WEST COAST REGIONAL COUNCIL: NATURAL HAZARDS REVIEW

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CONTENTS

EXECUTIVE SUMMARY

The aims of this report, prepared for the WCRC, are to summarise current natural hazard literature relevant to the region, identify gaps in hazard knowledge and information, and provide a comprehensive reference list. Specifically examined hazards were:

1) River flooding and aggradation hazards.
2) Landslides and landslide dam hazards.
3) Coastal hazards (stability, storm surge, tsunami, sea level rise).
4) Earthquakes hazards (ground shaking, surface rupture, liquefaction, seiches).
5) Climatic hazards (strong wind, tornadoes, hail, snow, ice, droughts, wildfires).

Each hazard was discussed in terms of causes, effects magnitude, frequency, and a literature review. Hazard awareness and information flows were also examined.

The main findings of the report are:

- The West Coast Region is affected by all natural hazards except active volcanism (discounting the remote possibility of ash fallout from a North Island event).

- The hazards result from the region's position across an actively deforming plate boundary, which controls the very steep, unstable topography and the extreme climatic conditions. The distinct nature of the physical features combine to make the West Coast region unique in New Zealand (and probably the world) in terms of hazard monitoring, data collection, planning and management.

- Natural hazards in the region are not usually mutually exclusive, and often more than one hazard occurs during significant events.

- River floods are the most frequent hazard and have caused the most damage. This is due to all the region's main settlements being located on very active flood plains. All have suffered to some extent in historical times.

- Earthquakes (especially those associated with the Alpine Fault) have the potential to cause the most severe damage during a single event.

- Research for this report has identified rainfall induced landslides as a major, frequent occurring hazard. The most common damage has been to transport routes throughout the region.

- River flooding, landslides, earthquakes, snow avalanches, lightning strike and hail have all been recorded as causing loss of life in the region. River flooding has probably caused the most deaths, followed by landslides.

- River flooding/aggradation, coastal stability, earthquakes and landslides (earthquake generated) have been the most researched of the region's hazards, although many knowledge/information gaps still exist and much of the existing information requires updating. Very little is known about the other hazards in the region.

- Given the WCRC's limited resources, acceptable ways of encouraging financial support need to be identified, so as the WCRC can effectively and efficiently carry out it's statutory obligations in relation to natural hazard and emergency planning.

The recommended top ten priority tasks for future information collection on natural hazards were:

1. Waiho River Aggradation Monitoring.
2. Liquefaction Mapping & Identification of lifelines affected by liquefaction.
3. Rainfall Forecasting & Flood Probability Mapping.
4. Rainfall Monitoring. Especially South Westland high altitude sites.
5. Landslide Inventory. Develop the inventory started in this report.
6. Coastal Database. Collect coastal erosion & accretion rates for further analysis.
7. Historical Flood Mapping. Update existing maps. Cover catchments not yet mapped.
8. Coastal Wave/Sea Level Data. From NIWA, observations and published reports.
9. Landslide Mapping. Basic; based on WCRC inventory and GNS database.
10. Worst Case Scenario Floods. For the major catchments and areas of concentrated population /assets.

Other report recommendations included:

- The WCRC and other authorities in the region with responsibilities in natural hazard and emergency planning and management, use this document as a basis for developing and improving service delivery, information gathering, and monitoring techniques.

- The WCRC should keep abreast of national and international developments regarding natural hazard planning, management and monitoring techniques.

- The hazard inventory databases developed in this report and other WCRC reports, should be updated as new information becomes available, or after the occurrence of significant events.

- The information priorities identified in Chapter 8, should be reviewed after 5 years, or after the occurrence of significant events.

- The WCRC should pool resources with other relevant organisations in regards to natural hazard research and information collection. This would eliminate duplication of effort, and spread the financial and logistical resources involved.

1.0 INTRODUCTION

1.1 Background

This report presents a general overview of natural hazards in the West Coast Region (Figure 1.). It has been prepared under contract by DTec Consulting Ltd (DTec), Christchurch, for the West Coast Regional Council, Greymouth (WCRC).

Historically, the West Coast has been subjected to a variety of natural hazards. The main hazards in terms of damage caused, include river flooding, landslides, coastal erosion and sea flooding (storm surge), earthquakes, and several climatic hazards such as lightning strikes, strong winds, tornadoes and natural fire outbreaks. Other hazards include drought, snow, hail, ice, and avalanches. More remote hazards include volcanic ash fallout from a North Island eruption, and epidemic disease outbreaks.

Due to their frequency and prominence, flooding, earthquakes, earthquake induced landslides, coastal erosion and sea flooding hazards have been the most researched and documented of all the hazards mentioned. Very little information exists for the other hazards, although climatological hazards such as strong winds and lightning strikes regularly cause extensive damage, and tsunamis have the potential to do the same along the coastal fringe of the whole the region. Virtually no information exists for the remote hazard of volcanic ash fallout, hence this hazard is not discussed in the report. The hazard of epidemic disease outbreaks is also not discussed in the report, as it was considered to be outside the project brief.

1.2 WCRC Natural Hazards Projects

The WCRC has legislative responsibilities and obligations under the RMA 1991 to gather and provide natural hazard information, and to avoid or mitigate the effects of natural hazards. How the council is to undertake these responsibilities is set out in the WCRC's Regional Monitoring Strategy (1998) and Regional Policy Statement (2000). The council also has responsibilities and obligations towards natural hazards under the Civil Defence Act 1983, and the its proposed replacement, the Emergency Management and Civil Defence Bill. All of these legislative responsibilities are discussed in detail in the WCRC Natural Hazard Identification and Emergency Management Strategic Directions 2001-2003 (Rouse 2001).

In fulfilling these responsibilities, the WCRC commenced a series of hazard research and mapping projects in the early 1990s. These projects included flood hazard maps and reports for the major river catchments, reviews of earthquake events, coastal hazards, and anthropogenic hazards including dam failures and potentially contaminated sites. In the late 1990s the WCRC commissioned, or assisted in several hazard projects including a hazard assessment for Franz Josef Glacier (McSaveney and Davies 1998), palaeo-tsunami investigations (Goff *et al*. 2000), hazard information flows between the WCRC and outside organisations (Burney 2001), and flood probability models for Westport (Connell Wagner Ltd, 2000) and Greymouth (Connell 2001).

In 2001, the report on strategic directions for natural hazard identification and emergency management (Rouse 2001) identified seven initiatives on natural hazard identification research. The most relevant to this report were:

Initiative 1:
The West Coast Regional Council will carry out a literature review of existing work of natural hazards on the West Coast.

Initiative 2:
The West Coast Regional Council will conduct a survey of District Councils in the Region to access how hazards information is currently transferred and how this process could be improved.

Initiative 4:
The West Coast Regional Council will work with the three District Councils within the West Coast Region and the West Coast Lifelines Group to identify gaps in hazards research and prioritise new research initiatives.

Initiative 5:
The West Coast Regional Council will conduct basic risk analysis for major hazards including: earthquakes, flooding, slope stability, coastal erosion, tsunami and extremes of weather.

1.3 Project Brief

The project brief stated that the aims of this natural hazards review were to:
Summarise hazards research that has been carried out which is relevant to the West Coast;
Identify gaps in hazards research; and
Make recommendations for future work research based on Regional council needs for hazard management.

Hence the objective of the project are to meet Initiatives 1 (literature review), and Initiative 4 (identifying and prioritising gaps in hazard research), as described in Rouse (2001).

The project brief contained the following statement about the desired output from the study.

"As it is possible that this document will need to be updated in the future as new information becomes available, the review could be produced as a loose-leaf folder with index and room for add-in chapters, or for chapter updates. A simple structure of a chapter per hazard, a chapter identifying gaps in hazard research, and a chapter of recommendations is envisaged. A comprehensive reference list is vital…"

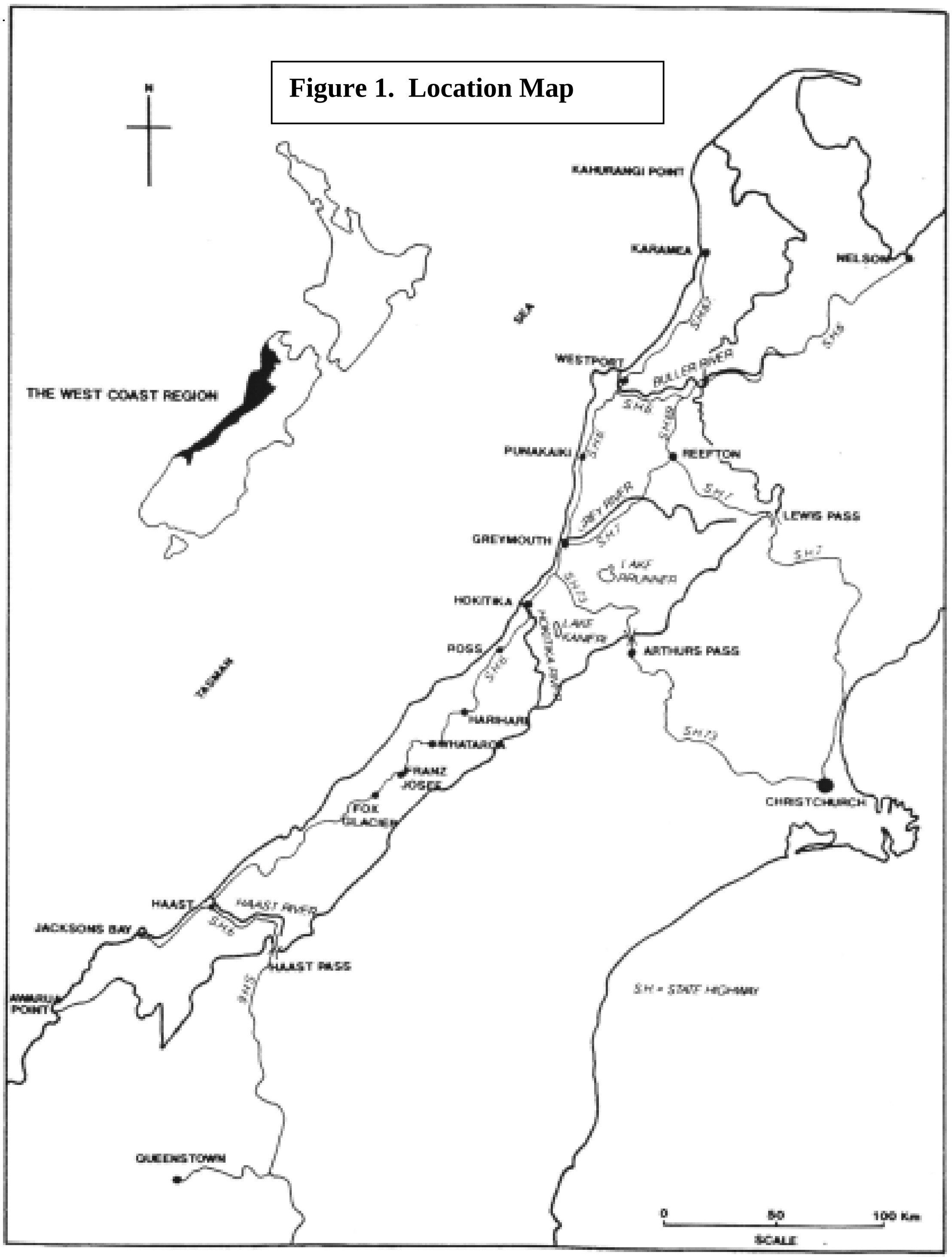


Figure 1. Location Map

1.4 Project Team

DTec undertook the project work during April – June 2002. The report was researched and co-authored by:

John Benn (sub-contactor for DTec): Has previously compiled a number of hazard reports for the WCRC (and other organisations), covering a variety of natural and anthropogenic hazards.

Derek Todd (Principle Director, DTec Ltd): Specialist in coastal processes and hazards, and resource management.

Dr Ian Owens (Associate Professor, Geography Department, University of Canterbury): Specialist in alpine research, avalanche hazards, and climate research.

1.5 References

BURNEY, T. (2001): Information Transfer for Management of Natural Hazards: case Study of Earthquake Hazard Information and Management Within the West Coast Regional Council and between the Grey District Council. M.App. Sci. (Enviro. Man.) Dissertation, Lincoln University, Lincoln. 50p.

CONNELL, R.J. 2001: Grey River – Greymouth: Hydraulic Review of Flood Capacity. Report Prepared for the West Coast Regional Council (Greymouth) by CH Modelling Ltd, (Christchurch). 41p.

CONNELL WAGNER LTD. 2000: Preliminary Flood Study of the Buller River at Westport. Report Prepared for the W.C.R.C., August 2000, by Connell Wagner Ltd, Wellington. 19p plus Appendices.

GOFF, JR., NICHOL, S.L, & CHAGUÉ-GOFF, C: 2001: Evidence for Catastrophic Inundation of the West Coast: Okarito Lagoon. Report prepared for The West Coast Regional Council, Greymouth. 34p.

McSAVENEY, M.J. & DAVIES, T. R. H. 1998: Natural Hazard Assessment for the Township of Franz Josef Glacier and its Environs. Report prepared for the West Coast Regional Council by the Institute of Geological and Nuclear Sciences Ltd (McSaveney), and Department of Natural Resources Engineering, Lincoln (Davies). Client Report 44714b.10. 52p.

ROUSE, H.L. 2001: Natural Hazard Identification and Emergency Management: Strategic Directions 2001-2003. WCRC Internal Report, Greymouth. 44p.

WEST COAST REGIONAL COUNCIL. 1998: West Coast Regional Council Regional Monitoring Strategy. WCRC Internal Report, Greymouth. 159p.

WEST COAST REGIONAL COUNCIL. 2000: West Coast Regional Council Regional Policy Statement. WCRC Internal Report, Greymouth.. 147p.

2.0 FLOODING AND RIVERBED AGGRADATION

2.1 Introduction

Floods are by far the most common natural hazard on the West Coast, and occur across the length and breadth of the region. Benn (1990) recorded details of 405 flood events occurring between 1846 and March 1990. Research for this report has added details of a further 69 events between April 1990 and June 2002. The high frequency of floods is not surprising given that in terms of mean annual rainfall, the region is officially one of the wettest places on earth, and unofficially *the wettest*. (Mosley and Pearson 1997). Floods can be generated in a number of other ways besides direct rainfall, and as there is no defined seasonal trend of occurrence, floods occur at any time of the year.

From the earliest known recorded flood event by Thomas Brunner in 1846 (in Brailsford 1984) to the present day, floods have regularly caused inconvenience, and extensive damage in economic, physical and social terms. Floods have also probably caused more loss of life than any other hazard, although establishing the exact number of deaths is difficult due to old reports being vague (especially those up to the early 1900s). In discussing West Coast rivers and flooding, Lord (1928) stated: *"…the rivers, as will be shown, claimed many victims, so many that drowning became known as the 'national death'"*

Given their frequency, and that the region's major settlements are on very active floodplains (eg Greymouth Westport, Hokitika, Karamea, Reefton, Franz Josef Glacier), floods maintain a higher public profile than other hazards. This is particularly true since the disastrous floods of May and September 1988 that devastated Greymouth and many surrounding rural areas, and the potential flood threat at Franz Josef Glacier with recent aggradation changes in the Waiho River. As a result much of the recent flood information relates to these two areas, although flood hazard research has also been extended in other areas of the region.

Included in this chapter are:

- An outline of the causes of flooding and aggradation.
- A summary of flood/aggradation frequency and effects.
- A summary of the major relevant literature.
- An identification of the gaps in local flood knowledge and how these may be filled.

Appendix 1, contained on a disc at the back of the report, contains flood event information from April 1990 to March 2002. This updates the information presented in Benn (1990). Figure 1 (Chapter 1) identifies most of the sites referred to in this chapter.

2.2 Causes of Flooding

Although rainfall is ultimately responsible for flooding in most cases, several distinct mechanisms of flooding can be identified. These are described in the following sub-sections.

2.2.1 Rainfall – Runoff

Moist westerly airflows travelling across vast tracts of ocean condense upon meeting and ascending over the Southern Alps. The resultant orographic rainfall can lead to extreme precipitation in terms of both intensity and duration. This combined with steep topography and short steep river catchments, leads to very rapid runoff of surface water (Griffiths and McSaveney 1983a), and is the principle cause of flooding in the region.

Mosley and Pearson (1997) described the synoptic conditions leading to heavy rain as:

"Heavy rains tend to be associated with slow, eastward moving frontal zones embedded in west or nor west airstreams, where a slow moving anticyclone lies to the north or northeast of the North Island, with a deep depression moving eastwards to the south of the Tasman Sea, and a strong northwest airstream moving ahead of it".

Some of the historically recorded rainfall figures presented are astounding. For example:

- In March 1982 at Alex's Knob near Franz Josef, it was estimated that 1810mm (nearly 6ft) of rain fell in three days (Henderson 1993). This estimate was based on the consistency of rain as officially 650mm was recorded for the 3 days, but rain gauges overflowed or were washed out long before it stopped raining (Benn 1990).
- At Franz Josef Glacier township, storms producing 200mm in 24hrs occur about once a year, and storms producing over 600mm in three days occur every few years (McSaveney and Davies 1998).
- A localised downpour near Lake Kaniere on 21 March 1981 produced 135mm (5.31 inches) in one and a half hours (Benn 1990).
- Otira and South Westland bear the brunt of many storms, and they often receive well in excess of 300mm in 12-24 hour periods (Benn 1990).
- Cropp River Basin, 5-6 October 1993. 800mm in a day (Greymouth Evening Star 6/10/93)
- The maximum daily rainfall recorded at Otira was 413mm and this had a return period of 1 in 100 years (1% chance in any given year) (Whitehouse & Williman 1986).

Annual rainfall figures are equally impressive. For much of the alpine main divide region, Tomlinson (1980) indicated annual rainfall at >8m/yr., and for coastal areas such as Greymouth, around 2.5m/yr. Even more impressive are figures for the Cropp River Basin in the upper Hokitika River Catchment. Griffiths and McSaveney (1983a,b) found the upper Cropp River basin averaged 11.315mm/yr, and the Remarkable Site =11.884mm/yr. Sections of the Southern Alps were estimated to receive between 12 and 15m/yr. It was noted by Mosley and Pearson (1997) that the Guinness Book of Records claims that Mawsynram in India, is the wettest place on earth, with an average annual rainfall of 11.87m/yr. They go on to state: *"Sections of the Southern Alps receive an estimated 12 to 15 metres of rain per year …but cannot claim the record because the alpine gauges are not part of an official weather station".*

Flood hydrographs and field observations (WCRC 1948-2002, Griffiths and McSaveney 1983b, Lowe 1988), and historical accounts (Cowie 1957, Benn 1990), show that all rivers can rise to very high levels extremely rapidly during high intensity rainfall events.

2.2.2 Riverbed Aggradation

Aggradation occurs when the volume of sediment introduced to a channel is more than the flow can remove. Sediment is therefore deposited into the channel. Most aggradation occurs at the head of an active fan, where a river/stream leaves the confines of a narrow valley, and spreads out over the fan., and where changes occur in the channel bed gradient. As the river flows further down the fan, the depth of flow and velocity decreases, leading to sediment deposition. This causes two main problems:

1. As the riverbed rises, the freeboard to the banks is reduced, leading to a corresponding increase in flood risk, as less discharge is needed to overflow the banks.
2. If so much sediment is deposited in a channel, the river may create a new channel or divert to an old channel to bypass the sediment slug.

The technical term for this second process is avulsion, but it is more commonly called a breakout. This process is one of the major hazards threatening Franz Josef at the present time (McSaveney and Davies 1998, Davies 1999, Hall 2000), and SH73 between Jackson's and the Otira Gorge (Whitehouse 1986, Whitehouse and McSaveney 1986, Whitehouse and Williman 1986, Paterson 1996).

Sediment injections into a river causing aggradation originate from landslides (all types e.g. debris flows, rock avalanches etc), bank collapses, and glacial input, and can range from small to huge volumes. Depending on how the sediment is introduced to the river system, downstream aggradation can be gradual (e.g. sediment introduced by riverbank erosion) or extremely rapid (e.g. sediment introduced by landslides). Sediment injections occur at irregular intervals forming sediment pulses or slugs that are moved through the system entirely by river flow. Smaller sediment slugs may be washed away in the next flood, whilst larger ones may need many large floods to disperse them (McSavaney and Davies 1998).

2.2.3 Backwater Effects (Back-Up)

River levels can be increased upon meeting an obstruction that restricts the flow, and creates a backwater effect. Such obstacles can include high tide/rough seas, river confluences, landslip dams, in-channel sediment slugs, culverts, and bridges. In Greymouth, river back up against high tides/rough seas has been attributed to increasing the level of several historic floods in the town (Cowie 1957, Benn 1990, Carson 1990, Benn, in prep). Connell (2001) found from hydraulic models, that maximum flood levels are almost always associated with maximum tide levels (see Section 2.5.6.).

Historical evidence also shows that when river levels are high, the major rivers can back up when entering narrow gorges: Tributary channels can also back up upon meeting a major channel that is in high flow. In both of these situations, considerable areas of farmland upstream of the gorge or tributary stream can be flooded. Information on the WCRC's flood hazard maps show this to be common at places like Walker's Flat, just upstream of the Buller Gorge, where the Buller River (when above normal level) backs up upon meeting the gorge and floods the flat. When the Grey River is high, Stillwater Creek backs up against it and floods adjacent farmland and SH7. In fact, it was the regular occurrence of this phenomenon in pioneering times that lead to the place becoming known as Stillwater.

Rivers can also flood when a landslide blocks the channel, creating a dam. Flooding occurs upstream of the dam as a lake forms, and down stream when the dam breaches. This is discussed in more detail in the following chapter dealing with landslides.

Numerous instances of backup water flooding roads and paddocks in rural areas have been recorded when small diameter culverts have become blocked with a variety of debris.

2.2.4 Local Surface Impoundment (Ponding)

Localised intense showers commonly cause surface flooding. This can be due to storm water systems in towns, and culverts in rural areas, being unable to cope with rapid inflow (either due to design or blockages with debris). Ponding also occurs when the ground is already saturated and water table levels are high, restricting subterranean drainage. Ponding may also occur where obstacles such as stopbanks impede return flow to a channel. This is one of the main reasons why pumping stations have been included in the Greymouth Flood Protection Scheme since it was built.

2.2.5 Back Up Through Urban Stormwater/Sewage Systems

High river flow levels may impede the drainage of stormwater/sewage flows, causing back up in the systems and subsequent surface flooding of streets. In the past this has been a particular problem in Greymouth, and to a lesser extent Hokitika, Franz Josef and Karamea. To help mitigate the problem, automatic floodgates are installed on the stormwater outfalls at these locations and pumps are used when necessary, at Greymouth and Hokitika (Mike Shearer, WCRC, pers.comm.).

2.2.6 River Mouth Blockages By Beach Sediments

Backwater flooding can occur when rough seas deposit beach sediment across river mouths, or ironically by lack of rainfall, leading normal coastal processes becoming dominant over low river flows. This process was responsible for major flooding in Hokitika in 1947 (Cowie 1957, Benn 1990), and has occurred on numerous occasions at many of the smaller river mouths such as Saltwater Creek (near Paroa, Appendix 1), Okarito (Westland Catchment Board 1986, Benn 1990) and Punakaiki/Pororari River (Kirk 1988, Benn 1990).

Little is known about river mouth dynamics on the West Coast. This phenomenon is discussed in more detail in the Coastal Hazards chapter.

2.2.7 Snowmelt

Although attributed to being the cause of numerous floods, and adding to already high river levels in many cases (Cowie 1957, Benn 1990), very little quantitative data exists on the contribution of snow melt to floods. Mel Sutherland (GDC, pers.comm.) considered that the relationship between snowmelt and river discharge and levels needed investigating.

2.2.8 Jokullhlaup (Glacier Burst)

This process caused by temporary blockages or changes in sub-glacial drainage system leads to a pressure increase at the terminal ice face. This can cause the ice to collapse and create rapid floods and massive rapid aggradation. The exact processes are little understood. Resultant floods inevitably contain huge quantities of ice and sediment. Ice blocks can be huge and boulders extremely large. The term Jokullhlaup is Icelandic, but such events are commonly called Glacier Bursts.

At least five glacier bursts have been recorded on the Franz Joseph Glacier, and they pose a real threat to Franz Josef township and the Waiho Valley in general. As glacier bursts are a relatively rare phenomenon on the West Coast, it is considered that the accounts of these events, recorded in Sara (1968), Marcus *et al*. (1985), Benn (1990), and McSaveney and Davies (1998), are worth presenting in Appendix 2 (on computer disc in the back of the report), to emphasise the magnitude of these hazards. The account of Marcus *et al*. (1985) is particularly interesting as it was actually observed and measured as it occurred.

2.2.9 Seiches

Landslides of terrestrial or submarine origin, fault ruptures disturbing the water body, or intense ground shaking can form large seiches on lakes. Seiches can cause general flooding and structural damage, and both have been recorded on the West Coast. This is discussed in the earthquakes chapter.

2.2.10 Tsunami and Storm Surge

Both have been recorded in the region and are discussed in the coastal hazards chapter.

