wave Group Velocity C_{gb} (m.sec^{-1})	Lonshore Energy Flux P_{ls} (N.s^{-1})	Q (m^3.yr^{-1}) using K=1290 (CERC, 1980)	Q (m^3.yr^{-1}) using K=14.9 (Neale, 1987)
0.5	2	3.3	36.3	46,827	540
1.0	2	4.7	206.8	266,772	3,081
1.5	2	5.8	574.1	740,589	8,553
2.0	2	6.7	1,179.1	1,521,039	17,569
2.5	2	7.5	2,062.3	2,660,367	30,728
3.0	2	8.2	3,246.8	4,188,372	48,377
4.0	2	9.5	6,687.2	8,626,488	99,639
5.0	2	10.6	11,658.7	15,039,723	173,714
0.5	5	3.3	88.1	113,649	1,313
1.0	5	4.7	502.2	647,838	7,483
1.5	5	5.8	1,394.3	1,798,647	20,775
2.0	5	6.7	2,863.4	3,693,786	42,665
2.5	5	7.5	5,008.4	6,460,836	74,625
3.0	5	8.2	7,885.2	10,171,908	117,490
4.0	5	9.5	16,240.4	20,950,116	241,982
5.0	5	10.6	28,313.9	36,524,931	421,877
0.5	10	3.3	176.3	227,427	2,627
1.0	10	4.7	1,004.3	1,295,547	14,964
1.5	10	5.8	2,788.7	3,597,423	41,552
2.0	10	6.7	5,726.9	7,387,701	85,331
2.5	10	7.5	10,016.7	12,921,543	149,249
3.0	10	8.2	15,770.3	20,343,687	234,977
4.0	10	9.5	32,480.9	41,900,361	483,965
5.0	10	10.6	56,627.8	73,049,862	843,754

Note: Q = Potential longshore sediment transport rate.

Table 4.1 details potential longshore sediment transport rates (Q) for the mid Canterbury coast using different parameter values and equations based on the data from October 1991 to February 1992. Different values for wave height and approach angle have been used. Transport rates have also been calculated using both the C.E.R.C. model (Equation 4.11) and Neale's equation (Equation 4.12). Table 4.1 presents a number of possibilities of potential longshore sediment transport, using various wave parameter values. Table 4.1 clearly shows a significant difference in potential longshore sediment transport rates when different wave parameters are used. For example when a wave height of 1.5m is combined with a wave approach angle of 5°, a potential transport rate is about 20,775$m^3.yr^{-1}$, using Neale's (1987) value for K. However, when storm conditions are present at the coast, the potential longshore transport is vastly bigger. With wave heights of 4m and approach angles of 5° and 10°, potential transport rates are 241,982$m^3.yr^{-1}$ and 483,965$m^3.yr^{-1}$ respectively. These figures assume that the given wave conditions are continuous for the entire year. However, while this is not the case, it is useful to examine the significance of wave height and wave approach angle on longshore sediment transport. Therefore, the rate of potential longshore sediment transport is highly variable, depending on the wave parameters of significant wave height at breaking and wave approach angle. Of these two parameters, change in wave height affects the potential longshore sediment transport more than changes to approach angle. For example, if the wave approach angle, for a given wave height doubles, Q is also doubled. On the other hand if the significant wave height at breaking, for a given wave approach angle, doubles, Q increases by a magnitude of 4. This is because in Equation 4.10, significant wave height at breaking is squared, while the wave approach angle is not.

Table 4.2: Potential longshore sediment transport rate for the mid Canterbury coast using a longshore energy flux of 534.6 $N.s^{-1}$ and different values of K

Source	K	Q, Potential Longshore Sediment Transport ($m^3.yr^{-1}$)
CERC (1984)	1,290	689,634
Hewson (1977) from Neale (1987)	92.1	49,237
Kirk (1984)	55.7	29,777
Neale (1987)	14.9	7,966
Neale (1987)	13.8	7,378

From the observations at the Ashburton River mouth between October 16, 1991 and February 25, 1992, every possible variation of wave height and wave approach angle was used to calculate the longshore component of wave energy flux, P_{ls}. Daily values of the longshore energy flux were calculated and averaged to give a mean value for the flux. This was done because Neale (1987) notes that it is incorrect to simply average the wave heights and wave approach angles, and then use those figures to calculate the longshore component of wave energy. The longshore wave energy flux from every observation was averaged to give a value of 534.6$N.s^{-1}$. This is similar to the average longshore energy flux observed by Hewson (1977), which was 557$N.s^{-1}$.

The K values used by Neale (1987), 13.8 and 14.9, may be more appropriate for lower energy type conditions, on which they were based. Neale (1987) also evaluated K values of 92.1 and 55.7. These figures may be more appropriate when calculating long-term average potential transport rates. Table 4.2 shows different potential longshore sediment transport rates using different K values and the average longshore component of wave energy flux, 534.6N.s^{-1}. The variations for the potential sediment transport rate are significant for different K values. However, because Neale (1987) believed that for long-term average potential sediment transport rate the higher K value should be used. Therefore, the average potential longshore sediment transport rate for the mid Canterbury coast, using a K value of 92.1, is 49,237m^3.yr^{-1}.

The method of calculating longshore sediment transport used above gives only a gross average transport rate. For a more accurate figure of longshore sediment transport on the mid Canterbury coast, the transport volume for every day of observations was calculated. These values were then separated into northward movement and southward movement. The present research found there to be northward sediment transport on the mid Canterbury coast 51 per cent of the time. Southward movement occurred for 24 per cent, and there was no longshore movement 25 per cent of time. Northward daily averages of sediment transport were then multiplied by the proportion of the year (51 per cent) that those conditions applied. Likewise, the same was done for southward movement. Total northward longshore sediment transport was calculated in the present research to be 48,231m^3.yr^{-1}. Southward transport amounted to 7,586m^3.yr^{-1}. Gross potential longshore sediment transport on the mid Canterbury coast is 55,817m^3.yr^{-1}, and there is transport 75 per cent of the time. Net longshore sediment transport on the mid Canterbury coast is in a northward direction and is 40,645m^3.yr^{-1}.

The net potential longshore sediment transport rate calculated for the mid Canterbury coast in the present research is of a similar magnitude to rates found elsewhere in the literature. Table 4.3 summarises past and present estimates of longshore sediment transport along the mid and South Canterbury coast. Of note is the estimate by Reinen-Hamill (1997). His is the only other research done at the Ashburton River mouth. He was using a numerical model to estimate longshore sediment transport.

However, his research does not say if the model he uses is calibrated for mixed foreshores. His figure of 140,700 $m^3.yr^{-1}$ seems to be an over-estimate, particularly when comparing this with other figures shown in Table 4.3.

Table 4.3: Past and present estimates of net longshore sediment transport rates on the mid and South Canterbury foreshore (After Neale, 1987 p.160)

Author	Location	Rate Estimate ($m^3.yr^{-1}$ northward)
McIntyre (1958)	South Beach	88,750
Tierney (1969)	South Beach	60,730
Kirk (1984)	South Beach	56,981
Tierney and Kirk (1978)	Washdyke	81,500
Neale (1987)	South Beach	51,288
Reinen-Hamill (1997)	Ashburton River mouth	140,700
Present Research	Ashburton River mouth	40,645

The potential longshore sediment transport rates presented in this research are an annual average only. As with cliff erosion, which was examined in Chapters 2 and 3, major amounts of longshore sediment transport occur during storm events. Kirk (1984) for example, reported that 26,000m^3 of sediment were transported along the Timaru Harbour breakwater during a single storm event. Therefore, the rate of longshore sediment transport along the mid Canterbury coast is variable.

4.3 Longshore Transport of Sediment 'Slugs'

Neale (1987) comprehensively examined longshore sediment transport along the South Canterbury coast. He measured and calculated longshore sediment transport in a number of ways. The present section will concentrate on only one of these methods, the evaluation of sediment slugs migrating alongshore in the direction of the predominant longshore transport direction.

4.3.1 Sediment 'Slug' Theory

Sediment slugs are the result of fluctuating rates of sediment transfer into and out of a beach profile section (Neale, 1987). The fluctuating rates result in changes of beach volume over time. The variations alongshore in beach volume then migrate due to longshore sediment transport, hence the term slug. Neale (1987) shows the offshore supply of sediment to a mixed beach is negligible, therefore, the variable supply of sediment responsible for the variations longshore in beach volume that create the slugs, are almost certainly from alongshore. Single (1992) notes the slugs reflect the episodic supply of sediment to the coast from large rivers during flood and from cliff erosion.

Neale (1987) reports that longshore sediment transport is variable across four dimensions: depth; width; length; and time. He also suggests the best way of examining these four dimensions is by repeated surveys of beach profiles along the coast. Depth and width are shown within each survey, the alongshore component can be determined by comparing profiles and the temporal aspect is represented by the repetition of surveys. Neale evaluated 19 profile sites from the Waitaki River to Timaru, surveyed approximately yearly for a period of ten years. However, he only analysed beach volume, because it is possible for width and height to not respond to variations, or net transfers of sediment alongshore. To make comparisons between profiles with different total volumes, Neale (1987 p.201) standardised the data using the formula:

$$B_Z = \frac{(B_t - B_X)}{B_X} \tag{4.14}$$

where B_Z is the standardised profile volume, B_X the mean of measured volumes at a given profile ($m^3.100m^{-1}$ above 1m AMSL), and B_t is the volume at time t ($m^3.100m^{-1}$ above 1m AMSL). This formula allows above and below average volumes at a profile to be assigned positive and negative standardised values respectively.

Neale's (1987) results will not be discussed in full in the present research because they are summarised in both Neale (1987) and Single (1992). However, Neale discovered that the slugs migrated northward along the South Canterbury coast at velocities that ranged from 0.3 to 5.61km.yr^{-1}, at an average of 1.4km.yr^{-1}. Neale determined that the velocities are influenced by the prevailing angle of wave approach.

Single (1992) notes that passage of slugs past a given position on the coast affects the shore morphology. Therefore, the response of the beach to the wave environment is altered. Figure 4.4 illustrates the migration of a slug past a given profile site. When a crest in the sediment slug is present at the site, there is an excess of sediment on the profile. This enhances the ability of the beach to dissipate wave energy. Therefore, the slug crest may protect the beach profile. Conversely, the presence of a slug trough has the opposite effect, reducing the volume of the beach and its ability to protect itself from erosion.

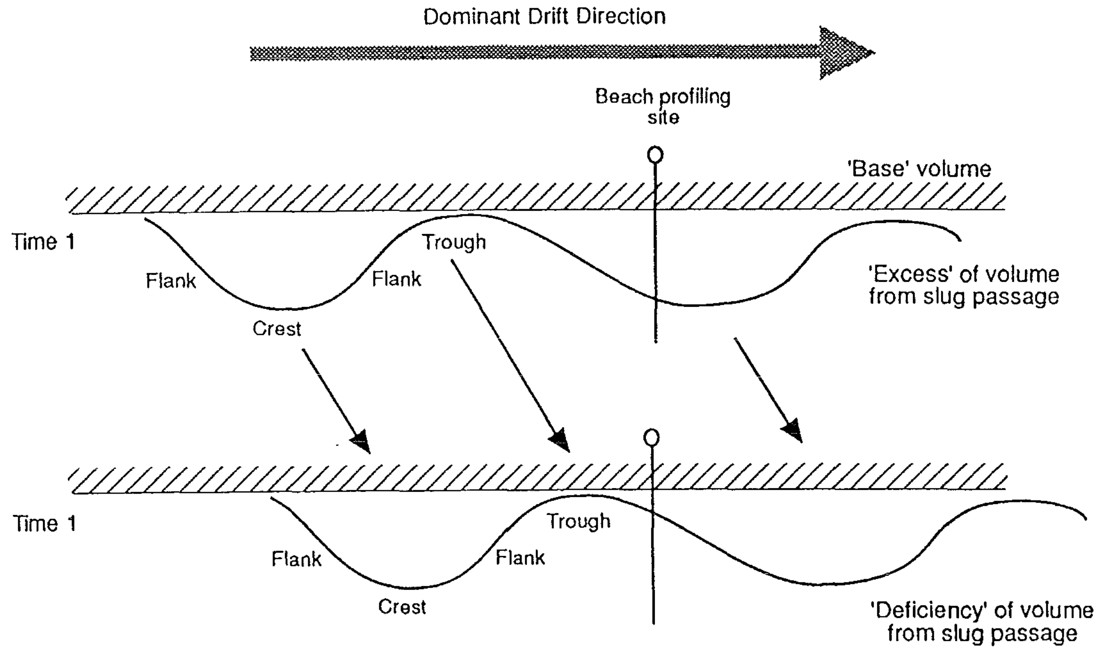


Figure 4.4: The translation of a 'slug' of sediment alongshore
(From Single, 1992 p.62 After Neale, 1987)

4.3.2 'Slugs' on the mid Canterbury coast

Neale (1987) demonstrated sediment slugs on the South Canterbury coast from the Waitaki River to Timaru. He noted that there appeared to be no pattern of slug migration for the Washdyke coast, just north of Timaru. This section will determine the presence of sediment slugs on the mid Canterbury coast. Beach surveys have accompanied the cliff surveys that were examined in Chapter Three. The Canterbury

Regional Council has measured profiles for 22 locations. The majority of the beach profiles were set up in 1986. However, some were set up earlier, while others were set up after 1986. The profiles have been resurveyed approximately yearly. Profile site locations are shown on Figure 3.1. The data set used for the present study is similar in type to that of Neale (1987).

Beach volume data were standardised using Equation 4.14. As mentioned, the standardisation produces a negative or positive value representing erosion or accretion of beach sediment volume respectively between surveys. Standardisation also allows direct comparisons between beaches of different volumes to be made. Results from the data set of the present study are presented on Figure 4.5. Each grey horizontal line represents the location of a profile site along the mid Canterbury coast. The horizontal lines also represent the measured mean profile volumes for each respective profile. The measured mean volumes of each profile from 1986-1996 are displayed on the right of Figure 4.5. The curved lines on Figure 4.5 exhibit fluctuations in beach volume over time around the measured mean for each profile.

Neale (1987) noted that this technique represents only long-term fluctuations in beach volume over several years. Short-term fluctuations due to storms are superimposed on the long-term changes. Therefore, short-term fluctuations can have an effect on the correctness of the interpolation for Figure 4.5. However, Neale (1987) says that while the short-term changes do have some influence, they do not account for the total variation shown on Figure 4.5.

Figure 4.5 shows that at a given time some profiles exhibit accretion, while others show erosion. This is even evident for profiles that are only a matter of 1-2km apart. Also of note on Figure 4.5 are the measured mean beach profile volumes displayed on the right of the diagram. These standardised volumes also vary greatly between profiles. However, volumes appear to be greater in the southern section of the study area, toward the Rangitata River. The explanation for this may be the proximity of the profiles to the Rangitata River, which may be a major sediment source for the coast. The sediment contributions of the Rangitata and Ashburton Rivers will be discussed in Chapter Five.

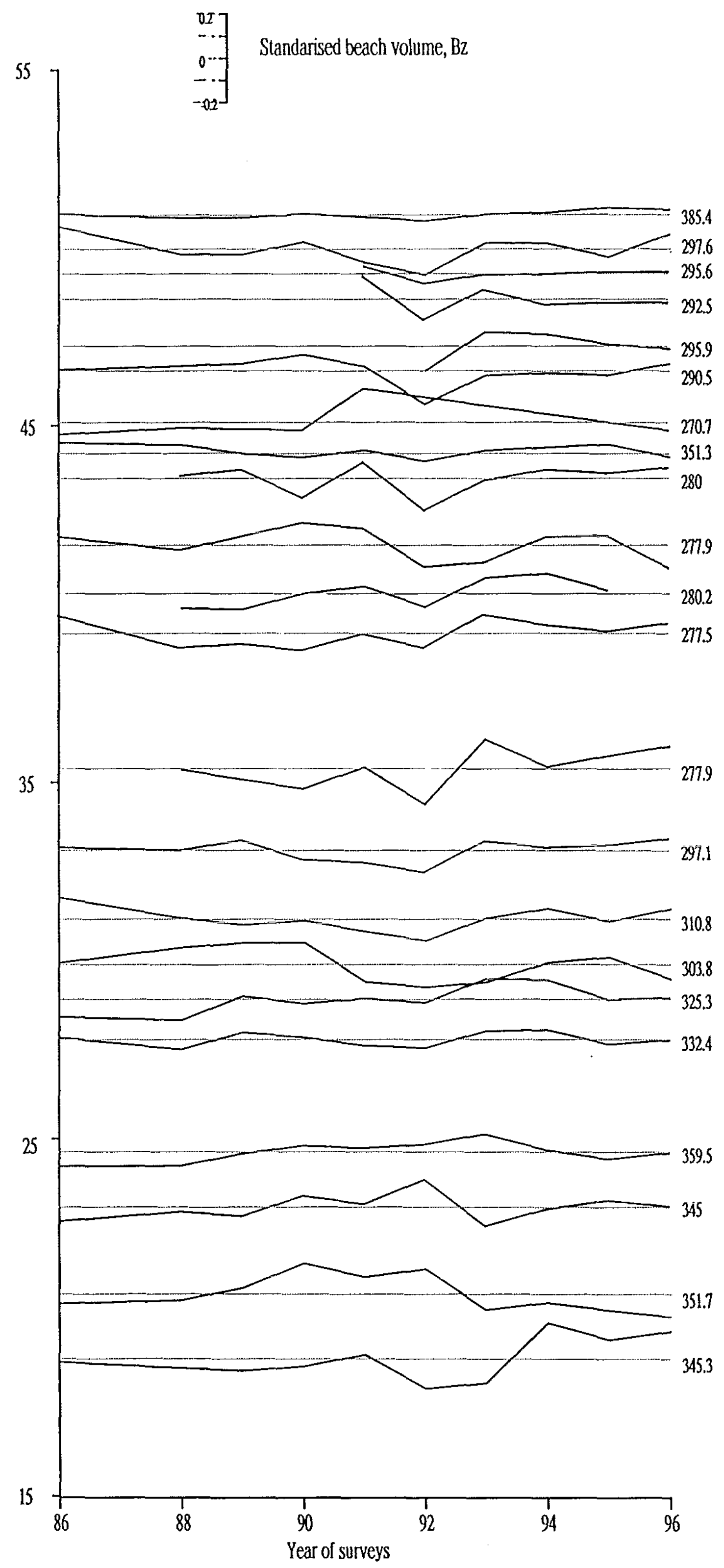


Figure 4.5: Foreshore volume variations between the Rangitata River to Wakanui Creek, 1986-1996. Measured mean profile volumes (Bx) are shown on right ($m^3.100m^{-1}$)

As mentioned, the fluctuations in beach profile volume over time displayed on Figure 4.5, involve fluctuating rates of sediment transfer into and out of the profile sections (Neale, 1987). Therefore, the fluctuations in profile volumes shown on Figure 4.5, can be explained as localised movements of fluctuating volumes of material drifting past each profile (refer Figure 4.4).

Neale (1987) hypothesised that above average volumes of sediment drifting past a profile can be imagined as being 'slugs' of material. The slugs are input to the foreshore by episodic river floods and by cliff erosion. They are then transported alongshore by coastal processes, which were outlined previously in the chapter. Figure 4.5 clearly shows that beach volume fluctuates over time at a given profile. It is then possible to link peaks, and troughs, in beach volume from one profile to another. Figure 4.6 shows linkages between profiles, of peaks and troughs of sediment volume migrating alongshore at a given velocity. This analysis is only possible because the general direction of longshore sediment movement along the mid Canterbury coast is known to be in a northward direction. Therefore, the linkages shown on Figure 4.6 are in a general northward direction.

Figure 4.6 shows that the velocity of sediment slug migration along the mid Canterbury coastline is variable between slugs. Velocities range from 0.94km.yr^{-1} to 3.54km.yr^{-1}, with an average velocity of 2km.yr^{-1}. Neale (1987) showed that for the South Canterbury coast there was a range from 0.3 to 5.61km.yr^{-1} for sediment slug velocity, and a mean rate of about 1.4km.yr^{-1}. Therefore, the results of the present research show average sediment slug velocities to be higher than those calculated by Neale (1987). These results are satisfactory given that they are of a similar magnitude as Neale's results. Section 4.2 showed that the calculated longshore sediment transport on the mid Canterbury coast in the present study is higher than the transport on the South Canterbury coast, as calculated by Neale (1987). Therefore, it would be expected that slug velocities would be greater for the mid Canterbury coast than the South Canterbury coast. The results from the present study reflect this.

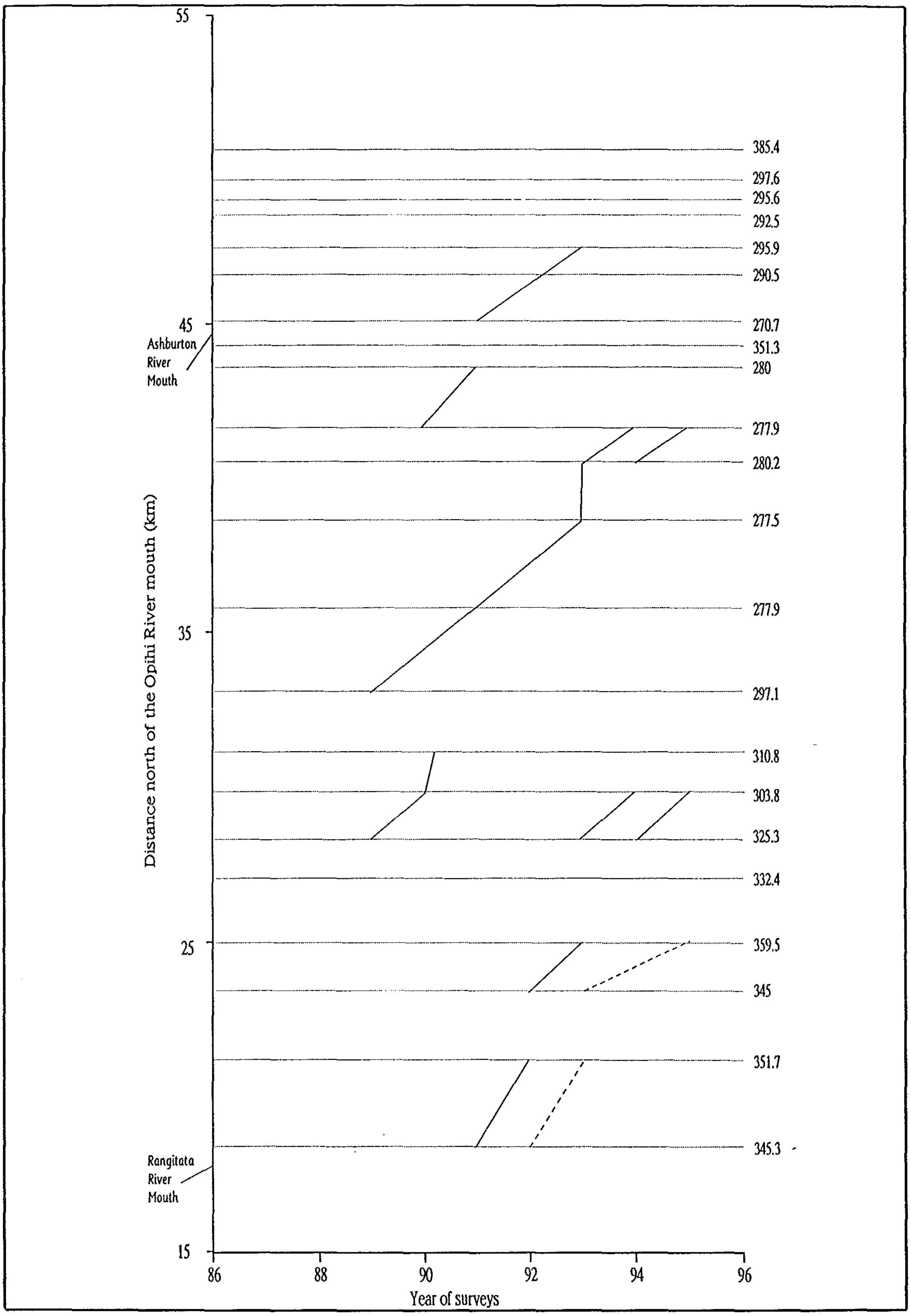


Figure 4.6: Possible linkages of high (solid lines) and low (dashed lines) profile volumes, suggesting movement of 'slugs' alongshore at a velocity (km.yr^{-1}). Velocities are shown alongside linkages. The diagonal lines represent linkages of slug peaks (solid lines) and troughs (dashed lines) as they migrate northward along the mid Canterbury coast.