2.2.11 Artificial Dam Failure

Many artificial dams are scattered throughout the region and some are of considerable size, containing large reservoirs. A number of these have failed in the past causing considerable damage. However this is classed as an anthropogenic hazard by the WCRC and thus it is not referred to further in this report. This type of hazard has been covered previously by the WCRC, in a report by Benn (1995a).

2.3 Effects of Flooding

As stated at the beginning of this chapter, floods have probably killed more people on the West Coast than any other natural hazard. There are also a number of other significant effects on the West Coast communities.

2.3.1 Rural Effects

The most obvious effect of river flooding is direct inundation from rivers overflowing their banks. This is most commonly seen in rural areas where stretches of river have little or no protection works along their banks. In most cases little damage is done, besides a short period of inconvenience. Conversely, in rarer larger magnitude events, river bank erosion, scouring, deposition of thick silt/debris, and high flow velocities and depths can cause serious damage (and destruction) to pastures (e.g. be put out of production for long periods or destroyed), fences, farm buildings/houses, and equipment. Floods also take their toll on farm animals – many get washed away and/or drowned, or get trapped on islands where they are unable to be fed or get milked.

Many of the region's community rubbish dumps and septic tank discharge sites are located in flood hazard zones (Benn 1995b), and this can lead to visual pollution and contamination of the ground water and river channels as rubbish and septic tank discharge is scattered during flood events.

Aggradation effects are closely related to flooding but can be more long term (e.g. floodwaters drain away in a few hours or days – sediment deposited by aggrading streams stays until something removes it (heavy machinery, subsequent floods, dredging, gravel extraction). A good recent example is this is the McKenzie farm on the banks of the Poerua River, where floods and thick debris deposition originating from the Mt Adams Landslide, has destroyed 80% of the farm (The Press 13/04/02).

2.3.2 Urban Effects

In the urban centres, direct inundation can be more devastating due to the concentration of people and assets. This is demonstrated in the numerous cases of severe flooding in Greymouth, culminating in the May and September 1988 floods, where millions of dollars of damage occurred. Effects of the 1988 floods in Greymouth included:

- Isolation of Greymouth due to flooded roads in and out of the town.
- Structural damage to homes and businesses, streets, rail tracks.
- Damage to business stock and personal property/possessions.
- Mass evacuation of people.
- Contamination of the town water supply.
- Sewage back-up in the streets.
- Permanent closure of some businesses.
- Numerous homes permanently condemned and subsequently demolished.
- Large financial losses (insurance companies refusing flood cover).
- General social disruption to the town for weeks after each flood (e.g shops and services such as banks closed, structural repairs of streets and buildings, residents having to boil drinking/washing waster etc).

It is worth noting that the Greymouth Flood Protection Scheme is designed to contain around 8 500m^3s^{-1} before overtopping of the stopbanks occurs. For comparison, a one in a hundred year flood for the Grey River, is calculated at 7 082m^3s^{-1} (Bowis & Faulkner 2000). It is considered likely that a flood of greater magnitude than this will occur at some future date. Rob Daniel (WDC, pers.comm.) noted that little had been done in Greymouth to prepare for a super-design flood.

Westport has a unique potential flood threat, as the town is surrounded by two river channels (Buller and the Orowaiti), and the sea. If flood levels are high enough to flow down the Orowaiti overflow channel, Westport effectively becomes an island, making access difficult (if the low lying roads nearby are flooded as well, or bridges are damaged).

Major aggradation in the Waiho River has the potential to cause the river to break out of its current channel and create a new course, probably down the Tatare River. Such a break out directly threatens residents on the south bank of the river, and millions of dollars of assets including SH6 (and bridge), the holiday park, and sewage oxidation ponds. If aggradation does continue and the Waiho River changes course, mass relocation of people, houses and assets may be the only feasible solution to avoid or mitigate the hazard.

2.3.3 Transport and Communication Effects

Floodwaters and aggradation can isolate communities from one another when transport and communication links get inundated/buried. Road and rail links are frequently cut by direct inundation and streambed aggradation, and power and telecommunication links get damaged frequently, by poles being washed away (Cowie, 1957, Benn 1990, Appendix 1). The whole West Coast Region can become isolated when the three alpine road passes are closed, and rail and communication links are cut. Westport and Greymouth airfields are prone to direct flooding although the risk has been reduced at Greymouth, with the Greymouth Flood Protection Scheme.

Rapid aggradation of steep mountain streams regularly causes damage to State Highways, district roads and rail links, by causing streams to breakout of their channels and bury the transport links.

At river mouths, aggradation can be a hazard to shipping, for example the river port of Westport needs regular dredging at considerable expense. To control aggradation at the Buller River Mouth, Buller Port Services have dredged a total of 2 242 875m^3 since 1991, at an annual average rate of 320 410m^3/yr (annual figures from Connell Wagner Ltd 2000). A large flood on the 2nd January 1868 provides possibly the earliest account of aggradation and avulsion being directly responsible for damage. The West Coast Times (06/01/1868 *in* Benn 1990), reported that on the south side of the river at Westport, a large shingle bank was 'thrown up', partially filling the channel formed by the islands: consequently the river changed course, flowed to the north, and washed away the bank south of the bonded stores, and wharves on this side were also destroyed.

The Karamea harbour/wharf became operationally redundant after the 1929 Murchison Earthquake partly due to structural damage, but mainly because of the harbour basin aggrading from earthquake debris (KDSCC 1975).

2.4 Magnitude and Frequency of Events

Establishing the relationship between flood magnitude and frequency reliably for the West Coast is difficult as the hydrological records are short and in many case non existent. River level recorders are only present on the major rivers, being established on the Karamea in 1978, the Buller in 1963, the Grey in 1968, the Hokitika in 1975, the Poerua in 1982, the Waiho (SH6 bridge) in 2000, and the Haast in 1973 (Bowis & Faulkner, 2000).

Determining the magnitude of flood and aggradation events is relative straight forward compared to determining the frequency. For magnitude, direct quantifiable, physical measurements can be made, whereas frequency determination is usually based on averaging known historical/pre-historical events over a certain time period, or by using predictive numerical models to estimate future events. Both methods have inherent flaws.

2.4.1 Flood Magnitude and Frequency

From all sources of flooding, Benn (1990) recorded details of 405 West Coast flood events occurring between February 1846 and March 1990. Research for this report has added details of a further 69 events between April 1990 and March 2002. This makes a total of at least 471 events over a 156 year period. In simple terms, this implies that flood damage/disruption occurs on average three times per year in the West Coast region.

Table 1 shows the maximum-recorded discharges at some of the major rivers in the region.

Table 1. Maximum Recorded Discharges for Major Rivers (Bowis & Faulkner 2000)

River	Date	Max. Discharge (m^3s^{-1})
Karamea	19/10/98	3 166
Buller	25-26/05/50	12 460
Grey	16/12/97	5 951
Hokitika	09/01/94	2 447
Whataroa	09/01/94	3 952
Haast	12/05/78	6 330

Note: Buller figure from Cowie (1957), Benn (1990).

As far as is known the May 1950 discharge for the Buller of 12 460m^3s^{-1} remains the largest *recorded* flood discharge in New Zealand. This recording was based on gaugings and cross section analysis at Berlin's swing bridge. However, the 1926 flood in the Buller River is presumed to have had a discharge significantly greater than this, based on known flood levels (Cowie 1957).

Fauth (1988b) presented Grey River flood magnitude/return periods for the September 1988 event (5 768m^3s^{-1} at Dobson) and assigned a 121+ year return period for the event. However this appears to have been based on the historical fact that the September event was the largest recorded in Greymouth to that date. More creditable calculations of discharges at certain return periods for a number of rivers were presented by Bowis & Faulkner (2000), and are shown in Table 2.

Table 2. Calculated Flood Discharges and Return Periods (Bowis & Faulkner 2000)						
Return Period (Years)	**Karamea (Gorge)**	**Buller (Te Kuha)**	**Grey (Dobson)**	**Whataroa (SHB)**	**Hokitika (Colliers)**	**Haast (Roaring Billy)**
	Discharge (m^3s^{-1})					
1	2 042	4 894	3 827	2 822	1 749	3 720
5	2 488	5 963	4 573	3 403	1 930	4 632
10	2 852	6 833	5 180	3 876	2 077	5 374
20	3 200	7 668	5 763	4 330	2 218	6 066
50	3 652	8 749	6 517	4 918	2 401	7 007
100	3 990	9 559	7 082	5 358	2 538	7 698

Return periods calculated by Connell Wagner Ltd (2000) for the Buller River are shown in Table 3, and generally agree with the figures in Table 2, although the 1988 discharge should be assigned as at least >20 years.

Table 3. Buller River Discharge Return Periods at Te Kuha (Connell Wagner 2000)		
Date	**Discharge (m^3s^{-1})**	**Return Period (Years)**
21/10/83	6 838	>10
20/05/88	7 778	>10
13/06/93 (?)	7 800	>20

Note: Discharges and dates from Benn (1990), and GES 13/06/93, return periods from Connell Wagner. Connell Wagner only specified the year: dates and discharges in Table 3 are assumed to correlate to Connell Wagner return periods of the floods they discuss.

Having more accurate flood return periods and levels, and being able to plot such data on flood probability maps is the most recognised gap in hazard information in the region (see district council responses in Chapter 7).

2.4.2 Aggradation Magnitude and Frequency

Besides predicting basic trends of aggradation and degradation phases, predicting the magnitude and frequency of such processes with any certainty is effectively impossible. This is due to the large number of variables involved, which themselves are hard enough to predict (e.g. extreme rainfalls, snowmelt, river discharges, landslide occurrence and magnitude, glacial behaviour etc).

Riverbed aggradation in the region in most cases is gradual, with a steady supply of sediment from bank erosion or other minor sources leading to a gradual rise in bed levels. This process was demonstrated for the Buller River below Te Kuha, where aggradation has been occurring since 1972 (Connell Wagner Ltd 2000). Fluctuations in this trend have occurred as floods periodically scour the channel.

In contrast, aggradation can also occur very rapidly (within minutes/hours) and be extreme in terms of bed level elevation changes, and sediment volumes involved. For example, during an intense rainstorm in December 1957, a landslide fell into the Otira River channel, aggrading the riverbed level between 6 and 8m, buried sections of the highway and diverted the river through the town causing serious damage (McSaveney 1982, Whitehouse 1986, Whitehouse and McSaveney 1986, 1989, Benn 1990). McSaveney (1982) also recorded aggradation of 3 to 4m in the Otira River bed during the December 1979 storm.

A similar event occurred in the Waitangitaona River in March 1967. After intense rain, debris from the Gaunt Creek landslip aggraded the Waitangitaona River bed, causing the river to divert from one side of its alluvial fan to the other. The river switched from its historical route to the sea to the north of Okarito Lagoon, to a more easterly direction, across SH6, via Lake Wahapo (6km away), Zalas Creek, Okarito River and Okarito Lagoon (Soons 1982, Griffiths and McSaveney 1986). The change in direction of the Waitangitaona River had the following effects (Soons 1982):

- Changed Lake Wahapo from a clear lake to a turbid lake.
- Killed a large stand of native forest by burying the tree root system.
- Increased stream flow leading to an increase in bank erosion down stream of Lake Wahapo.
- Increased stream flow may have been responsible for changes at the outlet of Okarito Lagoon.
- SH6 was blocked.

For small creeks in the Otira –Arthur's Pass section of SH73, Whitehouse and Williman (1986) stated that the principle hydrological factor affecting bridge design was aggradation, and noted that recent bridge renewals all had an allowance of around 3m for aggradation incorporated into their designs. Many sections of SH73 and bridges between Griffin's Creeks and Otira Gorge have been buried by rapidly aggrading creeks during rainstorms over the years (Cowie 1957, Benn 1990, Appendix 1). Rapid aggradation is also a common problem at creeks crossing SH6 between Harihari and Fox Glacier, Haast Pass, between Greymouth and Westport, and SH67 Granity-Ngakawau and the Karamea Bluffs.

The most spectacular aggradation in the region in both long and short-term has occurred in the Waiho River channel, at Franz Josef Glacier. When settled by Europeans the Waiho River was contained in a deep incised channel. This channel was so deep the settlement was originally called Waiho Gorge. In the last 140 years the river has aggraded so much it now threatens much of Franz Josef township by breaking out and flowing down into the Tatare River – something that it has never done in the past. Glacier bursts have been responsible for the greatest magnitude of aggradation recorded. Appendix 2 provides a detailed account of the aggradation that occurred in 1965 after a glacier burst: The river aggraded 9.1m (30ft) for a distance of 2km downstream of the terminal face. McSaveney and Davies (1998) considered short term aggradation of about 4m to be normal.

2.5 Flood Hazard Research

2.5.1 Technical Reports

During the 1980s storm rainfalls and runoff rates were studied, and a number of technical papers were produced by organisations such as The Ministry of Works and Development (e.g. Griffiths and McSaveney 1983a,b, Whitehouse and Williman 1986, etc) and the Forestry Research Centre (e.g. Lowe 1988). In relation to flood hazards, the main significance of Griffiths and McSaveney's reports was to highlight the high frequency of extreme rainfall events within the region, and the extremely rapid rates of runoff that lead to steep flood peaks and rapid flooding. Regular mass movements triggered by rainfall were found to be the main source of sediment supply to the rivers.

A series of papers assessing natural hazards and risk along SH73 between Jackson's and Arthur's Pass was produced by Whitehouse (1986), Whitehouse and McSaveney (1986, 1989), Whitehouse and Williman (1986), containing details of geology, geomorphology, hydology and climatic factors influencing a number of hazards, including flooding. These reports defined rainfall intensities, runoff rates, flood discharges and return periods for rivers and creeks along the section of highway, and described the implications of these in terms of bridge and road design (especially for the relocation of the Otira Gorge zig-zag).

Hawke (2001) researched the influence of precipitation and temperature induced glacier melt on flow discharges of the Waiho River, and found that both factors were very even, although precipitation was very slightly dominant. Hawke concluded:

"Precipitation is the general cause of major floods and of abrupt short term bed movements. Temperature produces moderate variations in stage levels, and is generally responsible for the base flow of the river…Identifying the causes of aggradation and degradation of the bed is important for the township's future safety from floods".

2.5.2 The Southern Alps Experiment (SALPEX)

This ongoing project, which commenced in 1993, is being undertaken by an international group of scientific organisations headed by NIWA. The project's aim to determine the influence of the Southern Alps on all aspects of local weather and climate. Wratt *et al*. (1996) discussed the experiment in detail and a summarised account is given in Wratt and Sinclair (1996).

Rainfall information in the experiment is based on data from series of historical rain gauges covering the lower half of the South Island, and a new series of rain gauges transecting the Southern Alps near Arthur's Pass, Hoikitika, Franz Josef Glacier and Haast. Complex computer and numerical models are also being used to predict rainfall under various airflow conditions and at sites where rain gauges are absent. Along with rainfall (and other climatic factors such as wind and cloud formation), snowfall intensities, durations, and snow ablation rates are also being considered in SALPEX.

The experiment will have beneficial implications in flood prediction for the West Coast, as better predictive models are developed from the data obtained. Wratt *et al*. (1996) stated that the experiment goals included:

"…understanding and quantifying factors that govern the intensity and spatial distribution of heavy rainfall, the west to east distribution of precipitation across the mountains…Linked research will explore the use of deterministic rainfall models to predict river flows from mountain watersheds".

2.5.3 Historical Records

Because of their frequency and the nuisance/damage they have caused, especially for early explorers, floods on the West Coast have been documented in numerous volumes about the local history of the West Coast (e.g. Lord 1928, Matthews 1957, Halket-Millar 1959, Jackson 1968, Hawker 1977 etc.), and they still receive detailed reporting in the local newspapers. From such information sources, and the little technical information available at the time, Cowie (1957) undertook the first detailed flood research for the region as a whole, compiling details of flood events between 1920 and 1953 accompanied by notes on earlier floods. In each event description, Cowie recorded wherever possible, details of the flood date, cause, duration, depths, discharges, velocities, and damage done. Comparisons of relative flood magnitude to earlier events were also made.

Many flood reports produced during the 1970s and 1980s were retrospective damage assessments relating to specific flood events. These reports were typical flood damage reports produced by the then Westland Catchment Board (WCB) (e.g. Clarke1978, Fauth 1998a,b), and disaster recovery reports produced by Civil Defence (e.g. Kerr 1998, Lovell 1991). Post flood event reporting between 1991 and the present has been mainly confined to WCRC monthly meeting papers, prepared by managers of the Operations, and Planning groups.

Initiated by the disastrous Greymouth floods of 1988, and the introduction of the RMA 1991, the WCB, and subsequently the WCRC, embarked on a series of flood hazard projects. The first report resulting from these projects was that of Benn (1990), which extended the work of Cowie (1957), to record similar details of flood events between 1846 and 1990. Using information from old newspapers, historical books, photographs, flood damage reports, technical reports, WCB/WCRC hydrological reports, and personal surveys, this report presented descriptions of 405 flood events, and technical appendices of maximum flood discharges, specific discharges, return periods, flood warning levels, and synoptic weather conditions leading to major flood events.

As a commemorative publication for the opening of the Greymouth Flood Protection Scheme, Carson (1990) produced a book on the history of flooding in Greymouth. As this book was prepared as a public interest document, it presents general descriptive accounts of major floods, and a good series of historical photographs. A similar, but more technical paper is currently being prepared by Benn, outlining 20 major historical floods in Greymouth between 1862-1988, providing details of the physical aspects of each event, and flood alleviation methods throughout the town's history.

2.5.4 Flood Hazard Mapping

Combining the information of Cowie (1957) and Benn (1990), with extensive fieldwork and personal survey information, the WCRC produced a series of flood hazard maps for the Grey, Buller, Hokitika, Karamea and Arahura catchments (Benn 1991a, 1991b, 1992, 1993 respectively). For the WCRC archives, field base maps were produced on 1:10 000 scale aerial photographs showing areas of inundation, with annotation on flow directions, depths, damage, relative frequency and damage descriptions. For the published reports, the areas of inundation were reproduced on 1: 50 000 scale topographic maps, overlain by transparent cadastral maps showing property boundaries.

These maps presented a quick, easy to understand, visual appraisal of areas known to be at risk from flooding. It is important to stress that these flood hazard maps were based on historical fact only, hence only showed areas that had been *known* to flood in the past. In no way were they intended to be flood probability maps or flood prediction maps. Therefore it recognised that for some areas, the flood hazard maps are not complete, as detailed historical records do not exist, or have not yet been located. This is especially true for Westport as is noted in Benn (1991b), and in Connell Wagner Ltd (2000). Despite their known shortcomings, the flood hazard maps are in regular use by planning and operation groups of the regional and district councils, and the general public. It was recommended in each hazard map report, that the maps be upgraded as soon as more historical information becomes available, or after flood events occur. To a large extent this has not been done.

2.5.5 Recent Buller District Flooding Investigations

Very recently, flood hazards in the Buller District have come under close investigation by Connell Wagner Ltd (2000) and Cooper (2000).

Connell Wagner Ltd (2000)

Commissioned by the WCRC, Connell Wagner Ltd (2000) completed a preliminary assessment of flood risk at Westport from the Buller River. Using historical flood information and data (discharges, level, river cross sections and long section data), and sediment inputs and outputs, a hydrological model (Mike 11) was used to identify flood extents in Westport and to determine what significance the Orowaiti Overflow Channel has on flood levels in Westport. Connell Wagner produced a page of conclusions highlighting flow paths at various river discharges, and assigned return period values to selected historical floods. The report was intended to be Stage 1 of a two stage project, with Stage 2 (yet to be commissioned) intended to produce Digital Terrain Model (DTM) flood hazard maps.

Although Connell Wagner used standard modelling techniques, some of their model inputs appear anomalous. For example:

- The August 1970 flood (referred to as '*the* 1970 flood' in their report) is ranked next in magnitude to the 1926 flood. However, as far as is known, the 1950 flood discharge of 12 460m^3s^{-1} in the Buller River is *still* the *largest recorded* in New Zealand's history, and by comparison the 1970 discharge was around 8 500m^3s^{-1} (Benn 1990, Connell Wagner 2000).
- For sediment inputs/outputs, it is stated by Connell Wagner (2000) that *"There are no records for the dredging* (Westport Harbour) *prior to 1991"*. This is not so, as reports dating back to at least 1892 exist, containing detailed information on specific areas of the Westport Harbour that were dredged, and the specific quantities of material that came out of those areas (AJHR 1892,1923-53, Furkert 1947).
- In 1970 two large floods and a small flood occurred in quick succession (Benn 1990). The August flood of 8 500m^3s^{-1}, was followed by another large flood on 17th September of 6 231m^3s^{-1} and a smaller event on 24th September of 4 038m^3s^{-1}. However, Connell Wagner (2000) only considered the August flood in their bed scouring assumption, and claimed, *"…an event of similar size will almost certainly have similar dredging effect on bed levels"*. A combination of scouring from the three

floods in quick succession is more likely to have been responsible for degrading the bed to the '1970' level mentioned in the report.

- It was considered likely by Connell Wagner that the August 1970 flood would have had the energy and duration to remove much of the 1968 Inangahua earthquake landslide debris from the river system. However, Johnston (1974) noted that since the 1970 flood(s) another large landslip blocked the Buller River in 1971 when heavy rainfall reactivated the massive slip produced by the 1968 Inangahua Earthquake.
- In determining long-term channel stability, Connell Wagner compared long section profiles from 1972 and 1999 and identified a trend towards medium to long-term aggradation, stating that the 1972 long section was the first recorded. However, long-sections dating from at least 1881 are available (e.g. AJHR 1881, 1904), and could have possibly been used to establish channel stability before 1972.

It is uncertain what significance, if any, these factors would have on the flood model results, but they are worth considering in any future flood modelling work. Notwithstanding the factors mentioned above, the Connell Wagner flood assessment is the most detailed so far undertaken for Westport, and thus provides useful indications of flow directions, depths and volumes for flood hazard planning in the Westport area.

Cooper (2000)

Flood hazards were included in Cooper's (2000) thesis investigation of all natural hazards in the Buller District. Flood hazards were classified using the HAZCLAS classification system, and along with additional information formed the basis of the flood hazard register in HAZREG. Information in HAZCLAS and HAZREG, and the accompanying hazards base maps were developed as a planning tool based on geotechnical and historical evidence. Cooper developed the hazard classification and register with the intent that it be expanded, and stated

"This set of base maps has been designed to cover all of the area within the WCRC boundary, including the Grey and Westland Districts, so that the HAZREG system can be extended to include them at a later date, providing a hazard management tool that is ideal for shared use by the regional and territorial authorities…

The applications of HAZREG for hazard and emergency management are extensive and include resource management, civil defence and emergency management planning and the selection of engineered hazard mitigation options. It is intended that the data collected during the course of this project be made available (through the WCRC) to the general public, allowing them to make informed development decisions".

Some confusion exists over the flood zones on Cooper's hazard maps. For example, the flood hazard zones for the Karamea area appear to have been taken straight from the WCRC flood hazard maps (Benn 1993), yet for much the Buller District, the appropriate hazard maps (Benn 1991b) showing historically flooded areas have not been included. As it stands, much of the Buller River Catchment known to have flooded historically (including significant areas such as Westport and Reefton, and much farmland) are not shown on Cooper's maps. Cooper used Punakaiki as a case study area to test the HazClass and HazReg system in an area subjected to multiple natural hazards. In a peer review for the Buller District Council, McCahon (2001, in McCahon and Yetton 2001) also expressed uncertainties about Cooper's flood zone for the Pororari River mouth. McCahon's main concerns were that Cooper presented no basis for the flood zone boundary, there was no indication given as to what probability (or history) of flooding the zone represented, and that the flood zone was likely to be too extensive for events of a 50 year return period, but may be too small for an extreme coastal flood event of low probability.

Todd (2002)
Todd (2002) assessed the storm surge and tsunami inundation hazards of the Pororari-Punakaiki area for the Buller District Council (see coastal chapter).

2.5.6 Recent Greymouth-Kaiata Flooding Investigations

Connell (2001) developed a flood model of the lower Grey River for the WCRC, examining various aspects of the flood protection works design, performance and effects. Connell stated that the modelling was:

"…undertaken to ascertain the stopbank heights on the Grey River below the Cobden Bridge to contain the original scheme design discharge of 6 100m^3s^{-1} and a revised 1 in 50 year return period flow of 6 600m^3s^{-1}…The model was then used to ascertain the effects of these flood protection works on flood levels at Kaiata".

The model employed was HYDRO2DE, a fully two-dimensional programme, used in conjunction with a DTM constructed from river cross-section information and calibrated against the floods of the 13th September 1988 and 19th October 1998. These floods had similar magnitudes of 5 840m^3s^{-1} and 5 670m^3s^{-1} respectively, although their stage levels were considerably different, with the 1988 event being 0.6m higher than the 1998 event. The main findings of Connell were:

- The 1998 ground topography and Greymouth Flood Protection Scheme stopbanks had increased flood levels at Cobden Bridge by 0.09m.
- The stopbanks increased the flood levels downstream of the wharf by up to 0.28m.
- Flood levels at the upstream end of the wharf were not affected by the stopbanks as their effect is offset by the construction of the secondary flood channel in Cobden Island.
- The effect of the stock car track is minimal, causing a maximum elevation increase of ~0.12m for a very short distance upstream.
- The Greymouth stopbanks will increase flood levels at Kaiata by up to 0.04m for an event comparable in size to the September 1988 event. However, this is less than can be expected due to natural fluctuations for such a discharge. Natural fluctuations include sediment movement, flood volume and bar growth and movement.
- The model indicated that the Greymouth stopbanks had an average freeboard of 0.54m at a discharge of 6 600m^3s^{-1}.
- The tide level does have an effect on flood level, as maximum flood levels were almost always very closely related to the maximum tide level. A tidal difference of 1.9m changes the flood level at the entrance to Erua Moana Lagoon by 0.4m.
- The river mouth bar could have a significant effect on flood levels upstream. A model run with a maximum bar level of 3.6m below MSL increased the flood level at Erua Moana Lagoon by ~0.65m (The bar level was based on soundings undertaken by the Port Company.
- *"A best explanation for the lower flood levels observed in the 1998 flood relative to the 1988 flood is that the sediment transport ability of the river during a flood has been increased within the confines of the stopbanks. Water that previously inundated*

the town now flows down the main channel". In other words, improved scouring effects may lower the riverbed level during flood events.

Connell (CH Flood Modelling Ltd, pers.comm.) is currently upgrading the model using more accurate data and a 150 year return discharge of ~7 400m^3s^{-1}.

2.6 Riverbed Aggradation (and Associated Flood) Research

Since the 1980s aggradation research has concentrated on four areas in the region.

2.6.1 Arthur's Park National Park Area

McSaveney (1982) assessed recent geomorphological changes in the Arthur's Pass National Park area for the then National Parks Authority. In this paper McSaveney described the massive aggradation of the Otira River in 1957 and 1979, and the effects this had on the riverbed morphology. The same series of papers assessing flood hazards and risk along SH73 between Jackson's and Arthur's Pass produced by Whitehouse (1986), Whitehouse and McSaveney (1986, 1989), Whitehouse and Williman (1986), examined aggradation. They reported incidences of rapid massive aggradation in the Otira River (same events as described by McSaveney 1982), and in numerous creeks and assessed the hazards of these in terms of bridge and road design for the area.

2.6.2 Waiho River, Franz Josef Glacier

Aggradation in the Waiho River came under intensive investigation since the 1980's and especially during the 1990s, as rising bed levels threatened to cause the river to breakout into a new course. Mosley (1983) considered that the Franz Josef Glacier would not advance beyond it's location in the rock gorge and concluded that prolonged aggradation was not expected to occur, although he expected the river to remain unstable with short episodes of aggradation and degradation. The glacier has since extended beyond the gorge and aggradation has continued. It was assumed by Hoey (1990) that most of the sediment causing aggradation in the Waiho River enters from the Callery and that sediment supply from the glacier would decrease once glacial retreat resumed. Hoey concluded that continued aggradation was likely, if not inevitable. In contrast to Hoey's assumption, long-term staff members in the Operations Group WCRC, and the WDC, do not believe most of the sediment comes from the Callery catchment (Rick Lowe, WCRC, pers comm.). In examining channel behaviour on the fan, Thompson (1991) considered that short-term aggradation would be followed by degradation of up to 100 years possibly.

Davies (1997) described the Waiho River system and summarised the predictions of river behaviour from previous research (outlined above), and long-term management options to alleviate flood and aggradation hazards in the Franz Josef area. Davies noted the variations in river predictions and stated that: *"There are simply not enough data on which to base reliable predictions …It is unlikely that reliable predictions of aggradation at the bridge* (SH6) *will become available to aid decision making about resource use or hazard mitigation in the foreseeable future"*. Davies concluded that the Waiho River was dangerous because its behaviour was not reliably predictable, the facilities at greatest risk (those on the south bank) should be relocated first to avoid disaster, and that continued monitoring to improve the understanding of the river behaviour should be undertaken.

Expanding on the above paper, McSaveney and Davies (1998) produced a detailed natural hazard assessment for the Franz Josef area (floods, aggradation, earthquake). This paper describes the Waiho and Callery catchments in detail, and geological, geomorphological and hydrological processes acting in them. In light of the historical aggradation, the paper considered the consequences of the following six river course options for hazard management purposes:

- Hold the river in its present course.
- Maintain the status quo.
- Let the river choose a new course (i.e. do nothing).
- Choose a new course for the river.
- Make a new course for the river.
- Choose where the river will not make a new course.

McSaveney and Davies attributed the current aggradation in the Waiho River as a direct response to the river protection works stating:

"Our analysis of the system's behaviour over the last 100 years leads us to a conclusion that is radically different from past studies: we believe that the immediate serious dangers now presented by the river result directly from the well intentioned, well constructed, but ad hoc works that attempt to hold this powerful river in too small a portion of its historic flood plain. After sixty years of sustained efforts to constrain the river, the Waiho has aggraded to an unprecedented level and is now poised to break out of its channel at a number of weak points along the river banks".

This conclusion is not accepted unanimously, as the Waiho River was known to have started aggrading *before* river works construction commenced, and hence the subsequent need for protection works in the first place (Rick Lowe, WCRC, pers.comm). Also, numerous other rivers on the West Coast are confined within stopbanks but do not have major aggradation problems.

An MSc thesis study by Turnbull (1998) aimed to explain the behaviour of the Waiho River system over mesoscale and micro scale time frames, based on historical information from the last 100 years, and on field data collected between January and June 1997. Specific information used by Turnbull included historical photographs, a literature search including old newspaper articles, published reports and residents association meeting minutes, residential interviews, rainfall data, river survey cross sections and sediment size data. The main findings of Turnbull were:

- Extreme precipitation was not always the only cause of flooding, as flooding was often related to temporal variations in sediment delivery and storage in the floodplain. Therefore, relatively minor rainfalls could cause flooding depending on bed levels.
- Below the Callery River confluence, sediment volume is dependent on Callery Catchment erosion and flow discharge.
- In the upper Waiho Catchment, sediment delivery is dependent on glacial behaviour, as sediment is stored on, in, and under the glacier.
- Massive aggradation occurs during glacier bursts. Glacier bursts are more frequent when the glacier is advancing.
- Sediment supplied by glacier bursts remained in the upper Waiho Catchment for a considerable period and thus aggradation occurred in this area.
- Over a 100 year period, (meso scale), a general trend of aggradation interspersed with brief periods of quasi-stability occurred.

- Over a 0-10 year period (micro scale), fluctuations in sediment mobilisation and storage may be related to specific events such as extreme rainfalls, landslides, and glacier bursts.
- Over periods greater than 100 years (macro scale) *"it is likely an equilibrium system will develop in response to tectonic activities, climatic change and variations in sea level"*

Davies (1999) further reported on the sediment production, transfer and deposition in the Waiho River, based on the analysis of riverbed cross section surveys undertaken in 1983, 1985, 1990, 1993 and 1999. The major findings of this report were:

- That from 1983 to1999, aggradation between the glacier terminal and the Callery confluence followed a cyclic pattern.
- Average aggradation ranged from <1m in the lower part of the fan head to 10.7m at Champness Rock.
- Most of the sediment in the Waiho River Bed came from the glacier and the Waiho itself. However Davies concluded that: *"Until information is available on sediment delivery from the Callery, any predictions of Waiho River behaviour will be subject to substantial uncertainty".*

Other conclusions were that aggradation was likely to increase in the next few years, although it was not possible to predict when the river will reach new slope and level equilibrium or what they may be; and that if glacial retreat continues, a significant reduction in aggradation is *not* likely to occur.

In evaluating the hazard management options put forward by McSaveney and Davies (1998), Hall (2000), noted that as aggradation causes a decrease in freeboard, there is an increased risk to:

- Accommodation and residential facilities on the true left bank
- SH6 bridge.
- Avulsion of the Waiho into the Tatare River, above the Waiho Loop.
- Oxidation Ponds.
- Mueller wing of Franz Josef Hotel.
- Franz Josef Township.
- Forest and farm land south and west of the Waiho River.
- SH6 on the true left bank as far as Docherty Creek.

Hall considered only two of the six hazard management options were feasible: the status quo, or relaxation of river works. Of these, Hall favoured the Relaxation option, which involved relaxing current fan constraints on the left bank. This would involve the following consequences:

1) Relocation of residential and accommodation facilities on the left bank.
2) Relocation of SH6 on the south side of the river.
3) Preventing avulsion into the Tatare River.
4) Protection of the Franz Josef Hotel, oxidation ponds and Franz Josef township.

The relaxation option is essentially a restoration of natural conditions and is considered sustainable in the long term. Other options were considered to be short term solutions.

Davies (2002) briefly discussed aggradation in his reassessment of dambreak flood hazards in the Callery River Catchment. He compared the details of the Mt Adams landslide dam (Hancox *et al*. 2000) to computer models for the Callery. Davies also used landslide/sediment influx data from Hovius *et al*. (1997), but found that their relationship between landslide area and landslide volume was a generalisation and had to be treated with caution (see Chapter 3, Section 3.5.12 for more details).

2.6.3 Buller River

Aggradation was considered as part of Connell Wagner's Buller River flood model as mentioned previously. They summarised the flood and aggradation history of the lower Buller and found that the river downstream Te Kuha had aggraded over the period between 1972-1999 and attributed this mainly to a lack of large floods (return period less than 2.5%) over the last 20-30 years. Connell Wagner concluded that it was undesirable to let excessive aggradation occur it the lower reaches of the Buller River, especially where it was localised, as this generally *"leads to more active meanders in the river, requiring bank protection works to prevent loss of alignment control"*.

2.6.4 Grey River

Connell (2001) included the effects of aggradation and degradation in his flood model for the lower Grey River. Connell found that there was little net difference in bed levels between the 1977 and 2000 cross section survey data. However, during the intermediate years, up to a metre variation could be seen. It was found that lowering the bed level by 1m during modelling runs, could explain the difference in flood levels between the 1988 and 1998 events. The lowering of the riverbed level in the Greymouth area could possibly be attributed to the Greymouth stopbanks increasing scour during large flood events, and episodic reduction in sediment supply from upstream.

2.7 Gaps in Knowledge and Information

In spite of the large amount of information on flood hazards and events on the West Coast, there are still numerous gaps in the knowledge of both baseline information on historical records of events and effects, and scientific/technical information on the processes, magnitude and frequency of events. These gaps have been prioritised into the following order:

1. On going monitoring of Waiho River aggradation.
2. Predictive flood probability mapping.
3. Update existing historical flood maps with new information, and cover areas not previously mapped.
4. Upper catchment rainfall data in South Westland.
5. Worst case flood effect scenarios.
6. Process investigations into the relationship between flooding and other climate or geomorphic driven processes such as glacier behaviour, snowmelt, and river mouth closure.

Each of these gaps is examined in more detail in the following sub-sections.

2.7.1 Waiho – Callery Aggradation

The Waiho River is given top priority as the river could break out at any time during a significant flood event; hence it presents an immediate threat to the Franz Josef community (people and assets). Therefore it is considered that it requires the most urgent attention in terms of hazard planning and management, and information/data collection. This is consistent with the WCRC Regional Monitoring Strategy (1998) that ranks river bed/channel stability higher than other naturals hazard in regards to State of the Environment monitoring. (rank = 3.75, see WCRC 1998 for ranking justification).

Davies (1999) highlighted the considerable variations in aggradation predictions, and difference of opinion still exists relating to the significance of the Callery River sediment input. To gain a better understanding, and to develop more accurate prediction of likely behaviour of the aggradation/degradation the Waiho River, the sedimentation patterns and volumes from both the Waiho and the Callery Rivers need to be quantified and qualified.

The minimum information needed is for the WCRC to continue regular river cross-section surveys and the collection of stage/discharge data. Surveys should continue at the current rate of about once every 2 years, or after significant events, over all 26 cross sections from 1100m upstream of the car park to Milton's Stopbank. Over the last 8-10 years the river has been surveyed at around 2 yearly intervals. (Mike Shearer, WCRC, pers. comm.). This is consistent with the monitoring frequency outlined by the WCRC (1998), which recommended that surveying of all rivers such be undertaken:

- After flood events of greater than 5yr return period, which equates to about once every 2yrs on average across all rivers.
- When rivers change course impacting on persons or communities.
- As requested.

The WCRC has made recent progress in river discharge and stage data collection by placing a river recorder on the SH6 Bridge in 2000.
Establishing a good inventory of vertical aerial photographs is also considered necessary, to relate to the cross section profiles and to identify river channel positional changes. Throughout the West Coast, sections of rivers in rating districts, containing protection works, are photographed annually, or after significant events (Mike Shearer, WCRC, pers.comm.). It is recommended that to record the rapid changes in the Waiho River channel, this frequency should be maintained.

A recent development in imagery data collection that is complimentary to ground surveying and aerial photography is Airborne Laser Surveying, which is a method of rapid data collection for mapping 3D features on the surface of the earth, that uses a high accuracy laser rangefinder mounted over an opening in the floor of an aircraft. Two GPS units, one in the plane and one on the ground are used to fix the position of the plane. In post–flight processing, the laser range, scan angle, and GPS data are combined to determine the position of a point on the earth's surface very accurately. The two primary applications of the technology are the development of high quality digital terrain models in stable areas and the rapid collection of quantitative data in areas where there are rapid changes in the land surface. The scanner data has an accuracy of ± 0.15m, so the resulting spot height differences can be measured to 0.3m and contour intervals can be measured to 0.5m. It is therefore considered that this technology would be ideal to measure and model changes on the Waiho and Callery Rivers.

Based on trials undertaken by Environment Bay of Plenty in 2000, costs for data acquisition and post processing are in the order of $7500 per hour of flying time, with flying time being dependent on the number of flight lines required to cover the area of interest. The scanning width of the rangefinder is determined by the height of the aircraft, with approximately 650m being scanned at a flying height of 1000m. It is estimated that the area of interest in the Waiho area could be flown in approximately one hour, hence costs are estimated to be in the order of $7500 per survey. The cost of plane hire and aerial photography is additional to theses estimates. There are other uses of Airborne Laser Surveying in hazard monitoring and modelling on other West Coast rivers and the coast, which may make this technique cost competitive with existing data collection techniques. It is therefore recommended that the WCRC investigate the use this technique further.

The collection and analysis of data/information could be multi-agency, including:

- Aerial Imagery Consultants: Undertake Airborne Laser Surveys and aerial photography.

- WCRC Operations and Planning Groups: Undertake/organise aerial photos, collect stage/discharge data, survey and plot river cross sections, calculations of river bed level sediment supply volumes.

- University Post Graduate Research Students: Assist with and add to WCRC data collection and analysis by field studies and individual research, identifying sediment sources, rates, volumes and patterns. It is considered that this would be an appropriate thesis study for natural resource engineering, geology or physical geography students that would warrant the support of WCRC**.**

- Environmental Consulting Companies or University Post Graduate Research Students: Computer modelling of potential breakout scenarios and effects. This would fine-tune the work of McSaveney and Davies (1998) by better defining flow directions, depths, velocities and durations. Once set-up, computer models can be readily updated as new information becomes available.

A second recent development is the use of CAM-ERA, a sophisticated computer based time-lapse photography system, to show the movement and rate of sediment pulses/slugs down the river channels. This system is being tested by Environment Canterbury and NIWA in monitoring sediment transport in the Waimakariri River. However, at the present time, quantitative data cannot be obtained from the system, although NIWA is currently developing computer programmes to address this (Murray Hicks, NIWA, pers.comm.). Hicks estimated the set up cost of CAM-ERA on the Waiho River would be in the order of $15 000 per site. It is recommended that the WCRC should keep abreast of the development of this technology, and consider it as a monitoring option when the quantitative analysis software becomes operative. An obvious site would be at the SH6 bridge, and possibly one upstream towards the glacier. Sites on the Callery River would be more difficult to set up due to the limited access, and presumably would be more expensive.

2.7.2 Flood Probability Mapping

Flood probability mapping has been undertaken at Westport by Connell Wagner (2000) and at Greymouth by CH Modelling Ltd (Connell 2001). However it is lacking for other major catchments with significant urban communities (eg Hokitika, Reefton, Karamea, Franz Josef). Discussions with the District Councils for this project confirmed that flood probability maps were the most noted gap in hazard information: This information was seen as essential for sound planning decisions as required under the RMA and Building Act.

The inputs required for these maps include:

- Topographical data of the floodplain, river banks and river channel.
- Hydrological data on flow magnitudes and frequencies.
- Historical information on past floods.

Computer models are used to determine the location and probability of likely river break out points in various sized river flows, and the resulting downstream inundation areas and depths. These computer generated outputs are then compared and verified against the historical flood information. The major limitations to undertaking this mapping at the present time are the lack of topographical data and historical flood information. It is considered that the first of these would be best addressed by Airborne Laser Surveying, as discussed in Section 2.7.1, and the second is addressed in the following section (2.7.3).

The most useable form of mapping outputs are considered to be Digital Terrain Maps (DTM), with a minimum requirement being a GIS mapping on to a topographical or cadastral basemap. The main advantages of DTM's are that flood depths and flow patterns are shown three dimensionally, and can be rapidly updated for a variety of scenarios as new information becomes available.

It is considered that this work could be undertaken by:

- Aerial Imagery Consultants: Undertake Airborne Laser Surveys.

- WCRC: Collection and collation of historical data as discussed in the following section. Verification of computer modelling outputs with historical flood information.

- University Post Graduate Students: Collection and collation of historical data. Set-up, calibrate and run computer modelling. Production of flood probability maps.

- Hydrological Consultants: Set-up, calibrate and run computer modelling. Production of flood probability maps.

2.7.3 Historical Flood Information

Despite of the amount of research and information gathering that has been undertaken in the past, there are still considerable gaps in the historical flood record. This was ranked 2nd equal in the WCRC (1998) monitoring priorities (rank =3.5. See WCRC 1998 for ranking justification). Of particular concern are the following three types of information, all of which were specifically requested in discussions with all three District Councils on gaps to be addressed in this project:

1. Known historical flood depths, which are an important reference line for floor level design, have not been analysed or searched for in many areas. This is relevant to areas that have already been flood mapped, and *includes* the major urban areas of Greymouth, Westport, Hokitika, Reefton and Karamea. There are numerous old photographs of historical floods from which levels could be obtained. These photographs are located in local newspaper collections, local museums, personal photograph albums, and local council offices.

2. Many of the major catchments have not been mapped for flood hazards and thus little documentation of the actual spatial extent of flooding exists. This situation has come about by the WCRC concentrating early hazard mapping on the catchments containing major urban settlements, or assets. It is considered a logical extension that the remaining major rural catchments be mapped with priority catchments being the Whataroa, Poerua, Wanganui, Taramakau and Totara.

3. The WCRC flood hazard maps have not been significantly updated since they were compiled early-mid 1990s. Since this time additional flood information has been found, and subsequent floods have inundated areas not previously mapped. This information, and any found from searches mentioned above, should be added to those maps. It is considered that in future the maps should be updated on an on-going basis, as soon as possible after significant flood events or significant additional information becomes available. This is consistent with the WCRC Regional Monitoring Strategy (1998) that recommended:

    - Collecting and recording historical information as it becomes available and analysing historical information when necessary.
    - Updating the flood hazard maps every 2-3 years.

It is considered that work to fill gaps in the historical database could be undertaken by:

- University post-graduate Students: Historical flood analysis and flood mapping of previously unmapped catchments, and/or better defining areas already mapped, would be a practical thesis/dissertation project, and would be worthy of assistance from the WCRC and relevant district councils.

- WCRC Operations Staff, District Council staff, registered surveying contractors: Depending on time and financial resources, any of these groups could carry out the surveying of 'tying-in' identified flood levels to known benchmarks or datum.

- WCRC (if time and resources allow) or Outside Contractors: Update existing flood hazard maps and compilation of new maps for other catchments from the information gathered above.

2.7.4 Rainfall Data (South Westland)

More high altitude (upper catchment) rain gauge information from the South Westland area is considered necessary to help provide better flood warnings for the major rivers between Whataroa and Haast. In particular, the catchments of the Whataroa, Waiho and Hasst need to be addressed. This is because the current WCRC rain gauges in those catchments are all at low altitude and provide minimum warning times (Mike Shearer, WCRC, pers, comm.). High altitude gauges would provide more warning time in those immediate areas once intense rainfalls have been identified in the upper catchments, and would help improve the monitoring of frontal systems moving along the Southern Alps. This would help in flood warning in the more northern sections of the region. There are two options for the installation and monitoring of these rain gauges:

- WCRC: Carry out as an extension of the current WCRC network. Installation and monitoring done by WCRC staff. This would ensure all sites are maintained and monitored to the same standards.

- Contract: WCRC have access to NIWA sites in the upper Buller and Karamea Catchments. Contracting NIWA or other organisations to install and monitor the rain gauges could be an option. Many rain gauges have in fact been installed across the Southern Alps as part of the SALPEX programme and rain/weather forecasting models are being developed from this data by NIWA and other contributing organisations. (Wratt *et al*. 1996, Wratt and Sinclair 1996).

2.7.5 Worst Case Flood Effect Scenarios

This approach has been used in numerous Engineering Lifelines studies undertaken in various places around New Zealand. The process involves using flood histories and/or computer models to produce a worst case flood scenario (e.g. 500 year return period), then estimates the vulnerability of communications networks, transport routes, water and power supply, wastewater disposal, emergency services, and buildings to the effects the resulting inundation, aggradation and/or erosion. In other Engineering Lifeline studies around the country, the results have been used to determine best location and operating methods for public assets and services, and to develop contingencies on how to deal with the interdependence of the vital services. The worst case scenarios can be developed for two situations: one the status quo situation with the existing works and measures in place and operational, and the second where the existing protection works and measures are not maintained. The outputs from the study can then be used to determine the maintenance priorities for existing protection works, the cost-benefits new protection works, and in Civil Defence planning.

An engineering lifelines approach is best managed by the WCRC, with input from relevant external consultants for development of the scenarios and cost- benefit analysis, from engineering lifelines providers and district councils for the determination of effects on services, and from civil defence personal.

2.7.6 Flood Processes

Although the common processes causing flooding (eg heavy rainfall and aggradation) have been well researched, information and knowledge gaps exist for the relationship other climate or geomorphic driven processes. Of particular importance for some catchments on the West Coast are the relationships of:

- Glacier behaviour and river stage/discharge.
- Snowmelt and flood stage/discharge.
- River mouth dynamics leading to mouth closures and backwater flooding.

Such projects could be carried out by:

- University Post Graduate Students: Thesis topics for students majoring in alpine and coastal studies in physical geography or geology.
- Environmental Consultants: Specialist in alpine and coastal studies.

2.8 Summary

This chapter has outlined the causes and effects of floods and aggradation, and summarised relevant research. Both flooding and aggradation can be rapid and extreme. It has been shown that floods are by far the most common hazard in the region, having historically caused frequent serious damage in social, economic and physical terms. All of the region's major settlements, and thus population and assets, are located on very active flood plains. Floods have probably been responsible for more deaths in the region than any other natural hazard.

Floods are most commonly caused directly by prolonged or intense rainfalls; the West Coast having the distinctions of being unofficially the wettest place on earth, and officially having the largest recorded, and unrecorded flood discharges in New Zealand. Numerous secondary causes of flooding were also identified, the major one being aggradation, which is currently of major concern in the Waiho River and threatening the township of Franz Josef. Aggradation is also an ongoing problem at the port of Westport, and at small creeks along numerous sections of state highways and district roads.

Flood research has focussed on the areas with the greatest concentration of population and assets, namely Greymouth, Westport, Franz Josef, and SH73 between Jackson's and Otira. Aggradation research has focussed on the same section of SH73 and more recently at Franz Josef, and to a lesser extent Westport and Greymouth.

Identified information gaps that require further investigation included:

- Aggradation processes and patterns of the Waiho Riverbed.
- Flood probability mapping (initially for the major urban areas).
- Information on historic flood depths.
- Update historical flood maps for new information and areas not previously mapped.
- Rainfall data from upper catchment areas in South Westland.
- Worst case flood effect scenarios.
- Special flood process investigations (eg river mouth closures, glacial changes, snowmelt).

2.9 Flood and Aggradation References

Note: See Benn (1990) for an extended, comprehensive reference list, containing general history books and other documents not referred to in this report.

APPENDICES TO THE JOURNALS OF THE HOUSE OF REPRESENTATIVES (AJHR). 1881: The Harbours of New Zealand. Report by Sir John Coode. 10p plus Maps. Drawing No.1: Distorted Longitudinal Section of Buller River Taken Along the Line of Deepest Water from Nine Mile Ferry to the Sea. Section HI9.

APPENDICES TO THE JOURNALS OF THE HOUSE OF REPRESENTATIVES (AJHR). 1892: The Westport Harbour Works. Section D17, pp 7-20.

APPENDICES TO THE JOURNALS OF THE HOUSE OF REPRESENTATIVES (AJHR). 1904: Section of the Buller River – Lakes to the Sea. Section D1A, Map 21.

APPENDICES TO THE JOURNALS OF THE HOUSE OF REPRESENTATIVES (AJHR) (1923-1953): Westport Harbour Annual Reports. Section H15 of Each Year.