4.3.3 Influences of 'Slugs' on Coastal Cliff Erosion

In Section 4.3.2 the presence of slugs of sediment migrating their way northward along the mid Canterbury coast was established. The presence or absence of a slug at any given point on the coast, at any given time, may have an effect on the shore morphology. Neale (1987) reviews the effects on shore morphology of sediment slugs. He showed that barrier overtopping occurred at the Wainono Lagoon barrier beach when the foreshore was low in height and volume.

One of the main effects of sediment slugs is their ability to locally increase beach volume for a time. Chapter Three outlined the extent that beach volume had on controlling cliff erosion on the mid Canterbury coast. Over short time periods of one year, beach volume has been shown in this study to be the major controlling factor influencing spatial variations in cliff erosion. Therefore, the presence of a sediment slug would result in reduced cliff erosion at sites landward of a slug crest. Conversely, a section of coast that had the trough of a passing slug present would have a greater chance of increased cliff erosion. For example, profile site RANG23.44 (situated 23.44km north of the Opihi River mouth) is the third from southern most profile on Figure 4.5. In 1992, a slug peak was present at the profile site and consequently no erosion took place. However, in 1993 the profile had a slug trough on its foreshore and 1.8m of cliff top retreat occurred. However, during 1993 site RANG24.94 (situated 1.5km north of site RANG23.44) had a slug peak and experienced no cliff erosion. Therefore, sediment slugs appear to have an influence on the erosion of the mid Canterbury coastal cliffs by affecting the foreshore volume and height.

4.4 Summary

This chapter has concentrated on the longshore transport of sediment along the mid Canterbury coast foreshore. As will be examined in Chapter Six, longshore sediment transport rates have an influence on the local sediment budget of a coastal area. Neale (1987) states that a stable sediment budget is dependent on a constant balance between the inputs and outputs of all sections of the beach. This includes the balance between inputs and outputs of longshore sediment transport. Therefore, it is necessary to examine the longshore sediment transport along a coast.

The examination of longshore sediment transport along a mixed sand and gravel foreshore is hindered by the lack of models that incorporate mixed sand and gravel into them. The majority of the models consider the transport of sand only. The first section of this chapter detailed models based on the transport of sand. It has been useful to acknowledge these models even though their applicability to the mid Canterbury coast is limited.

Models that estimate the potential longshore sediment transport rate are sensitive to the longshore energy flux and a dimensionless coefficient, K. The longshore energy flux is dependent on wave approach angle and wave height at breaking. The longshore energy flux is the same for both pure sand beaches and mixed beaches. However, the coefficient K, is different for the two beach types. Much lower values for K should be used when calculating the potential longshore sediment transport on a mixed sand and gravel beach. This is because the efficiency of incident waves to transport material along a mixed foreshore is less than on a pure sand foreshore. Therefore, potential longshore sediment transport was calculated for the mid Canterbury coast, using both a sand based value for K and a number of K values more appropriate for use on a mixed beach. Sand based models proved to vastly over-estimate longshore sediment transport. Using models adapted for use on mixed sand and gravel foreshores, the present research calculated a potential net longshore sediment transport on the mid Canterbury coast to be 40,645$m^3.yr^{-1}$ in a northward direction.

This chapter also examined the theory that slugs of sediment migrate alongshore, influencing shore morphology and cliff erosion. The present chapter has shown the existence of slugs on the mid Canterbury coast. It has also been argued that they migrate in a northward direction at an average of 2$km.yr^{-1}$. The size and extent of the slugs was not examined but they are dependent on the input of sediment from river floods and cliff erosion. The sediment slug velocity discovered in the present research is comparable to that of Neale (1987). The present research also showed that the presence of slug peaks contributed to less erosion of the cliffs while slug troughs facilitated more cliff erosion.

The volumes of longshore sediment transport on the mid Canterbury coast have been calculated because of the importance of longshore sediment transport to the sediment budget of a coastal environment. Longshore sediment transport along the mid Canterbury coast will be compared with volumes of sediment contributed by cliff erosion (Chapter Three) and the sediment yields of the Rangitata and Ashburton Rivers (Chapter Five), in Chapter Six which will focus on a sediment budget for the mid Canterbury coast.

Chapter Five

The
mid Canterbury
Rivers

Zenkovich (1967 p.551) argues that rivers, and their sediment loads can have a variety of effects on the dynamics and morphologies of sea coasts. He goes on to say that rivers may sometimes be decisive factors in the development of sea coasts. The mid Canterbury coastline is bisected by two major rivers. Chapter Two outlined the importance of the Ashburton and Rangitata Rivers in the formation of the Canterbury Plains during the Quaternary. They remain important features of the mid Canterbury coastal environment in the present day. This chapter will investigate the Ashburton and Rangitata Rivers to examine their role in the coastal sediment budget of the mid Canterbury coast.

The Ashburton and Rangitata Rivers have gravel beds and are braided in channel form. It is not the objective of this thesis to examine in detail the morphologies and processes of braided rivers. However, a brief examination is both useful and interesting. The process of water flow and sediment movement is important to the sediment budgets of the coastline onto which the rivers discharge. This chapter will review the nature of braided river channels, with particular reference to sediment movement within the river channel. As mentioned, Chapter Six will provide a sediment budget for the mid Canterbury coast, of which river inputs are an integral part.

Kirk (1991) examined interactions at river-beach interfaces on mixed sand and gravel beaches. Within his study Kirk (1991) enlarged on the 'large' river, 'small' river concept first put forward by Zenkovich (1967). Zenkovich (1967) suggested that rivers should be classified in terms of their sediment contribution to the coast. 'Small' rivers do not provide enough sediment to prevent coastal erosion, while 'large' rivers provide enough sediment so that the coast either stabilises or accretes. Kirk (1991) also investigated the river mouths on the East Coast of New Zealand's South Island, and noted that they have been incorrectly classified as estuaries. This chapter will examine both of these matters, with regard to the Ashburton and Rangitata Rivers. The first part of this chapter will deal with concepts and research from previous work on not only the mid Canterbury rivers, but where applicable on braided rivers in general. The second section will examine daily discharge data for both the Ashburton and Rangitata Rivers, putting the mid Canterbury rivers within the context of existing literature and extending knowledge of the role that they have on the mid Canterbury coastal environment.

Kelk (1974), as part of his study into process interactions on the mid Canterbury coast, investigated the Ashburton River mouth lagoon in detail. He proposed that a lagoon sequence of 12-19 months takes place in the Ashburton River mouth lagoon. The sequence will be examined and tested within the present chapter. Kirk (1991) advanced the theory that river mouth lagoons can be sinks of sediment as well as being sources. This concept will also be explored.

The main purpose of this chapter is to calculate the sediment yield of the Ashburton and Rangitata Rivers. Knowledge of the sediment yield is crucial. The discharge data will show that river discharge is episodic. That is, a large amount of the annual sediment yield for the Ashburton and Rangitata Rivers is deposited on the coast during a small number of large magnitude events. The sediment yield will be discussed in terms of an annual average and single event yields.

River mouths are an extremely important, highly visible part of any coastal environment. The mouths of the Ashburton and Rangitata Rivers are no exception to this.

5.1 The mid Canterbury Rivers: A Review

A large amount of literature exists on rivers, their morphologies and the processes that act upon them. It is not intended to fully examine hydrological literature on river beds and sediment transport within rivers. However, an investigation into the nature of gravel bed braided rivers and sediment transport within these rivers is necessary when sediment yields are required. Therefore, the nature of the mid Canterbury rivers and sediment transport within them will be examined. The investigation into the Ashburton and Rangitata Rivers includes an examination of their mouths and the interactions that occur at the river-beach interface.

5.1.1 Sediment Transport in Braided Rivers

The Ashburton and the Rangitata, as with other rivers of the Canterbury Plains are predominantly braided, and remain so until the point where they enter their river mouth lagoons (Plate 2.1a). They emerge from narrow gorges respectively 480 and 370m above sea level at the eastern extent of foothills of the Southern Alps. East of these gorges the river beds take on a braided nature.

Bridge (1993) says that the term 'braided river' denotes a channel pattern as seen in plan view. There are numerous definitions of what is a braided river. Bridge (1993) examines these definitions, with perhaps the best being that of Lane (1957):

> *"a braided stream is characterised by having a number of alluvial channels with bars or islands between meeting and dividing again, and presenting from the air the intertwining effect of a braid."*
>
> (Bridge, 1993 p.15)

The Ashburton and Rangitata Rivers come within Lane's (1957) definition. Braided rivers are also characterised as having a high streambed gradient and dominantly coarse grain floodplain sediments (Selby, 1985). The high streambed gradient results in relatively high velocities of water flow through the channel. Coupled with the largely unconsolidated alluvium in which they form, braided channels tend to have low stability. Braided fluvial streams, due largely to alluvium sediment deposits, are agents of considerable erosion and sediment transport (Bristow and Best, 1993). Therefore, sediment supply from braided rivers is usually high (Selby, 1985).

The Ashburton and Rangitata Rivers are both characterised by streambed gradients of approximately 6m/km (Leckie, 1994). High flow velocities result in these rivers having unstable channels, which leads to large sediment yields. These two mid Canterbury rivers, along with the other Canterbury Plains rivers are different to many other gravel-bed rivers worldwide, because their banks are composed primarily of gravelly alluvium (Carson and Griffiths, 1987). Banks of cohesive sediment often bind many gravel-bed rivers in other parts of the world.

Carson and Griffiths (1987) explain that transport of sediment by rivers has been studied extensively because of its significance for planning river use. The present study is not concerned with increases in channel bed level that lead to flooding. Rather, the interest is in sediment transport by the Ashburton and Rangitata Rivers, with particular regard to the amount of sediment that these rivers discharge into the mid Canterbury coastal environment. The remainder of this sub-section will briefly examine sediment transport, particularly bed-load transport, by gravel bed rivers.

The ultimate sediment source for the Ashburton and Rangitata Rivers is the Southern Alps, which provide vast amounts of sediment to the rivers (Chapter Two). The eroded sediment is then deposited into the braided channels of the mid Canterbury rivers. Transport of this sediment takes place over time until, eventually, the sediment arrives at the mid Canterbury coast.

Sediment load is characterised by three major types: bed load, dissolved load, and suspended load. Adams (1980) estimated that for the South Island rivers, suspended load was by far the largest transporter of sediment (93 per cent). Dissolved load (4 per cent) and bed load (3 per cent) transported far less sediment. Suspended and dissolved sediment, upon deposition at the coast, is soon, if not immediately, deposited on the continental shelf and is lost to the coastal foreshore. Bed load on the other hand is of more importance to the coastal foreshore. Bed load, which is coarser than suspended or dissolved load, can be an important source of sediment for a coastal environment.

Traction flow and/or saltation transport bed load. Traction flow involves particles having continuous contact with the bed, so are dragged along by the friction of the water and the bed. Saltation is the bouncing of particles downstream where the water current is strong enough to get the particle up but is not strong enough to keep it up. However, for sediment to be transported it must first be set in motion. Carson and Griffiths (1987) state that for sediment to become entrained, critical velocities of water flow have to be met. Flow within the stream exert a stress on particles resting on the bed. When flow velocity reaches a certain level, stress becomes sufficient enough for sediment to become entrained. Bed conditions and sediment size affect the threshold velocities when sediment will become entrained. Table 5.1 gives threshold velocities of sediment entrainment for different sediment sizes for gravel bed rivers. Table 5.1 shows that as sediment size increases so does the critical velocity required to entrain it. Once the sediment is entrained, its behaviour also depends on flow velocity. Figure 5.1 demonstrates average velocities, at which sediment will be eroded (entrained), transported or deposited. Again, as sediment size increases, so do the velocities required to transport the sediment.

Table 5.1: Critical velocities for sediment entrainment and deposition (From Carson and Griffiths, 1987 p.8)

Sediment Size, Diameter, d (mm)	Crit. Vel. for Entrainment ($m.s^{-1}$)	Crit. Vel. for Deposition ($m.s^{-1}$)
5	1.1	0.5
10	1.4	0.7
15	1.6	0.8
25	1.9	1.1
40	2.2	1.4
75	2.7	1.9
100	3.0	2.2
150	3.4	2.6
200	3.6	3.0

Flow velocity is the major control on the transportation of sediments in a gravel bed channel. The coarser the sediment, the higher the velocity required to firstly entrain the sediment, and secondly to transport the sediment. When a stream is in flood and discharge increases significantly, so does flow velocity. This enables a stream to transport more sediment. Therefore, floods enable a stream to transport more sediment than during times of mean flow.

5.1.2 'Small' or 'Large' River

Zenkovich (1967) advanced a classification system for rivers as they enter the coastal environment. This classification categorises rivers in relation to their sediment load and the consequent effects the load has on the coast. Rivers can be classified as being either 'small' or 'large'. 'Small' rivers cannot maintain their coasts against erosion while 'large' rivers can.

Small rivers seldom affect the coast significantly (Zenkovich, 1967). They produce insignificant sediment load to protect the coast from direct marine erosion (Kirk, 1991). Sediment load should only be thought of, in this case, in terms of the sediment that is capable of forming beaches (Kirk, 1991). In the mid Canterbury context, the beach forming sediment is coarse sands or gravels. It has already been mentioned that only coarse sediment remains on the foreshore from river discharge. Finer sediments, those is suspension or those dissolved, do not stay on the coast and in the case of the mid Canterbury rivers these sediments are deposited onto the continental shelf. The lack of nourishment that small rivers contribute to the coast means that mostly marine processes control river mouth landforms.

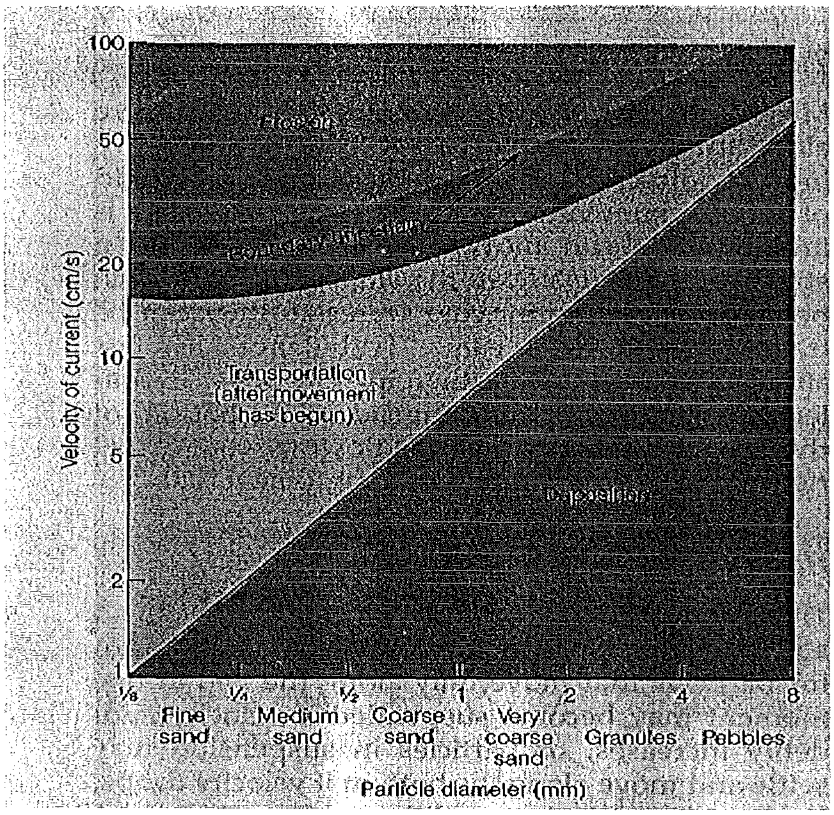


Figure 5.1: Average velocity at which uniformly sorted sediment particles of different sizes are eroded, transported and deposited.
(From Skinner and Porter, 1987 p.284)

Large rivers, on the other hand, can have great effects on the coast (Zenkovich, 1967). Kirk (1991) notes that large rivers contribute large amounts of sediment to the coast so that the coast maintains either a stable position against losses due to abrasion and longshore transport, or actively accrete. In contrast to small rivers, river influences, rather than marine processes control the mouths of large rivers.

The concept of 'large' and 'small' rivers is relative with respect to the receiving coast (Kirk, 1991). Both the size and quantity of the sediment is important. The mid Canterbury rivers, with regard to the concept of 'large' and 'small', suggested by Zenkovich, will be examined in Section 5.3.4.

5.1.3 River Mouths

The mouths of the Ashburton and Rangitata Rivers are similar to the other river mouths of the Canterbury Bight coast. The main river channel flows into a coastal lagoon. The lagoon is a long, narrow feature that is aligned normal to the coast. The Ashburton River mouth lagoon can be up to 1km long and only a few hundred metres in width. Plate 5.1 illustrates the elongated nature of the Ashburton River mouth lagoon. Kelk (1974) states that within the coastal environment adjacent to the Ashburton River mouth, the lagoon forms a focal point of process interplay between the river, sea, beach and cliffs. Therefore, the lagoons of the Ashburton and Rangitata Rivers are important features of the coastline.

Plate 5.1: Ashburton River mouth Hapua illustrating its elongated nature parallel to the coast

River mouth lagoons have often been incorrectly ascribed as being estuaries. For example, Hume and Herdendorf (1988) describe the Rakaia River mouth lagoon, which is similar to the mouths of the Ashburton and Rangitata Rivers, as being a 'type 10 estuary.' Kirk and Lauder (1994) express concern over the Hume and Herdendorf (1988) definition. Hume and Herdendorf make no distinction between an estuary and a lagoon. Kjerfve (1994) defines an estuary as being:

> *"an inland river valley or section of the coastal plain, drowned as the sea invaded the lower course of a river during the Holocene sea level rise, containing sea water measurably diluted by land drainage, affected by the tides and usually shallower than 20m."*
>
> (Kjerfve, 1994 p.2)

Kirk and Lauder (1994) note that neither the Ashburton or Rangitata River mouth lagoons meet the above definition. The lagoons of the mid Canterbury rivers cannot be classified as estuaries, therefore they require a separate definition. Kjerfve (1994 pp.2-3) describes coastal lagoons as being:

> *"an inland body of water, usually orientated parallel to the coast, separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets, and having depths which seldom exceed a couple of metres. A lagoon may or may not be subject to tidal mixing, and salinity can vary from that of a coastal fresh water lake to a hypersaline lagoon, depending on the hydrologic balance."*

The lagoons of the Ashburton and Rangitata River mouths conform to this definition with the added restriction that tidal circulation is not dominant (Kirk and Lauder, 1994).

Kirk and Lauder (1994) state that the river mouth lagoons of the South Island's East Coast, including the mouths of the Ashburton and Rangitata Rivers, are not fully described in the international literature. However, there have been some examinations into the morphologies and processes of coastal river mouth lagoons (Kelk, 1974; Kirk et al., 1977; Kirk, 1991; Goring and Valentine, 1995).

River mouth lagoons, such as those found at the mouths of the Ashburton and Rangitata Rivers, are situated at many locations on the south and east coast of the South Island. Kirk and Lauder (1994) state that these features have long been referred to by the

Tangata Whenua as 'Hapua'. For the remainder of the present study, the term Hapua will be used to describe the coastal river mouth lagoons situated at the mouths of the Ashburton and Rangitata Rivers.

Hapua are transient features created by the northward displacement of the river mouth due to littoral drift along the enclosing beach (Kirk, 1991). Kirk and Lauder (1994) note that Hapua occur in coarse grained sediment where there are steeply graded braided river channels. Discharges of these rivers are highly variable. Other boundary conditions of Hapua are that they occur in microtidal regimes (less than 2m) and are dominated by high energy wave regimes where longshore drift is very strong. Hapua outlets vary in position according to channel flow and longshore sediment transport. Changes to the Ashburton and Rangitata Hapua, due to varying channel flow will be discussed in following section.

5.2 Discharge of the Ashburton and Rangitata Rivers

As mentioned, many aspects of the role of the Ashburton and Rangitata Rivers are influenced by discharge. Discharge can be termed the "rate of flow of a river at a particular moment in time, related to its volume and its velocity" (Whittow, 1984 p.148). Discharge is measured in 'cumecs', cubic metres per second ($m^3.s^{-1}$). The present chapter will examine the discharge from both the Ashburton and Rangitata Rivers. Mean daily discharge data has been attained from the Canterbury Regional Council from January, 1982 to March, 1997 for both rivers, including both branches of the Ashburton River. Variations in discharge and changes to the Ashburton and Rangitata Hapua due to the variable flows will be discussed.

5.2.1 Mean Discharge

The mean daily discharge data attained expands over a 15 year time period. This data is the only reliable, long-term discharge data available. However, there are a number of problems associated with it.

The measuring sites for all three locations (Rangitata, North and South Ashburton) are at the western extent of the Canterbury Plains, approximately a distance of 50-60km from the mouths of the rivers. The major problem lies in the distance that the rivers flow over beds of porous gravels. Goring and Valentine (1995) identified this problem for their study on the Rakaia River, which was discussed in Section 3.2. Goring and Valentine stated losses of river flow to ground water to be minimal for the Rakaia River. Scarf and Waugh (1986) examined the same problem for the Rangitata River. They found that losses to groundwater over a distance of about 34km were less than 7 per cent and in some cases flow was enhanced slightly (Scarf and Waugh, 1986 p.10). Therefore, losses of river flow to groundwater seepage are taken here as negligible for the Ashburton and Rangitata Rivers.