BENN, J.L. 1990: A Chronology of Flooding on the West Coast, South Island, New Zealand: 1846 – 1990. The West Coast Regional Council, Greymouth. 159p

BENN, J.L. 1991a: Grey River Catchment Flood Hazard Maps. The West Coast Regional Council, Greymouth.

BENN, J.L. 1991b: Buller River Catchment Flood Hazard Maps. The West Coast Regional Council, Gremouth. 6p plus 21 Flood Hazard Maps

BENN, J.L. 1992: Hokitika River Catchmemt Flood Hazard Maps. The West Coast Regional Council, Greymouth. 6p plus 4 Flood Hazard Maps.

BENN, J.L. 1993: Karamea and Arahura River Catchment Flood Hazard Maps. The West Coast Regional Council, Greymouth. 5p plus 3 Flood Hazards Maps

BENN, J.L. 1995a: West Coast Dam Inventory and Potential Hazard Ratings. The West Coast Regional Council, Greymouth. 13p plus Inventory.

BENN, J.L. 1995b: Potentially Contaminated Sites in the West Coast Region. The West Coast Regional Council, Greymouth. 24p plus Inventory.

BENN, J.L. (In Prep.): Major Historical Flood Events In Greymouth: 1862 -1988.

BOWIS, S., & FAULKNER. F. (2000): Hydrometric and Meteorological Data Summary Report to 2000. Technical Report No. 005. The West Coast Regional Council, Greymouth. 194p.

BRAILSFORD, B. 1984: Greenstone Trails; The Maori Search for Pounamu. A.H. and A.W. Reed Ltd. 192p.

CARSON, K. 1990: No Surrender: Greymouth's Battle to Beat the Floods. Greymouth Evening Star. 64p.

CLARKE, H.E. 1978: Report on the Storm of 13/14 April 1978 Affecting the Boroughs of Greymouth and Runanga and Karoro County Town. Westland Catchment Board and Regional Water Board, Greymouth. Unpublished Report, 17p.

CONNELL, R.J. 2001: Grey River – Greymouth: Hydraulic Review of Flood Capacity. Report Prepared for the West Coast Regional Council (Greymouth) by CH Modelling Ltd, (Christchurch). 41p.

CONNELL WAGNER LTD. 2000: Preliminary Flood Study of the Buller River at Westport. Report Prepared for the W.C.R.C., August 2000, by Connell Wagner Ltd, Wellington. 19p plus Appendices.

COOPER. L.L. 2000: Geotechnical Hazard Analysis, Management and the Development of Hazreg for the Buller District. MSc Thesis, Department of Geological Sciences, University of Canterbury. Vol. 1 (205p), Vol. 2 (Appendices).

COWIE, C.A. 1957: Floods in New Zealand; 1920-1953, With Some Notes On Earlier Floods. New Zealand Conservation and Rivers Control Council, Wellington. 239p.

DAVIES, T.R.H. 1997: Long Term Management of Facilities on an Active Alluvial Fan – Waiho River Fan, Westland, New Zealand. New Zealand Journal of Hydrology, Vol. 36 (2), pp 127 – 145.

DAVIES, T.R.H. 1999: Sediment Production, Transfer and Deposition in the Waiho River System: Interim Report for the West Coast Regional Council. Natural Resources Engineering, Lincoln University, Lincoln. 10p.

DAVIES, T.R.H. 2002: Landslide Dambreak Floods at Franz Josef Township, Westland, New Zealand. New Zealand Journal of Hydrology, Vol. 41 (1), pp 1-17.

FAUTH, B.J. 1988a: Buller and Westland – Report on Major Flooding 19/20 May 1988. Westland Catchment Board and Regional Water Board, Greymouth. Unpublished Internal Report. 24p plus Maps.

FAUTH, B.J. 1988b: Buller and Westland – Report on Major Flooding 13 September 1988. Westland Catchment Board and Regional Water Board, Greymouth. Unpublished Internal Report. 21p plus Maps.

FURKERT, R.W. 1947: Westport Harbour. Transactions of the Royal Society of New Zealand. Vol. 26, pp373-402.

GRIFFITHS, G.A. & McSAVENEY, M.J. 1983a: Hydrology of a Basin With Extreme Rainfalls – Cropp River, New Zealand. New Zealand Journal of Science, Vol. 26, pp293 – 306

GRIFFITHS, G.A. & McSAVENEY, M.J. 1983b: Distribution of Mean Annual Precipitation Across some Steepland Regions of New Zealand. New Zealand Journal of Science, Vol. 26, pp197-209.

GRIFFITHS, G.A. & McSAVENEY, M.J. 1986: Sedimentation and River Containment on Waitangitaona Alluvial Fan – South Westland, New Zealand. Zeitschrift Fur Geomorphology, Vol. 30 (2), pp215-230.

HALKET-MILLAR, J. 1959: Westland's Golden Sixties. A.W. & A.H. Reed Ltd, Wellington. 223p.

HALL, R.J. 2000: Evaluation of Options for the Management of the Waiho River Aggradation Threats. Civil and Environmental Consulting Ltd, Timaru. 26p plus Maps.

HAWKE, A.R. 2001: Flow Variability of the Waiho River. Unpublished M.A. Thesis, Geography Department, University of Canterbury, Christchurch. 93p.

HAWKER, E. 1977: Centennial Survey of the Grey County, 1877-1977. Greymouth County Council, Greymouth. 96p.

HENDERSON, R.D. 1993: Extreme Storm Rainfalls in the Southern Alps, New Zealand. Proceedings, Joint IAMAP-IAHS Symposium on Extreme Hydrological Events: Precipitation, Floods and Droughts, Yokohama, Japan. International Association for Hydrological Sciences, Publication 115 (10), 44p.

HOEY, T. 1990: Aggradation in the Waiho River. Final Report for the West Coast Regional Council. 23p.

JACKSON, 0. 1968: Greymouth: The First 100 Years. A Centennial Publication. Greymouth Borough Council. 96p.

JOHNSTON, M.R. 1974: Major Landsliding in the Upper Buller Gorge, South West Nelson. New Zealand Institute of Engineers Transactions, Vol 1., pp239-244.

KARAMEA DISTRICT & SCHOOL CENTENNIAL COMMITTEES (KDSCC) 1975: Karamea – A Story of Success. Buller Printing Ltd, Westport. 96p.

KERR, P. 1988: Diaster Recovery Co-ordinator's Report (Flood September 1988). Unpublished Internal Report prepared for the Civil Defence Organisation. 51p.

KIRK, R.M. 1988: Coastal Erosion and Inundation at Punakaiki Village (Pororari), Westland, 1983-1986. Unpublished Report Prepared for the Department of Conservation. 28p.

LORD, E.I. 1928: Te Wai Poumamu – Souvenir of the Grey District Diamond Jubilee, 1868 – 1928. Andrew Batey and Co. Ltd., Christchurch. 136p.

LOVELL, J: 1991: Floods and Earthquakes, West Coast, January 1991. Report Complied by the Assistant Civil Defence Commissioner. 18p.

LOWE, L.K. 1988: Mai Mai Hydrological Study – Report on the Storm 19 May 1988. Unpublished Report by the Forestry Research Centre, Christchurch. 2p.

MARCUS, M.G., MOORE, R.D., & OWENS, I.F. 1985: Short-Term Estimates of Surface Energy Transfers and Ablation on the Lower Franz Josef Glacier, South Westland, New Zealand. New Zealand Journal of Geology and Geophysics, Vol. 28, pp 559-567.

MATTHEWS, E. 1977: Yesterdays in Golden Buller. Published by the Author. 216p.

McCAHON, I. & YETTON, M.D. 2001: Peer Review of Information Regarding Punakaiki Rockfall and Flood Hazard Assessment and Zonation Included in the MSc Thesis Entitled "Geotecnical Hazard Analysis, Management and the Development of Hazreg for the Buller District". Letter to Terry Archer (Buller District Council) from Mark Yetton (Geotech Consulting Ltd), 17 September 2001, 15p.

McSAVENEY, E.R. 1982: Recent Geomorphic Changes in the Bealey, Otira, Mingha and Deception Valleys, Arthur's Pass National Park. A Report to the National Parks Authority of New Zealand. Department of Lands and Survey. 83p.

McSAVENEY, M.J. & DAVIES, T. R. H. 1998: Natural Hazard Assessment for the Township of Franz Josef Glacier and its Environs. Report prepared for the West Coast Regional Council by the Institute of Geological and Nuclear Sciences Ltd (McSaveney), and Department of Natural Resources Engineering, Lincoln (Davies). Client Report 44714b.10. 52p.

MOSLEY, P, 1983: Response of the Waiho River to Variations in Franz Josef Glacier, Westland New Zealand. Internal Report, WS 858. Hydrology Centre, Christchurch. 17p.

MOSLEY, P, & PEARSON, C.P. (1997): Introduction: Hydrological Extremes and Climate in New Zealand. <u>*In*</u> Historic Floods and Droughts in New Zealand: The New Zealand Experience. Edited by Mosley, P., and Pearson, C.P. New Zealand Hydrological Society. pp 29-50.

PATERSON, B.R. 1996: Slope Instability Along State Highway 73 Through Arthur's Pass, South Island, New Zealand. New Zealand Journal of Geology and Geophysics, Vol 39, pp 339-351.

SARA, W A. 1968: Franz Josef and Fox Glaciers, 1951-1967. New Zealand Journal of Geology and Geophysics. Vol. 11, pp768-780

SOONS, J.M. 1982: Westland: The West Coast of the South Island. <u>*In*</u> Landforms of New Zealand. Edited by Soons, J.M. and Selby, M.J. pp 299-315.

THOMPSON, S.M. 1991: SH6: Waiho Bridge Waterway Requirements. Report CR 91.01. Hydrology Centre, Christchurch. 11p plus Appendices.

TODD, D.J. 2002: Coastal Flooding Hazard At Pororari River Mouth. Report Prepared for the Buller District Council. as part of the Punakaiki Development Plan. DTec Consulting Ltd, Christchurch.

TOMLINSON, A.I. 1980: The Frequency of High Intensity Rainfalls in New Zealand. Part 1. Water and Soil Publication N° 19, New Zealand Water and Soil Division, Ministry of Works and Development, Wellington. 36p.

TURNBULL, J. 1998: Patterns and Processes of Sediment Transfer: Waiho River, Westland New Zealand. Unpublished MSc Thesis, Geography Department, University of Canterbury. 179p.

WEST COAST REGIONAL COUNCIL, 1948 - 2002: Flood Hydrograph and Raw Hydrology Data. Held at the West Coast Regional Council Office, Greymouth.

WEST COAST REGIONAL COUNCIL. 1998: West Coast Regional Monitoring Strategy. Internal Report. The West Coast Regional Council, Greymouth. 161p

WESTLAND CATCHMENT BOARD. 1986: Okarito Township; Proposed Flood and River Protection Scheme. Internal Report for the Westland Catchment Board and Regional Water Board, Greymouth. 15p.

WHITEHOUSE, I.E. 1986: Arthur's Pass Roading Project; Geology, Geomorphology, and Climate. Works Consultancy Services Ltd, Christchurch. 21p.

WHITEHOUSE, I.E. & McSAVENEY, M.J. 1986: Hazard Assessment State Highway 73: Cass to Jacksons Via Arthur's Pass. Internal Report for the Ministry of Works and Development, Christchurch. 20p.

WHITEHOUSE, I. E. & McSAVENEY, M.J. 1989: An Alpine Highway At Risk. Streamland No.74. DSIR Publishing, Wellington. 4p.

WHITEHOUSE, I.E., & WILLIMAN, E.B. 1986: Arthur's Pass Roading Project: Hydrological Factors. Ministry of Works and Development, Christchurch. 13p.

WRATT, D.S., RIDLEY, R.N., SINCLAIR, M.N., LARSEN, H., THOMPSON, S.M., HENDERSON, R., AUSTIN, G.L., BRADLEY, S.G., AUER, A., STURMAN, A.P., OWENS, I.F., FITZHARRIS, B., RYAN, B.F., & GAYET, J-F. 1996: The New Zealand Southern Alps Experiment. Bulletin of the American Meteorological Society. Vol. 77 (4), pp 683-692.

WRATT, D.S. & SINCLAIR, M.R. 1996: SALPEX: The Southern Alps Experiment. Water and Atmosphere. Vol. 4 (2), pp 26-28.

3.0 LANDSLIP HAZARDS

3.1 Introduction

Next to flooding, the historical record shows landslides to be the most common occurring natural hazard in the West Coast Region. Landslides have very frequently caused widespread damage to property and assets, considerable inconvenience (such as blocking transport routes), injury, and the loss of numerous lives. Slope instability events have ranged in scale from singular rocks falling, to massive, catastrophic failures of whole mountainsides over large portions of the region, as occurred during the 1929 Murchison earthquake.

Because of the damage done by historical landslides (see Appendix 3), and the potential for future catastrophic events to occur (Yetton *et al*. 1998, Stirling *et al*. 1999), it is considered important to have a good understanding of the processes that cause them, where they have occurred, where they are likely to occur, and what potential damage or disruption may prevail. To date, the WCRC has collected little information on landslides, and landslides events are generally not recorded or monitored in the same detail as flood events. Lowe (2001) stressed this fact in a letter stating: *"I have researched historical information regarding slips on the West Coast. The information supplied is not necessarily a full record of all events. Unfortunately we do not have documented evidence for all events"*. Lowe supplied limited details of seven landslides from six events, occurring between September 1988 and February 2000.

This chapter therefore covers the following points:

- Discussion on the causes of landslides.
- The general effects of landslides.
- Summary of the current scientific knowledge.
- A chronology of historical landslides, emphasising the frequency at which they have occurred, where they have occurred, and the damage and inconvenience they have caused. As can be seen from the list of events, many location names keep reoccurring; thus the list may be useful in helping identify where future landslide events are likely to occur.

As it is beyond the scope of this report to categorise recorded historical landslides (in engineering geology terms), all soil and rock movements (e.g. debris flows, mudflows, rock falls, rock avalanches etc.) are discussed in this chapter collectively as landslides. Liquefaction is dealt with in the following chapter on earthquake hazards, as this process can only result from earthquake shaking. Landslides and slope movements of other kinds (discussed in this chapter) can be generated by a number of factors.

3.2 Causes of Landslides

The West Coast is prone to landslides due to a combination of steep topography, intense and prolonged rainfalls, regular seismic activity, and continuous tectonic activity. Bell (1994) stated that *"Slope instability involves ground failure by falling, sliding and/or flowage of material downslope, and may occur within bedrock or in the mantling soils"*. He also noted that landslides are generated by a number of factors but for simplicity, landslide hazards could be grouped as:

- Those generated by earthquakes.
- Those generated by intense or prolonged rainfall.
- Other.

As all of these sources of generation have been confirmed in the West Coast historical record, it is appropriate that this classification is used in this report. Other factors contributing to slope instability, are recorded by Hawley (1984) as:

- Changes in vegetation cover (most commonly the replacement of forest by pasture).
- Changes in land management, such as grazing intensities.
- Gradual tectonic distortion.
- Slope undercutting by rivers or man.
- Other human activities such as increasing runoff in urban areas.
- Rise in ground water tables.
- Increase in loads on slopes (natural such as snow/ice or artificial such as buildings).

It is reasonable to say that the relative specific influence of these factors on West Coast slope stability is little known and would justify further investigation; the possible exception may be tectonic activity, which has come under close investigation in recent years. Hawley also noted that most instances of slope instability were generated either by very intense rainstorms and/or above average rainfalls continuing for periods of weeks or months. Exceptions to this were those failures generated by earthquakes: these usually occur in the rock (or in the rock and soil) as opposed to in the soil alone as with rainfall-induced failures.

Keefer (1984a) analysed 40 major earthquakes worldwide (including the Inangahua Earthquake) supplemented by several hundred examples from the USA, to determine the characteristics, geological environments, and hazards associated with landslides. Fourteen types of landslides generated by earthquakes were identified, with the most abundant being rockfalls, disrupted soil slides, and rockslides. However, rock avalanches, rapid soil flows, and rockfalls caused the greatest loss of life. The correlation made by Keefer between earthquake magnitude, landslide type and distribution, showed that:

- The maximum area likely to be affected by landslides in a seismic event ranges from $0km^2$ at Magnitude 4 (M4) to $500\ 000km^2$ at M9.2.
- Weakest shaking initiated four types of internally disrupted landslides; rockfalls, rockslides, soil falls, disrupted soil slides.
- Progressively stronger shaking was needed to initiate coherent deeper seated slides, lateral spreads and flows, and highly disrupted rock and soil avalanches.
- Materials most susceptible to failure during earthquakes included weakly cemented rocks, closely fractured rocks, residual and colluvial sands, volcanic sands containing

sensitive clays, loess, cemented sands, granular alluvium, deltaic deposits, and man made fills.

- Most earthquake slides were in materials that had not previously failed (few earthquake induced landslides were found to re-activate old slides).

For earthquake initiated rock avalanches, Keefer (1984b) found that:

- Slopes most likely to fail were higher than 150m and steeper than 25^{o}.
- Slopes undercut by river or glacial erosion, composed of intensely fractured rocks, and characterised by at least one or more of the geological indicators of slope stability already mentioned were most likely to fail by rock avalanching.

Keefer (1984b) also noted that: *"Rock avalanches are amongst the most dangerous landslides triggered by seismic events, with the possible exception of rapid flows in unconsolidated soil, they have killed more people than any other type of landslide in recent earthquakes…The destructive power of these avalanches derives from their large volume (>0.5 x $10^6 m^3$) and their ability to transport material thousands of metres at velocities of tens or hundreds of kilometres per hour on slopes as gentle as a few degrees"*

Historical events recorded support the observations of Hawely (1984), Keefer (1984a. 1984b), and Bell (1994), with many West Coast slides having occurred in areas fitting the geological parameters outlined by Keefer. From Appendix 3, it can be seen that 224 landslide events are attributed to rainfall generation, 9 events to earthquake generation, and 14 events are classed as other or unknown. Whilst no detailed analysis of the record has been undertaken (as it has just been compiled for this report and is by no means complete), some generalised observations can be made:

- Slips are commonly associated with intense/and or prolonged rainfalls.
- Most slips are localised around the cell of highest rainfall recordings.
- Rainfall events tend to generate slips over a wider geographical area than earthquake generation (Slips are often recorded over the whole region, from Karamea to Haast, during a single storm).
- Most rainfall induced slips are relatively small in size and volume compared to earthquake slips.
- Most rainfall induced slips are generally shallow slips in unconsolidated sediment.
- Earthquake slips commonly range from relatively small to catastrophic (millions of cubic metres in volume).
- Earthquake slips are commonly deep seated bedrock failures.
- Earthquake slips generally have a higher density of occurrence than rainfall induced events (i.e. number of slips per km^2).
- Slips *can* be re-activated by subsequent rainfalls or earthquake shocks, or toe undercutting.
- Recently formed slips tend to be more prone to re-activation than older slips.
- Slips do not always occur *during* a trigger event (e.g. rain or earthquake). Delays can and do occur – the initial trigger may weaken a slope, then gravity, subsequent triggers, or a combination of both may cause the slope to fail.
- In many cases, more than one trigger may be responsible for slope failure.
- Landslide dams tend to fail quickly by river overtopping and breaching.

There are of course exceptions to the above observations. For example, in many instances, landslides have occurred when very little or no rainfall has been recorded, and rainfall has also been responsible for some massive slips of catastrophic proportions. Likewise, significant earthquakes do not necessarily generate widespread, large scale sliding.

Sometimes identifying the trigger mechanism responsible for slope failure can be difficult. For example, Yetton (1999) reported on the Doherty Creek landslides, where a combination of rain, underground mine workings leading to subsidence, and rock failure were all considered likely causes. Although most landslide dams fail rapidly, some landslide dams and lakes are hundreds and possibly many thousands of years old.

Little detail is known of other landslide generating mechanisms such as subsidence, or slope loading (natural and artificial) in the West Coast region, and surprisingly little research has been done identifying the relationship between rainfall (intensity and duration) and landslide occurrence, considering the frequency of such events.

3.3 Effects of Landslides.

Benn (1992) noted that landslides present three distinct types of hazard:

- Direct impact/burial.
- Blocking river channels forming dams and lakes.
- Falling into water bodies, potentially creating waves of damaging proportions.

All three scenarios have been recorded on the West Coast. As is demonstrated in Appendix 3, direct impact and burial are by far the most common consequence of landslides in the region. The effects of this have most commonly resulted in repetitive damage to sections of major national highways, district roads, and the only rail link to the West Coast. On numerous occasions, slips cutting such transport links have isolated West Coast communities from one another, and indeed, have isolated the whole West Coast Region from the rest of the South Island. Exacerbating cuts in transport links, landslides have also cut power lines and telephone lines, and damaged town water supplies. Direct impact/burial has also ruined good quality farmland, buried livestock (Rea 1991) and wrecked or damaged numerous houses. Last, but by no means least, at least 13 people[1] in the West Coast Region have been killed by being directly hit by landslides, and numerous others injured (Appendix 3).

Landslide dammed lakes have been recorded on numerous occasions and have caused considerable damage when the dams has breached. Examples include the flooding of Seddonville in 1929, destruction of mining and farm equipment, and farmland. Landslides falling into rivers can also have severe consequences in terms of riverbed aggradation. Riverbeds can rapidly fill up with sediment leading to flooding and sedimentation problems downstream (e.g. Whitehouse and Williman 1986, Davies and Scott 1997).

For the Matiri River catchment (Buller River tributary in the Tasman District), Pearce and Watson (1986) concluded that the long sediment retention times and the volumes of debris supplied by landslides during a large earthquake suggested that *"earthquake-induced landsliding is the principle sediment-supply mechanism in this area".* Aggradation caused by landslides could potentially have effects on the region's hydroelectric reservoirs, and river mouth ports (Greymouth and Westport). In fact the closure of Karamea as an operational port was attributed to sediment aggradation after the 1929 Muchison Earthqauke.

Finally, landslides have been the cause of at least one tsunami on the West Coast. Numerous coastal landslides occurred in the Karamea area during the 1929 Murchison Earthquake, with de Lange & Healy (1986) noting that this generated a tsunami that was recorded from Buller to Farewell Spit.

All of the above effects can be expected in future landslide events.

[1] Of the three people killed in the 1968 Inangahua earthquake, two died as a result of the Whitecliffs landslide, and taxi driver was killed when his car hit a bridge abutment, due to the approaches having *subsided*. This death takes the total landslide deaths to at least 14 in the region. This figure excludes most of those killed by landslides during the 1929 Murchison Earthquake, in the upper Buller Catchment (i.e. in the Matakitaki and lower Maruia Valleys). This area is now in the Tasman District.

3.4 Magnitude and Frequency of Events

The frequency of landslide occurrence has only been addressed at a few specific sites, as outlined below.

Metcalf (1993) identified and mapped several areas in urban Greymouth that have a high risk of moving with the next 50 years, and numerous areas of moderate risk, that have not moved in the last 50 years but are likely to do so.

For the Callery River near Franz Josef Glacier, Davies & Scott (1997) advocated that the probability of a landslide dam break in the Callery River is in the order of 1% per annum (i.e. 1 in a 100 years), although they do note the difficulty in calculating realistic numerical models in the absence of any data on landslide dam breaks in the Callery. In terms of magnitude, Davies & Scott suggested that at the most likely site for slope failure, the material involved in the potential landslide would be very approximately $0.75 \times 10^6 m^3$, creating a dam about 90m high containing a reservoir of around $13x10^6 m^3$, and the resulting dambreak flood could have a discharge several times greater than a one in hundred year flood. McSaveney & Davies (1998) reported that such events (especially the larger landslides) are likely to be generated in earthquakes and so their probability of occurrence would be similar to that of large earthquakes, as described by Yetton *et al*. (1998).

At Little Wanganui, Yetton (1997) identified two large debris slides having occurred in the last 250 years and suggested that another large slide failure will likely affect the subdivision within the next 100 years. Smaller (but still potentially destructive) rockfalls would continue to occur at smaller time scales, and larger events, extending forward of the talus slope may only happen on a 50-100 year frequency.

Whitehouse & McSaveney (1986, 1989), identified numerous areas classed as very high risk and high risk, for the Otira Gorge – Jacksons area, where the hazard will be realised about once in every 20 years and once every 20-60 years respectively. Magnitudes were also assigned to each class of landslide. The risk and effects of some of these hazards (such as rock falls) has been reduced with the relocation of SH73 from the Otira Gorge zig-zag to the new viaduct (Paterson 1996).

For the region as a whole, Hovuis *et al*. (1997) calculated that rainfall generated landslides of 1 million m^3 would occur about once every 30 years, and a 50 million m^3 slip would occur about once in every 500 years. Yetton *et al*. (1998) estimated that widespread catastrophic land sliding associated with movement of the Alpine Fault, can be expected about once every 250 years, although they stated that there is an 85% probability of this happening in the next 100 years, and a 65% probability of happening in the next 50 years (see next chapter). Whitehouse and Griffiths (1983) found that rock avalanches of >1 million m^3 in the Southern Alps occur at a frequency of 1 per 94 years, and on average, the largest rock avalanche in any century is $56x10^6 m^3$, and in any millennium, $103x10^6 m^3$. At about one per 100 years, most large rock avalanches were probably generated by large earthquakes, and only a few by storms.

Very basic analysis of the inventory in Appendix 3 shows that at least 250 landslide events[*] have occurred in 135 years. Hence, landslide events in the region cause

[*] No. of events; Rainfall induced = 225, Earthquake induced = 9, Other = 16.

inconvenience/damage on average nearly two times per year (1.85). Rainfall induced landslide events occur on average 1.65 times per year, earthquake induced landslide events once every 15 years, and other/unknown induced events, once every 8.43 years. It is considered that with further investigation, the average annual frequency of landslide events would be greater than two per year.

3.5 West Coast Landslide Research

3.5.1 General Landslide Research

A considerable amount of research relating to landslides on the West Coast has been undertaken in the last 20 or so years. This research can be divided into the following broad categories:

- Post earthquake related research (e.g. Hendersen 1937, Lensen & Suggate 1968, Lensen & Otway 1971, Adams 1981, Pearce & O'Loughlin 1985).
- Landslide hazard research at specific localities (e.g. Nathan 1984, Power & Anderson 1992, Metcalf 1993, McSaveney & Davies 1998, Yetton 1999).
- Geological studies of historical and pre-historical landslips (e.g. Whitehouse & Griffiths 1983, Whitehouse and McSaveney 1986, 1989, Pearce & 0'Loughlin 1985).
- Impact reports on major recent individual slips (Hancox *et al*. 1999, Hancox *et al*. 2000).
- Landslide dams and lakes (e.g. Adams 1981, Perrin & Hancox 1992).

3.5.2 Research on Production Forestry Effects on Landslides

Laffan (1979) studied a 365km^2 area around the Punakaiki-Charleston area to distinguish the landslide potential in areas of production forestry. He created five classifications for landslide potential based on nine soil types identified. These ranged from Negligible to Very Severe. Laffan reported that:

"The results generally show a greater incidence of landsliding in disturbed than in undisturbed forest. Woodpecker Soils which had been clear felled and have a cover of grass and scrub showed the greatest percentage area affected by landslides…It is concluded that soils with very severe landslide potential (class 5), are not suited for primary production and the existing indigenous forests on them should remain undisturbed as protection forests".

An important point noted by Laffan, which is very relevant to the West Coast was:

"The impact of road construction on slope stability in the region has not been fully assessed. Studies overseas have indicated a high level of slide erosion resulting from road construction on potentially unstable slopes. In the Charleston-Punakaiki region, any road on soils with severe landslide potential must be constructed to high engineering standards to minimise the problems of instability…At least 7 of the 9 landslides in the Tiromoana area are attributable to such undercutting".

3.5.3 Southern Alps Landslides

Whitehouse & Griffiths (1983), studied large rock avalanches in the central Southern Alps, to determine their frequency of occurrence and potential hazard. Forty-two rock avalanches with an arbitrary volume of greater than $1x10^6m^3$ were measured and dated (by various techniques). Although only five of the samples were on the West Coast Region, the results are still applicable. The report also notes that such large-scale landslide events are rare in human lifetime but commonplace on the geological time scale; thus, generally the hazard is remote but may be significant in special circumstances and worth considering in the development of mountain lands.

Hovius *et al*. (1997) and Hovius (2000) produced very technical papers assessing the probability of rainfall generated landslides on the western side of the Southern Alps. The papers were based on the analysis of an aerial photograph record spanning 60 years. Although the papers were focussed on geological and geomorphological processes, some interesting hazard information can be extracted. They found that:

- The probability of 1 million m^3 (10 hectare area) landslide occurring is about once in thirty years on average (0.03 chance per year).
- A 50 million m^3 landslide would occur about once in 500 years on average.
- Bedrock landsliding is the principle erosion component on the western side of the Alps (i.e. usually deep seated, large volume).
- Landsliding is the dominant mass wasting process in the Southern Alps.
- Sediment discharge from the western side of the Alps is dominated by landslide material (thus related to river aggradation/avulsion and landslide dams. See sections 2.6. and 3.5.2 respectively).

The Institute of Geological and Nuclear Sciences (GNS) is currently compiling a landslide database for the whole country (Hancox 1998, Hancox, GNS, pers.comm.). The project is based on information derived from aerial photographs and scientific/technical reports and publications. Initial efforts have concentrated on landslides with volumes of greater than 100 000m^3, and almost of these have been recorded. Some smaller landslides have also been recorded. Information such as landslide type, rates of movement, and landslide ages etc, will be added to the database as it becomes available. The information is being recorded in GIS format and is available for purchase, the price dependent on the detail requested by the client.

GNS has also completed a study describing the conditions and effects of historical earthquake induced landslides in New Zealand (Hancox *et al*. 1998). The study was based on 22 earthquakes. The main findings were:

- Modified Mercalli intensity (MM, see Chapter 5, Section 5.4.2) of MM6 was the minimum shaking intensity required for landsliding, although very small slides occurred at about MM5. The most common intensities for significant landsliding were MM7-MM8, during earthquakes of equal to Magnitude 6 (M6, see Chapter 5, Section 5.4.1).
- The maximum area in which earthquakes induce landsliding, ranges from about 100km^2 at M5 to 20 000km^2 at M8.2.
- Landslide size is strongly dependent on magnitude, intensity and distance from the epicentre.
- Smaller slides (equal to, or less than 104m^3) are formed at distances of 200-300km from the epicentre during larger earthquakes of M7-8, with intensities of at least MM6.
- Larger failures (equal to, or greater than 105m^3) occurred at distances of up to 100km from the epicentre, for earthquakes equalling M6 with intensities of MM8-10.
- *"Overseas, earthquake induced landslides have often occurred at greater maximum distances at lower shaking intensities (MM5), and affect larger areas, probably due to a combination of topographic, climatic, geologic and seismic factors".*

- After earthquake magnitude and intensity, landsliding is most strongly controlled by topography, and rock/soil types, with most failures occurring on moderate to very steep slopes (20^o-50^o).
- Rock and soil falls on very steep cliffs, gorge escarpments, gravel banks and unsupported man-made cuts were the most common landslides during an earthquake.
- A good correlation was found between landsliding and rock/soil type, and the fault rupture zone indicated by aftershocks and regional seismicity levels.

3.5.4 Landslides from the 1929 Murchison Earthquake

Pearce & O'Loughlin (1985) investigated landslides produced by the 1929 Murchison Earthquake, to determine their influence on the geology and topography. The study area was in the epicentral region of the earthquake, around the upper Buller River Catchment – Karamea area (much of this is now in the Tasman District, but still applicable for hazard research in the West Coast region). This research showed over 1800 landslides larger than 0.25ha occurred in an area of 1 200km^2 (about 25% of area in which earthquake generated landslides occurred), and an estimated 2.5x10^{8}m^3 of debris was transported in the study area. Land sliding was found to be most common in well-bedded and jointed, calcareous, Tertiary mudstones, and fine sandstones, on scarp slopes in areas of gentle to steep dip. In mudstones of moderate to steep dip, scarp faces orientated away from the seismic wave origin were particularly prone to land sliding. Large dip-slope landslides were common in thick-bedded Tertiary mudstones, and in granitic rocks, landslides were generally smaller, shallower and composed of finer grained debris than those of sedimentary rocks.

Pearce & Watson (1986) undertook research of a similar nature. They investigated the effects of landslides generated during the Murchison Earthquake on sediment budgets over a 50 year period, in the Matiri River catchment – a tributary of the upper Buller River. The main findings of this paper were that:

- Land sliding delivered up to about 400 000m^3/km^2 of sediment to stream channels.
- 1st to 3rd order channels were buried to depths of up to 10m with sedimentary rock debris for distances ranging up to 2 000m.
- Little sediment has been transported out of a large portion of the study area because of the coarse grain size of the sedimentary rock, debris and trapping of sediment in landslide dammed lakes.
- Sand to pebble size debris originating in granitic rocks had travelled less than 10km.
- At least 50-75% of granitic debris is retained in the 4th order catchment 50 years after the earthquake.
- Earthquake induced landsliding is the main sediment supply mechanism in the area.

3.5.5 Otira Gorge Landslides

In recent years landslide research has concentrated on hazard classification and prediction at specific sites. Not surprisingly these studies have concentrated on areas of high public use (eg tourist areas, state highways, urban areas). In this respect, the landslide hazards in the Otira Gorge area (SH73) came under close scrutiny in the 1980s, as roading alternatives for the zig-zag were considered. In a series of reports by Whitehouse (1986), Whitehouse & McSaveney (1986, 1989), and Whitehouse & Williman (1986), the geology, geomorphology and climate of the Otira –Arthur's Pass region were examined in detail. This lead to the identification and classification of types of landslides threatening SH6, and each landslide being assigned as a low, moderate high or very high risk. Along a 3.6km stretch of the Otira Gorge road, Whitehouse & McSaveney (1986, 1989) identified 12 high risk and 13 very high risk landslide sites, and in another 1.9 km long stretch, there were nine very high risk landslide sites. Some of the risks and effects of these hazards in the Otira Gorge have been reduced due to road relocation from the zig-zag to the viaduct. However, the rest of the hazards identified by Whitehouse (1986), and Whitehouse & McSaveney (1986, 1989), between the Otira Gorge and Jackson's are still applicable.

A similar study by Paterson (1996) described in detail, the landslide hazard between Arthur's Pass and the Otira Gorge. This report focussed on how various types of slope failures would affect the proposed engineering options for relocating the highway. Paterson described the geology, geomorphology, climate and seismicity of the region, as well as individual types of slope failures (and their history of movement) at specific sites along SH73. It was noted that the Otira Gorge section of the highway was the most vulnerable to slope failures, that fatalities had occurred due to rockfalls (no details are given) and that:

"A further large rock avalanche at the Zig Zag is possible, but the probability of occurrence is low. There is no surface evidence to indicate that such a failure is imminent, but it remains a possibility in the event of a large earthquake. This could result in the damage, or burial of the viaduct. Potential for future rock avalanches during very strong earthquake shaking (MM8) also exists on the ridge north of the Zig Zag".

3.5.6 Punakaiki Rockfalls

Nathan (1984) examined the distribution of fallen rocks from the cliffs around Punakaiki township to establish rockfall hazard zones in the settlement. The Press (27.9.1984) quoted Nathan as saying:

"Two small rock falls from the limestone cliffs have occurred in the last year…From the distribution of fallen blocks, it is clear there is a danger to the houses immediately west of SH6. A hazard zone can reasonably be defined along the outer edge of the fallen blocks, and it is recommended that no building be allowed within the proposed zones."

It was also noted by Nathan that larger blocks probably fell during earthquakes and smaller rock falls were rain induced. Nathan's hazard zone could be over simplistic, as debris from further out of the zone may have been removed during development of the area.

Landslides were included in Cooper's (2000) comprehensive thesis investigation of natural hazards in the Buller district (discussed in previous chapter). All mass movement types were defined in detail by Cooper, and were classified using the HAZCLAS system, and along with additional information formed the basis of the landslide hazard register in HAZREG. Cooper used Punakaiki as a case study to test the system where multiple hazards exist, with the township being identified as being subject to six distinct types of hazard. The resulting analysis extended the rockfall hazard zone of Nathan (1984) almost 100m seaward to include nearly all the houses and sections in the village adjacent to the cliffs. Cooper concluded that further field investigations and analysis was required for more precise definition of landslide hazard zones at Punakaiki.

In a peer review of Cooper's thesis for the Buller District Council, Yetton (2001, *in* McCahon & Yetton 2001) was of the opinion that Cooper's rockfall hazard zone for Punakaiki was too wide. His opinion was based on his own field observations, suggesting Cooper had misinterpreted geological evidence, left out critical geological information, and her rock trajectory model analysis was too simple. Yetton acknowledged that Cooper's work was never intended to present a final, definite hazard zone for Punakaiki, and that the value of her work lies in the hazard issues she had raised. He concluded: *"While some may consider this to be adverse and negative publicity that is detrimental to property values, it is much better to have the issues raised in this way than after some hazard event that has resulted in serious consequences".*

3.5.7 Little Wanganui Landslides

Rose & Anderson (1990) and Power & Anderson (1992) produced geotechnical reports examining the rock fall hazard at Little Wanganui, to determine if the subdivision is a safe place for habitation. The Rose & Anderson (1990) report was of limited scope and found to be erroneous in the fact that major failures of the cliff face during the 1929 Murchison earthquake were not identified. Power & Anderson (1992) produced a revised report detailing the engineering geology of the cliff structure, the geomorphological processes acting on the cliff, and the history of slope failures. From this, it was concluded that the most important hazard identified was debris flow, and that most of the subdivision was at risk from large, rapid debris flows triggered by either earthquake shaking or heavy rainfall, and that such failures would be disastrous for occupants of the houses in the affected areas.

Yetton (1997) also examined the cliff stability at Little Wanganui from an engineering geology perspective and found that rock falls, debris flows and basal slides (following weathered surfaces) had all affected the subdivision in the recent past. Rock falls were found to be the most common form of failure. Yetton also considered that another debris flow of similar magnitude to the 1929 example occurred within the last 250 years. The major findings of Yetton were that:

- Rock falls were potentially serious on a local scale (property was more likely to be affected than the occurrence of injury or loss of life).
- Block slides of similar magnitude to historical examples would be catastrophic with likely injury or loss of life.
- He agreed with the assessment of risk and the hazard zoning of Power & Anderson (1992).

Further investigations by Brown (1997) generally agree with most of the findings of Power & Anderson (1992), and Yetton (1997). However, one major discrepancy exists between Yetton and Brown, relating to the mitigation of the hazards. Yetton (1997) stated: "*There are no feasible remedial methods to stop this type of failure developing*". He goes on to suggest that the only way to mitigate the risk is to abandon the site. In contrast, Brown (1997) reported:

"...that the area could be stabilised carrying out suitable earthworks. This would involve removing all the unstable material from the cliff face, as well as providing passive restraints to other vulnerable areas…It is technically feasible to do such work, although it will require landowner permission, resource consents, a suitable dumping site, and adequate funding".

Brown recognised that more engineering studies and investigations were required to determine the right type of preventative methods to be undertaken.

3.5.8 Franz Josef Area Landslides

As part of a natural hazard assessment for Franz Josef township, McSaveney & Davies (1998) described the potential threats from debris avalanches, debris flows, rock avalanches, and landslide dams. They concluded that only the slope immediately above the township poses a direct threat due to rock avalanche runout, but although it *could* fail in the next great earthquake, it is *unlikely* that it will fail. This was deduced by the fact that the slope does not appear to have failed since the last glaciation (13 000 ago), and hence has survived at least 50 major episodes of ground shaking (equating to Alpine Fault movement every 250 years or so). Debris flows were considered only to be a problem if a particularly large one is generated in the Callery Gorge during the break-up of an earthquake generated landslide dam, where there is likely to be a huge quantity of material in the channel bottom to be picked up by the flood.

3.5.9 Fox Glacier Valley Landslides

Hovius (1995) produced a landslide hazard assessment of the Fox Glacier valley for the Department of Conservation. This report identified landslide erosion sites that posed a direct threat to motor and pedestrian traffic in the valley. The three major landslide hazard sites identified were the catchments of Undercite Creek, Yellow Creek, and the Straight Creek/Boyd Creek complex. Hovius found that precipitation was the most common cause of land sliding in the valley, although he did recognise the potential of large magnitude earthquakes to generate landslides that would alter the profile of the valley completely. A sequence of events was identified that preceded large scale collapse of steep valley sides in the region: A few years before wholesale collapse, unstable valley sides would begin to develop and show elongate, arcuate streaks in which weathered bedrock would be exposed, due to minor debris avalanches. Hovius observed these scars on photographs preceding the January 1994, Undercite Creek event (~1-1.3 x $10^6 m^3$) and noted that similar scar patterns recognised in many places between Hokitika and Haast, have subsequently produced large magnitude landslides and debris avalanches.

Hovius concluded that visitor traffic to and from the glacier terminal is mainly on the true right hand side of the valley and is exposed to the following hazards:

1. Large rock avalanches from the Undercite Creek Catchment and adjacent steep rock faces.
2. Re-occurring debris flows and mudflows from the Yellow Creek Catchment.
3. Instability of channel sides below the Yellow Creek Fan.
4. Slope instability between White Creek and the glacier terminal.
5. Occasional debris flows from an un-named catchment to the NW of the upper Yellow Creek basin.
6. Debris avalanching in the lower valley side between Undercite Creek and Yellow Creek.

Hazard 1 was considered the most immediate threat and a list of management options and recommendations was presented to address this, and the other five hazards.

3.5.10 Landslides in the Greymouth Urban Area

An engineering geology thesis by Metcalf (1993) examined landslides around the Greymouth urban area in terms of their structure and history of movement, and then created hazard zones for the study area. Metcalf identified seven types of failure ranging from rock block slides to debris flows, and found that intense and prolonged rainfalls were the primary cause of landslides involving surface material in Greymouth. He also noted that earthquakes were an important initiating factor and will continue to be so in the future. The main conclusion of Metcalf was that the vast majority of the Greymouth area fell in the Negligible to Low hazard zones, with numerous patches of Medium Hazard, and very few patches of High Hazard. Metcalf's hazard zones were defined as thus:

- HIGH: Slope movement having occurred within the last 50 years.
- MEDIUM: No sign of slope movement activity in the last 50 years.
- LOW: Slope angle greater than 15^{o} with no history of slope movement.
- NEGLIGIBLE: Slope angle less than 15^{o} with no history of slope instability.

Metcalf's study is useful for building and planning purposes, in providing detailed maps identifying relative slope stability in the Greymouth urban area, and engineering geological documentation relating to the slope structures. However, for planning purposes, the time scales in the hazard zones may need refining. For example, most buildings are designed for a 100 year life and thus Metcalf's medium hazard zone may underestimate the actual risk of slope failure.

3.5.11 Landslide Dams (and Lakes) General Research.

Landslides that block river channels by forming dams and lakes, pose a real threat to the West Coast, as is shown by the frequency of their occurrence in the historic record. Landslides forming such dams and lakes can be generated by *any* means (i.e. earthquake, rain, other), and present a potential flood hazard both upstream of the slide, as water backs up and forms the lake, and downstream of the slide, when the dam fails allowing the lake to drain. Research in recent years has focussed on this phenomenon. Cowie (1957) and Benn (1990) recorded numerous cases of landslide dams, as part of their respective flood research. These sources are descriptive only and were intended to emphasis the location, frequency, causes, and effects of flood hazards.

Adams (1981) presented a detailed study of historical and pre-historical earthquake landslide dammed lakes in New Zealand, focussing on the earthquake conditions needed to form them. He found that ground shaking intensities of MM9 – MM10 were required for the formation of many earthquake dammed lakes in a given area, and in New Zealand only earthquakes greater than M6.75 are likely to form dams and lakes. Adams described the dams and lakes formed by the major 1929 and 1968 West Coast earthquakes (Murchison and Inangahua), noting that the Buller Catchment and Karamea area was particularly affected in both cases. Many of these significant dams are now in the Tasman District but still need to be considered in this report as they are in the Buller Catchment, and thus still geographically on the West Coast. To emphasise the hazards these dams and lakes present to the region, Cowie (1957) and Adams (1981) noted that the most serious aftermath of the Murchison Earthquake was the breaching of an earthquake dam on the Mokihinui River (Lake Perrine – 1.6km in length and 20m deep). When the dam breached, the lake lowered by 8m and the resultant wall of water inundated the township of Seddonville, completely submerged some houses, and moved a hall nearly 100m downstream. Adams concluded *"To date, the formation and failure of landslide dammed lakes have caused little damage in New Zealand, although they are a significant geologic hazard."*

Perrin & Hancox (1992) described the geological and geomorphological characteristics of landslide dammed lakes in New Zealand, and the potential hazard they present. They noted: *"The particular hazard presented by landslide dammed lakes is that of sudden and catastrophic failure of the natural dam"*, and that they were unusual by posing a flood hazard both upstream during the lake formation, and downstream, when the dam failed. Major findings of this study were:

- Most landslide dams were short lived and fail within a few days or years (although some do last a long time).
- Most rainfall induced landslide dams are small and ephemeral. Some very large ones have occurred but these have been the reactivation of old landslides by the river undercutting the toe rather than by rainfall.
- South Island landslide dammed lakes are nearly all in hard rocks such as schist, granite and gneiss.
- The only known example of landslide dammed lakes in Tertiary rocks are from the West Coast (Falls and Glasseye), formed during the Murchison Earthquake.
- Rain induced landslide dams tend to be more fluid and spread out than earthquake generated dams.

An engineering geology thesis in preparation by Tim Nash (Geology Dept, Canterbury Universiy), is examining landslide dams generated by the 1929 Murchison Earthquake and the 1968 Inangahua Earthquake. The primary focus of this investigation is to try and determine why some earthquake landslide dams remain intact indefinitely and why some fail at different times (often quite rapidly after filling first). Bell (2002) stated: *"..that such work is an essential part of the hazard and risk management process for a territorial authority whose jurisdiction includes steep topography and numerous seismotectonic sources for landslide dam generation"*

3.5.12 Callery River Landslide Dam Research

Dam break flood hazards caused by landslides in the Callery River valley (right bank tributary of the Waiho River) are considered to pose a major threat to Franz Josef township. Davies & Scott (1997) identified past and potential future sites of landslide dams in the Callery River valley, based on geological and geomorphological evidence. They found that the largest threat was from a site about 4km up from the confluence with the Waiho River, where a dam of around 90m in height, and containing about $13x10^6m^3$ could potentially form. Sites of potential landslide dam formation further upstream were also identified although they were considered less of a risk. Davies & Scott assumed any landslide will block the valley due to it's steepness and that the probability of such an event will be associated with significant earthquake occurrence. It was thus determined that such an event has at least a 1% chance of occurring in any year (equivalent to 1 in a 100 years). Rainfall was also noted as a potential landslide trigger mechanism. An addendum to this report quotes a report dated 1957, from the residents of Franz Josef to the Tourist Hotel Corporation, as saying:

"Another possible factor contributing to the instability is the possibility of major landslides in the Callery Gorge. One such landslide in 1930 completely blocked the Callery for one day. The resulting flood was extremely high and the debris from these slips, when carried further down add to the river bed problems".

The significant point about this event was that it occurred in fine weather and no earthquakes were reported at the time.

McSaveney & Davies (1998) briefly reviewed the landslide information of Davies & Scott (1997), and Hovius *et al*. (1997). Using the magnitude/frequency data of Hovius *et al.* (1997), McSaveney & Davies calculated that the probability of a landslide dam break with a flood flow of around 1 000m^3s^{-1}, could be expected about three times per hundred years.

Ollett (2000) identified five potential sites of landslide dam formation in the Callery, and calculated landslide volume and flood discharges for various dam scenarios. His study used numerical models based on aerial photographs and 1:50 000 scale contour maps. Ollett found that peak flows at the Waiho/Callery confluence depended on landslide location and volume. For an extreme case (based on dam remnants described by Davies & Scott 1997), the maximum dam break flood discharge was calculated at 14 000m^3s^{-1}. However it was noted that medium sized dams with a sediment volume of around 1 000 000m^3 and potential flood discharges of 2 000-3 000m^3s^{-1} presented the greatest risk to Franz Josef, as these dams would fill and fail quickly, and thus provided the minimum warning time.

Davies (2002) re-assessed the dam break hazard findings of Davies & Scott (1997). This latest examination was based on recently published information pertaining to landslide frequency (Hovius *et al.* 1997), earthquake frequency (Yetton *et al.* 1998), dam break flood simulations (Ollett 2000), and the Mt Adams landslide dam (Hancox *et al*. 2000). Taking all these factors into account, Davies concluded that the total annual risk[1] of a dam break flood at Franz Josef was between 0.01 and 0.02 (1% - 2% chance in any given year), and that a 1 million m^3 landslide dam should produce peak flood discharges of 2 000-3 000m^3s^{-1}. Such discharges would cause severe damage to the SH6 bridge, accommodation facilities adjacent to the bridge, as well as considerable damage to surrounding assets.

3.5.13 Mt Adams Landslide Dam Research

Hancox *et al*. (1999, 2000) described in detail the 6th October 1999 Mt Adams landslide, and dam formation on the Poerua River. The landslide contained 10-15 million m^3 of sediment, brought down from 1 800m up the mountain. The landslide formed a dam about 100m high and formed a lake containing about 5-7 million m^3 of water. The landslide caused a local earthquake of M3.2. No immediate cause of the landslide was identified, as it had not been raining and no earthquakes had been recorded. The two reports described the sequence of events that lead to the failure of the dam on the 12th. The dam breach was estimated by Hancox *et al*. (2000) to be about 20 minutes in duration. The flood level at the SH6 bridge indicated a peak flow of 500-1000m^3s^{-1}, which was considerably less than the possible maximum flows that were estimated prior to failure. At the dam, the discharge was probably in the order of 1 400m^3s^{-1}. By the 22nd about half the dam had eroded away and considerable aggradation of the Poerua River downstream was noted, particularly at McKenzie's farm.