The other major problem of the discharge data set is that the raw data are not adjusted for any abstraction. Significant volumes of water are removed regularly from both the Ashburton and Rangitata Rivers at points between the measuring sites and the mouths. The three major abstracters of water are irrigation, stockwater and municipal water supplies. The dominant abstraction from the Rangitata River water resource is the Rangitata Diversion Race (RDR). The RDR supplies water for the irrigation of 67,000ha of the Canterbury Plains and for the generation of hydro-electric power at the Montalto and Highbank power stations (Scarf and Waugh, 1986). Scarf and Waugh note that the other significant water loss from the Rangitata River is stockwater abstraction. Abstractions from the Ashburton River include: water for municipal uses by Ashburton; stockwater; and irrigation, including a small amount to the RDR (Scarf, 1983). The amount of water abstraction from the Ashburton and Rangitata Rivers requires further investigation.

The RDR intake, approximately 50km from the coast at Klondyke, abstracts up to $30.7m^3.s^{-1}$ continuously from the Rangitata River (Scarf and Waugh, 1986 p.13). Initially abstraction was unlimited. Problems were created when, during winter low flow of less than 40 cumecs, 30 cumecs were abstracted, leaving a residual flow of only about 10 cumecs. Therefore, restrictions have been placed on water abstraction, depending on initial flow levels. Tables 5.2 and 5.3 detail water abstraction restriction levels for the period September 1-May 31 and from June 1-August 31 respectively.

These tables show that as river flow drops, so does the amount of permitted abstraction. However, the abstraction guidelines displayed on Tables 5.2 and 5.3 are maximum levels only. The actual amount of abstractions taken out daily are unknown. Because of the lack of data on actual abstraction, the discharge data for the present research has been adjusted for the maximum levels of abstraction.

Table 5.2: Water abstraction restriction levels for the Rangitata River for the period September 1-May 31 (From Scarf and Waugh, 1986 p.22)

Flow ($m^3.s^{-1}$) at Klondyke	RDR Abstraction	Other Irrigation	Stockwater	Residual Flow in River
64-60.1	30.7	0.3	1.0	32.0-28.1
60-50.1	26.2	0.3	1.0	32.5-22.6
50-43.1	21.8	0.2	1.0	23.0-20.1
43-40.1	18.9	0.1	1.0	27.0-20.1
40-38.1	16.9	0.1	1.0	22.0-20.1
38-36.1	14.9	0.1	1.0	22.0-20.1
36-34.1	12.9	0.1	1.0	22.0-20.1
34-32.1	10.9	0.1	1.0	22.0-20.1

Table 5.3: Water abstraction restriction levels for the Rangitata River for the period June 1-August 31 (From Scarf and Waugh, 1986 p.22)

Flow ($m^3.s^{-1}$) at Klondyke	RDR Abstraction	Other Irrigation	Stockwater	Residual Flow in River
Above 64	30.7	Nil	1.0	GT32.3
64-60.1	30.7	Nil	1.0	32.3-28.4
60-50.1	26.5	Nil	1.0	32.5-22.6
50-40.1	21.5	Nil	1.0	27.5-17.6
40-38.1	22	Nil	1.0	17.0-15.1
38-36.1	20	Nil	1.0	17.0-15.1
36-34.1	18	Nil	1.0	17.0-15.1
34-32.1	16	Nil	1.0	17.0-15.1
32-30.1	14	Nil	1.0	17.0-15.1

Abstraction levels from the Ashburton River are more difficult to calculate. Minimum flow levels were established in the Ashburton River Water Management Plan 1983-1990 (Scarf, 1983). Minimum flows of approximately 30 per cent of the mean monthly flow have to be maintained. Water resources for the Ashburton River are allocated depending both on the flow level and the month (Scarf, 1983 Appendix 1). Again, actual abstraction rates are unknown. Therefore, the discharge data used for the present study has been adjusted using the water resource allocation guidelines set forth in the Ashburton River Water Management Plan (Scarf, 1983).

The present research, using data from the Canterbury Regional Council collected from 1982-1997, shows mean annual discharge for the Ashburton and Rangitata Rivers to be vastly different from one another. The Ashburton River has a mean annual discharge of only $11.6m^3.s^{-1}$. The Rangitata River mean annual discharge is $70.2m^3.s^{-1}$. The size and western extent of the catchment areas of the respective rivers (refer Chapter Two), contribute to the different mean annual discharges. The Rangitata River has a mountain catchment nearly twice the area of the Ashburton River, and it extends to the main divide. However, annual discharges mask variabilities in the discharge of rivers. To further examine the variability of discharge of the Ashburton and Rangitata Rivers, mean monthly discharge will be discussed.

Soons (1968) and Scarf (1983) note that snow-melt contributes to the discharge of both the Ashburton and Rangitata Rivers. Toward the end of September the snowpack, accumulated during the winter, starts melting. Ablation of the snow pack sustains higher flows until early January. At this time the seasonal snow storage becomes exhausted (Scarf, 1983). Figure 5.2 illustrates the impact of seasonal snow-melt on the discharge of the Ashburton and Rangitata Rivers. Higher discharges from October-January are particularly noticeable for the Rangitata River. Discharges for the Ashburton River are more variable. This variability in the Ashburton River discharge, as opposed to the Rangitata River, is due to headwaters of the river not extending to the main divide. Therefore, river discharge is less reliant on snow-melt. The Rangitata River on the other hand receives large quantities of melt water from ablating snow packs. The yearly boost in melt water from the melting snow packs, makes the Rangitata River more predictable than the Ashburton River (Soons, 1968).

5.2.2 Discharge Variations

It has been stated many times in the present study that most erosion and sediment transport occurs during high magnitude events. Therefore, it is necessary to examine flood events for the Ashburton and Rangitata Rivers.

Flooding can occur at any time (Soons, 1968; Kirk, 1991). Chandler (1967) reports that the Rangitata River floods are caused by north-westerly rains in the upper catchment towards the main divide. Easterly storms on the other hand cause the Ashburton River to flood. The two rivers seldom flood together (Soons, 1968).

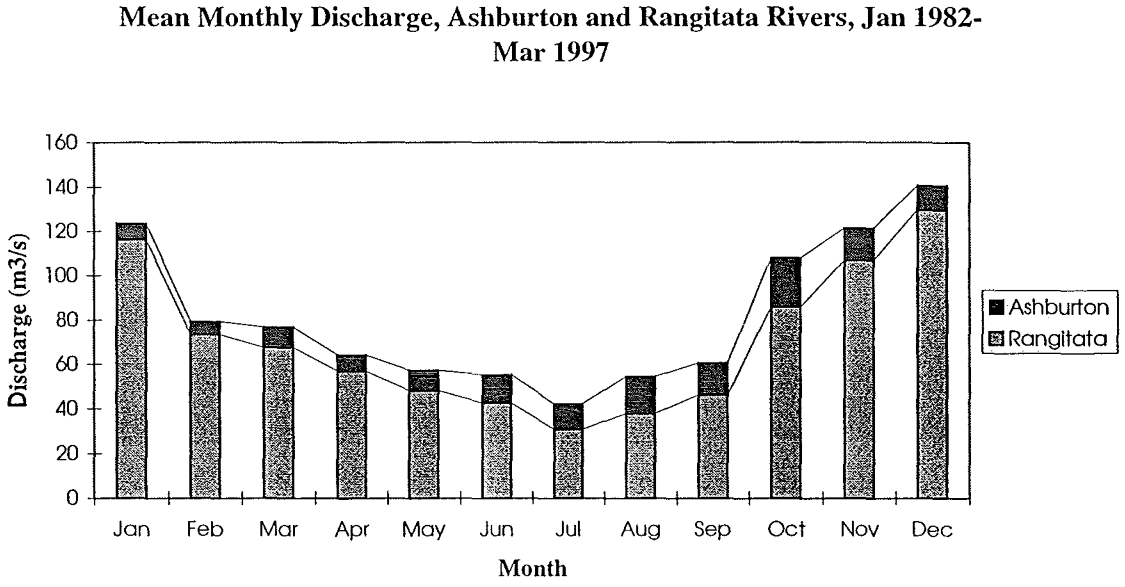

Mean Monthly Discharge, Ashburton and Rangitata Rivers, Jan 1982-Mar 1997

Figure 5.2: Mean monthly discharges for the Ashburton and Rangitata Rivers from January 1982-March 1997
(Data from the Canterbury Regional Council)

The maximum flow of the Rangitata River from 1982-January 1997 was 2,964 cumecs. However, flows of over 1,000 cumecs are infrequent and occurred on only five days throughout the study period. These extreme events all occurred in the months of November, December and January. Snow-melt accentuated by north-westerly rain may be required for extreme flood events. Floods of lesser magnitude occur more frequently. Scarf and Waugh (1986) state that these floods have a higher probability of occurring from October to May. This general trend is shown on Figure 5.2. Average monthly discharges are lower in the months from May to September.

The maximum mean daily discharge for the Ashburton River during the study period was 360 cumecs. However, flows of this magnitude are rare, with a discharge of over 300 cumecs recorded only once from 1982 to March 1997. Floods of over 150 cumecs occur more regularly, at an average of approximately one every eighteen months. Unlike the Rangitata River, where flooding generally occurs from October to May, the Ashburton River can and does flood at any time. This is due to the Ashburton River being less reliant on seasonal snow melt.

5.2.3 Lagoon Sequence

Kelk (1974) determined that the Ashburton River Hapua experienced a sequence that lasts approximately between 12 to 19 months. The sequence begins with a river flood of a large enough magnitude to breach the barrier beach opposite the main river channel. The mouth opening remains opposite the river channel as long as the river flow is sufficiently high. However, as flow begins to decline, sea conditions begin to dominate the mouth, similar to the 'small' river concept discussed in Section 5.1.2. The sea opening of the mouth will then migrate alongshore in the direction of the predominant littoral drift. Chapter Four showed the predominant littoral drift direction for the mid Canterbury coast to be northward. Therefore, the river mouth will migrate to the north. The northward migration continues until the mouth becomes elongated parallel to the coastline. From Kelk's (1974) plotting of mouth positions, the northward migration rate of the mouth opening at an average of 140m/month. The lagoon during this stage is fully developed and there are few tidal influences on the lagoon water level. The sequence returns to the beginning when river flow breaches the barrier again and flows directly into the sea opposite the main river channel. The remnant mouth to the north closes and the lagoon drains. Figure 5.3 illustrates the lagoon sequence for the Ashburton River mouth.

As stated, river flows have to be a certain magnitude for the barrier to be breached. Kelk (1974) believes that this can happen at any time during the sequence, as can mouth closure, but occurs on average once every 12 to 19 months. The Canterbury Regional Council (1993) reports that it is difficult to establish the river flow required to breach the barrier and initiate the cycle. However the CRC (1993 p.4) suggest that flows of 20 cumecs and 15 cumecs for the South and North branches of the Ashburton River respectively at their upstream measuring sites, may be required for breaching to occur.

It is difficult to examine the lagoon sequence proposed by Kelk (1974) based simply on river discharge, mainly because of the uncertainty surrounding the actual discharge required to breach the barrier. However, because of a lack of continual lagoon observations, analysing daily river discharge data is the next best option.

The river flow required for barrier breaching suggested by the CRC may be inaccurate in terms of Kelk's (1974) 12 to 19 month mouth sequence. Daily discharge data for the North and South Ashburton Rivers shows that flows of 15 and 20 cumecs occur regularly from 1982 to March 1997. The months of October to December, for all but three years, had at least two floods of a magnitude that exceeded the flow conditions suggested by the CRC (1993). This suggests that either greater flows are required for the barrier to be breached, or Kelk's 12 to 19 month time frame for his lagoon sequence may be inaccurate. Kirk (1991) suggests that the barrier at the mouth of the Ashburton River can be breached at flows of twice the mean flow. The present research has shown (in Section 5.2.1) that the mean flow for the Ashburton River is 11.6 cumecs. Therefore, flows of about 20 cumecs, over a period of 2 to 3 days, are sufficient to breach the barrier. Allowing for abstraction, this figure is similar to that suggested by the CRC (1993). Therefore, from daily discharge over the period 1982 to 1997, Kelk's (1974) 12 to 19 month lagoon sequence appears to be an over-estimate. However, Kelk based his sequence on observations during 1973 and 1974. This length of observation has not been undertaken in the present research. Also, other conditions such as longshore sediment transport and sea state may contribute to the lagoon sequence. For example, heavy seas and strong longshore drift can cause a mouth to close at much higher flows (Kirk, 1991).

A lagoon sequence definitely appears to be present at the Ashburton River mouth. From December 1996 to May 1997, the mouth opening to the sea was observed to fluctuate in position. In December 1996, the mouth opening was positioned about 600m north of the main river channel. The river breached the barrier opposite the main channel when flows of the North and South Ashburton Rivers reached maximums of 69 and 29 cumecs respectively from February 4 to 6. From February to May the mouth opening remained 50 to 150m north of the main river channel. Kelk's (1974) sequence suggests that the mouth displaces northward at an average rate of 140m/month. This does not appear to be the case in the present study. However, there does appear to be a sequence similar to Kelk's. Therefore, Kelk's river mouth sequence appears to be accurate except for the 12 to 19 month time frame. Because mouth breaching and closure can occur at any time it may be inappropriate to constrict the lagoon sequence within a 12 to 19 month time frame.

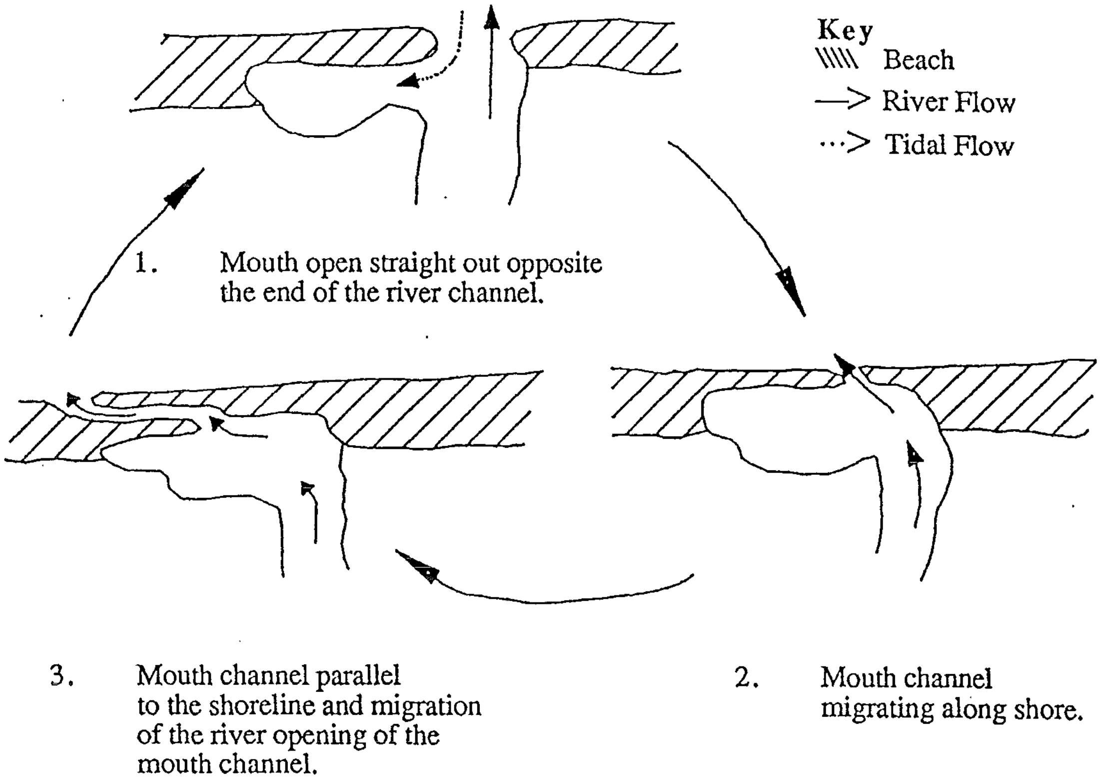


Figure 5.3: Lagoon sequence for the Ashburton River mouth (From Canterbury Regional Council, 1993 p.3)

5.3 Sediment Yield

Knowledge of sediment yield, for both individual basins and larger areas, is required for a wide range of purposes including: engineering work design; ecological, water quality and recreational considerations; and improved understanding of fluvial processes (Griffiths, 1981). River catchment sediment yield is also a vital contributor of sediment to many coastal environments.

5.3.1 Concepts and Measurement

Griffiths and Glasby (1985) note that despite the importance of river derived sediment yield the quantities of suspended load and bedload reaching the worlds oceans from rivers are not well determined. Milliman and Meade (1983) estimate that the global suspended sediment load delivered to the oceans by rivers is about 13.5×10^9 tonnes. Bedload and flood discharge may account for an additional $1\text{-}2 \times 10^9$ tonnes. The amount of sediment supplied to the oceans by rivers is significantly greater than the sediment supplied by glaciers and atmospheric dust fallout (Griffiths and Glasby, 1985).

Sediment supplied by New Zealand's rivers has been well documented (Thompson and Adams, 1979; Adams, 1980; Griffiths 1981, 1982; Griffiths and Glasby, 1985; Young and Davies, 1990). Thompson and Adams (1979) estimated sediment yield by analysing generalised sediment rating equations and flow duration curves. However, they discovered this type of estimation to be inaccurate (Griffiths, 1981).

The most comprehensive sediment yield estimation in New Zealand has been performed by Griffiths (1981, 1982) and Griffiths and Glasby (1985). Griffiths (1981) used stochastic analysis multiple regression to investigate relationships between specific annual suspended yield (as the dependent variable) and catchment characteristics for South Island rivers. The catchment characteristics are all easily measured and include hydrological, physiographical and climatic characteristics of the catchment. Table 5.4 lists the variables analysed by Griffiths (1981). Through his analysis, Griffiths discovered precipitation (mean catchment rainfall) to be the main controlling variable on suspended sediment yield. However, he discovered precipitation to only be important in the western, southern and central rivers of the South Island. The eastern rivers, of which the Rangitata and Ashburton are two, rely on two different independent variables. The regional specific annual suspended sediment yield, G, for rivers in the eastern portions of the South Island is expressed by:

$$\log G = 2.35 + 0.26 \log A + \log R_{mf} \tag{5.1}$$

where A is the catchment area (km^2) and R_{mf} is mean annual flood runoff ($m^3 s^{-1} km^2$) (Griffiths, 1981). Therefore, the suspended sediment yields for the Ashburton and Rangitata Rivers are controlled by catchment area size and mean annual flood runoff.

Suspended sediment is not retained on the beach system because high flows flush fine sediment into deeper water. Only bedload, gravels on the Wentworth scale (Griffiths and Glasby, 1985), is retained on the beach. Griffiths and Glasby (1985) suggest that bedload is between 2 and 5 per cent of total suspended load. Therefore, bedload, B, can be calculated using:

$$\mathrm{B} = \mathrm{S} \times \mathrm{x} \tag{5.2}$$

where S is the suspended load and x has a value of 0.03 ± 0.01 (Griffiths and Glasby, 1985). Therefore, total sediment load, T, is given by:

$$\mathrm{T} = (1 + \mathrm{x})\mathrm{S} \tag{5.3}$$

The calculation of bedload is required for sediment budget analysis and because it is the portion of the load that remains within the beach system. Total load is calculated also for sediment budget analysis.

Bagnold (1980) used empirical models to predict sediment yield, specifically examining bedload transport. Bagnold attempted to calculated the transport rate of bedload (by immersed weight per unit width), i_b. Bagnold (1980 p.457) calculated bedload transport rate using:

$$i_b = (i_b)_* \left(\frac{\omega - \omega_0}{(\omega - \omega_0)_*} \right)^{1.5} \left(\frac{Y}{Y_*} \right)^{-0.66} \left(\frac{D}{D_*} \right)^{-0.5} \tag{5.4}$$

where ω is stream power per unit bed area (kg.m^{-1}.s^{-1}), ω_0 is a nominal threshold value of ω at which bed movement starts, Y is mean depth of flow (m), and D is the mode size of bed material. Subscript * denotes reference values for the respective variables. Stream power is given by $\omega = \rho QS$ where ρ is density of the water, Q is stream discharge and S is the gravity gradient. Young and Davies (1990) evaluated Bagnold's (1980) formula on the North branch of the Ashburton River. Without entering into too much detail, Young and Davies (1990) discovered Bagnold's equation for predicting braided river bedload transport rates to be relatively accurate.

Table 5.4: Variables used in multiple regression analysis explaining sediment yield (From Griffiths, 1981 p.667)

Factor	Variables
Independent Variables:	
Hydrologic Characteristics	Mean Flow ($m^3.s^{-1}$)
	Mean Annual Flood ($m^3.s^{-1}$)
	Ten-Year Recurrence Interval Flood ($m^3.s^{-1}$)
	Mean Annual Runoff (m)
	Mean Annual Flood Runoff ($m^3.s^{-1}.km^2$)
	Ten-Year Flood Runoff ($m^3.s^{-1}.km^2$)
Physiographic Characteristics	Catchment Area (km^2)
	Catchment Mean Elevation Above Sea Level (m)
	Channel Length (km)
	Channel Slope ($m.m^{-1}$)
	Forest Cover (percent)
Climatic Characteristics	Catchment Mean Rainfall (m)
Dependent Variable	Specific Annual Suspended Sediment Yield ($tonnes.km^{-2}.yr^{-1}$)

5.3.2 mid Canterbury River Sediment Yields

Using Equation 5.1, Griffiths and Glasby (1985) calculated the annual specific sediment yields for the Ashburton and Rangitata Rivers to be 574 and 946 $tonnes.km^{-2}yr^{-1}$ respectively. They calculated this load to equate to a suspended load delivered to the ocean by the Ashburton and Rangitata Rivers to be 1,500,000 and 1,680,000 $tonnes.yr^{-1}$ respectively. However, as stated, bedload is of more significance to the beach system than suspended load. Using Equation 5.2, the bedload contributed by the Ashburton River is 45,000 ± 15,000 $tonnes.yr^{-1}$. The Rangitata River contributes approximately 50,400 ± 16,800 $tonnes.yr^{-1}$. From Equation 5.3, the total sediment loads contributed by the Ashburton and Rangitata Rivers respectively are 1,545,000 ± 15,000 and 1,730,400 ± 16,800 $tonnes.yr^{-1}$.

In Chapter Two it was stated that the rock that comprises the catchments of the Ashburton and Rangitata Rivers is largely greywacke. Greywacke gravel has an approximate bulk density of 1,800 $kg.m^{-3}$ (Young and Davies, 1990). Therefore, the Ashburton River supplies a total sediment load of $858{,}333m^3.yr^{-1}$, with bedload contributing 25,000$m^3.yr^{-1}$ of the total. The Rangitata River contributes 961,333$m^3.yr^{-1}$ total sediment load, of which 28,000$m^3.yr^{-1}$ is bedload.