Based on hydrographs from physical and computer models of dam break flood, and from field records, Davies (2002) suggested that the peak flow at the dam must have been in the order of 2 000- 2 500m^3s^{-1} and the average flow would have been about 1 000m^3s^{-1}.

[1] Total risk = combined chances of rainfall and earthquake generated landslides

3.6 Gaps in Knowledge and Information

As can be seen from the above, a considerable amount of research relating to landslides has been undertaken in the region. Nonetheless, for hazard planning and management, it would be useful for more information to be collected in particular areas. In order of priority these would be:

1. Landslide inventory development.
2. Landslide hazard maps.
3. Landslide generating research.

Each of these areas is examined in more detail in the following sub-sections.

3.6.1 Landslide Inventory Development

Continuing to develop the landslide inventory already started in this report is considered to be important baseline information gathering. It is assigned the highest priority, as the other tasks of hazard mapping and generating process research require this baseline information.

An important output of this work will be to identify locations where repeated landsliding occurs, particularly during heavy/prolonged rainfall events. This is important for identifying where engineering lifelines such as transport routes, power lines, telecommunication links, and water supplies are vulnerable, and ultimately, where people/communities get isolated or stranded. It is appreciated that there is difficultly in predicting where future landslides will occur, especially in areas where none have been recorded historically. However, in many locations, landslides can almost be *expected* during storms, such as the area between Jackson's and the Otira Gorge, the Coast Road between Greymouth and Westport, the Weheka Hills between the glaciers, and the Buller Gorge.

Obvious information sources to extend the landslide inventory would include further newspaper searches (Westport and Hokitika newspapers as most details thus far have been obtained from the Greymouth Evening Star, which naturally concentrates on the Grey District), damage records/reports from Tranzrail, Transit, district councils, Telecom, and geotechnical consultants such as Opus. The three local newspaper offices and the three district councils are very accommodating in allowing access to papers and files (i.e. free of charge), but information from the other mentioned sources might have to be paid for.

It is considered that this work could be undertaken by:

- WCRC staff: On-going collection of relevant newspaper articles, reports or any other information as it becomes readily available, and adding details to the inventory.

- University Students & Consultants: Retrospective searches for landslide information from technical reports, newspapers, photographs from museums and personal collections. WCRC staff could also do this but it is considered that such searches would not be appropriate use of the limited staff resources.

3.6.2 Landslide Hazard Maps

From the information contained in the inventory, basic landslide hazard maps should be compiled, showing areas of historical sliding accompanied by annotation describing historical damage, type of failure, debris flow paths, debris depths, frequency of occurrence etc. These maps could be a continuation of Cooper's hazard map system, or be similar to the 1:10 000 scale flood hazard field maps already compiled by the WCRC. Mapping should initially concentrate on areas where infrastructure or assets are at high risk. Such areas would include SH73 between Kumara and the top of the Otira Gorge, SH6 in the Buller Gorge; between Greymouth and Westport (the Coast Road), and between Franz Josef and Fox Glacier (the Weheka Hills), SH67 between Granity and Little Wanganui, and the Lake Brunner Road between Inchbonnie and Stillwater.

Construction of such maps could be undertaken by:

- WCRC staff, or consultants: If staff resources were available this work could be undertaken by WCRC staff as done with the flood hazard maps, otherwise it is best to be contracted out to appropriate consultants. It would also be worth considering the purchase of relevant GIS landslide database information from GNS.

- Specialist Geotechnical Consultants: If more detail were required (e.g. engineering geological documentation, probability analysis etc), specialist slope stability consultants would need to be employed.

3.6.3 Landslide Generating Factors

Relatively little research investigating rainfall as a landslide generating factor in the region has been undertaken, when compared to earthquake generation (with the exception of Hovius *et al.* 1997). However, as is clearly demonstrated, rainfall is by far the most common landslide generating mechanism, and a better understanding of its influence in landslide generation is fully warranted. Of particular interest would be defining the rainfall conditions that commonly generate slides, and the relationships of rainfall duration/intensity to slope aspect and angle, soil and rock type, and to the distribution, size and type of landslides. Information of this nature would help to identify areas at risk from potential land sliding.

This type of research would be particularly suited to:

- Post-graduate thesis study, in the fields of Engineering, Natural Resources Engineering, Geology, or Physical Geography (Geomorphology or Alpine Studies).

The effects of undercutting slope toes needs to be considered by the WCRC and the District Councils when processing future resource consent of road construction and building permit applications. Laffan (1979) noted that little was known about this phenomenon on the West Coast, even though it was a significant factor in his study area. Collecting data of this nature is the responsibility of those actually planning and constructing roads or other structures undercutting slope toes.

3.7 Summary

Landslides are a frequent occurring natural hazard on the West Coast. Although most recorded landslide events have been small, and reported damage has been mainly confined to disrupting transport arterials, they have nevertheless caused damage of catastrophic proportions historically. Landslides events are most commonly associated with intense or prolonged rainfall events, and in some areas of the region, they can almost be expected to occur during such rainfalls. Hence, it follows that landslides are very commonly associated with flood events.

Landslides are also associated with moderate to large-scale earthquakes, although historically this source of generation has been far less common than rainfall. Unknown/other sources of landslide generation are relatively uncommon although they are still present a significant factor of risk (e.g. Mt Adams)

Landslides have frequently caused considerable damage, inconvenience, injury and loss of life in the region, and will continue to do so in the future. Landslides have been ignored somewhat in terms of hazard planning, and until now, there has been little comprehension of how frequently such events have occurred over the region as a whole. The inventory compiled for this report highlights just how common landslides are, and suggests that they deserve a higher profile in terms of hazard planning and information gathering than has been done in the past: this would to help minimise potential risks in the future. At the very least, the inventory created in Appendix 3 should be upgraded by a thorough historical search of the sources mentioned, and recording subsequent events from newspaper articles etc. This would help to define areas prone to repeated land sliding, and landslide magnitudes and frequencies.

Ultimately, for hazard planning and management purposes, landslide hazard maps should be created, especially for areas of intense development and along main transport links. Such hazard maps have obvious implications in the issuing of building permits and resource consents for development in hazardous areas, and for engineering lifelines planning purposes.

3.8 Landslide References

ADAMS, J. 1981: Earthquake Dammed Lakes in New Zealand. Geology, Vol. 3, pp 215-219.

BENN, J.L. 1990: A Chronology of Flooding on the West Coast, South Island, New Zealand. The West Coast Regional Council, Greymouth. 159p.

BENN, J.L. 1992: Review of Earthquake Hazards on the West Coast. The West Coast Regional Council, Greymouth. 62p.

BELL, D.H. 1994: Landslide Hazards. *In* Natural Hazards In Canterbury. Canterbury Regional Council Report 94 (19), pp 55-76.

BELL, D.H. 2002: Letter to Terry Archer (Manager Regulatory Services), Buller District Council, from Dave Bell (Senior Lecturer, Department of Geological Sciences), University of Canterbury. 18 March 2002. 2p.

BROWN, I.R. 1997: Draft of Brief of Evidence, Little Wanganui: Smaill & Ors vs. Buller District Council & Ors. June 23 1997. 6p.

COOPER. L.L. 2000: Geotechnical Hazard Analysis, Management and the Development of Hazreg for the Buller District. MSc Thesis, Department of Geological Sciences, University of Canterbury. Vol. 1 (205p), Vol. 2 (Appendices).

COWIE, C.A. 1957: Floods in New Zealand, 1920-1953, With Some Notes On Earlier Floods. New Zealand Conservation and Rivers Control Council, Wellington. 239p.

DAVIES, T.R. 2002: Landslide-Dambreak Floods at Franz Josef Glacier Township, Westland, New Zealand. New Zealand Journal of Hydrology, Vol 41 (1), pp 1-17.

DAVIES, T.R., & SCOTT, B.K. 1997: Dambreak Flood Hazard from the Callery River, Westland New Zealand. New Zealand Journal of Hydrology, Vol. 36 (1), pp 1-13.

de LANGE, W.P. & HEALY, T. 1986: New Zealand Tsunamis 1840 – 1982. New Zealand Journal of Geology and Geophysics, Vol. 29 (1), pp 115-134.

HANCOX, G.T. 1998: GNS Database of Large Landslides in New Zealand. Geological Society of New Zealand/New Zealand Geophysical Society, 1998 Joint Conference, 30 November –3 December: Programme and Abstracts. Edited by Basset, K.N. & Nobes D.C. Geological Society of New Zealand, Wellington. p104.

HANCOX, G.T, PERRIN, N.D., & DELLOW, G.D. 1998: Historical Earthquake-Induced Landsliding in New Zealand. Geological Society of New Zealand/New Zealand Geophysical Society, 1998 Joint Conference, 30 November –3 December: Programme and Abstracts. Edited by Basset, K.N. & Nobes D.C. Geological Society of New Zealand, Wellington. p105.

HANCOX, G.T., McSAVENEY, M.J., DAVIES, T.R., & HODGSON, K. 1999: Mt Adams Rock Avalanche and Subsequent Formation and Breaching of a Large Landslide Dam in the Poerua River, Westland, New Zealand. 22p plus Maps and Photographs.

HANCOX, G.T., McSAVENEY, M.J., DAVIES, T.R., HODGSON, K, & DANIEL, R. 2000: The 1999 Landslide Dam in the Poerua River, Westland, New Zealand. *In* Dams-Management and Best Practice. NZSOLD Symposium, Wellington. Institute of Professional Engineers of New Zealand (IPENZ). Proceedings of Technical Groups, pp 81-94.

HAWLEY, J.G. 1984: Slope Stability in New Zealand. *In* Natural Hazards In New Zealand New Zealand Commission for U.N.E.S.C.O. (Edited by Spenden, I., and Crozier, M.J.), pp 88-133.

HENDERSEN, J. 1937: The West Nelson Earthquakes of 1929. New Zealand Journal of Science and Technology, Vol. 4, pp 65-143.

HOVIUS, N. 1995: A Geological Hazard Assessment for the Lower Fox Valley, Anno 1994: Consevation Advisory Science Notes 121. Department of Consevation, Wellington. 14p plus Maps.

HOVIUS, N. 2000: Macroscale Process Systems of Mountain Belt Erosion. *In* Geomorphology and Global Tectonics. (Edited by Summerfield, M.A.), pp 77-105.

HOVIUS, N., STARK, C.P., & ALLEN, P.A. 1997: Sediment Flux from a Mountain Belt Derived by Landslide Mapping. Geology, Vol. 25 (3), pp 231-234.

JOHNSTON, M.R. 1974: Major Landsliding in the Upper Buller Gorge, South West Nelson. New Zealand Institute of Engineers Transactions, Vol. 1, pp 239-244.

KEEFER, D.K. 1984a: Landslides Caused by Earthquakes. Geological Society of America Bulletin. Vol. 95, pp 406-421.

KEEFER, D.K. 1984b: Rock Avalanches Caused By Earthquakes: Source Characteristics. Science, Vol. 223, pp 1288-1290.

LAFFAN, M.D. 1979: Slope Stability in the Charleston-Punakaiki Region, South Island, New Zealand: Landslide Potential. New Zealand Journal of Geology and Geophysics, Vol. 22, pp 183-192.

LENSEN, G.J & OTWAY, P.M. 1971: Earthshift and Post-Earthshift Deformation Associated with the May 1968 Inangahua Earthquake, New Zealand. *In* Recent Crustal Movements, Royal Society of New Zealand, Bulletin 9, pp 107-116.

LENSEN, G.J. & SUGGATE, R.P. 1968: Inanagahua Earthquake – Preliminary Account of the Geology. *In* Preliminary Reports on the Inangahua Earthquake, New Zealand, May 1968. D.S.I.R. Research Bulletin 193, pp 17-36.

LOWE, R.J. 2001. Letter from Rick Lowe (Operations Manager, WCRC) to Paddy Luxford (Babbage Consultants Ltd, Auckaland). 16 May 2001. 2p.

McCAHON,I., & YETTON, M.D. 2001: Peer Review of Information Regarding Punakaiki Rockfall and Flood Hazard Assessment and Zonation Included in the MSc Thesis Entitled "Geotecnical Hazard Analysis, Management and the Development of Hazreg for the Buller District". Letter to Terry Archer (Buller District Council) from Mark Yetton (Geotech Consulting Ltd), 17 September 2001, 15p.

McSAVENEY, M.J. & DAVIES, T. R. H. 1998: Natural Hazard Assessment for the Township of Franz Josef Glacier and its Environs. Report prepared for the West Coast Regional Council by the Institute of Geological and Nuclear Sciences Ltd (McSaveney), and Department of Natural Resources Engineering, Lincoln (Davies). Client Report 44714b.10. 52p.

METCALF, P.L. 1993: Landslide Investigation and Hazard Zonation in the Greymouth Urban Area. Engineering Geology MSc Thesis (Geology Department, University of Canterbury). 184p plus Maps.

NASH, T. In Preparation: Engineering Geology Thesis (Dept of Geological Sciences, Canterbury University), Examining the Stability of Landslide Dams Caused by the 1929 Murchison Earthquake and the 1968 Inangahua Earthquake.

NATHAN, S. 1984: Rockfall Hazard at Punakaiki Township. Immediate Report K30/942. New Zealand Geological Survey, Christchurch.

OLLETT, P.P (2000): Landslide-Dambreak Flooding in the Callery River, Westland. Unpublished M.E. (Natural Resources) Thesis, Lincoln University. 91p plus Appendix.

PATERSON, B.R. 1996: Slope Stability Along State Highway 73 Through Arthur's Pass, South Island, New Zealand. New Zealand Journal of Geology and Geophysics, Vol. 39, pp 339-351.

PEARCE, A.J., & O'LOUGHLIN, C.L. 1985: Landsliding During a M7.7 Earthquake: Influence on Geology and Topography. Geology, Vol. 13, pp 855-858.

PEARCE, A. J. & WATSON, A.J. 1986: Effects of Earthquake–Induced Landslides on Sediment Budget and Transport Over A 50-Yr Period. Geology, Vol. 1, pp 52-55.

PERRIN, N. D., & HANCOX, G. T. 1992: Landslide Dammed Lakes in New Zealand-Preliminary Studies on Their Distribution, Causes and Effects. *In* Landslides (Bell, D. H., Editor), A. A. Balkema, Rotterdam. pp1457-1466.

POWER, J., & ANDERSON, C., 1992: Geotechnical Report; Assessment of Hazard and Risk to the Little Wanganui Subdivision. Report prepared by Barrett, Fuller and Partners for the Buller District Council, January 1992. 8p plus appendices.

ROSE, R., & ANDERSON, C. 1990: Engineering Geological Report, Little Wanganui Subdivision: Hazard and Risk Assessment of Slope Stability. Report Prepared by Barrett, Fuller and Partners, 2 November 1990, for the Buller District Council. 7p plus Appendices.

REA, J. 1991: Honey and Cheese (History of the Whataroa Area). The Greymouth Evening Star, Greymouth. 58p.

STIRLING, M., YETTON, M.D. PETTINGA, J., BERRYMAN, K., & DOWNES, G., 1999: Probabilistic Seismic Hazard Assessment and Earthquake Scenarios for the Canterbury Region, and Historic Earthquakes in Christchurch. Stage 1 (Part B) of Canterbury Regional Councils' Earthquake Hazard and Risk Assessment Study. Report prepared for Canterbury Regional Council by Institute of Geological and Nuclear Sciences, Geotech Consulting Ltd, and Natural Hazards Research Centre, University of Canterbury. 79p plus Appendices.

WHITEHOUSE, I.E. 1986: Arthur's Pass Roading Project; Geology, Geomorphology, and Climate. Works Consultancy Services Ltd, Christchurch. 21p.

WHITEHOUSE, I.E. & GRIFFITHS, G.A. 1983: Frequency and Hazard of Large Rock Avalanches in the Central Southern Alps, New Zealand. Geology, Vol. 11, pp 331-334.

WHITEHOUSE, I.E., & McSAVENEY, M.J. 1986: Hazard Assessment State Highway 73: Cass to Jacksons Via Arthur's Pass. Internal Report for the Ministry of Works and Development, Christchurch. 20p.

WHITEHOUSE, I. E., & McSAVENEY, M.J. 1989: An Alpine Highway At Risk. Streamland No.74. D.S.I.R. Publishing, Wellington. 4p.

WHITEHOUSE, I.E., & WILLIMAN, E.B. (1986): Arthur's Pass Roading Project: Hydrological Factors. Ministry of Works and Development, Christchurch. 13p.

YETTON, M.D. 1997: Evidence given by Geotech Consulting Ltd in the case of Smaill and Ors v. Buller District Council and Ors. 14p.

YETTON, M.D., WELLS, A., TRAYLEN, N.J., 1998: The Probability and Consequences of the Next Alpine Fault Earthquake. EQC Research Report 95/19 Prepared by Geotech Consulting Ltd, Christchurch. 161p.

YETTON, M.D. 1999: Doherty Creek Landslides, Greymouth Coal Field. Report prepared by Mark Yetton (Geotech Consultants Ltd) for the West Coast Regional Council. 18p.

4.0 COASTAL HAZARDS

4.1 Introduction

The region's coastline extends for 600km from Kahurangi Point in the north, to Awarua Point in the south. Trending along a NE-SW axis, the coast is orientated towards the dominant westerly wind and wave direction. Thus, for much of its length it is a high energy, open coast subjected to a variety of hazards including coastal erosion and accretion, storm surge, tsunami, and river mouth blockages. All have been historically recorded in the region (Benn & Neale 1992). Long-term sea level rise may exacerbate existing hazards, and may create new hazards in the future.

Coastal hazards of erosion and sea flooding have been recorded since the earliest times of European settlement (e.g. Rochfort 1870, Campbell 1878), and a variety of protection works have been historically used to combat the hazards, although most of these have been unsuccessful (Benn & Neale 1992). However, for large sections of the coast, little or no information relating to coastal processes exists, and thus coastal processes and hazards are generally poorly understood.

Several tsunamis have been recorded in the region (de Lange & Healy 1986, Benn 1992, Benn & Neale 1992). To date these have caused minimal damage, although there is the real threat of catastrophic damage from near-field tsunami generated by local earthquakes (Benn & Neale 1992, Goff *et al.* 2001).

This chapter covers the following topics:

- Causes of coastal hazards.
- Effects of coastal hazards.
- Magnitudes and frequency of coastal hazards.
- Coastal hazard research.
- Knowledge and information gaps.

4.2 Causes Of Coastal Hazards

4.2.1 Erosion/Accretion

Processes that cause coastal hazards have been discussed in detail in numerous reports (see following section on research), and were reviewed in Benn & Neale (1992). Therefore only a brief summary is appropriate for this report.

Coastal erosion occurs in two ways. First, when there is a net sediment volume *loss* from the beach, either by alongshore-offshore transport, being washed over the top of the beach to the backshore, or gravel extraction/mining operations. Secondly, when there is a net migration landward of a beach reference line, such as Mean Sea Level (MSL), vegetation line, beach crest or beach toe. This usually occurs with a combination of overtopping and sediment losses, and is common on barrier beaches.

Accretion occurs when there is a net sediment volume *gain* on the beach, from onshore-alongshore transport, coastal cliffs and rivers, or artificially supplied (as in beach reconstruction/renourishment programmes, or unauthorised dumping).

The degree of coastal stability is influenced by sea and wave conditions, sediment supply and beach type. Benn & Neale (1992) identified the following broad pattern (with a few anomalies) of beach types along the West Coast:

- South of Hunt's Beach-Bruce Bay: Sand and mixed sand-gravel beaches dominant.
- Karangarua- Punakaiki: Mixed sand–gravel beaches dominant.
- North of Charleston: Sand and mixed sand- gravel beaches dominant.
- Rocky coasts interrupt the above pattern where ranges meet the sea.

Sand and mixed sand-gravel beaches behave quite differently from one another, and hence erosion and accretion patterns and rates will differ on each type of beach. As yet little work has been done to correlate historical erosion/accretion rates with beach type throughout the region.

4.2.2 Sea Flooding

Coastal inundation is most commonly caused by the superimposition of several individual processes producing extremely high sea water levels, which is termed *storm surge*. These processes include:

- Astronomical high spring tides: Due to combined gravitational pull of the sun and the moon being aligned every 14-15 days.
- Wave set up: The onshore mass transport of water by wave action.
- Wind set up: When onshore wind causes water to pile up at the shore.
- Barometric up-lift: The inverse relationship that exists between sea level rise and air pressure. Although there are variations, as a general rule of thumb, water level rises 10mm for each mb drop in air pressure, below a mean air pressure of 1014mb over the ocean.
- Storm wave run-up: Wave height is proportional to wind speed, hence higher wind speeds cause larger waves, which in turn run further up the shore following breaking.

When the first four processes combine, deeper than usual water occurs in the nearshore zone. This leads to larger waves breaking at the shore, and subsequently, run-up occurring farther up the beach and inland. Storm surge events in the region are most closely associated with westerly winds, and El Nino conditions (de Lange 1996, Neale 1996).

4.2.3 Tsunami

Tsunamis are long period ocean waves (i.e. long time between crests) that are generated by disturbances of the water column from the sea floor to the surface. The most common modes of generation include:

- Shallow focus earthquakes involving a dip-slip displacement of the sea floor.
- Landslides (terrestrial or submarine origins) into open coastal waters or confined areas such as Fiords displacing the water body
- Volcanic eruptions ejecting material into the water or due to the coupling of atmospheric pressure waves with resonance of the water body.

Tsunamis are classified into the following two types:

- Far-field tsunamis, which are generated remotely from the target coast (trans-oceanic) and provide significant warning times for New Zealand, of up to 15 hours from around the Pacific Rim. Ridgeway (1984) reported

  "The hazard from tsunami of distant origin is perceived to come mainly from the South American Coast…The regions of highest risk are from the Bay of Plenty to Akaroa and from New Plymouth to Westport". Todd (2002) noted that *"…the West Coast is largely sheltered from these types of tsunamis generated in Pacific Ocean (due to the need to be reflected or refracted into the Tasman Sea)"*

- Near field tsunamis, which are generated close to the target coast and no effective warning time is available. They have been responsible for all of the historically recorded damage in the region (de Lange & Healy 1986), are likely to cause the most damage in the future.

4.2.4 River Mouth Blockages By Beach Sediments

Backwater flooding can occur when beach sediments block river mouths. This can occur due to rough seas depositing beach sediment across river mouths, or ironically, by lack of rainfall, leading to normal coastal processes (littoral drift and/or onshore sediment transport) becoming dominant over low-river flows. This has occurred on numerous occasions at many of the smaller river mouths such as Saltwater Creek near Paroa (Appendix 2), Watson Creek , Karoro (Benn & Neale 1992), and most notably at Okarito (Westland Catchment Board 1986, Benn 1990) and Punakaiki/Pororari River (Kirk 1988, Benn 1990). Even major rivers are prone to mouth blockages, such as the Hokitika in 1947 (Cowie 1957, Benn & Neale 1992), and the Arahura River mouth (Benn 1990). Apart from the investigations of Hastie *et al*. (1986) and Kirk *et al*. (1986, 1987) on the Buller River mouth, very little is known about river mouth dynamics (river/coastal interaction) in the region.

4.2.5 Sea Level Rise

The trend of sea level rise throughout the twentieth century is attributed to global warming, the associated thermal expansion of the oceans, and to a lesser degree the melting of polar ice caps. The Inter-Governmental Panel on Climate Change (IPCC 2001) stated that sea level has risen at a global average of 0.3m since the mid 1800s. Bell *et al*. (2001), incorporated New Zealand sea level data into the IPCC predictions, and found the most likely sea level rise for the country would be in the order of 0.16m by the year 2050 (just over 3mm/yr), and 0.4m by 2100 (just over 4mm/yr). Thus the rate of sea level rise is expected to accelerate over the next century.

Beaches try to maintain an equilibrium profile position in relation to the nearshore water depth, hence a long-term rise in sea level is associated with a potential retreat of the shoreline as the beach attempts to retain the relationship between profile position and water depth. An increase in sea level would also be *additive* to the components of storm surge and would lead to increases in nearshore storm wave heights and run up. Hence there is greater potential for beach erosion and/or hinterland inundation to occur during storm events.

4.3 Effects Of Coastal Hazards

Coastal hazards occur on different scales in time and space, and therefore the effects at any one location are dependent on the scales being considered. For example, sea level rise and long-term coastal erosion are slow gradual processes occurring on a regional scale, and thus, they are far more manageable and predictable than sudden, localised coastal changes incurred by storms, landslides (coastal cliffs) or tsunami events. Benn & Neale (1992) described the localised effects of coastal hazards throughout the region.

4.3.1 Coastal Erosion Effects

From north to south, the following effects of coastal erosion have been reported. The source of this information is Benn & Neale (1992) unless otherwise stated.

Kongahu – Little Wanganui:
Eroding since 1879 with farmland being the most affected, although SH67 at Little Wanganui has been periodically affected by dune blowouts, and the Little Wanganui School was relocated in 1937 because of erosion (Gibb 1978). The coast was severely affected by the 1929 Murchison earthquake with many coastal landslides, one of which generated a tsunami that caused damage at Farewell Spit (de Lange & Healy 1986).

Mokihinui River – Waimarie Settlement:
Historically eroding (Gibb 1978, Benn 2002), and subjected to sea flooding. Backshore gravels were bulldozed up in 1978 to try and stop sea flooding, and a stopbank was built in the 1970s to stabilise the river mouth.

Hector-Ngakawau-Granity:
History of stability is uncertain. Some authors considered that large fluctuations occurred within a trend of long-term stability (Gibb 1978, McMillan, 1983, Neale 1989), whilst Gower (1982), Hicks (1996) and Benn (2002) considered that long-term erosion was occurring.

Orowaiti:
Orowaiti Lagoon has migrated eastwards over 1km since 1954 due to accretion of North Beach (Westport) leading to erosion of farmland on the river mouth's south bank. There has been random illegal dumping of car bodies to combat erosion.

Westport (Carter's Beach-North Beach):
Massive accretion of both beaches, due to river mouth retaining works. Sedimentary processes related to this can pose a hazard to shipping over the river mouth bar that requires regular and expensive dredging.

Taraunga Bay – Okari:
Eroding between 1950-1975, mainly affecting farmland (Gibb 1978). Continued erosion could threaten the gravel coastal road. Shoreline changes at Taraunga Bay are thought to be associated with stream channel changes at the Bay's southern end.

Tiromoana – Woodpecker Bay:
Long-term erosion. Much of historic township of Brighton has been obliterated (Gibb 1978). SH6 at Fox Beach and several baches are also threatened, resulting in rockwork being placed in 1994.

Pororari – Punakaiki:
Large short-term beach changes as well as a long term erosion trend at Pororari Beach. Waves regularly overtop the beach and inundate properties, causing damage (Kirk 1988). A gravel bund was placed on the top of the foreshore in 1998 and has been successful in preventing sea flooding to date. However, the effectiveness of the bund will be lost if erosion continues (Todd 2002).

Barrytown:
Erosion at the southern end of the beach flats changes to accretion at the northern end (Gibb 1978, Kirk 1991, Jones 1992). SH6, under attack from erosion at the southern end of the flats, has been protected by randomly tipped rock. However, there is still potential for the road to be cut in times of storm (Kirk 1991). Continued erosion will affect farmland and possibly a proposed ilmenite mining project.

State Highway 6 (Coast Road, Barrytown – Rapahoe):
Although much of the coast is hard bedrock, there are patches of localised erosion threatening sections of road where it crosses unconsolidated sediment. This has resulted in protection works for road and some illegal protection works for baches, involving the random dumping of rubble.

Rapahoe:
Long-term erosion may be due to shadow zone of Grey River mouth works (Pfahlert 1983). Gibb (1978) reported that the beach front road is unstable and that SH6 at northern end of beach was undercut. Benn & Neale (1992) reported that the beach was very close to the hotel. Sea flooding of the camping ground is reported to have occurred in August 1996.

Cobden:
Gibb (1978) reported long term-erosion, which Pfahlert (1983) suggested, was due to groyne effects of Grey River works. Beach gravel washes over Point Elizabeth Road and if erosion continues, Point Elizabeth Road, Cobden dump and houses will be threatened.

Greymouth (South Beach to Blaketown):
Long-term massive accretion due to Grey River works trapping northerly littoral drift sediments (Pfahlert 1983). Gravel is extracted by a number of operators, which may aggravate erosion phases at Karoro.

Karoro:
Erosion in the early 1990s resulted in sections of the Karoro sewage outfall pipe being destroyed. If erosion continues, the ponds themselves will be threatened as well as several industrial properties. It is considered that gravel extraction may contribute to the problem (Benn & Neale 1992).

Hokitika:
In terms of assets and property affected by coastal erosion and periodic sea flooding, Hokitika is the most significant coastal hazard area in the region. Four major erosion phases have been

identified in 1868, 1914, 1943 and the 1980s, which appear to be large fluctuations in the long term stability of the shoreline. On several occasions properties in Beach Street and Revell Street have been destroyed or badly damaged during the erosion phases (Gibb 1985, 1986, 1987). In the early 1990s, the sewer outfalls from the town's oxidation ponds and Seaview Hospital were both badly affected by erosion and the ponds themselves may be affected in the near future. Numerous protection schemes have been tried over the years, although most of these have failed (Benn & Neale 1992). The current groyne field was built in the 1980s-1990s. Beach sediments can block the Hoikitika River mouth and backwaters flood the town (Rochfort 1870, Cowie 1957).

Hunt's Beach:
Locals reported severe erosion between 1930 and 1975: up 300m at a rate of –6.67m/yr (Gibb 1978). Unfortunately there has been no accurate ground surveys or aerial photograph interpretation to confirm this retreat. Benn & Neale (1992) noted that if erosion continued at this rate, several baches could be threatened.

Okuru River-Turnbull River Mouth:
In 1991, the river mouth position changed and broke through the lagoon spit at the southern end. Ocean waves entered the lagoon through the new entrance and eroded land near the motels, threatening large amounts of grazing land and deer fencing.

Bruce Bay:
Gibb (1978) recorded long-term erosion between 1884 and 1950, with the northern section of bay being the most affected. SH6 was threatened to the extent that rockwork has had to be placed to protect it. No erosion measurements have been made since 1950.

Hannah's Clearing (North Jackson's Bay):
Large scale, long-term erosion recorded by Gibb (1978). Little recent data exist for the area, however Benn & Neale (1992) considered that continued erosion could threaten houses and baches at the settlement.

For specific areas not mentioned above, it can be implied from Gibb (1978) that most of the region's coast is eroding.

4.3.2 Sea Flooding Effects

The historical effects of sea flooding from storm surge have been described in several reports concentrating on Hokitika (Gibb 1985, 1986,1987, Hicks 1988), Punakaiki-Pororari (Kirk 1988, Jones 1994, Moynihan 1996, Neale 1996, Todd 2002). At the Okarito River mouth blockages caused by low river flow, calm seas and littoral drift have lead to river backup and Okarito itself being flooded on numerous occasions since the 1880s (Westland Catchment Board 1986a). Various engineering schemes to prevent the flooding over the years have been proposed, but as yet none have been implemented. However, planning measures by the Westland District Council require floor levels to be 1m above the 1985 flood level (Benn & Neale 1992).

For locations such as Waimarie, Granity, Cobden and Rapahoe (and other unidentified areas), the historical effects of sea flooding are little known, as no thorough search for historical information has been undertaken, nor has there been any scientific research/modelling done. The few historical reports so far found have been incidental to other research, such as river flooding. Until such a search is undertaken, combined with storm surge run-up modelling, it is difficult to assess the future distribution and potential effects of sea flooding throughout the region.

4.3.3 Tsunami Effects

De Lange & Healy (1986) recorded four historical tsunamis in the region, two of which were generated by far-field earthquakes (Chile 1868 and Alaska 1964), and two generated by near-field earthquakes (Westport 1913, Murchison 1929). In the 1913 event, very high tides were recorded from Karamea to Westport, and at Westport a campsite close to the sea was flooded. The 1929 tsunami caused some damage at Farewell Spit, to the north of the regional boundary. The two far-field tsunamis were recorded as bores in the Buller River (1868 event; bore 1.2-1.5m high), and in the Grey River (1964 event; bore 0.4m high) (de Lange & Healy 1986).

Based on newspaper articles, Benn & Neale (1992) reported another possible two tsunami events for the region. The first was after the M7 Fiordland earthquake on 25 May 1960 (Eiby 1968), when 'unusual tides' were reported in Greymouth, either being well ahead or well behind the predicted times of arrival. In Greymouth,*"…the water rose and dropped 3 feet or so for no apparent reason. The Blaketown lagoons presented an unusual picture with quite a vigorous current flowing into them at various times then receding just as urgently" (*Greymouth Evening Star 25.5.1960). Although these observations may be refracted tsunami waves from the 22 May 1960 Chilean earthquake, which was recorded around much of the country, it is possible that this is not the case for the following reasons:

- It was recorded in Greymouth less than 4 hours after the Fiordland Earthquake.
- It was recorded three days after the Chilean Earthquake.
- de Lange & Healy (1986) make no reference of the Chilean event being recorded *anywhere* on the west coast of New Zealand (i.e. North Island or South Island).

The other possible tsunami event occurred during the Westport earthquake of 10 May 1962 (M5.9+, Eiby 1968). The Greymouth Evening Star (25/2/1962) reported that: *"Off the coast of Charleston, the sea appeared to boil"*. However, no other details were given.

4.3.4 Sea Level Rise

Bell *et al*. (2001) identified the most serious physical effects of sea level rise on the coastal margin as being:

- Coastal inundation, causing landward movement of estuaries, wetlands and marshes.
- Coastal erosion and shoreline change through sediment movement.
- Increased vulnerability to coastal storm damage and flooding.
- Increased difficulty in draining coastal and river lowlands.
- Possible increased sediment loads into estuaries, associated with projected increases in rainfall intensity and runoff.
- Surface, river, and ground water in coastal lowlands becoming saltier from saltwater intrusion.

It was also noted that with climate warming there would be an increase in westerly winds, which is similar to El Nino conditions. Storm surge events occur more frequently during El Nino conditions on the West Coast.

4.4 Magnitude and Frequency

4.4.1 Coastal Erosion and Accretion

In general, coastal erosion and accretion are gradual, continuous processes occurring throughout much of the region (Gibb 1978, Benn & Neale 1992), and thus 'frequency' is non-applicable. The magnitude and rates of coastal change (erosion or accretion) vary widely throughout the region, ranging from negligible change on hard rock/cliff coasts to extreme long-term erosion and accretion on sand and mixed sand-gravel beaches. Within these long-term trends, large fluctuations of shoreline advance and retreat can occur.

The most severe erosion rates recorded in Gibb (1978) were:

- Hunt's Beach: 300m of retreat at an average rate of -6.67m/yr between 1930-1975 (based on local resident reports)
- Hannah's Clearing: 350m of retreat at an average rate of -5m/yr between 1904-1975
- Hokitika: Shoreline fluctuations in the order of 140m around a position of quasi-equilibrium. Gibb (1985) stated: *"Severe erosion phases occur at Hokitika once every 30-50 years, migrating northwards as an erosion trough, destroying property and assets in its wake".*

Maximum accretion in the region has been associated with the river training works at Westport and Greymouth, altering littoral drift and coastal sedimentation patterns. Examples of the most extreme accretion recorded include:

- 1454m of accretion occurring between 1890-1968 at Carters Beach (Westport) at an average rate of +16.52m/yr (Gibb 1978)
- 508m of accretion occurring between 1874-1981 at Blaketown Tip (Greymouth) at an average rate of +4.75m/yr (Pfahlert 1983).

As most erosion/accretion data is now 20+ years old, there is justification to up-date it and to collect data for areas not already covered.

4.4.2 Tsunami

The only historical recorded measurements are from de Lange & Healy (1986), Benn (1992) and Benn & Neale (1992). These are summarized in Table 4.

Goff *et al.* (2001), produced evidence of pre-historical tsunami events at Okarito Lagoon, (and an historical tsunami, if Brunner's 1846 account referred to is interpreted as a tsunami). Goff *et al*. found saltwater inundation had covered the whole lagoon, and soil sequences and fossils suggested tsunamis were the most likely cause. In relation to soil sequences deposited by tsunamis, Goff *et al*. stated:

"As a rule of thumb, researchers in New Zealand have operated in the belief that to preserve a recognisable signal of tsunami inundation, wave height must be at least 5.0m (Lowe & de Lange 2000). Initially this scenario seems unlikely, but with a small lagoon entrance it is improbable that any catastrophic inundation will pass completely through this gap, and some, if not most, will overtop the 4.0m high sand barrier between the lagoon and the sea. Given this possibility, tsunami inundation of Okarito Lagoon may have taken the form of a rapid rise in water level, rather than as a catastrophic wave form"

Such events were noted to be large magnitude, low frequency events, interspersed with smaller, more frequent events.

Table 4. Historical Tsunami Magnitudes			
Date	**Location**	**Tsunami Magnitude**	**Source**
13/8/1868	Westport	Bore 1.2-1.5m high.	de Lange & Healy (1986)
22/2/1913	Westport Ngakawau Karamea Cape Foulwind	Tide *"extraordinarily high"*. Tide 0.9-1.5m above normal high spring tide. Tide *"Highest for years"*. Sea receded during high tide.	de Lange & Healy (1986)
16/6/1929	Karamea – Farewell Spit	2.5m high.	de Lange & Healy (1986)
25/5/1960	Greymouth	Water in the Grey River *"rose and dropped 3 feet or so"*.	GES 25/5/1960 Benn (1992), Benn & Neale (1992)
28/3/1964	Greymouth	Max. Rise 0.2m for 20 mins.	de Lange & Healy (1986)

Predicting when, where, and how often tsunamis will strike the coast is practically impossible, as it relates to the prediction of local and distant earthquakes and other generating mechanisms (eg submarine and coastal cliff landslides, volcanic activity). Based on the evidence of de Lange & Healy (1986), Benn (1992), and Benn & Neale (1992), all that can be said with any confidence about tsunami frequency for the region, is that possibly 6 tsunamis (5 definite, 1 marginal) have been recorded on the West Coast in 89 years (1913-2002). This gives an average of one event every 15 years. There have been no recorded tsunamis in the region since the 1964 Alaskan event.

4.4.3 Storm Surge

Todd (2002) stated:

"Indications of the magnitude of storm surge that is possible on the Buller coast can be taken from Connell Wagner (2000), who note a 0.5m surge up the Buller River during an August 1970 storm event. This is in good agreement with observations of storm surge on the North Island west coast such as Heath (1979), who reported surge levels of 0.5 m at Wanganui and New Plymouth during a September 1976 storm, and Agnew (1966) who reported surge levels up to 0.8 m at the Manukau Harbour during a July 1965 storm".

For wave run-up modelling, Todd (2002) used a worst-case sea level scenario for Punakaiki . This was based on the astronomical high spring tides at Westport (1.42m above MSL), and a surge component of 0.8m, based on Agnew (1966). This produced a potential sea level elevation of 2.22m above MSL during storms: Wave heights were additive to this water level.

There has been no specific search for historical records of storm surge events; hence it is difficult to determine the frequency of sea flooding from these. The frequency of beach overtopping is dependent on a combination of high sea levels, large wave heights, and the elevation of the beach at the location of interest. From the analysis of the Department of Conservation wave observations (Jones 1994, Neale 1996), Todd found that at Punakaiki, the sea had overtopped the beach 39 times in 13 years (3 times per year on average), and had inundated private property on eight of those occasions (1.5 times per year on average).

4.4.4 Sea Level Rise

As mentioned previously, the current projections by the IPCC (2001), which are considered by Bell *et al*. (2001) to be appropriate for New Zealand, are of the order of 0.14 to 0.18m by 2050 (average 3.26mm/yr), and 0.31 to 0.49m by 2100AD (average 4.08mm/yr).

4.4.5 River Mouth Blockages

As for storm surge, there has been no specific search for historical records of this nature. The following examples highlight the hazard:

1 September 1947.
"Backed up to a record height of 5m above normal low-water level by a sand bank, the Hokitika River broke its banks and caused one of the worst floods in the recent history of the town" (Cowie 1957). The Greymouth Evening Star (2/9/1947) quoted the Hokitika Harbour Master: *"The whole trouble …was the drift of sand from the south, creating a bank at the mouth of the river and thus preventing the water from getting away."*

3 September 1952:
Heavy seas forced a shingle bank across the mouth of the Arahura River mouth. Adjacent farmland flooded (Cowie 1957, Benn 1990).

13-15 March 1965:
Backed up against high seas (and assumed to be partially blocked by beach sediments), the Pororari River flooded a house (150mm deep) and adjacent farmland. According to the house owner, this type of flooding had occurred at least 4 times in the last year (Benn 1990).

20-25 March 1985:
High seas produced a sand bar, which blocked the outlet of Okarito Lagoon and flooded parts of the town. This has been a problem since the 1880s (Westland Catchment Board 1986a).

A search of historical information may provide sufficient data to help identify more precisely which river and creek mouths get blocked, how often they do, and the effects of such events.

4.5 Coastal Hazard Research

4.5.1 Coastal Erosion and Sea Flooding Hazards

Coastal hazard records on the West Coast extend back to at least Rochfort (1870) who described coastal changes around the Hokitika River mouth, and Campbell (1878) who proposed a series of groynes to abate the coastal erosion problem at Hokitika. Since then many more coastal hazard reports have been written although these have been site and project specific. Most of the research thus far, has concentrated on the central section of coast between Westport and Hokitika. With very few exceptions, little work has been done for the areas north of Westport and south of Hokitika.

Benn & Neale (1992) produced an annotated bibliography of the most significant research on coastal hazards and processes produced up until 1992. Rather than repeat all that information in this report, a generalised summary of major research is presented here along, with more recent work since that time.

Karamea Bight:
Mangin (1973) described and analysed beach processes and coastal changes in the Karamea Bight (from Westport to Kahurangi Point). Gower (1982), McMillan (1983), Neale (1989) examine coastal erosion in the Granity – Ngakawau area.

Hicks (1996) re-examined the Karamea Bight area originally researched by Mangin (1973). Hicks focussed his attention on coastal processes around the proposed coal jetty near Granity, describing coastal and seabed geomorphology and processes. Among other issues, Hicks described coastal stability and erosion trends at Granity. The main findings with relevance to coastal hazards were that short–medium term cycles (1-20yrs) of erosion and accretion occur within a long-term erosion trend. These short-medium term shoreline fluctuations characteristically ranged in width from 1m to 10m and affected between 500-1000m along shore. Hicks noted that the net average historical erosion rates were estimated at 1.3m/yr although this had not been established with any certainty. Hicks suggested: *"A detailed assessment of historical shoreline shifts from aerial photographs and survey plan is recommended"*. At the proposed site of the stockpile yard, stream mouth blockages occur at the local lagoon (Little Ditch Creek). This is caused by wave action, and re-opening occurs when the ponded water gains sufficient head to breach the barrier.

Benn (2002) assessed coastal erosion between Granity and Waimarie; this was based on a literature review of technical reports, and the analysis of aerial photographs taken at intervals between 1950 and 2002. The analysis was undertaken to determine the potential effects of commercial gravel extraction along that section of coast. Benn agreed with Gower (1982) and Hicks (1996) that a long term erosion trend could be identified, and concluded that gravel extraction was likely to exacerbate erosion and sea flooding problems by:

- Reducing the beach sediment volume, which is already known to be small.
- Reducing the overall sediment size on the beach.
- Reducing beach slope, height and coarseness.

Westport:
AJHR (1896), Furkert (1947), Simpson & Fyson (1971), Gower (1987), Hastie, *et al*. (1986), Hagyard *et al*. (1969), Kirk *et al*. (1986, 1987), all deal with coastal processes and river mouth dynamics at Westport harbour, in relation to the hazard the river mouth bar presents to shipping. Nevens (1938) assessed the erosional effects of levelling coastal sand dunes for the construction of Westport aerodrome.

Cape Foulwind:
Gower (1987), and R.W. Morris & Associates (1989) examined the coastal process around Cape Foulwind and assessed the feasibility of a deep water port in the location.

Punakaiki:
Kirk (1988) assessed the coastal erosion and sea flooding hazards at Punakaiki-Porarari.

Jones (1994) summarised the Department of Conservation's 11 year long database of wave observations from Punakaiki and found that beach overtopping and erosion can occur from all wave directions, but most often occurred as a result of a westerly approach. For significant overtopping to occur, Jones noted that the necessary factors needed were, elevated water levels resulting from high spring tides occurring at the spring and autumn equinoxes, storm surge (due to approaching cyclones and strong winds), and wave heights exceeding 1.5m.

Moynihan (1996) reviewed coastal processes and hazards at Punakaiki (based on the work of Kirk 1988), and used this information in the design the gravel bund proposed by the Buller District Council. Coastal erosion was assessed to be occurring at rates of –1m/yr at the motels and -0.5 m/yr to the north of the motels. The bund was designed (and built) with the intention of reducing erosion, wave overtopping and subsequent inundation of properties. The main design parameters proposed by Moynihan were:

- Bund height = 1.5m above dune crest.
- Bund length ~ 300m.
- Bund toe = 3.2m below existing dune crest.
- Seaward batter angle 1:2.
- Sediment volume ~7 000m^3 (~30m^3/m).

In presenting evidence on behalf of the DoC, relating to the design of the Punakaiki beach bund, Neale (1996) also summarised the results of the Punakaki wave observation programme. He found that waves reached the top of the beach on 77 days over the 13 year from 1983 to 1996, and that they overtopped the beach on 39 of those occasions. From survey profile data, Neale suggested long-term erosion at an average of –0.26m/yr was occurring on the Punakaiki beachfront. In the past 10-20 years (short-term), erosion was most severe in the region of the motels at the southern section of the beach, averaging –0.52m/yr. Neale considered the bund design of Moynihan (1996) to be:

- Erroneous in the elevations used.
- Excessively high and steep (eroding face would prevent beach access and alter the natural character of the beach).
- Too close to the beach, hence would be attacked by storm waves twice as often as the natural dune.
- Composed of the wrong material (Canoe Creek gravels which were coarser and more poorly sorted than the native beach gravels).

Neale concluded that Moynihan presented an over-optimistic view of the stopbank performance and as a re-nourishment scheme it would fail to survive its projected design life of 10 years, as the quantity of sediment in the design was insignificant to that being transported in the natural system.

Cooper (2000) included coastal hazards in her University thesis (see previous chapters), and reviewed coastal processes and hazards as described by other authors. Cooper used Punakaiki as a case study (because of being subjected to multiple hazards), and created a flood hazard zone for village, which included coastal flooding. However, this flood zone is ambiguous and is probably too large. The shortcomings of this hard zone were described in detail by McMahon (*in* McCahon & Yetton 2001) and have been discussed in Chapter 2.

Todd (2002) reassessed the coastal hazard at Punakaiki Village–Pororai River as part of the BDC proposed development plan for the area. In this assessment, Todd reviewed previous research, and did further analysis of the DoC wave observation database. Todd compared coastal positions from aerial photographs, taken in March 1951 and June/July 2001 (a 50 year comparison as opposed to 7 and 18 periods of Kirk 1988 and Moynihan 1996 respectively), finding that the average erosion over the whole beach had been in the order of 10m (-0.2m/yr). From comparing the original surveyed position of Dickenson Parade (assuming MHWS on the original survey was the vegetation line, as it often was on old plans) to the current vegetation line, Todd estimated beach retreat in the order of –20m over approximately 100 years (-0.2m/yr). This equates well with his aerial photograph analysis.

From the wave database, Todd noted that waves as low as 1m had been reported as overtopping the beach, and found no relationship between overtopping and strong local winds, hence he disagreed with Jones (1994) about overtopping being associated with storm events. Instead, Todd concluded that wave conditions that caused overtopping were generated from distant storm events in the Tasman Sea, rather than by local winds. Todd noted that the wave observations also indicated that most overtopping waves arrive nearly perpendicular to the shore (west to nor-west), and he thus assumed that overtopping conditions were different to longshore sediment transport conditions, and that sediment losses incurred during overtopping events are more likely to be offshore than alongshore.

Based on profile surveys, Todd measured changes in the position of the bund, and found that between November 1999 and November 2001, the bund crest and toe had retreated by –2m and –4.5m on average respectively (maximum erosion at Profile 2 was –2.8m at the crest, and –5.8m at the toe). This was significantly higher than measured erosion from the adjacent non-bund beach profiles, where the crest and toe retreated about –1m. Todd noted that the bund had not be built to design specifications (e.g. generally 2m higher than the natural crest as opposed to the design of 1.5m above crest height) and stated:

"This lack of construction to design, combined with the substantial volume losses already suffered, indicates that at some sites it is extremely unlikely that the bund will provide protection from inundation for the time period for which it was intended (assumed from Moynihan to be 10 years). From information on arbitrary profile levels compared to MSL datum obtained from the surveyor, Chris Coll, it is also clear that Moynihan's assumed MHWS elevation was in the order of 1m too low".

From beach profile information, Todd considered that the inundation protection offered by the bund was already compromised by erosion at some sites, and that the bund would most likely be removed by erosion within ten years. Based on several assumptions, including sea level rise, erosion rates over the next 50 years were estimated to be –15m for most of the beach (possibly -25m at Profile 2), at an average rate of –0.3m/yr. It was thus concluded that if no maintenance of the bund is undertaken, erosion of private property to the south of Marbel Street and around Webb Street will occur within 35 years. At the camping ground, the dune and hinterland were considered to offer protection against erosion for at least 50 years. Todd also found that as long as the height of the gravel bund remains at its current level (6.4m above MSL), the elevation is sufficient to prevent overtopping for all combinations of wave heights and water levels. This included the worst case scenario of 8m storm waves and water levels 2.2 m above MSL. However, under natural beach heights, sea flooding could occur with the combination of water levels around 2 m above MSL and wave heights in the order of 1.5 m.

Barrytown:
Kirk (1991) described the coastal processes and potential erosion hazards in relation to the proposed ilmenite-mining project.

Jones (1992) examined coastal processes, wave and weather patterns, and beach responses at Barrytown. He concluded that significant beach profile changes *"can be directly attributed to the largest energy events, that is, storms"*. For the period 1951-1988, Jones calculated erosion rates from aerial photo analysis, and found a trend of maximum erosion at the south end of Barrytown Flats, south of Fagan's Creek (-80m), to minimum erosion at Lawson's Creek (-20m) in the mid reaches of the flat. To the north, up to Hibernia Creek, accretion of up to 40m occurred in the same period.