Griffiths (1981) also discusses the relationship between river flow and suspended sediment concentration. He discusses that for the Ahuriri River, situated in the central South Island, sediment concentrations vary significantly when flows are below 1.5 times the mean flow. When flows are above 1.5 times the mean, suspended sediment concentrations exhibit a dependence on flow. Therefore, when rivers are in flood, sediment yield is correlated with flow levels. When rivers experience low flows (<1.5 times the mean), sediment yield is probably controlled more by catchment basin characteristics than river flow. However, the bulk of sediment yield is transported by freshets and floods that have peak discharges less than the mean annual flood (Griffiths, 1981). Griffiths suggests that 75 per cent of sediment yield is transported during freshets and floods. This confirms the theory of slugs of river sediment input on the coast during flood events outlined in Chapter Four. Griffiths (1981) outlined a method of calculating sediment yield from individual flood events. He prescribed that flood sediment yield for either bedload or suspended load, g_f, is approximately proportional to:

$$g_f \propto Q_p^b t_f \tag{5.5}$$

where Q_p is the peak water discharge, t_f is the hydrograph duration and b is a constant of a value normally between 2 and 3. While this type of analysis will not be attempted in the present research, it is interesting to note the dependence of flood sediment yield on flood discharge and flood duration.

Bagnold (Equation 5.4), shows that bedload sediment transport depends partly on stream power, which is in part a function of stream discharge. Therefore, as stream discharge varies so will sediment yield. Figure 5.4 displays mean yearly discharges for the Ashburton and Rangitata Rivers. Discharges vary significantly from year to year for both rivers. Sediment yields should be larger during a year when stream discharge is above the mean discharge. Conversely, when discharges are low, sediment yields will also be less than the average.

The Rangitata River had three distinct years when stream discharge was well above the mean: 1983, 1994 and 1995 (Figure 5.4). These years had stream discharges of 25 to 33 per cent above the mean discharge. On the other hand, 1985, 1991, 1992 and 1993 had flows 20 to 30 per cent below the mean. Therefore, while the average bedload sediment yield for the Rangitata River is 28,000m^3.yr^{-1}, the variations in stream discharge shown on Figure 5.4 suggest sediment yields will vary from year to year depending on discharge. The Ashburton River exhibits a similar trend. The discharges for both rivers vary around the mean. However, the data set is not long enough for a pattern of stream discharge variation to become evident.

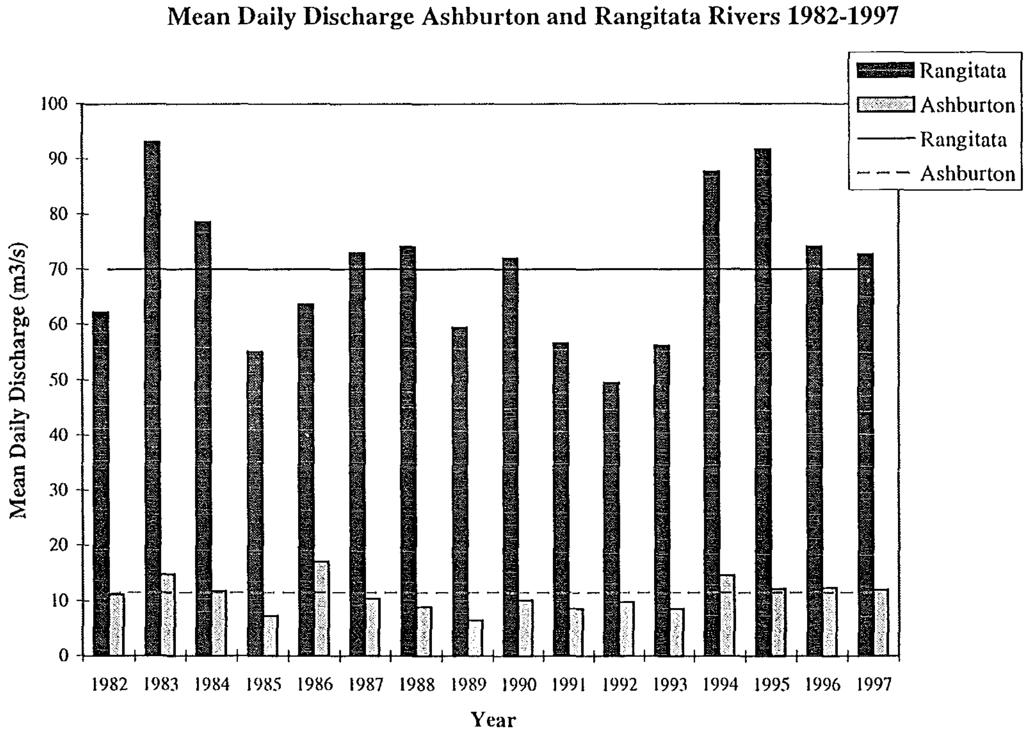

Mean Daily Discharge Ashburton and Rangitata Rivers 1982-1997

Figure 5.4: Mean discharge for the Ashburton and Rangitata Rivers, 1982-1997
(Bars denote mean yearly discharge. Lines show mean discharge 1982-1997)
(Data from the Canterbury Regional Council)

When discharge increases so does sediment yield. Therefore, the sediment provided by the rivers would increase the sediment on the beaches. Chapter Four examined slugs of river derived sediment. Figure 5.4 shows that larger sediment yields could be expected in 1983, 1994 and 1995 from the Rangitata River. Figure 4.5 shows the profile adjacent to the Rangitata River mouth has beach volumes well above the mean volume for 1994 and 1995. Figure 4.5 also shows for 1992 and 1993, beach volumes are below the mean for the Rangitata River mouth profile. 1992 and 1993 had stream discharges 30 and 20 per cent below the mean discharge respectively. A correlation between stream discharge and beach volume for profile RANG18.30 (Figure 3.1), which is adjacent to the Rangitata River mouth, is positive with an r value of 0.42 ($p=0.26$). The relationship is a tentative one because $p = 0.26$. However, stream discharge does appear to effect beach volume. Chapter Three discussed the relationship between beach volume and cliff erosion. This proved, over the short-term that beach volume changes affect cliff erosion. Therefore, stream discharge has an indirect affect on cliff erosion, particularly on cliffs adjacent to river mouths.

5.3.3 Hapua as Sediment Stores

The location of Hapua at the mouths of the Ashburton and Rangitata Rivers are significant because they are located at the focus for the dissipation of the energy of the sea, river, cliffs and winds (Kelk, 1974). Kelk (1974) noted that during his study period there was significant sedimentation of the Ashburton River Hapua. Sediment is contributed to the Hapua by the cliff slumping and more importantly by the river. Kelk goes on further to say that no great accumulation of sediment occurred in the Hapua during his study because the lagoons efficiency to accumulate sediment is limited. This is certainly the case over the long term. Because the coast is retreating (Chapters 2 and 3) the lagoon is being progressively displaced landward (Kirk, 1991).

However, Hapua still have the ability to accumulate sediment in the short term from washover from the beach and direct injection from the river (Kirk, 1991). Kirk et al. (1977) suggested that short-term lagoon storage can be as high as 80 per cent of the coarse sediment load of the river, although this figure is difficult to estimate. Lagoon storage for the Ashburton Hapua can range from 0 to $20{,}000\text{m}^3.\text{yr}^{-1}$ and the Rangitata Hapua can store up to $22{,}400\text{m}^3.\text{yr}^{-1}$. Therefore, Hapua can be an important sink of sediment from both the river and the beach. Conversely, the lagoon can act as an important source of sediment for the coastal environment. Kirk (1991) suggests that the Hapua act as a source of coastal sediments during and immediately after high river flows and as a sink during moderate to low flows.

5.3.4 mid Canterbury Rivers as 'Small' Rivers

Section 5.1.2 outlined the concept of classifying rivers in terms of their sediment supply to the coastal environment. The Ashburton and Rangitata Rivers deliver a sizeable amount of sediment to the mid Canterbury coast (858,333 and 961,333m3.yr^{-1} respectively). However, only 3 per cent of the suspended sediment load is retained on the coastal foreshore from bedload. Therefore, sediment supplied to the coast by the Ashburton and Rangitata Rivers is not a particularly large amount. The relatively small sediment yields are accentuated by Hapua sediment storage. Conversely, Hapua can be sources of sediment during flood events. Because of the small sediment yields, the Ashburton and Rangitata River mouths are dominated by marine processes.

The domination of marine processes is illustrated by Kelk's (1974) lagoon sequence. Longshore sediment transport, predominantly in a northward direction, offsets the river mouth outlet for distances of up to 1 km to the north. River processes only dominate during floods, when the barrier is breached opposite the main river channel. Continuing coastal erosion of the entire mid Canterbury coast by marine processes suggests that not enough sediment is provided by the rivers to hamper coastal erosion. The mid Canterbury coast and the Ashburton and Rangitata River mouths are dominated by marine processes. Therefore, according to Zenkovich (1967), the Ashburton and Rangitata Rivers can be classified as being 'small' in nature.

5.4 Summary

The present chapter has examined the role that the Ashburton and Rangitata Rivers play on the coastal environment of mid Canterbury. The mid Canterbury rivers are steep and braided in nature. This steepness of the river channels leads to high flow velocities. When these velocities are coupled with the large amounts of sediment being eroded out of the respective catchments, large sediment yields result. In fact, specific sediment yields from South Island rivers are among the highest recorded in the world (Griffiths, 1981; Griffiths and Glasby, 1985).

The mid Canterbury rivers, as well as the majority of braided streams, are also characterised by highly variable flow regimes. The Rangitata River, for example, during the study 1982 to January 1997 had a discharge variation from about 30 cumecs to as high as 2,964 cumecs. This variation centred on a mean daily discharge of 70.2 cumecs. The Ashburton River, while being smaller, exhibits a similar discharge trend. Flows of the mid Canterbury rivers have a seasonal component to them. Mean monthly daily discharges are higher during the months of October to early January. Seasonal melting of the alpine snowpack ensures higher discharges during these months. However, the Ashburton River discharge has less reliance on the melting of the snowpack. Flooding of the mid Canterbury rivers can occur at any time. North-westerly rain causes the Rangitata River to flood, while easterly storms are the main catalyst for the Ashburton River to flood. Therefore, the two rivers seldom flood together.

Sediment yields for the Ashburton and Rangitata Rivers are important contributors to the mid Canterbury coastal environment. They contribute approximately 858,333 and 961,333 $m^3.yr^{-1}$ of sediment to the coast respectively. However, only the bedload portion of this total sediment yield provides sediment of a large enough size so that it remains on the beach when discharged from the river. Total bedload for the Ashburton River is about $25,000m^3.yr^{-1}$ and $28,000m^3.yr^{-1}$ for the Rangitata River. Floods also affect sediment yields. Griffiths (1981) suggested that 75 per cent of sediment yield is transported by floods. Therefore, 18,750 and $21,000m^3.yr^{-1}$ of bedload are transported by the Ashburton and Rangitata Rivers respectively during floods. River floods are vital sediment suppliers to the coastal environment of mid Canterbury. The relative contribution of the river derived sediment to the sediment budget for the mid Canterbury coast will be examined in Chapter Six.

River flow is also significant in terms of the Hapua of the Ashburton and Rangitata Rivers. Flooding causes not only the breaching of the beach barrier between the Hapua and the sea but 'flushes' out the sediment stored in the lagoon. Therefore, creating a source of sediment for the beach. Conversely, during times of low flow the river opening migrates alongshore and may even close. This provides a sink for river sediment. Up to 80 per cent of coarse river sediment can be stored in the Hapua. Hapua act as a sink during low to moderate river flows and as a source during and immediately after high river flows.

The mid Canterbury rivers contribute significant quantities of sediment to the mid Canterbury coast. The sediment provided by the rivers has the capability of increasing local beach volumes which hinders coastal erosion. However, other processes such as longshore transport and abrasion may affect the river derived sediment. How these processes relate to each other will be examined in detail in Chapter Six.

Chapter Six

Sediment Budget for the mid Canterbury Coast

"A sediment budget is a sediment transport volume balance for a selected segment of the coast" (C.E.R.C., 1984 p.4-113). Komar (1976) reports that estimation of a sediment budget is extremely useful when evaluating the relative importance of various sediment sources and losses to the nearshore zone. They show the relative contributions of various sources, sinks and transport pathways to the over all state of the coast. In mid Canterbury it is of interest to explore the relative roles of cliff erosion, river sediment supply and longshore transport in the overall erosional status of the coast. Sediment budgets enable quantification of the relations between sediment production, transport, storage and discharge (Best and Griggs, 1992).

The concept of sediment budget analysis has been discussed in the literature for a number of years (Shuisky and Schwartz, 1983). Sediment budgets have been performed by numerous authors (Kirk and Hewson, 1978; Gibb and Adams, 1982; Shuisky and Schwartz, 1983; Best and Griggs, 1991; Simpson et al., 1991). The present chapter will present a sediment budget for the mid Canterbury coast between the Rangitata River and Wakanui Creek (refer Figure 3.1). Previous chapters have examined various components of a sediment budget, such as sediment supplied by cliff erosion, river inputs and longshore sediment transport. The present chapter will review how these factors, along with many others, relate to each other on the mid Canterbury coast in the form of a sediment budget.

Section 6.1 will examine the concept of sediment budgets and the numerous components that comprise them. Sources and sinks of a typical sediment budget will be reviewed, along with their relative importance. Section 6.1 will be a review of the concepts of a sediment budget from the literature. Section 6.2 will examine a sediment budget for the mid Canterbury coast. Sediment sources and sinks for the mid Canterbury coast will be identified and quantified. Comparisons between the present research and previous estimates of sediment budgets on the Canterbury coast will also be made.

6.1 Components of a Coastal Zone Sediment Budget

As stated, sediment budget analysis allows the quantification of various aspects of the budget. By quantifying the importance of sediment sources and sinks, regions of beach erosion or deposition may be accounted for (Komar, 1976). C.E.R.C. (1984) also suggest that another purpose of a sediment budget is to assist the coastal engineer by identifying relevant processes, estimating volume rates required for design purposes and singling out of processes for special attention. Therefore, a sediment budget is a useful tool for evaluating processes and the nature of the coastal zone. It is also possible to characterise and estimate the effects of changing amounts of material moved under different processes both spatially and temporally (Shuisky and Schwartz, 1983), for example, sporadic input from rivers or erosion of cliffs in stormier years.

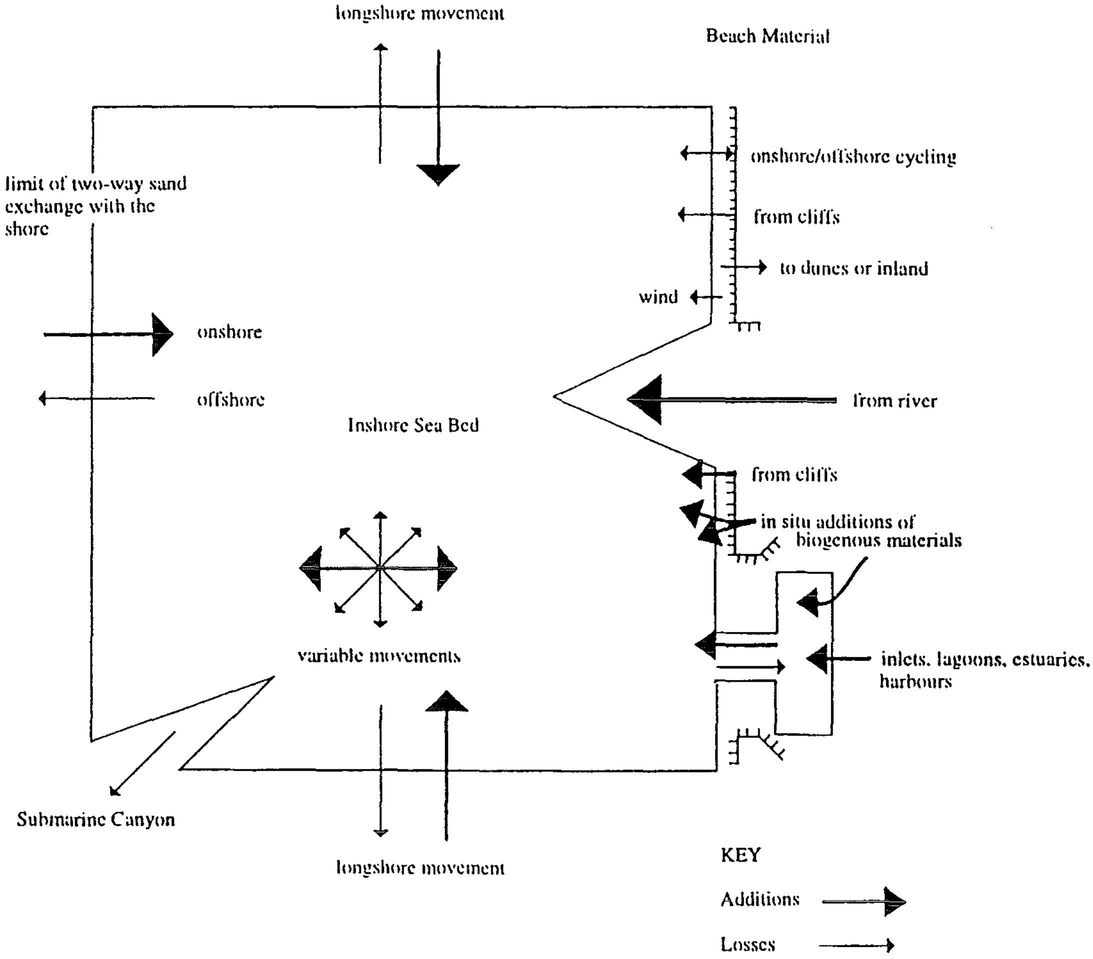


Figure 6.1: The sediment budget model
(From Pieters, 1996 p.25 After Miller and Zeigler, 1958)

Sediment budgets involve the notion of continuity, or conservation of mass (Komar, 1976; Shuisky and Schwartz, 1983). The term 'budget' is appropriate in terms of a sedimentary budget because there is the sense of balancing of amounts: inputs versus outputs, erosion versus deposition, of deficit versus surplus (Shuisky and Schwartz, 1983). In a complete sediment budget the difference between sediment added by all sources and the sediment removed by all sinks should be zero (C.E.R.C., 1984). However, a sediment budget is usually calculated to estimate an unknown erosion or deposition rate, which will be the difference resulting from equating known sources and sinks (C.E.R.C., 1984). Therefore, knowledge of the sources and sinks, and their quantities, is required for sediment budget analysis.

Table 6.1: Possible sources and sinks of sediment to the coastal zone
(From Komar, 1976 p.228)

Source	Sink
Longshore transport into area	Longshore transport out of area
River transport	Wind transport out
Sea cliff erosion	Offshore transport
Onshore transport	Deposition in submarine canyons
Biogenous deposition	Solution and abrasion
Hydrogenous deposition	Mining
Wind transport onto beach	
Beach nourishment	

Sources and sinks of sediment in the coastal zone are perhaps best illustrated by Figure 6.1. The sediment budget model exhibits flows and storages of sediment within and between coastal systems. The nature and quantities of the flows determine the state of the coastal system. The coastal system examined by a sediment budget involves the important problem of setting boundaries. The coastal system identified within chosen boundaries is called a 'coastal compartment'. C.E.R.C. (1984) suggest that these boundaries are determined by the area under study, the time scale of interest, and the study purpose. Boundaries will vary between studies and sediment budgets, depending on conditions and morphologies such as the presence of cliffs, river mouths and so on. A seaward boundary is usually established at or beyond the limit of active sediment movement, while the landward boundary is beyond the limit of wave effects anticipated for the life of the study (C.E.R.C., 1984). Sediment is either gained or lost among a variety of sediment sources or sinks, as summarised in Table 6.1 across the coastal compartment boundaries.

6.1.1 Sediment Sources

A source is any factor or situation that adds sediment to a coastal compartment. Sources may be of a point (eg. a river mouth) or line (eg. cliff) nature.

River Transport

Komar (1976) suggests that the principal sources of nearshore sediments for most coastal areas are the rivers that transport large quantities of sediment directly to the coastal zone. It is estimated that approximately 14.2 billion $m^3.yr^{-1}$ of sediment is supplied to the coast by the world's rivers (C.E.R.C., 1984). However, only a fraction of this sediment has particle sizes large enough to remain part of the coastal zone and not be transported offshore. The percentage of coarse sediment commonly varies between rivers and coasts.

The supply of sediment to the coast by rivers is dependent upon the nature of the hinterland from which the river drains. Komar (1976) states that the elevation, rock type, vegetation density and climate of the hinterland are all important factors when determining the amount and type of load carried by the rivers. C.E.R.C. (1984) suggest that most of the sediment carried to the coast by rivers is deposited in relatively small areas. This coupled with the small amount of sediment that is large enough to remain on the coast (as little as 2 per cent of total load), rivers may not be the immediate source of sediment for much of the world's coastline (C.E.R.C., 1984). Therefore, other sediment sources must be important.

Sea Cliff Erosion

Komar (1976) suggests cliff erosion is the second most important sediment supplier to beaches, behind river derived sediment. The relative importance of cliff erosion in supplying sediment to the world's beaches varies between coasts. However, in general Komar (1976 p.235) believes cliff erosion accounts for 5 to 10 per cent of the material on most beaches. Sea cliff erosion contributes about 120 million $m^3.yr^{-1}$ to the coastlines of the world (C.E.R.C., 1984). This is only approximately 1 per cent of the total amount of sediment transported by rivers. However, cliff erosion can be a major source of sediment because of the high proportion of coarse sediment contained within the cliffs (C.E.R.C., 1984).

Onshore Transport

C.E.R.C. (1984) suggest that even though it is uncertain, the contribution to the sediment budget from the offshore slope may be significant. Onshore transport occurs by a number of processes. If wave energy decreases, it is possible that finer sediment may find its way onshore (Komar, 1976). Komar (1976) also states that sediments may also erode from offshore sources on the continental shelf and drift shoreward. Onshore transport may also take place within the longshore zone due to seasonal and storm-induced profile changes (C.E.R.C., 1984). However, this source of sediment is the most difficult to evaluate quantitatively and in most sediment budgets onshore transport remains unknown (Komar, 1976).

Longshore Transport

Longshore transport is a major source of sediment for many coasts. The amount of longshore sediment transport can be calculated in a number of ways. Chapter Four outlined the calculation of longshore sediment transport by analysing wave parameters. Other methods include measuring rates of accretion at littoral barriers such as breakwaters and measuring the rate of dilution of heavy minerals within the beach sands (Komar, 1976). Net longshore sediment transport is required for sediment budget analysis (Komar, 1976).

Other Sources

There are other sources of sediment to the coastal zone that are not generally as quantitatively significant as the ones already mentioned. Wind blown sediment sources may be important on a smaller scale but are not generally an important source of sediment (Komar, 1976). Windblown sediment must also come from a land source whose sediment is not derived from the same littoral zone (C.E.R.C., 1984). Biogenous and hydrogenous deposition are sources generally only important in the tropics where shell and coral fragments and calcium production occur though some beaches of temperate latitudes have an appreciable sand fraction derived from shell material. Potentially a significant source of sediment to the coastal zone is beach nourishment. Komar (1976) and C.E.R.C. (1984) both recognise the significance of beach replenishment to help in the protection of the beach from erosion. Komar (1976) reports that the sediment added to the beach must be of a similar or larger size than the existing sediment, or it will soon be lost offshore.

6.1.2 Sediment Sinks

Sinks are factors or situations that remove sediment from coastal compartments. Sinks may be of a point nature (eg. commercial gravel extraction site) or a line nature (eg. offshore sediment transport).

Longshore Transport

Longshore sediment transport can also be a significant sink of sediment for the coastal zone. Longshore sediment transport into a coastal cell is not always the same as transport out of the cell. Depending on the availability of sediment, longshore sediment transport can vary significantly. Rivers, cliff erosion and other sources can all increase the potential for increased longshore sediment transport. The processes for longshore sediment transport may also vary along the length of a cell. Therefore, affecting the rate of longshore sediment transport.

Wind Transport

Komar (1976) comments that while wind transport can be both a source and sink of sediment for the coastal zone, it is more commonly a sink. Sea breezes predominantly blow onshore so they are more effective in removing sand from the beach and transporting the sediment inland (Komar, 1976). Komar suggests that rates of sediment loss from the beach by wind transport can be calculated by estimating the volume of sand in a dune field and dividing it by the time of formation.

Offshore Transport

The offshore zone can potentially be a significant sink of sediment from the coastal foreshore (C.E.R.C., 1984). Sediment transport offshore occurs generally when sediment is too fine to remain on the beach, is placed in suspension and carried offshore into deeper water and lost from the beach (Komar, 1976). Sediment is lost offshore mainly by storm waves and a slight offshore component of gravity which acts on individual particles and on the sediment-water mixture (C.E.R.C., 1984). C.E.R.C. (1984) state that to calculate quantities of sediment lost offshore requires extensive, accurate and costly surveys. Therefore, the amount of sediment lost offshore is generally unknown (Komar, 1976).

Solution and Abrasion

Solution and abrasion involve reduction of sediment grain sizes so that eventually particles become too fine to remain on the beach and are transported offshore. Abrasion is the mechanical destruction of the sediment by the forces of the sea (Zenkovich, 1967). Solution involves the chemical weathering of sediment in water. Both C.E.R.C. (1984) and Komar (1976) believe losses of sediment through processes of abrasion and solution to be insignificant.

Other Sinks

Other major sinks of sediment can include lagoon storage, sediment lost to submarine canyons and mining. Chapter Five outlined the significance of lagoon storage as a sink of sediment. Up to 80 per cent of river borne sediment can temporarily be stored within the lagoon. Submarine canyons can be an important sink of sediment at many locations. The heads of these canyons are in shallow water and funnel sediment into them so that the sediment is lost to the coast (Komar, 1976). Abstraction of sand and gravels from the beach is another major sink that has been occurring for hundreds of years (C.E.R.C., 1984). Komar (1976) reports that significant mining of sediment from the Devon coast in England lead to rapid erosion and the destruction of a village. These sinks all vary in importance between localities but they must be included in any sediment budget if they are present.

6.2 A Sediment Budget for the mid Canterbury Coast

Kirk et al. (1977), Kirk and Hewson (1978), Gibb and Adams (1982) and Kirk (1991) have all evaluated sediment budgets for various parts of the Canterbury coast. Kirk and Hewson (1978) examined the South Canterbury-North Otago coast from Oamaru to Timaru. Gibb and Adams' (1982) sediment budget detailed the entire Canterbury coast, south of the Banks Peninsula. The Rakaia River mouth and the adjacent coast was the focus of Kirk's (1991) sediment budget. Only Kirk et al. (1977) has specifically examined the mid Canterbury coast in a sediment budget. However, their examination only involved a 7.5km portion of the mid Canterbury coast around the mouth of the Ashburton River. Therefore, detailed sediment budget analysis has been lacking in the past for the mid Canterbury coast. The one study that concentrated on mid Canterbury was completed over twenty years before the present research and did not have a long record of cliff erosion data with which to work. This section will offer a new sediment budget analysis for the mid Canterbury coast between the Rangitata River mouth and Wakanui Creek (Figure 3.1).

6.2.1 Important Sources and Sinks

Sections 6.1.1 and 6.1.2 identified the majority of important sources and sinks of sediment for a coastal sediment budget. The majority of coastal sediment budgets are done so that a better understanding of the coastal environment can be attained. Also, most sediment budgets in the international literature examine predominantly sandy coastlines (Komar, 1976; Shuisky and Schwartz, 1983; C.E.R.C., 1984; Best and Briggs, 1991; Simpson et al., 1991). The same problem was encountered in Chapter Four on longshore sediment transport. There is a lack of literature on sediment budgets for coasts of mixed sand and gravel. Chapter Four highlighted the vast differences between pure sand beaches and beaches that are comprised of mixed sand and gravel when calculating longshore sediment transport. Sediment budget analysis is similarly affected. Therefore, the various sources and sinks for mixed coastlines may well be different than those for pure sand coasts. This section will examine the important sources and sinks of sediment for a mixed sand and gravel coastline, particularly for mid Canterbury. The sources and sinks will also be quantified so that a sediment budget for the 32km of the mid Canterbury coast can be constructed.

Cliff Erosion

Section 6.1.1 identified that generally erosion of sea cliffs only contributes 5 to 10 per cent of beach material. Therefore, cliff erosion can be considered to be only a secondary source of sediment to the coastal zone. However, the cliffs and beaches of the Canterbury coast, south of Banks Peninsula, are different. Using data from Kelk (1974), Kirk et al. (1977 p.243) calculated that cliff erosion provided about 34 per cent of sediment to the coast around the Ashburton River mouth. Gibb and Adams (1982 p.350) estimated in their sediment budget for the entire Canterbury Bight coast that 46 per cent of sediment input is derived from cliff erosion. The unconsolidated gravel cliffs of the Canterbury coast thus appear to be more significant contributors of sediment to the coast than is commonly the case elsewhere.

Chapter Three examined cliff erosion for the mid Canterbury coast. The present research has shown that cliff height is a major controlling factor on cliff erosion. Therefore, because of the varying cliff heights along the mid Canterbury coast, both cliff erosion rates and volumes vary significantly between the Rangitata River mouth and Wakanui Creek. Chapter Three presented calculated cliff erosion volumes for different sections of the mid Canterbury coast. Also calculated was the total of sediment eroded from the cliffs for the 32km of the mid Canterbury coast. The total volume loss rate for cliff erosion on the mid Canterbury coast amounts to $228{,}339\text{m}^3.\text{yr}^{-1}$.

Chapter Five drew attention to the fact that only sediment particles that are large enough to form beaches are significant in terms of river derived sediment yields. The same can be said of cliff erosion. The cliff erosion volume mentioned above was calculated taking no account of non-beach forming material. Gibb and Adams (1982) estimate the cliffs of the Canterbury Bight coast are 95 per cent gravel and only 5 per cent mud. Therefore, the mid Canterbury cliffs provide approximately $216{,}922\text{m}^3.\text{yr}^{-1}$ of sediment to the coast that is of beach forming particle sizes. The other $11{,}417\text{m}^3$ of sediment is comprised of mud and will be quickly transported offshore by wave action.

The volume of sediment provided by the mid Canterbury cliffs calculated in the present research is comparable to estimates from other research. Kirk et al. (1977 p.242) calculated that the 7.5km of cliffs near the Ashburton River mouth produced about $68{,}000m^3.yr^{-1}$, or $9{,}066m^3.yr^{-1}.km^{-1}$. The Canterbury coast from the Orari to the Rakaia River, a distance of 66km, produced $523{,}000m^3.yr^{-1}$, or $7{,}924m^3.yr^{-1}.km^{-1}$ (Gibb and Adams, 1982 p.341). The spatially averaged cliff erosion rate calculated in the present research ($6{,}779m^3.yr^{-1}.km^{-1}$), is about 50 per cent lower than that of Kirk et al. (1977). This 50 per cent reduction in cliff erosion volume may be function of the longer-term survey data used by the present research. Kirk et al. (1977) used data for a nine-month period only.

River Transport

River derived sediment is generally believed to be the primary source of sediments for the world's coastal regions. The contribution of rivers to the coast varies between localities. However, in most cases rivers are the dominant source of sediment. For example, Best and Griggs (1991 p.2273) report that streams provide about 75 per cent of the sediment to the Santa Cruz littoral cell in California.

The supply of sediment from rivers to the mid Canterbury coast was examined in Chapter Five. Research by Griffiths (1981) and Griffiths and Glasby (1985) was used to calculate the contribution average of the Ashburton and Rangitata Rivers to the sediment budget of the mid Canterbury coast. As mentioned in Chapter Five, these rivers are gravel bed and braided in channel form. They have the potential to transport significant quantities of sediment to the coast. Floods of varying discharge carry up to 75 per cent of total annual sediment yield. However, significant flow abstractions for both rivers and variability of flow leads to deposition and aggradation of the riverbeds (Wilson, 1985). Therefore, sediment yields for the Ashburton and Rangitata Rivers are larger than the impression given by the use of an average input to the sea.

However, only the sediment that is transported the entire way to the coast is of significance. Even allowing for the aggradation of their beds, the Ashburton and Rangitata Rivers have large sediment yields. Chapter Five calculated the two rivers to have a combined total sediment yield of $1{,}820{,}000m^3.yr^{-1}$. Due to the high-energy environment of the mid Canterbury coast, only the coarse bedload is capable of remaining on the beach. Griffiths and Glasby (1985) estimate bedload to be 3 per cent of suspended sediment load. While the suspended load is important for the sedimentation of the continental shelf off the South Island's east coast, only bedload remains on the coast. Chapter Five estimated the combined bedload contribution to the mid Canterbury coast from the Ashburton and Rangitata Rivers is 53,000$m^3.yr^{-1}$. The Rangitata River contributes 28,000$m^3.yr^{-1}$ and the Ashburton River provides 25,000$m^3.yr^{-1}$ of the total. The sediment supplied by the mid Canterbury rivers is only about 25 per cent of the contribution of cliff erosion. Therefore, cliff erosion is a far greater contributor of sediment to the mid Canterbury coast.

The quantities of sediment provided by the mid Canterbury rivers, as calculated in this study, are in the same order of magnitude as calculated in previous research. Kirk et al. (1977 p.242), using data from Kelk (1974), estimated the Ashburton river contributed 44,000$m^3.yr^{-1}$ of sediment to the coast. Reinen-Hamill (1997 p.362) suggests the Rangitata and Ashburton Rivers provide 46,700$m^3.yr^{-1}$ of sediment to the mid Canterbury coast.

Also of major importance is the role of sediment storage within the Hapua of the Ashburton and Rangitata Rivers. Kirk (1991) suggests that up to 80 per cent of river sediment yield can be temporarily stored in the Hapua. Kirk et al. (1977 p.243) estimated that in 1974 35.6 per cent of the direct river contribution was stored in the Ashburton River Hapua. Therefore, the role of Hapua sediment storage has to be considered when calculating a sediment budget for the mid Canterbury coast.

Longshore Transport

Longshore transport of sediment along the mid Canterbury coast can be both a source and sink of sediment. Total sediment transfers within the mid Canterbury cell are not required for use in a sediment budget. However, net sediment transport is needed. Also required are the quantities of sediment entering and leaving the mid Canterbury coast by longshore transport. Kirk and Hewson (1978) suggest that if a beach loses more material that it receives then the sediment budget will be in deficit and the coast will retreat. Given the long-term erosion of the mid Canterbury coast it can be assumed that the sediment budget is in deficit. If the sediment inputs from cliff erosion and rivers are considered, it can also be assumed that longshore sediment transport out of the mid Canterbury coast will be larger than the sediment input from longshore transport.

Chapter Four calculated the potential longshore sediment transport rate from wave observations. Using this method net potential longshore sediment transport was calculated to be $40{,}645m^3.yr^{-1}$ in a northward direction. However, the calculation of longshore sediment transport by this method may be flawed. Inputs and availability of sediment to be transported were not considered. As noted above, considerable amounts of sediment are introduced into the mid Canterbury coastal zone by erosion of cliffs and sediment yields from the Ashburton and Rangitata Rivers. Therefore, the actual amount of longshore sediment transport out of the mid Canterbury coast will often be different to the amount coming in from the coast south of the Rangitata River.

Also the actual quantities of longshore sediment transport entering and exiting the mid Canterbury coastal zone will be limited by sediment supply and may be vastly less than the potential transport rate calculated in Chapter Four. The amount of sediment lost through longshore sediment transport will be discussed further on.

Offshore Transport

Sediment transported offshore can be a major sink of sediment for any coastal environment. This is the case for the mid Canterbury coast. Because of the high-energy wave environment, fine sediment is transported offshore from the mid Canterbury beaches with ease. The fine sediment is then deposited offshore onto the continental shelf. As mentioned in Chapter Two, the mid Canterbury coast is comprised of sand and gravel. One of the features of mixed sand and gravel beaches is that they are characterised by the presence of a steep nearshore face, usually present at the line of breakers (McLean, 1969; Kirk, 1980). The nearshore step means that there is very little, if any, onshore transport of sediment onto mid Canterbury beaches. Therefore, any sediment moved offshore from the mid Canterbury coast is lost entirely to the coastal system.

The sediment transported offshore comes from a variety of sources. Suspended sediment load from the Rangitata and Ashburton Rivers provides the bulk of the sediment transported offshore. Cliff erosion also provides a significant amount of fine sediment. However, the sediment transported offshore that is provided by river sediment transport and cliff erosion is not being considered in the sediment budget for the present research because the sediment spends virtually no time on the mid Canterbury beaches.

The offshore sediment transport to be considered by the present research comes from the swash-backwash abrasion of beach sediments. Chapter Two noted that the swash zone drives mixed sand and gravel beaches. Therefore, it is within the engine-room of the swash zone that sediment is broken down and abraded.

Abrasion involves the destruction of sediment by the rubbing of pebble against pebble (Marshall, 1927). Other processes that break down sediment on a beach are impact and grinding. 'Impact' is the effect of definite blows of large pebbles on small pebbles and 'grinding' is the crushing of small grains by continued contact and pressure with large pebbles (Marshall, 1927). Marshall (1927; 1929) and Adams (1978) have examined rates of abrasion for greywacke in New Zealand. Marshall (1927) notes that abrasion is by far the slowest of the three denudation agents. However, impact is only significant when the 'impactor' is at least ten times larger than the 'impactee' and grinding occurs mainly with sands (Marshall, 1927). Marshall (1927), in his study of greywacke from Napier beaches in New Zealand's North Island, discovered that contrary to his expectations, no sand was formed by the abrasion of the greywacke. Of the abraded sediment, only 0.01 per cent was coarser than 0.07mm in diameter (Marshall, 1927 p.508). Therefore, on a high wave energy coast, such as mid Canterbury, abraded sediment will be of too fine a nature to remain on the beach.

Adams (1978) calculated abrasion coefficients for torlesse sandstones (greywacke) obtained from Lowcliffe Beach, approximately 5km north of the mouth of the Rangitata River. He calculated the abrasion mass loss coefficient for greywacke to be on average 0.0015km^{-1}. Over the approximately 32km of mid Canterbury coastline this coefficient would amount to 0.048. This means that over length of the mid Canterbury coast, 4.8 per cent of beach sediment may be lost to abrasion. This rate of abrasion has been calculated from tumbler experiments. Adams (1978) notes that natural rates of abrasion can be much higher. Because pebbles move back and forth across the beach by swash and backwash processes as well as along it, they abrade without moving large distances alongshore. This abrasion rate estimated from distance travelled in a drum may not be well matched by simple longshore distances in the field. Adams suggests that abrasion rates on a beach may be as much as 30 times faster than for abrasion rates in tumbler experiments. Gibb and Adams (1982) confirm this suggestion. They show that the abrasion rates between the Rangitata and Rakaia Rivers is 0.024km^{-1}, a rate 16 times faster than the rate calculated by Adams (1978). That is for every linear metre that a pebble moves alongshore it may move 16m in the swash and backwash. Therefore, sediment lost by abrasion processes along the mid Canterbury coast could amount to 76.8 per cent of the total sediment. This is an important result because it suggests that coarse grained, beach forming sediments have a short 'lifetime' and only persist for short distances alongshore in the Canterbury Bight.

Sediment Budget Equation

The sediment sources and sinks for the mid Canterbury coast, mentioned above, can be expressed empirically by the equation:

$$\Delta st = C + R + (L_I - L_O) - O \qquad (6.1)$$

where: Δst represents change in the net annual storage of the coastal system;

C is the direct contribution by cliff erosion;

R is the direct river contribution;

$(L_I - L_O)$ are longshore sediment transport into and out of the area respectively;

O is the total sediment moved offshore, predominantly through abrasion.

Equation 6.1 allows the change in net annual sediment storage of the mid Canterbury coast to be calculated thus, partly explaining the nature of the mid Canterbury coast.

6.2.2 Total of Sediment Sources

There are three major sediment sources for the mid Canterbury coast. They are cliff erosion (C), river transport (R) and longshore transport (L_l). Unlike coasts that consist predominantly of sand, onshore transport and windblown transport are negligible on mixed sand and gravel coasts. The sediment sources, along with the sinks, are schematically represented on Figure 6.2.

In this study it has been calculated the total contribution of sediment from cliff erosion for the mid Canterbury coast is 216,922$m^3.yr^{-1}$. Sediment supplied by the mid Canterbury rivers, traditionally the primary source of sediment for most coasts, provides 53,000m^3yr^{-1} of sediment. As mentioned in Chapter Five and Section 6.2.1, a proportion of this sediment can be stored in the Hapua of the Ashburton and Rangitata Rivers. However, because of the erosional equilibrium nature of the coast, the Hapua would supply an equal amount of sediment. Therefore, Hapua sediment storage is negated by Hapua sediment supply. The third source, longshore transport, is more difficult to quantify. It has already been mentioned that potential longshore sediment transport, calculated from wave observations at the Ashburton River mouth, is 40,645$m^3.yr^{-1}$ in a northward direction. Assuming that the same processes are active at the mouth of the Rangitata River, this figure will be the same there. Without direct observations this longshore transport rate is the best available. Also, Kirk and Hewson (1979 p.12) estimated 38,000$m^3.yr^{-1}$ of sediment moved longshore northward past Timaru. No cliffs exist between just north of Timaru and the Rangitata River mouth that are capable of providing any sediment to the coast. Therefore, a longshore sediment transport input figure of 40,645$m^3.yr^{-1}$ is reasonable. Table 6.2 summarises the sediment sources.

Total sediment sources, or inputs, for the mid Canterbury coast amount to 310,567$m^3.yr^{-1}$. Cliff erosion accounts for 70 per cent of the total. This appears large, but when comparing the amount of sediment contributed per kilometre of coast with Kirk et al. (1977) and Gibb (1978), as mentioned in Section 6.2.1, it is less than these two previous studies. River transport contributes 17 per cent of total sediment input. Clearly river transport is not the major source of sediment for the mid Canterbury coast. Longshore transport (13 per cent) is the smallest contributor of sediment.

6.2.3 Total of Sediment Sinks

Section 6.1 noted that sediment budgets work on the concept of the conservation of mass. Therefore, outputs (or sinks) of sediment should equal inputs. Total inputs have been calculated to be 310,567m^3.yr^{-1}. However, the mid Canterbury coast is in a state of long-term erosion so the coast must lose more sediment than it gains on average. Therefore, outputs (or sinks) must be greater than the total inputs of 310,567m^3.yr^{-1}. Two methods can be employed to calculate the total sum of the sediment outputs.

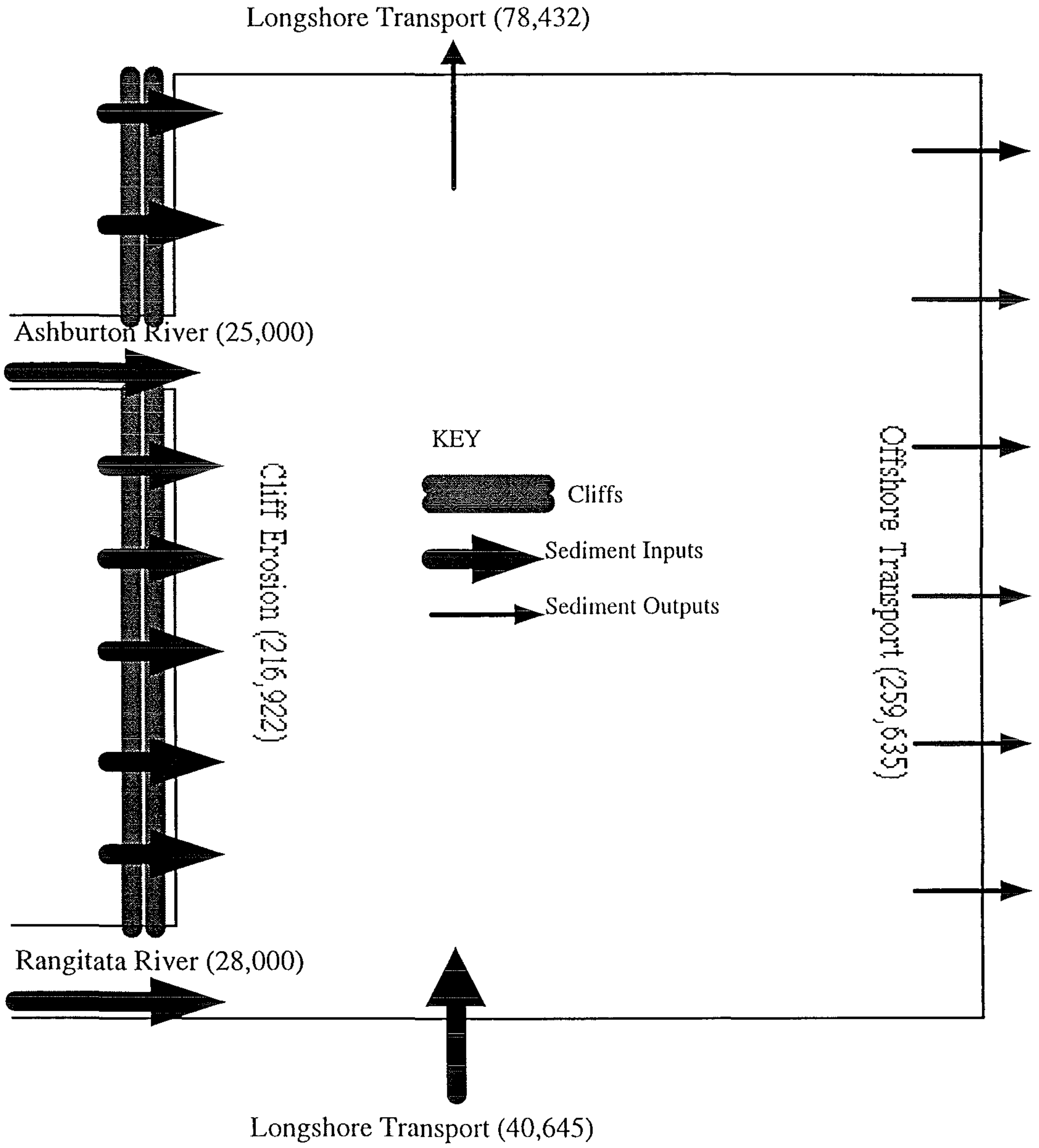


Figure 6.2: Sediment budget for the mid Canterbury coast. All values are in m^3.yr^{-1}.

The first method involves the entire coastal system. This includes the beach and the eroding cliffs of the mid Canterbury coast. This total view of the sediment budget is of interest to managers of the land because it accounts for the land lost through the cliff erosion. Because the mid Canterbury coast is eroding, all of the inputs are not enough to stabilise the coast. Therefore, outputs equal the inputs plus the amount of sediment that is removed annually. Cliff erosion, while also being an input, can be classed as an output because sediment eroded from the cliffs travels through the beach and is transported, either offshore or alongshore, out of the sediment budget compartment. Sediment is also being lost from the beach system every year. Figure 6.3 illustrates the total beach volume for the mid Canterbury coast from 1987 to 1996. The main feature of this graph is the variability in total volume from year to year. A maximum beach volume of about 2,420,000m^3 can be compared to the minimum of 2,040,000m^3. The minimum beach volume is approximately 16 per cent lower than the maximum. Year to year variations are also large with the 1989 volume being about 10 per cent lower than the 1990 beach volume. The large variations shown on Figure 6.3 mask another trend in the beach volume of the mid Canterbury coast. There is a downward trend in the total yearly beach volume. On average approximately 27,500m^3 of beach sediment is being lost every year from the mid Canterbury coast. Therefore, the total sediment outputs for the entire mid Canterbury coastal system is equal to: the total inputs (310,567m^3.yr^{-1}), plus the sediment lost through cliff erosion (216,922m^3.yr^{-1}) plus the sediment lost from the beach (27,500m^3.yr^{-1}). This amounts to a total sediment output of 554,989m^3.yr^{-1}.

The second method of calculating the total sediment outputs involves the examination of only the beach system. Total outputs are equal to the total inputs plus the amount of sediment lost from the beach yearly (Figure6.3). Therefore, total output from the beach system only is 338,067m^3.yr^{-1}.

There are only two major sinks of sediment from the mid Canterbury coast and they are longshore (L_O) and offshore transport (O). Other sinks such as beach overtopping and wind transport are not significant. Wind transport has been discovered to be quantitatively unimportant at the Ashburton River mouth (Kirk et al., 1977). Beach overtopping by storm waves may also be an important sink of sediment. However, the presence of cliffs along the majority of the mid Canterbury coast means that overtopping is unimportant. It has already been noted that longshore and offshore transport are difficult to quantify. This task is made easier because longshore and offshore transport are the only significant sinks of sediment along the mid Canterbury coast. With knowledge of the total outputs it is only a matter of finding the proportion of the outputs that longshore and offshore transport make up.

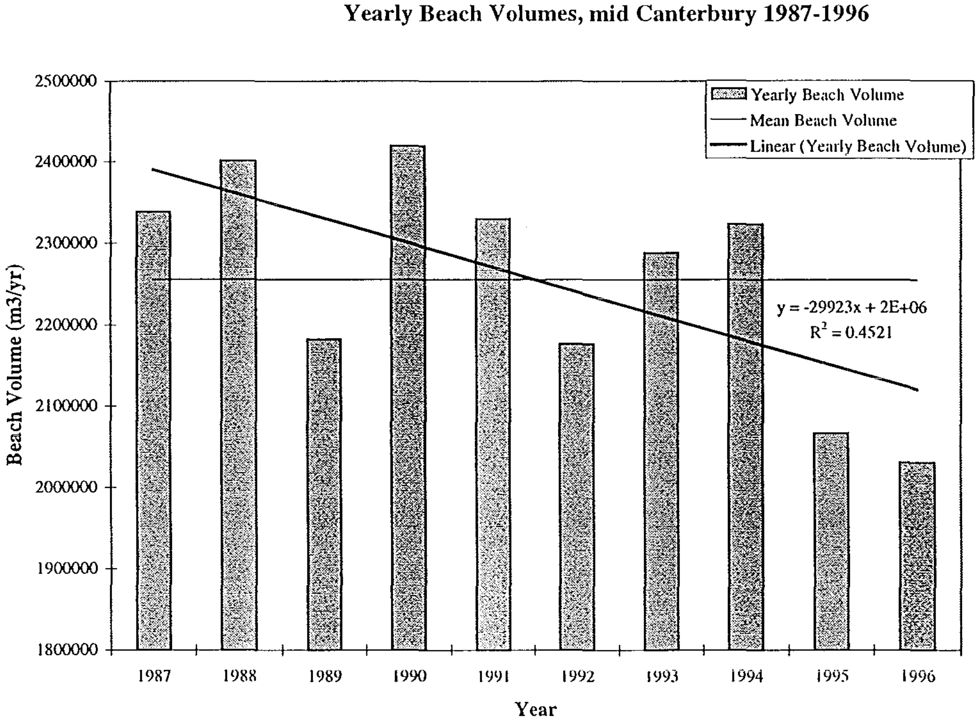


Figure 6.3: Yearly beach volume change, mid Canterbury 1987-1996

Of the two output processes, offshore transport is the easiest to estimate. Sediment transported offshore is the provided by the process of abrasion. Using the abrasion coefficients for greywacke from Adams (1978) and Gibb and Adams (1982), finding the proportion of total sediment output accounted for by offshore transport is a relatively easy exercise. However, an assumption must first be made. Sediment that is being transported alongshore must be doing so at a constant average rate.

Total sediment outputs from the beach system amount to 338,067$m^3.yr^{-1}$ from the mid Canterbury coast. Using the abrasion coefficient from Adams (1978) and using a coast length of 32km, 4.6 per cent of the sediment losses can be attributed to offshore transport. Therefore, 15,551$m^3.y^{-1}$ of sediment is lost offshore from the mid Canterbury coast. This leaves 322,516$m^3.yr^{-1}$ of sediment to be transported alongshore out of the mid Canterbury coast. This longshore component appears to be too large. As mentioned in Section 6.2.1, natural rates of abrasion are much higher than those calculated in tumbler experiments. Using the natural abrasion rate for greywacke from Gibb and Adams (1982), 76.8 per cent of the total sediment losses is through the abrasion process. For the 32km of the mid Canterbury coast offshore transport accounts for 259,635m^3.yr^{-1} (O) of the sediment lost from the coast. Longshore transport accounts for only 78,432m^3.yr^{-1} (L_I) (Table 6.2).

The amount of sediment lost through abrasion (76.8 per cent) appears to be a fair estimation. Gibb and Adams (1982 p.345) estimate that for the entire Canterbury Bight, 95 per cent of the total gravel input is lost by abrasion along the 136km of coast. Gibb and Adams also suggest that between the Rangitata and Rakaia Rivers, longshore transport remains at a reasonably constant level. This implies that gravel supplied by the eroding cliffs is to abraded. The present research is consistent with the view of Gibb and Adams. For the mid Canterbury coast, sediment supplied by cliff erosion (216,922m^3.yr^{-1}) is lost through abrasion (259,635m^3.yr^{-1}).

Table 6.2: Sediment transfers for the mid Canterbury coast

Sediment Transfers (m3.yr-1)	
Sources	
Cliff Erosion (C)	216,922
River Transport (R)	53,000
Longshore Transport (LI)	40,645
Sinks	
Offshore Transport (O)	259,635
Longshore Transport (LO)	78,432

The remaining 23.2 per cent of sediment that is lost from the mid Canterbury coast through longshore sediment transport (78,432m^3.yr^{-1}). Sediment that is transported alongshore northwards along the Canterbury Bight ultimately ends up on the Kaitorete Barrier (Figure 1.1). However, Kaitorete Barrier has remained stable since at least the 1860s (Kirk, 1994). Therefore, any longshore sediment that is deposited on Kaitorete Barrier is only sufficient to maintain it. This would suggest that longshore transport onto the barrier is not large and abrasion is active, which is consistent with the view that once sediments arrive on the Canterbury Bight coast they have short 'life span' and get disintegrated rapidly through abrasion. The longshore sediment transport out (L_O) of the mid Canterbury coast is nearly twice as large as the longshore sediment in (L_I). Longshore transport out will be larger than longshore transport in because of the other inputs, cliff erosion and river transport, supplying more sediment to be transported alongshore.

The total sediment lost from the total coastal system will not be examined further. However, it has been mentioned to illustrate that outputs from a coast can be different depending on the chosen boundaries of the sediment budget compartment are examined.

6.2.4 Nature of the mid Canterbury Coast

The purpose of sediment budget analysis is to evaluate the relative importance of sediment sources and losses to the coast (Komar, 1976). Figure 6.2 summarises the quantities of the sources and sinks (for the beach system only) of sediment for the mid Canterbury coast. The relative significance of the various sources and sinks of sediment for the mid Canterbury coastal zone will be the focus of this section.

When comparing the sediment budget from the present study (Figure 6.2) with the commonly used sediment budget model (Figure 6.1), the most obvious difference is the apparent simplicity of the sediment budget for the mid Canterbury coast. Sources and sinks such as onshore transport, wind transport and biogenous and hydrogenous deposition are either negligible or non-existent along the mid Canterbury coast. However, this should not detract from the complexity of the mid Canterbury coast and its sediment transfers.

The quantities of the sediment transfers, exhibited on Figure 6.2, also show differences between the international literature and the present research as to the relative significance of the various sediment sources and sinks. Section 6.1.1 discusses that rivers tend to be the primary source of sediment to the coast while cliff erosion is only a secondary source at best. The present research shows that for the mid Canterbury coast the roles are reversed. Cliff erosion accounts for 70 per cent of the sediment gained, while the rivers only contribute 17 per cent. Kirk et al. (1977) estimated that fluvial contribution of sediment to the Canterbury Bight would not exceed 15 to 20 per cent in a given year. This reversal in significance may be a result of the high-energy wave environment that the mid Canterbury coast is subject to. Only coarse sediment is capable of remaining on the beach. Therefore, the unconsolidated gravel cliffs of the mid Canterbury coast provide sediment that is coarse enough to remain on the beaches. Section 6.1.1 also suggests that longshore sediment transport is a major supplier of sediment. However, the present research shows that only 13 per cent of the total sediment input are from longshore transport. The relative insignificance of longshore sediment transport as a source of sediment to the mid Canterbury coast may be a function of the abrasion rate. Abrasion has been demonstrated to break down up to 76.8 per cent of sediment along the length of the mid Canterbury coast.

Section 6.1.2 discussed various sinks of sediment from the coast. It was noted in this section that both Komar (1976) and C.E.R.C. (1984) believe losses of sediment from sand beaches through abrasion to be insignificant. However, Figure 6.2 shows that abrasion is a major sink of sediment for the mid Canterbury coast. The relative importance of abrasion along the mid Canterbury coast is probably due to the coarseness of the sediment on the beaches. Marshall (1927) notes that sand cannot remain on a beach where wave action keeps gravel in movement. Gravel movement is prolific along the mid Canterbury coast. Therefore, gravel is the dominant sediment size on the mid Canterbury coast. Abrasion is most effective on beaches where coarse material is dominant.

Similar to the nature of the North Otago-South Canterbury coast studied by Hewson (1977), the mid Canterbury coast is in a state of long-term erosion and short-term erosional equilibrium. When re-examining Equation 6.1 using the figures from Table 6.2, the net change in sediment storage for the mid Canterbury coast is negative. The mid Canterbury coast is in deficit of 27,500$m^3.yr^{-1}$ of sediment. Sediment supplied by the erosion of the cliffs maintains the beach sediment volume at what appears to be a relatively constant level. Figure 6.3 shows that beach volume is decreasing over time. However, any attempt to mitigate the cliff erosion would result in the beach receiving even less sediment to maintain the beach from the losses of sediment through abrasion.

The present chapter has presented and analysed a sediment budget for the mid Canterbury coast. It should be noted that quantities used for the various sediment inputs and outputs have been yearly averages from a 15 year data set, 1981 to 1996. From the discussions in Chapter Three, 4 and 5, cliff erosion, longshore sediment transport and river derived sediment yields can all vary over time. Therefore, for a given year all three of these processes may supply a quantity of sediment that is vastly different to that which has been described in the present chapter. Similarly a sediment budget using data from any specific year may differ significantly from the one presented in the present study.

6.3 Summary

Coastal sediment budget analysis is a useful tool when examining the relative importance of various sediment inputs and outputs for a length of coast. The present chapter has analysed a sediment budget for the mid Canterbury coast, which is approximately 32km long. The major geomorphological features of this coast are the unconsolidated gravel cliffs that lie on the landward boundary of much of the coast and the river mouths of the Ashburton and Rangitata Rivers.

The mid Canterbury coast receives its sediment from only three major sources: cliff erosion, longshore transport and river transport. Chapters Three, Four and Five examined these three components of the sediment budget respectively. Of significance is the relative contribution of the three sediment sources. Coastal cliff erosion is by far the major contributor. Cliff erosion provides over 4 times the amount that is provided by the Rangitata and Ashburton Rivers and over 5 times the amount contributed by longshore sediment transport. Of the outputs of sediment, offshore transport through abrasion accounts for the majority, ahead of longshore transport. Total transfers of sediment (inputs plus outputs) amount to 648,634$m^3.yr^{-1}$. This amounts to about 29 per cent of the mean total volume of material stored on the mid Canterbury coast (2,253,097m^3). The total beach volume was calculated from above mean sea level to the beach toe. This means that 29 per cent of the beach volume is affected by the sediment budget in a given year. Kirk and Hewson (1978 pp.102-103) calculated only 17 per cent of the total beach volume is affected annually by the total sediment transfers for the North Otago-South Canterbury coast. However, this works out to be 41,884$m^3.km^{-1}.yr^{-1}$ for the entire North Otago-South Canterbury coast. Spatially averaged transfers per kilometre of coast work out to be 20,270$m^3.km^{-1}.yr^{-1}$. This figure is within an order of magnitude of the findings of Kirk and Hewson (1978)

The two outputs studied both had to be estimated. Because of the sediment budget concept that mass is conserved, total outputs equalled total inputs. Offshore transport, through abrasion, proved to be the most significant accounting for about 77 per cent of the total outputs. Longshore transport out of the mid Canterbury coast, while being larger than that which entered, accounted for only about 23 per cent of the total sediment lost from the coast. The proportion lost through abrasion seems large but is realistic considering that the Kaitorete Barrier, to the north of mid Canterbury, has not been aggrading since at least 1860 (Kirk, 1994). Therefore, large amounts of longshore derived sediment have not been reaching the barrier, meaning that the sediment must be being lost offshore through abrasion.

The mid Canterbury coast is dominated by two major processes, cliff erosion and abrasion. These two account for the vast majority of the mid Canterbury coasts sediment sources and sinks respectively. The coast is also in a state of long-term erosion. However, this erosion is of an equilibrium nature with the beach retreating at virtually the same rate as the cliffs but still maintains its volume. Hewson (1977) believes that the North Otago-South Canterbury coast is in a state of short-term erosional equilibrium but a long time span will be required before the coast reaches a state of stable equilibrium. The mid Canterbury coast is of a similar nature to the North Otago-South Canterbury coast and was both formed under and continues to experience similar conditions. The mid Canterbury coast is also in a long-term state of erosion which will continue under the present process regime.

Chapter Seven

Conclusions

7.1 Objectives Re-examined

This study has examined change along the mid Canterbury coast. The main focus has been erosion of the unconsolidated gravel cliffs that run the length of most of the coast. These cliffs range in height from about 9m at the Rangitata River mouth to 21m just north of the mouth of the Ashburton River. A long-term approach to examining cliff erosion has been possible for the first time because of a history of monitoring by the Canterbury Regional Council. This thesis has been in a position to describe and quantify coastal cliff erosion in more detail than has been possible in previous research.

The thesis has examined three main aims that were presented in Chapter One. These aims were:

1. To describe coastal cliff erosion;
2. To determine the processes that cause it; and
3. To examine the role of coastal cliff retreat in the coastal sediment budget.

All three of the above aims have been successfully met. Completion of the third aim required examination of processes such as longshore sediment transport, river sediment transport and abrasion. The present chapter will conclude this thesis by presenting a summary of the principal findings and by providing some suggestions for further research.

7.2 Summary of Major Findings

The mid Canterbury coastline was formed with the Holocene rise in sea level cutting into the alluvial outwash fans that form the Canterbury Plains. Approximately 16,000 years B.P. sea level was 100-130m below the present level and the coastline was about 50km seawards of the present position of the coast. The rise in sea level that followed the end of the Pleistocene glaciations adjusted the mid Canterbury coastal environment resulting in cliffing and erosion of the Canterbury Plains alluvial fans. Sea level has stabilised over the last 5,000 years but the erosion of the alluvial fans has continued. The high-energy wave environment of the Canterbury Bight and the presence of strong longshore sediment movement have resulted in the continued erosion. Chapter Two estimated that since sea level has been at its current highstand there has been retreat of the coastal cliffs of between 2.5 and 5km.

Erosion of unconsolidated coastal cliffs involves the interaction of many processes. Chapter Two reviewed the current knowledge of the cliff erosion process. Cliff erosion involves the interaction of three types of factors. The lithology of the cliff is vitally important. Unconsolidated cliffs are more prone to erosion than hard rock cliffs because they are subject to weakening by weathering and degradation by mass movement. Permeability and porosity of the cliffs are also important because moisture affects the strength of the cliff forming material. Beach factors such as beach height, beach width and the presence of talus slopes all affect the ability of waves to 'attack' the base of a cliff and erode them. Wave factors are also important in the erosion of coastal cliffs. Erosion of the mid Canterbury coastal cliffs involves the interaction of the above mentioned factors. However, mid Canterbury coastal cliff erosion is predominantly subaerial in origin. Marine processes only facilitate the erosion by removing the slumped material from the base of the cliff, which in effect steepens the cliff enabling erosion to continue. Erosion of the mid Canterbury cliffs requires the presence of both subaerial and marine processes.

Chapter Three examined a network of over twenty cliff and beach profile sites surveyed yearly from 1981 to 1996 to investigate spatial and temporal variations in cliff erosion along the mid Canterbury coast. Cliff erosion varies significantly over space. Along the length of the mid Canterbury coast, cliff erosion rates varied from as high as $1.09m.yr^{-1}$ to as low as $0.03m.yr^{-1}$. Factors that affected the spatial variation of cliff erosion also varied, depending on the time scale of the investigation. Over the long-term (15 years) the major factor controlling spatial variation in cliff erosion was cliff height. As cliff height increased so did the erosion rate. Cliff height explained 54 per cent of the spatial variations in cliff erosion along the mid Canterbury coast in the long-term. Over the short-term (1 year) beach volume is the major controlling factor, explaining 59 per cent of the spatial variance in cliff erosion rates.

Cliff erosion along the mid Canterbury coast also varies over time. However, temporal variations in coastal cliff erosion are harder to explain than spatial variations. The annual erosion rates from two profile sites were examined against a number of variables. Coastal storm frequency was discovered to be the main controlling factor. A coastal storm was defined by wave heights of over 3m. Regression analysis showed that between 40 and 46 per cent of the temporal variations in coastal cliff erosion are explained by this measure of coastal storm frequency.

The third aim of the present research was to examine the role of coastal cliff erosion on the sediment budget of the mid Canterbury coast. For this to be completed the amount of sediment contributed by the cliffs to the coast had to be calculated. The mid Canterbury coast was divided into a number of cells, all of which centred on one of the survey sites. Using cliff heights, cliff lengths and erosion rates from each cell the amount of sediment provided was calculated to be 228,339$m^3.yr^{-1}$.

In order for the third aim of the present research to be completed the processes of longshore sediment and river sediment transport were investigated in Chapters Four and Five respectively. Longshore sediment transport along a mixed sand and gravel foreshore is significantly different to longshore transport along a predominantly sand foreshore. Longshore sediment transport, on both beach types, is sensitive to the longshore energy flux and a dimensionless coefficient, K. The longshore energy flux is the same for both beach types and is dependant on the wave height at breaking and the angle of the approaching wave. However, the coefficient K is different for the two beach types. Lower K values should be used when calculating potential longshore sediment transport on a mixed beach. This is because the efficiency of incident waves to transport material along a mixed foreshore is less than on a pure sand foreshore. Using models adapted for use on mixed beaches, it was calculated from wave observations, that the potential net longshore sediment transport rate on the mid Canterbury coast is 40,645$m^3.yr^{-1}$ in a northward direction. Chapter Four also examined the northward movement alongshore of 'slugs' of river derived sediment. These slugs are pushed along the mid Canterbury coast by the longshore sediment transport mechanism at an average rate of 2km.yr^{-1}. The presence of these slugs on beach profiles contributes to there being less erosion of the cliffs while the absence of a slug facilitates more erosion. This explains why beach sediment volume is a predictor of cliff erosion rates.

Another important feature of the mid Canterbury coastal sediment budget is the supply of sediment from rivers. Because of the rapidly eroding nature of the mountains from which they drain, the Ashburton and Rangitata Rivers are braided in channel form and have gravel beds. Braided rivers are characterised by having a high streambed gradient which produce high velocities of water flow. This coupled with alluvium sediment deposits, braided rivers are agents of considerable erosion and sediment transport. Therefore, braided rivers tend to have large sediment yields.

River sediment load is characterised by three major types: bed load, dissolved load, and suspended load. Suspended and dissolved load constitutes 97 per cent of sediment yields. However, only the bed load is of importance to the coastal environment of mid Canterbury. Due to the high-energy wave environment of the mid Canterbury coast only coarse river sediment will remain on the beach. While the total sediment yields from the Ashburton and Rangitata Rivers are high, only the bed load proportion is capable of remaining on the foreshore. The Ashburton River provides on average 25,000m^{3}.yr^{-1} of beach forming material while the Rangitata River produces 28,000m^{3}.yr^{-1}. As mentioned, the mid Canterbury coast is in a state of erosion. The mid Canterbury rivers can be classified as being 'small' rivers because their sediment yields are not sufficient to maintain the coast against erosion.

Over 75 per cent of the total sediment yield from the Ashburton and Rangitata Rivers is transported and deposited on the coast during floods. These floods can occur at any time of the year and are of varying discharges. The large deposits of sediment on the coast due to river floods can be seen in the 'slugs' mentioned above.

As mentioned, one of the aims of this thesis was to examine the relative role of cliff erosion on the coastal sediment budget of mid Canterbury. Contrary to much of the international literature, cliff erosion on the mid Canterbury coast is the primary source of sediment, providing about 70 per cent of the total sediment inputs, which are estimated at 310,567m^3.yr^{-1}. River sediment yield only supplies 17 per cent of the total sediment input, while the remaining 13 per cent is provided by longshore sediment transport. Because the mid Canterbury coast is in a state of erosion, total sediment outputs from the sediment budget compartment must be greater than the total inputs. The total volume of beach sediment, while fluctuating significantly from year to year, has been decreasing by about 27,500m^3.yr^{-1}. Therefore, total sediment losses are 338,067m^3.yr^{-1}. Only two processes contribute to the loss of sediment from the mid Canterbury coast, offshore transport through abrasion and longshore sediment transport out of the sediment budget compartment. It is concluded that offshore transport through abrasion accounts for 76.8 per cent of the losses. Even though vast quantities of sediment are deposited on the mid Canterbury coast from the cliffs and rivers, the sediment is rapidly ground up by the abrasion process. Therefore, sediment that arrives on the mid Canterbury coast spends only a small amount of time on the beaches before the high-energy environment abrades the sediment and it is transported offshore. This conclusion is consistent with the long-term budget state of the shore downdrift (Kaitorete Barrier) of the present study area.

The mid Canterbury coast is in a state of long-term erosion. The coastal cliffs are eroding at an average rate of 0.43m^3.yr^{-1} even though this erosion varies through both space and time. Both subaerial and marine processes cause this erosion with subaerial processes dominant. The mid Canterbury coast itself is losing 27,500m^3 of sediment on average every year and in the present process regime this erosion and sediment loss will continue, long term.

7.3 Suggestions for Future Research

Examinations of the process environment of the mid Canterbury coast are limited because of the high-energy environment. The use of sensitive equipment such as current-meters would be impossible because of the damage that would be sustained by the equipment from moving gravel. However, there is scope for continued research along not just the mid Canterbury coast but the entire coast of the Canterbury Bight.

The present research has been the only study to date that has examined a long-term set of detailed ground survey data. Continued investigation of the Canterbury Regional Council surveys will result in a clearer picture of the patterns and causes of coastal cliff erosion along the mid Canterbury coast. The Canterbury Regional Council profiles extend along the entire Canterbury Bight coast. Therefore, examination of the coastal change similar to the present research is possible for the entire Canterbury Bight. Already it has been shown that sediment quantities produced by cliff erosion are, on a spatially averaged basis, less than have been previously estimated.

The present study has concentrated on the investigation of time and space average patterns of erosion. Also the coastal sediment budget detailed in Chapter Six concentrated on yearly averages of sediment inputs and outputs. However, the majority of the erosion and sediment transport on the mid Canterbury coast occurs during low frequency, high magnitude events. There is scope for examining the sediment budget on a yearly basis using sediment input and output data from individual years. The effect on the coast of the sediment inputs and outputs and the entire sediment budget would most probably be very different from year to year to the averaged sediment budget presented in this research.

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Appendix 1

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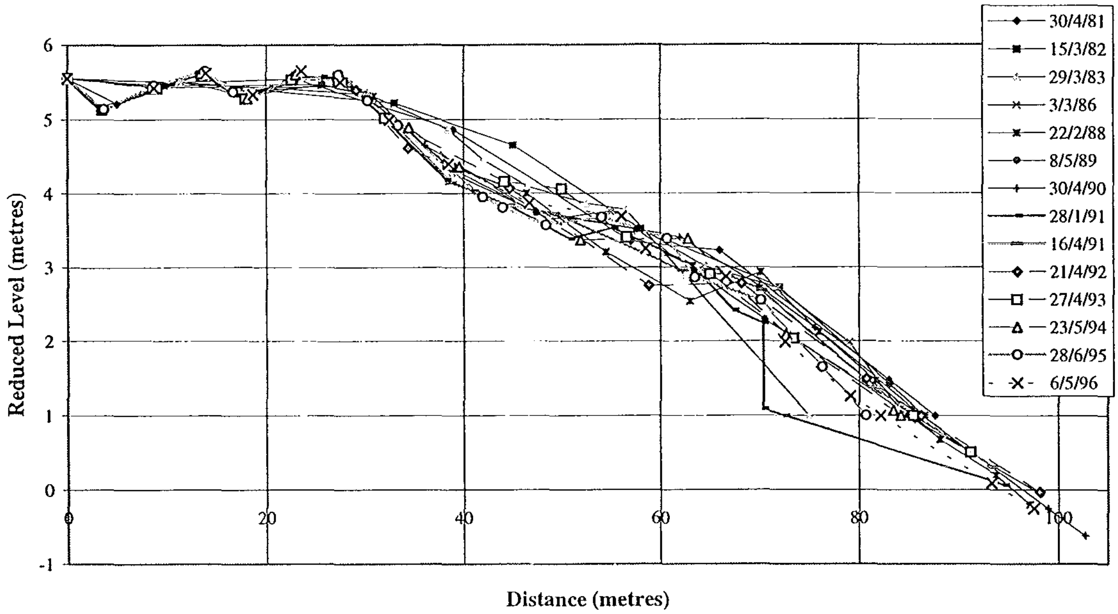

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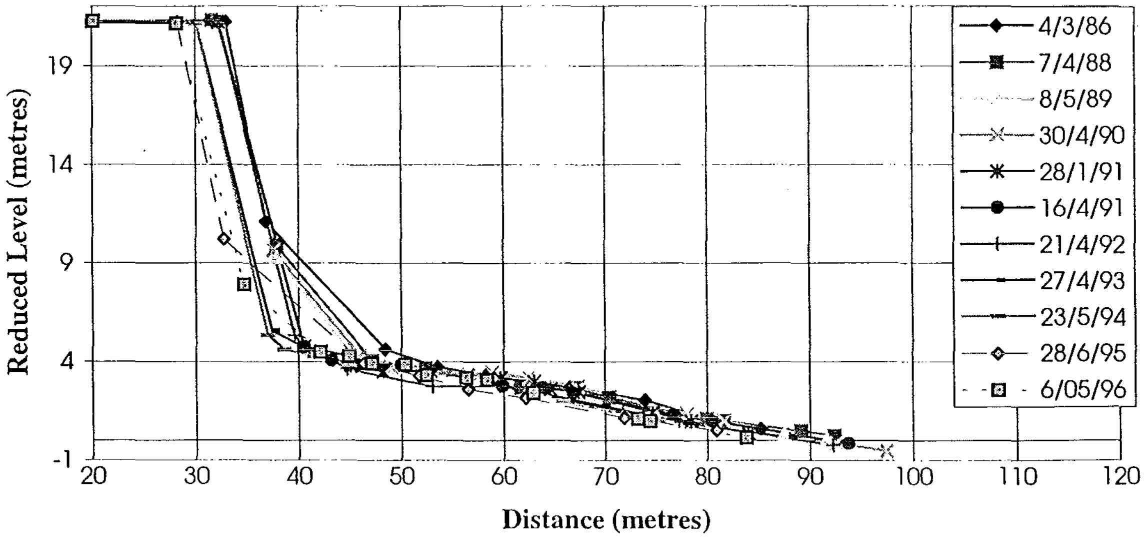

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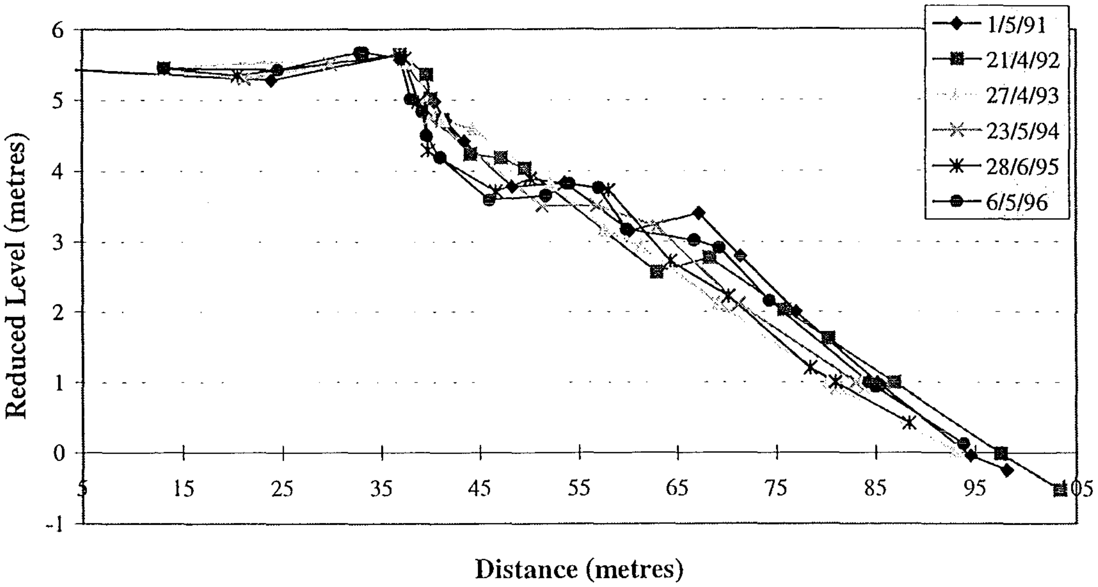

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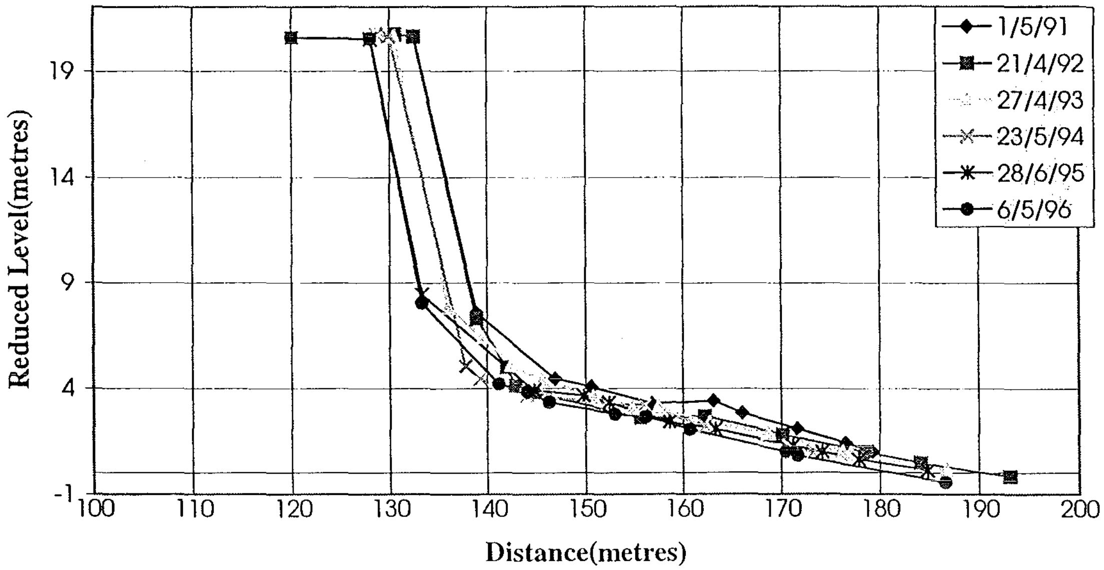

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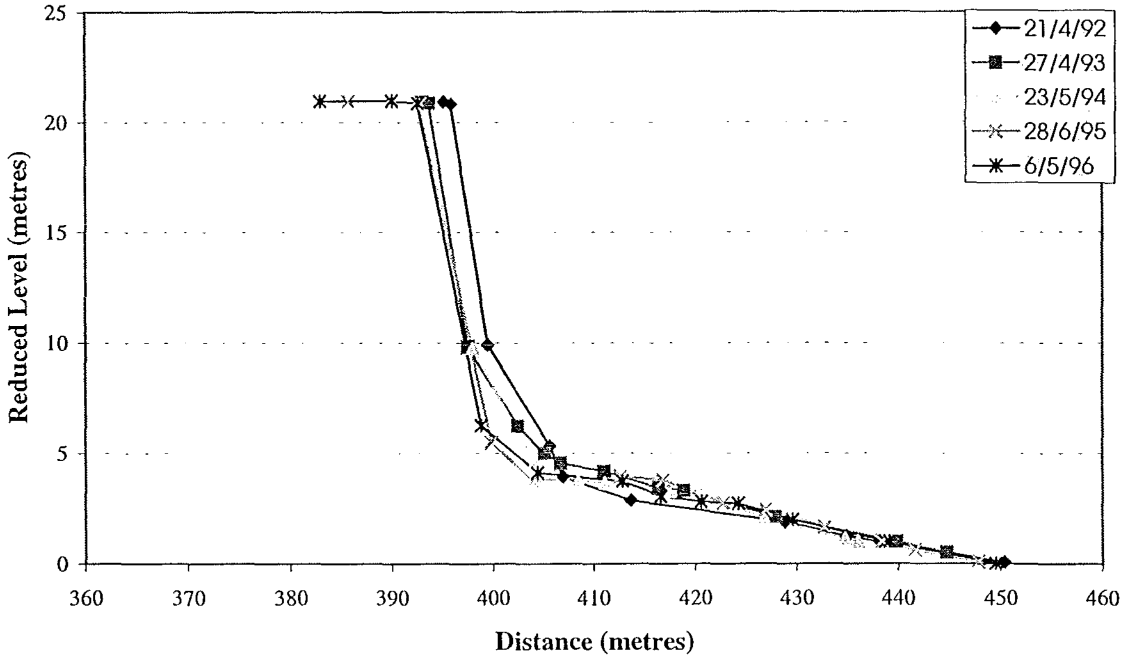

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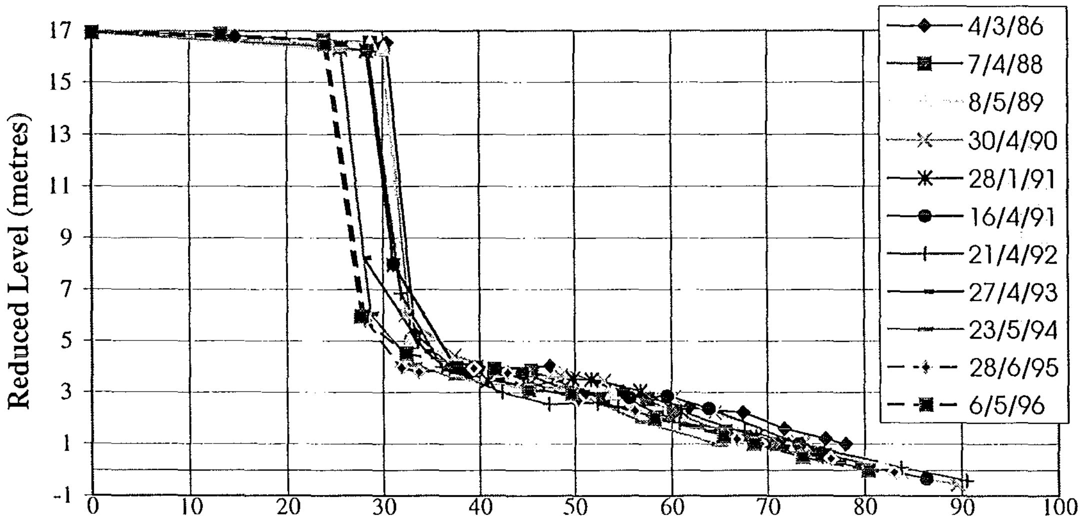

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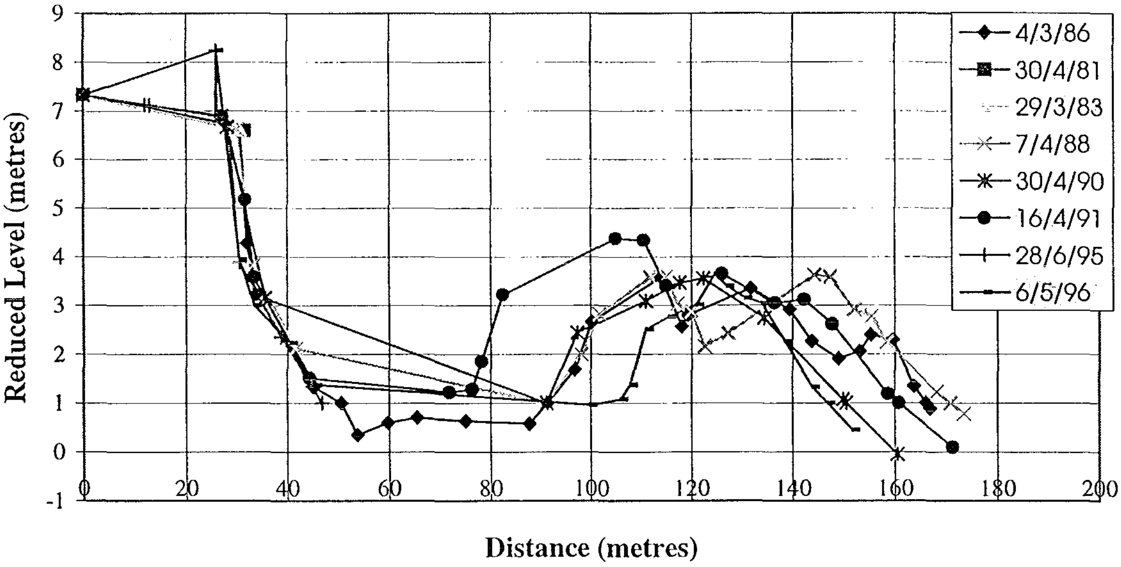

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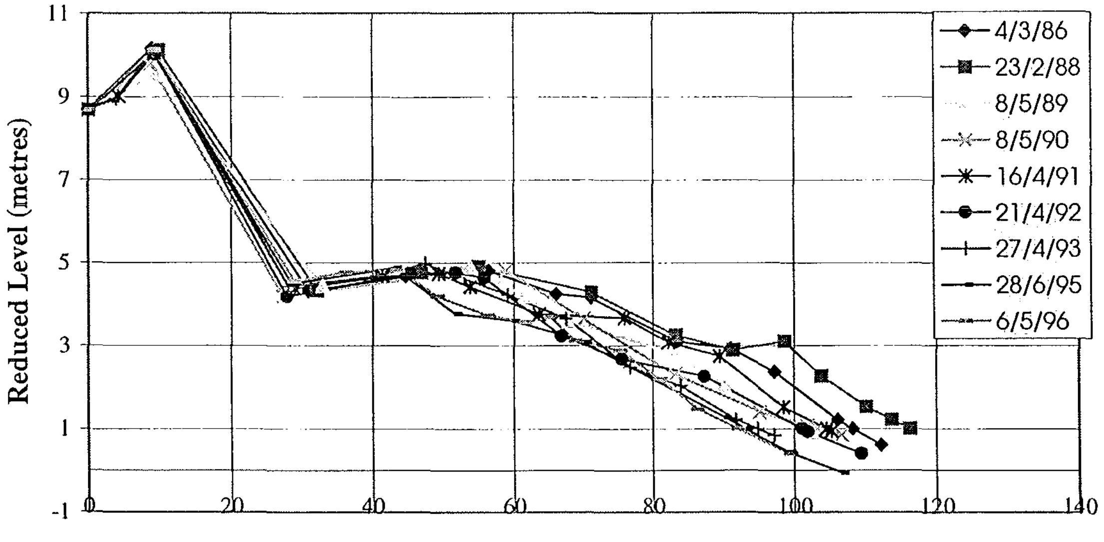

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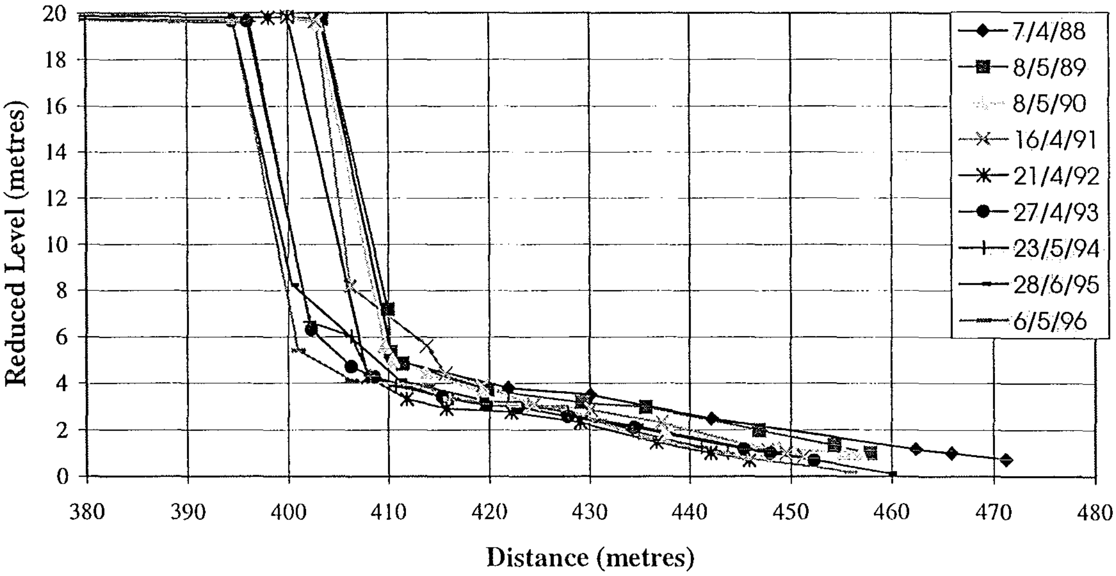

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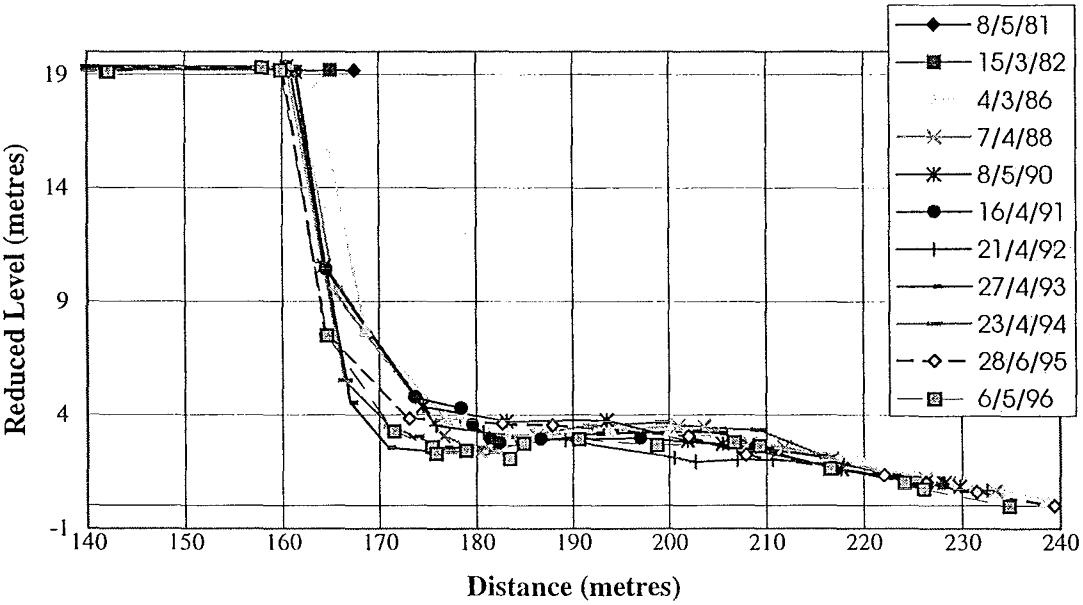

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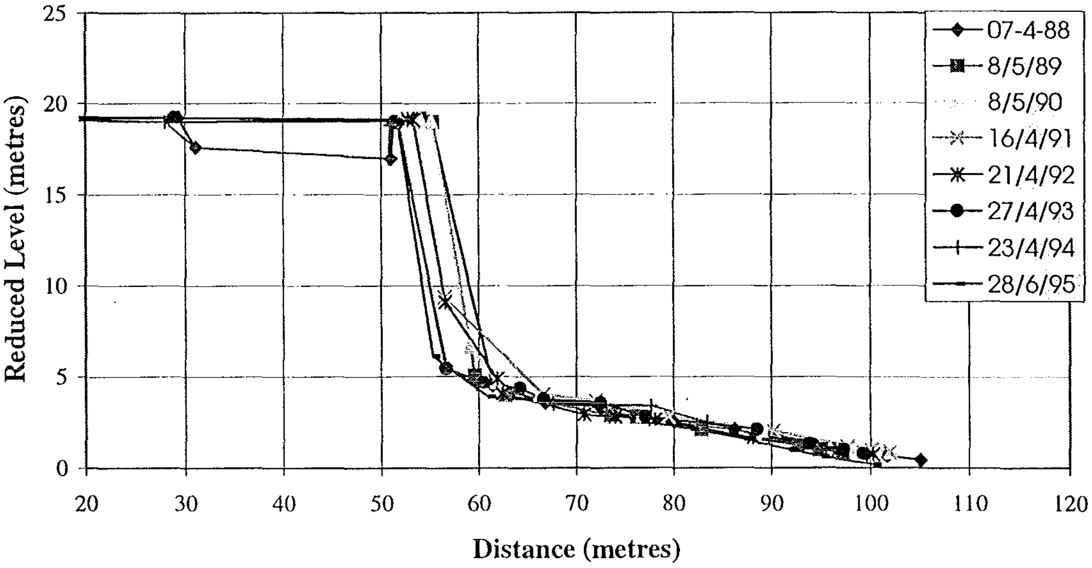

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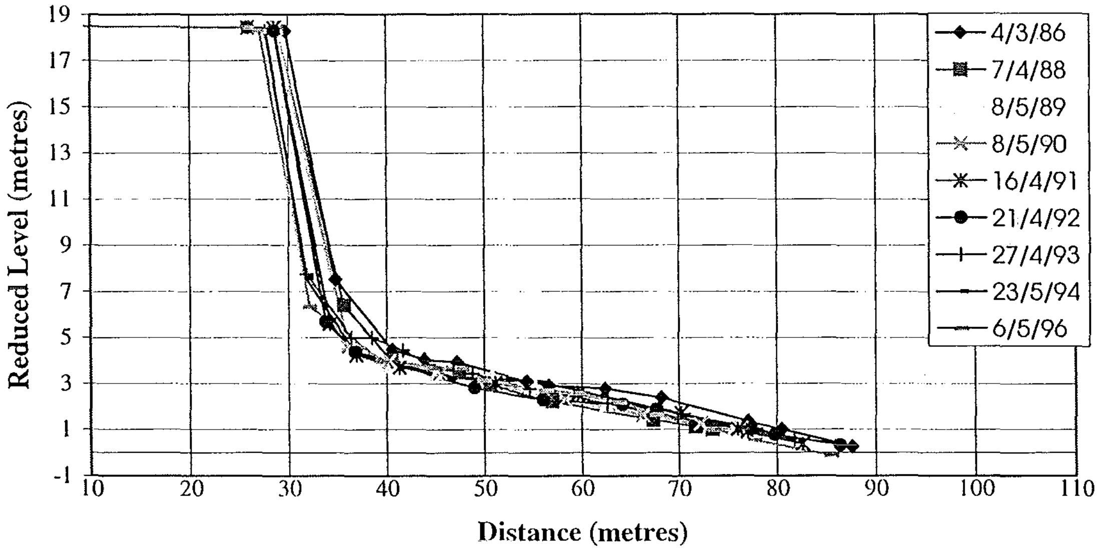

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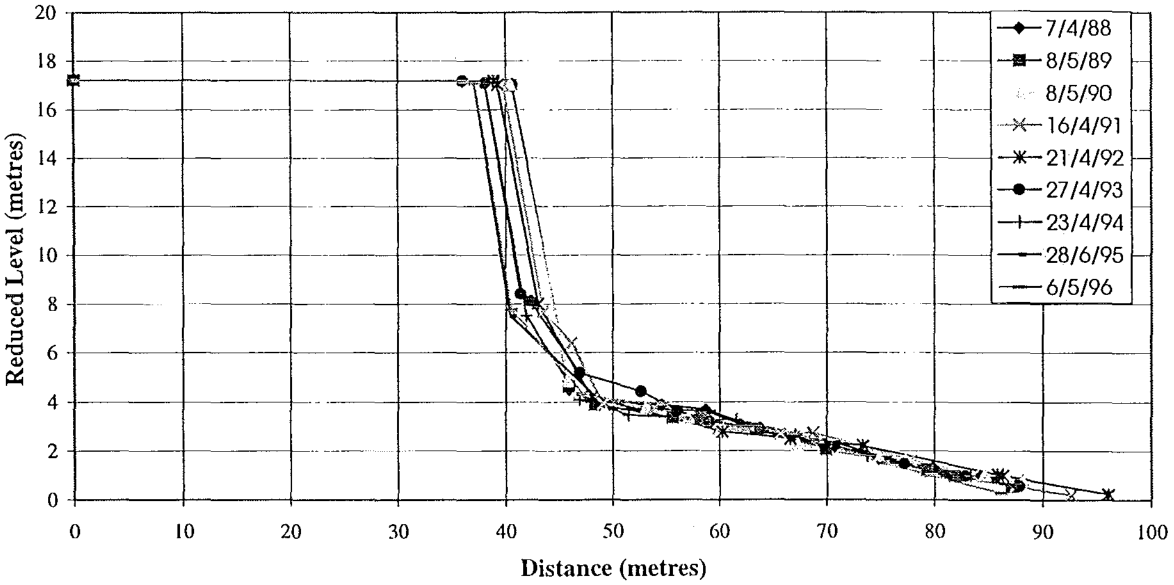

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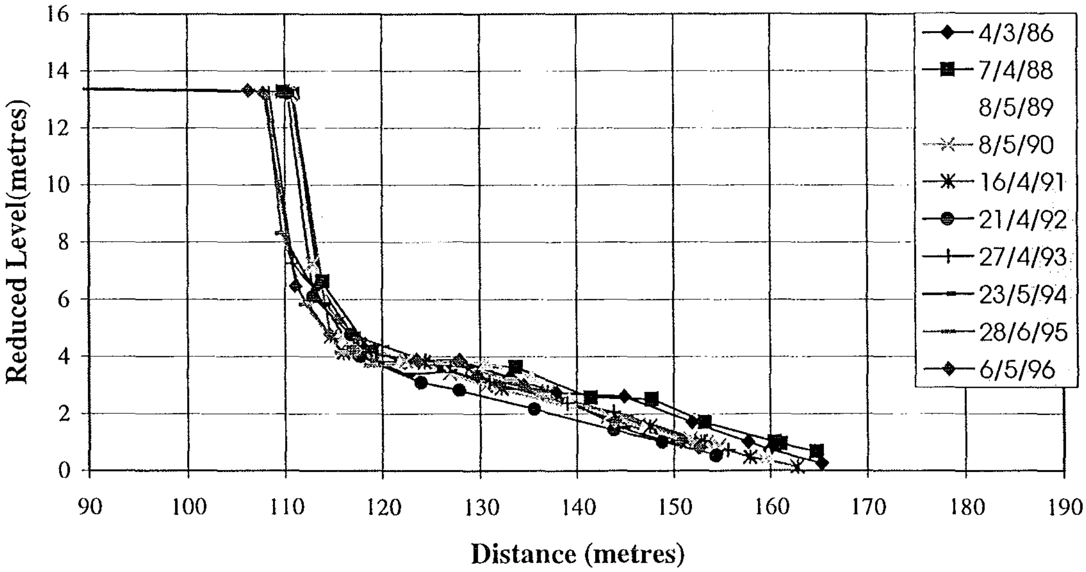

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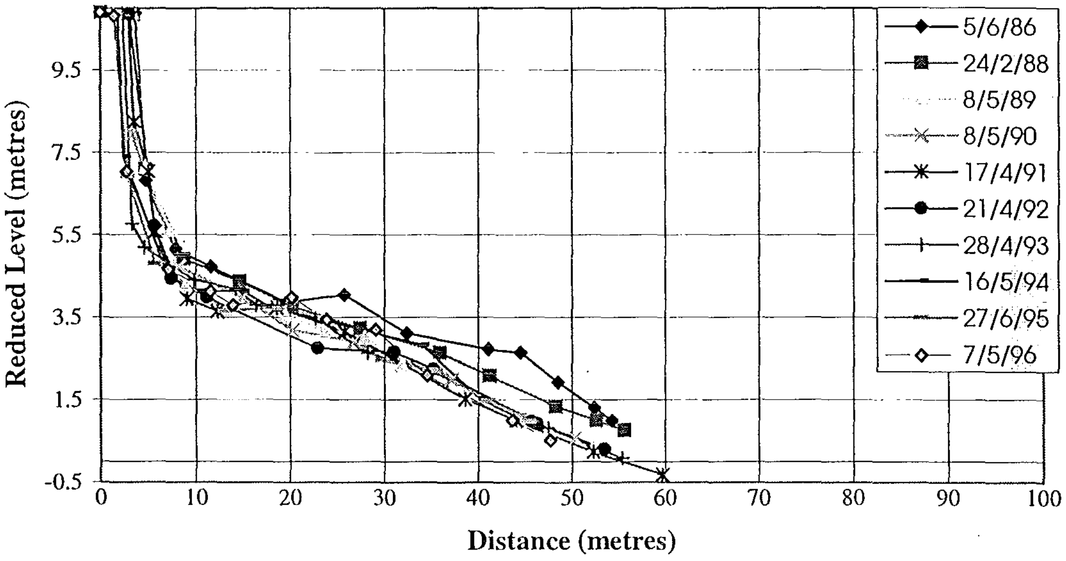

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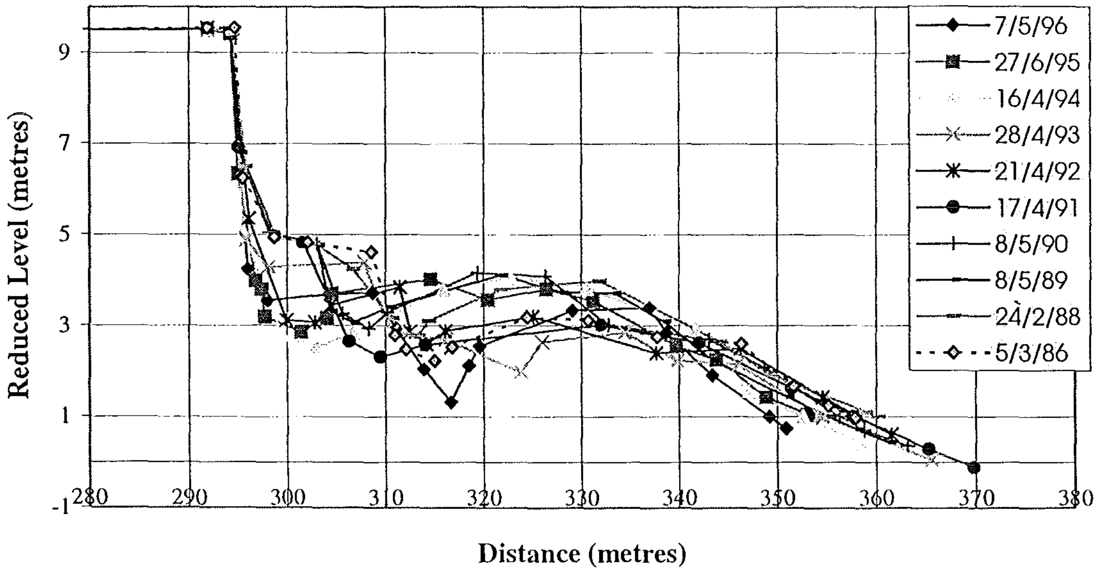

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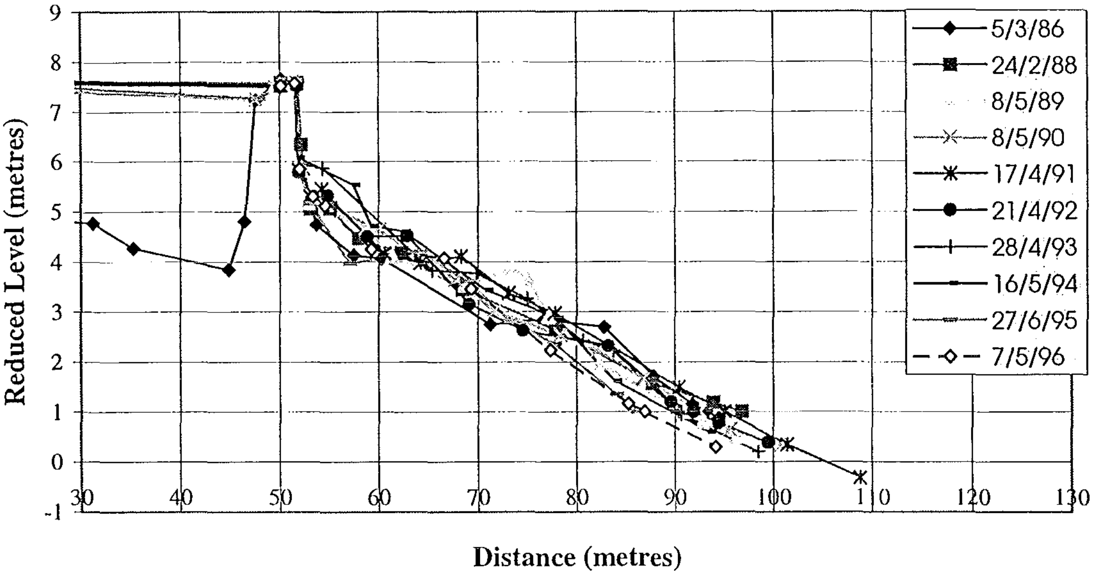

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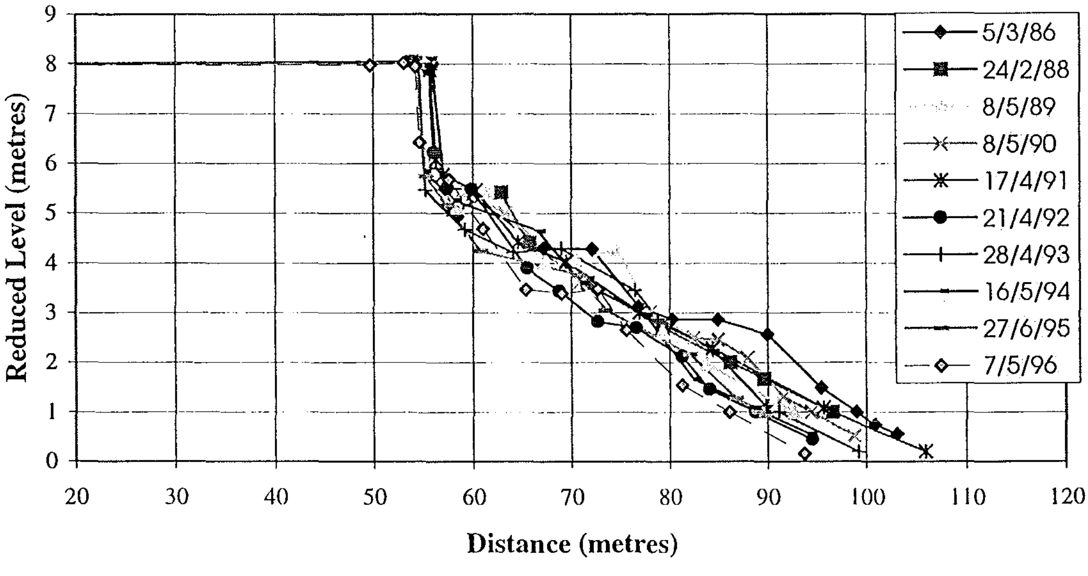

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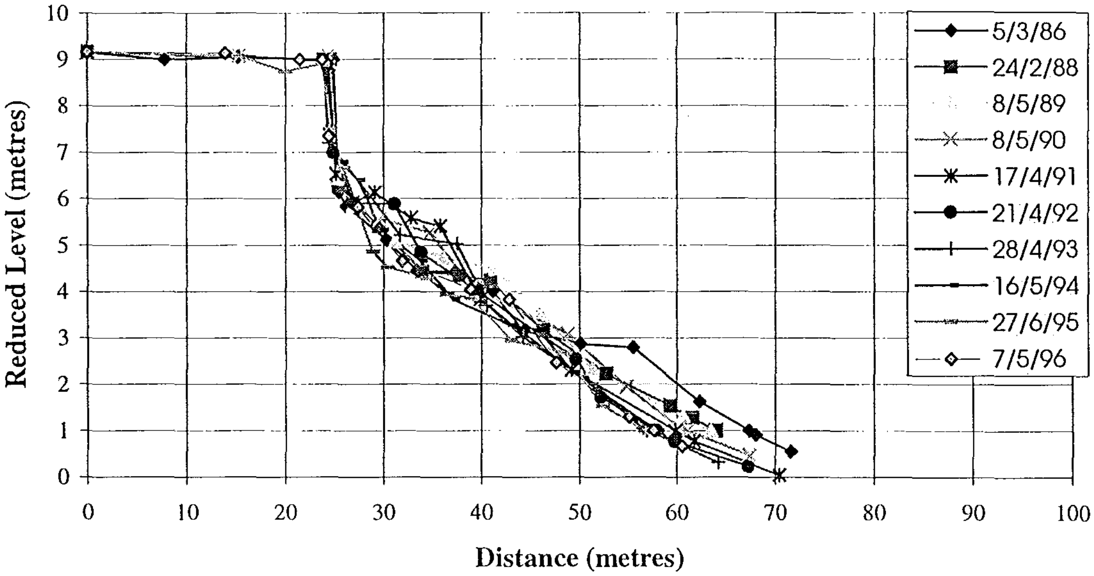

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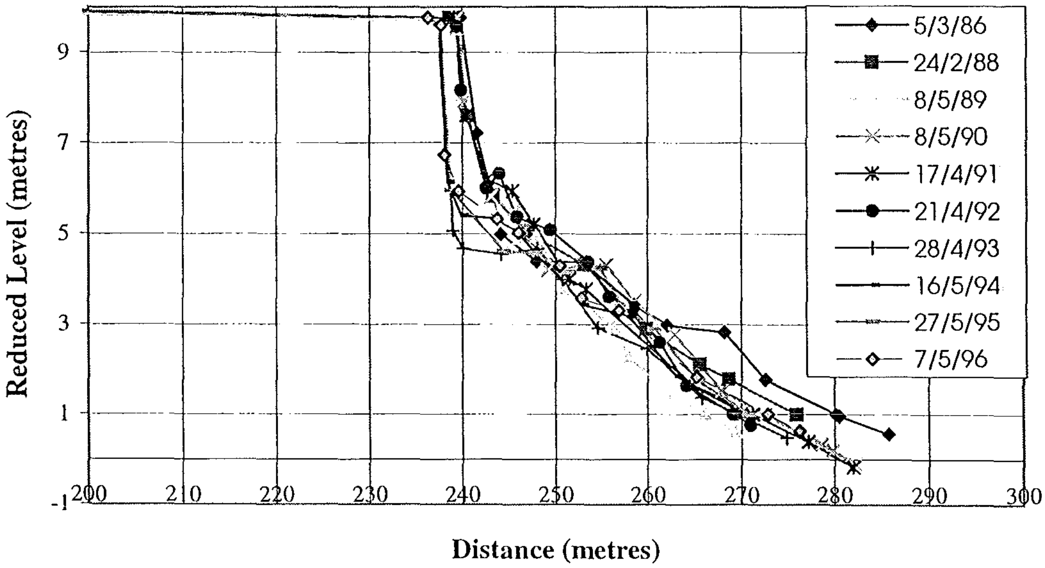
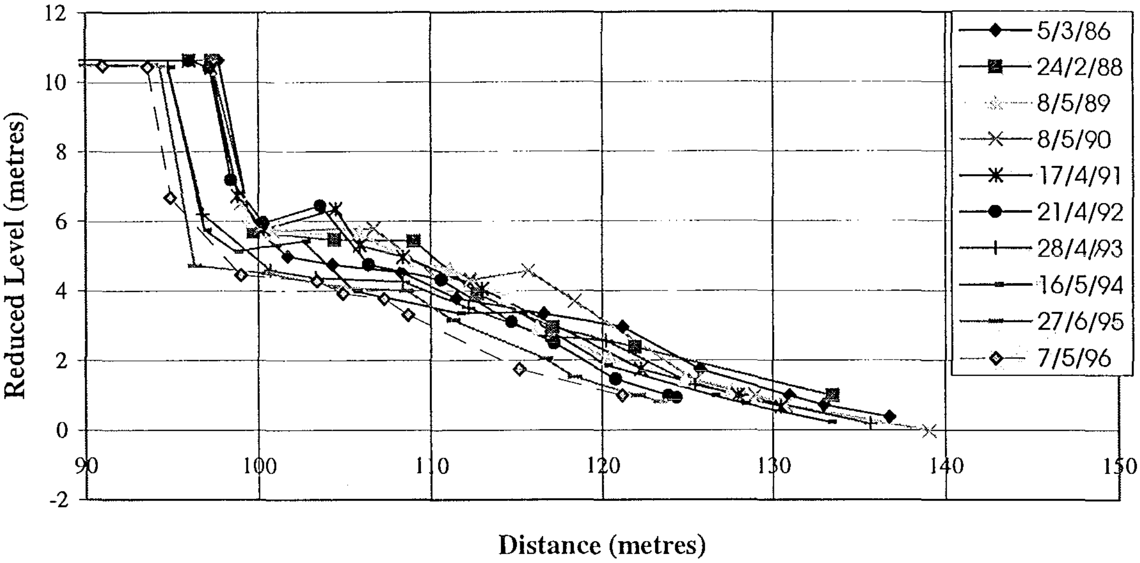


RANG21.23



RANG18.30