Greymouth (Blaketown-Rapahoe):
Coode (1879a) quantified river and coastal parameters for the design of the Greymouth Harbour. Pfahlert (1983) analysed coastal process, changes and erosion hazard along this section of coast.

Expressions of concern over beach erosion at Karoro (see above section on effects) in the early 1990s lead to the WCRC and DoC jointly establishing a series of coastal profile surveys between Blaketown and the Pandora Ave, near the Taramaku River mouth. These profiles were set up to determine the effects of gravel extraction operations by monitoring beach positions, and calculating sediment budgets. The profiles were surveyed at monthly intervals for the first 12 months, and it was intended that they be resurveyed every year (or after significant coastal storm events). A preliminary report noting profile changes over the first 12 month period was produced by Benn & Neale (1993). Coastal profile surveying between Serpentine and Blaketown Tip is continuing as a requirement of mining license consent conditions, although these have not yet analysed in full (Helen Rouse, WCRC, pers. comm.)

Hokitika:
Coode (1879b) quantifies coastal and river parameters for the design of the Hokitika Harbour. Rochfort (1870), Cambell (1878), Sharp (1915), Westland Catchment Board (1984, 1986b) Gibb (1985,1986,1987), and Hicks (1988), all discussed the coastal erosion problem at Hokitika and presented ways of dealing with the problem.

Okarito:
Westland Catchment Board (1986a) investigated ways to reduce river mouth blockages and flooding hazards at Okarito township.

Goff *et al.* (2001) presented geological, biological, and chemical evidence for large scale, palaeo-tsunami occurring at Okarito Lagoon. These related to probable fault rupture of the Alpine Fault. Sediment samples from trenches and cores were analysed for grain size (for wave energy determination), ^{210}Pb isotopes (for dating sediments), and foraminifera/micro-macro fossils (for determination of salinity/saltwater depth, and for spatial extent of saltwater margins). Goff *et al.* proposed that compaction (from ground shaking) and subsidence (from probable fault rupture) of the lagoon sediments during ground shaking from large seismic events, has lead to numerous tsunamis entering Okarito Lagoon. The implication from this study is that populated coastal areas in the region are at risk from catastrophic scale tsunami based on recent pre-historical evidence (and historical evidence if Brunner's 1846 account is considered a tsunami event).

4.5.2 Wave Characteristics and Water Levels

Waves and sea water levels are key process parameters in coastal erosion and sea flooding, hence information on these parameters is required for the analysis of these hazards.

Wave Characteristics

Benn & Neale (1992) noted that there are three reasonable length wave data sets for the West Coast: from ship observations between 1957-1980 (Reid & Collen, 1983), from waverider buoys placed at Ngakawau, Westport and Carters Beach for periods up to 3 years (Valentine & Macky, 1984), and from beach observations at Punakaiki Village between 1983-1994 (Summarized in Jones, 1994). Jones made the following conclusions on the wave climate from the 11 years of beach observations on the wave climate.

- The average significant wave height was 1.35m.
- Wave heights above 1.5m occurred 36% of the time, and this was considered to be the lower threshold for storm events.
- 3m high waves occurred 0.5% of the time.
- The ratio of southerly to northerly waves was 2:1, indicating net northerly littoral drift.
- Autumn storms were most likely to cause erosion. This was due to an increased intensity of south-westerly waves associated with an increase in latitude of the sub-tropical ridge, allowing strong southern hemisphere westerlies to reach New Zealand frequently.
- Conversely, summer was characterised by a period of fair weather wave conditions and associated beach accretion.

NIWA have developed a nation wide hindcast wave generation model based on 20 years of wind record that can provide extreme wave occurrence statistics for the any area of the country. This model could be used to generate these wave statistics for sites on the West Coast.

Water Levels

Sea water levels from both tide and storm surge are important components in whether sea flooding occurs. Although tide levels records are collected at Buller Port, and Greymouth Harbour, the contributions of the Buller and Grey Rivers have not been separated out, hence they cannot be used to determine sea water levels. Indications of the magnitude of storm surge that is possible on the Buller coast, can be taken from Connell Wagner (2000), who noted a 0.5m surge up the Buller River during the August 1970 storm event.

Cooper (2000) noted that storm surges are at their greatest in La Nina weather phases. However, it is considered that is in error, as de Lange (1996) noted: *"However, due to the increased incidence of south-westerly storms during El Nino phases, southern New Zealand experiences an increased frequency of storm surges during El Nino and a reduction during La Nina"*. Neale (1996) also noted such patterns based on the wave observations at Punakaiki, stating that: *"Such events* (wave inundation) *are related to westerly storms and elevated sea levels that are produced by 'El Nino' weather patterns…"*

In recent years NIWA have operated a high precision sea water level recorder site at Charleston as part of their national network. The calculation of extreme water level occurrence statistics is possible from the data already collected from this site.

4.6 Knowledge And Information Gaps

Although a considerable amount of historical research has been carried out on coastal hazards in the region, most of it has concentrated in four areas (Granity, Westport, Punakaki, and Hokitika) and much has been has been general descriptive accounts. For much of the region's 600km of coastline, very little or nothing is known of basic coastal processes and hence coastal hazards. With this in mind, the following knowledge/information gaps should be filled in the given order of priority.

1) Establish regional shoreline movement database (eg erosion /accretion)
2) Contribute to the collection and analysis of wave and sea level data.
3) Collect and analyse historical coastal inundation event information.
4) Construct historical sea flood hazard maps.
5) Predictive coastal modelling and mapping (Shoreline positions and coastal inundation maps. Based on historical information combined with predictive sea level and climatic changes)
6) River mouth – beach interaction.

4.6.1 Regional Shoreline Movement Database

To date Gibb (1978) provides the most comprehensive erosion/accretion data for the region. Other authors have sporadically added subsequent data. Gibb's rates were based on the analysis of aerial photographs, cadastral maps, plans, survey information and personal accounts. As Gibb's data is now 25 years old, many sections of the coast were not included and at other sites the information was subjectively based, it is recommended that this original work be updated. It is considered that this would involve the following two methods:

1). Collect, collate, and analyse historical coastal erosion/accretion data and information.
This requires the following steps:

- Design of computer database for existing historical information on shoreline change. The database to contain information on site location, beach type, date recorded, source of data, net coastal change (m), rate of change (m^3/yr), accuracy, observation notes.
- Use more recent aerial photographs (taken since 1978 by the WCRC and other organisations) to update change since Gibb (1978) at the sites used in that study.
- Determine shoreline change at new determination sites for areas not covered by Gibb (1978) or subsequent authors from aerial photographs.
- Supplement aerial photograph analysis with a search of technical reports, theses, newspapers, and beach profile survey information.

All of these tasks could be undertaken by a combination of the following groups depending on time, availability and costs:

- WCRC staff.
- University Students (Geography - Coastal/Geomorphology, Geology).
- Specialist Coastal Consultants.

2). On-going monitoring and analysis of shoreline change.
It is recommended that the following three data collection techniques to be employed:

- Establish coastal profile networks at high risk urban areas and where key infrastructure is at risk (eg roads). These places include Hokitika, South Beach-Karoro (Greymouth), Cobden-Rapahoe, Granity-Hector, Waimarie, and Little Wanganui. Profile analysis adds accuracy to coastal positional changes determined from historical accounts and air photos, and allows for the calculation of beach sediment budgets to be undertaken. This is particularly important when assessing resource consents for beach mining and gravel extraction operations, and other developments in the coastal zone. These profiles should be surveyed on a regular basis (e.g. 6-12 monthly initially) to establish trends, and following significant storm events. Information from the profile surveys would be added to the database as outlined above.
- Establish a commitment to on-going long-term aerial photography of the coast that can be used to determine longer-term change in other areas of shoreline movement not covered by coastal profiles.
- The relatively new technique of airborne laser surveying, which provides information on elevation as well as position, should be considered rather than conventional aerial photography.

It is recommended that for areas with greatest shoreline instability and lowest beach elevations (e.g. Hannah's Clearing-Hunt's Beach, Hokitika, South Beach-Karoro, Punakaiki, Granity-Hector, Waimarie, Little Wanganui-Karamea), be flown on a 10 yearly basis, and the whole coast that is accessible or used, be covered on a 20 year basis, or after significant coastal events. These flying frequencies are for both standard photography and airborne laser surveying

This work could be undertaken by a combination of:

- WCRC: Regular surveying of coastal profile network; update of shoreline movement database, commission of new air photographs/airborne laser surveys.

- Registered Surveyors: Establishment and regular surveying of coastal profile network.

- Coastal Specialist Consultants: Design of coastal profile network, analysis of coastal profile and airborne survey information.

- University Students (Geography – Coastal or Geomorphology, Geology): Analysis of coastal profile and airborne survey information.

4.6.2 Contribute to the Collection and Analysis of Sea Level and Wave Data:

Wave and sea level analysis are essential components in determining the causes of coastal erosion and sea flooding. Such data are needed for predictive storm surge and tsunami wave run-up models. It is recognised that much of the existing data on these components is sub standard, but it is also recognised that the WCRC do not have the resources to undertake the necessary level of data collection on their own. However, the opportunity exists for the WCRC to obtain much of the necessary data by contributing to existing data collection and analysis programmes.

For example, in recent years NIWA have operated high precision, sea water level recorder sites at Charleston and Jackson Bay, as part of their national network. It is recommended that the WCRC should make a regular annual financial contribution to the operation of these sites in return for access to real time storm data, and annual data summaries. The calculation of extreme water level occurrence statistics for the West Coast is possible from the data already collected from these sites. It is recommended that the WCRC commission NIWA to undertake these calculations so they can be used as design water levels in predictive modelling of sea flooding and erosion.

NIWA have also developed a nationwide hindcast wave generation model based on 20 years of wind record, that can provide extreme wave occurrence statistics for the any area of the country. It is recommended that the WCRC commission NIWA to run this model to generate these wave statistics for key sites on the West Coast such as the Karamea area, Waimarie-Granity, Westport, Punakaiki, Greymouth, and Hokitika.

4.6.3 Collect and Analyse Historical Coastal Inundation Event Information.

This information would help identify areas that are prone to sea flooding more precisely, and help determine the magnitude, frequency, and sea and weather conditions of local storm surge/overtopping events. To date this type of work has focussed on Hokitika and Punakaiki. Other areas prone to sea flooding, and for which very little is known, include Mokihinui River Mouth-Waimarie settlement, Waimangaroa - Hector, Rapahoe, and Point Elizabeth-Cobden. Other areas of low lying coast, such as farmland are probably prone to sea flooding, but records are scant, and the assets at risk may not warrant time and resources being spent on them.

A database should be developed to contain information on date of event, area affected, inundation depths, inundation damage, sea conditions, weather conditions, and information sources. The sources of such information include newspaper accounts, technical reports, personal surveys (preferably of long-term residents), weather summaries, regional and district council files/records.

It is considered that this work type of work could be carried out by:

- University Students.
- WCRC staff.
- Coastal Specialist Consultants.

4.6.4 Construct Historical Sea Flood Hazard Maps

Using information derived from the historical search, construct hazard maps showing the distribution of known sea flooding. Given the limited width of areas likely to have been effected by this hazard, it is recommended that the maps be at a scale of 1:10,000, and overlaying aerial photo basemaps with annotation on depths and dates of inundation.

It is considered that this work type of work could involve input from:

- WCRC: Provide air photo basemaps, development of hazard maps

- University Students - Geography (Coastal, Geomorphology) or Specialist Coastal Consultants: Development of hazard maps in hard copy form.

- University Students, Consultants, District Councils: Produce GIS versions of hazard maps.

4.6.5 Predictive Coastal Modelling (Shoreline Positions and Inundation Areas)

Shoreline Stability and Position

As well as sea level rise there are a number of other potential climate changes that will affect shoreline stability and position. These include dominant wave approach direction, sediment supply rates from rivers, storm intensity and frequency. It is recommended that the WCRC accept the national scenarios for the magnitude of these climate driven changes, and undertake modelling of the potential effects of these changes on West Coast shoreline stability. This modelling should be concentrated on major population centres (Karamea, Granity-Hector, Westport, Greymouth from Rapahoe to South Beach, Hokitika and Okarito), and areas of potential maximum impact on infrastructure (e.g. SH67 near Little Wanganui and Granity-Ngakawau; SH6 at Tiromoana-Woodpecker Bay, Barrytown Rapahoe and Bruce Bay; district roads at Granity-Ngakawau, Okari–Tauranaga Bay, Punakaiki, Rapahoe, Point Elizabeth-Cobden, Hannah’s Clearing and Hunt’s Beach; Oxidation ponds at Hokitika and South Beach, Greymouth).

Due to the specialised nature of modelling investigations, it is recommended that Specialist Coastal Consultants should be engaged to undertake the work.

Storm Surge

This type of modelling involves calculating wave run-up elevations for various scenarios of water level and wave heights, calculating the volume of water which will overtop the beach, and determining where and at what depths this water will travel across the coastal hinterland. The minimum data requirements for undertaking this type of modelling include:

- Design water levels, usually expressed as various return periods.
- Design wave heights, usually expressed as various return periods.
- Beach profile data.
- Detailed ground topography of the coastal hinterland.

At present none of these parameters are available to the WCRC in sufficient detail to enable the modelling to be undertaken. However, the first three points are addressed in the higher priority work outlined above. Appropriate models of run-up, overtopping and overland flow models are also required for the local conditions found at the modelling sites. This can be a major limitation for the applicability of the modelling outputs.

Areas to focus this modelling work on should be those which are known to have historical sea flood problems, and with the most assets at risk. This should include:

- Waimarie settlement –Mokinui River mouth.
- Hector-Granity-Orowaiti coast.
- Punakaiki-Pororari Beach.
- Rapahoe.
- Point Elizabeth – Cobden.

- South Beach-Karoro (Greymouth).
- Hokitika.

This type of modelling is relatively specialised, so it is recommended that it be carried out be specialist coastal consultants. Prior to any modelling, data on the detailed topography of the coastal hinterland will be required. This could be provided by private or WCRC surveyors, or by airborne laser survey as discussed in the regional shoreline change database section (4.6.1).

Tsunamis
Similar input data is required for tsunami modelling except that the water level will be the scenario tsunami level. As no tsunami modelling or mapping has been done for the region, it is recommended that the focus is on the three main centres (Greymouth, Hokitika, Westport) followed by major infrastructural assets (eg SH6).

4.6.6 River Mouth – Beach Interaction

Beach sediments block many river mouths in the region; this causes river back-water effects and subsequent flooding of surrounding areas. This is known to have been a problem at various times at Granity/Little Ditch Creek, Waimarie/Mokihinui River, Punakaiki/Pororari River, Karoro/Watson Creek, Paroa/Saltwater Creek, and Okarito/Okarito River (Cowie 1957, Benn 1990, Benn & Neale 1992, Hicks 1996, Appendix 1.). Records show that even major rivers such as the Hokitika and Arahura rivers have been blocked on occasions by beach sediments (Cowie, 1957, Benn 1990).

Despite the fact that this coastal hazard exists at these locations, historical records are scant (there has been no specific search), and virtually nothing is known of the river mouth/coastal dynamics that cause the problem. It is therefore considered that river mouth closures warrant further investigation to help understand and mitigate the backwater flood hazard. Based on the historical frequency of events, and effects, investigation priorities should commence with the Pororari and Okarito river mouths. Other rivers and creeks that are known to block and cause flooding problems are considered secondary order importance.

4.7 Summary

This chapter has shown that a variety of hazards affect the region's 600km long coastline. These hazards include coastal erosion and accretion, sea flooding by storm surge and tsunami, and backwater flooding caused by beach sediments blocking river mouths. Predicted sea level rise may exacerbate coastal erosion and sea flooding problems in the future. Historically, coastal erosion and storm surge have caused the most damage although near field tsunamis have the potential to cause the most physical damage and loss of life. This is due to potential wave velocities and volumes of water involved, the fact that most of the region's population lives on low-lying coastal lands, and the almost non-existent warning times of such events.

Despite records extending back to the 1860s, coastal hazards are still poorly understood for most of the region, and for many areas, virtually nothing is known at all. As the coastal zone and resources in the region are coming under increasing pressure, this should be of concern to local authorities. To protect people, property and indeed, the coastal zone itself, and to allocate coastal resources appropriately, a good understanding of coastal processes and potential hazards is necessary. In relation to this, several important knowledge and information gaps can be identified including:

- A regional shoreline movement database (eg erosion /accretion).
- The availability of wave and sea level data.
- Historical coastal inundation event information and hazard maps.
- Determination of potential changes in shoreline position with climate change.
- Predictive coastal inundation models and hazard maps (storm surge and tsunami).
- River mouth – beach interaction.

4.8 Coastal References

Note: See Benn and Neale (1992) for annotated bibliography of West Coast coastal research and reports. See Jones (1992) and Cooper (2000) for further coastal references.

AGNEW, R. 1966: Storm Tides in the Tasman Sea. New Zealand Journal of Geology and Geophysics, Vol. 9, (3), pp 239-242.

APPENDICES TO THE JOURNAL OF THE HOUSE OF REPRESENTATIVES (AJHR). 1896: Correspondence between the Westport Harbour Board, Public Works Department, and Sir John Coode (Harbour designer). *In* Appendices to the Journals of the House of Representatives.

BELL, R.G., HUME, T.M., & HICKS, D.M. 2001: Planning for Climate Change; Effects on Coastal Margins. A Report for the Ministry for the Environment as Part of the New Zealand Climate Change Programme, Hamilton. 73p.

BENN, J.L. 1990: A Chronology of Flooding on the West Coast, South Island, New Zealand: 1846 – 1990. The West Coast Regional Council, Greymouth. 159p

BENN, J.L. 1992: A Review of Earthquake Hazards on the West Coast. The West Coast Regional Council, Greymouth. 62p.

BENN, J.L. 2002: Evaluation of the Effect of Stone Removal North of Westport. Prepared for the West Coast Regional Council (Greymouth), by DTec Consulting Ltd, Christchurch. 18p plus Appendices.

BENN, J.L. & NEALE, D.M. 1992: A Report on Coastal Hazards in the West Coast Region, South Island, New Zealand. The West Coast Regional Council, Greymouth. 73p.

BENN, J.L. & NEALE, D.M. 1993: Greymouth-Taramakau Coastal Profiles: A Preliminary Analysis. The West Coast Regional Council, Greymouth. 2p plus Profiles.

CAMBELL, W.D. 1878: On Beach Protection. Transactions of the New Zealand Society, Vol. 11, pp 146-149.

CONNELL WAGNER LTD. 2000: Preliminary Flood Study of the Buller River at Westport. Report Prepared for the WCRC, August 2000, by Connell Wagner Ltd, Wellington. 19p plus Appendices.

COODE, J. 1879a: Greymouth Harbour. *In* Appendices to the Journals of the House of Representatives, E9, pp 5-11.

COODE, J. 1879b: Hokitika Harbour. *In* Appendices to the Journals of the House of Representatives, E9, pp 9-13.

COOPER. L.L. 2000: Geotechnical Hazard Analysis, Management and the Development of Hazreg for the Buller District. MSc Thesis, Department of Geological Sciences, University of Canterbury. Vol. 1 (205p), Vol. 2 (Appendices).

COWIE, C.A. 1957: Floods in New Zealand; 1920-1953, With Some Notes On Earlier Floods. New Zealand Conservation and Rivers Control Council, Wellington. 239p.

de LANGE, W. P. 1996: Storm Surges on the New Zealand Coast. Tephra, Vol. 15, (1). pp 24-31.

de LANGE, W.P, & HEALY, T.R. 1986: New Zealand Tsunamis 1840-1982. New Zealand Journal of Geology and Geophysics, Vol. 29, pp 115-134.

EIBY, G.A. 1968: An Annotated List of New Zealand Earthquakes, 1460 – 1965. New Zealand Journal of Geology and Geophysics, Vol. 11 (3), pp 630-647.

FURKERT, R.W. 1947: Westport Harbour. Transactions of the Royal Society, Vol. 76, pp 373-402.

GIBB, J.G. 1978: Rates of Coastal Erosion and Accretion in New Zealand. New Zealand Journal of Marine and Freshwater Science, Vol. 12, (4) pp 429-456.

GIBB, J.G. 1985: The Problem of Sea Erosion at Hokitika, Westland, New Zealand, and Possible Solutions. Australasian Conference on Coastal and Ocean Engineering, Christchurch, pp 381-390.

GIBB, J.G. 1986: A Coastal Hazard Management Plan to Combat the Problem of Coastal Erosion and Flooding from the Sea at Hokitika, Westland, New Zealand. Report to the Hokitika Borough Council, Ministry of Transport, and Westland Catchment Board. Ministry of Works and Development. 44p.

GIBB, J.G. 1987: A Coastal Hazard Management Plan for Hokitika. Water and Soil Technical Publicaton, No 29, National Water and Soil Conservation Authority, Ministry of Works and Development. 44p.

GOFF, JR., NICHOL, S.L, & CHAGUÉ-GOFF, C: 2001: Evidence for Catastrophic Inundation of the West Coast: Okarito Lagoon. Report prepared for The West Coast Regional Council, Greymouth. 34p.

GOWER, R. 1982: Beach Morphology and Coastal Erosion, Granity Area. Unpublished Report to the Westport Harbour Board. 4p.

GOWER, R. 1987: Westport: Planning for the Future. Unpublished Report by the Westport Harbour Master. 15p.

GREYMOUTH EVENING STAR. 1947: Extract from 2/9/1947.

GREYMOUTH EVENING STAR. 1960: Extract from 25/5/1960

GREYMOUTH EVENING STAR. 1962: Extract from 25/2 1962.

HAGYARD, T., GILMOUR, I.A., & MOTTRAM, W.D. 1969: A Proposal to Remove Sand Bars by Fluidisation. New Zealand Journal of Science, Vol. 12, pp 851-864.

HASTIE, W.J., KIRK, R.M., & LUMSDEN, J.L. 1986: Options for Improving Entrance Conditions at Westport Harbour, New Zealand. Proceedings of the First Australasian Port, Harbour and Offshore Engineering Conference, 1986. pp 321-325.

HEATH, R.A. 1979: Significance of Storm Surge on the New Zealand Coast. New Zealand Journal of Geology and Geophysics, Vol. 22 (2), pp 259-266.

HICKS, D.M. 1988: Uplift, Sea level Rise, Shoreline Stability, and Hazard Management at Hokitika. Report to Hokitika Borough Council. Water Sciences Division, Depaartment of Scientific and Industrial Research. 20p.

HICKS, D.M. 1996: Coastal Geomorphology South of Granity, Westland. Report Prepared for Connell Wagner Ltd, by D.M. Hicks, NIWA, Christchurch. 29p.

INTER-GOVERNMENTAL PANEL ONCLIMATE CHANGE (IPCC) 2001: Climate Change 2001: The Scientific Basis. Summary for Policy Makers and Technical Summary of the Working Group I Report. Part of Working Group I Contribution to the Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, England.

JONES, C.J.L. 1992: Surf Zone Processes and Storm-Induced Beach Profile Response at Barrytown, West Coast, South Island, New Zealand. Unpublished MSc Thesis, Geography Department, University of Canterbury. 156p.

JONES, C.J.L. 1994: Pororari Beach Wave Analysis Report. Department of Conservation, Hokitika. 13p.

KIRK, R.M. 1988: Coastal Erosion and Inundation at Punakaiki Village (Pororari Beach), Westland; 1983-1986. Report prepared for the Department of Conservation. 28p.

KIRK, R.M. 1991. Barrytown Ilmenite Project – Coastal Geomorphology of the Barrytown Flats as it Relates to Environmental Impact and Mining Management Issues. Report to Westland Ilmenite Ltd. 30p.

KIRK, R.M., HASTIE, W.J., & LUMSDEN, J.L. 1986: Sedimentary Processes Operating Around a River Mouth Port, Westport, New Zealand. New Zealand Journal of Marine and Freshwater Research, Vol. 20, pp 337-347.

KIRK, R.M., HASTIE, W.J., & LUMSDEN, J.L. 1987: Harbour Entrance Morphology and Sediments at a River Mouth Port, Westport, New Zealand. New Zealand Journal of Marine and Freshwater Research, Vol. 21, pp 689-691.

MANGIN, C.M. 1973: Coastal Processes and Development in the Southern Karamea Bight. Unpublished MA Thesis, Geography Department, Canterbury University. 112p

McCAHON, I. 2001: In McCahon, I. & Yetton, M.D. 2001: Peer Review of Information Regarding Punakaiki Rockfall and Flood Hazard Assessment and Zonation Included in the

MSc Thesis Entitled “Geotechnical Hazard Analysis, Management and the Development of Hazreg for the Buller District”. Letter to Terry Archer (Buller District Council) from Mark Yetton (Geotech Consulting Ltd), 17 September 2001. 15p.

McMILLAN, B.A. 1983: Coastal Erosion, Granity School. Letter from the Ministry of Works and Development to the Education Department, 28 April 1983. 6p.

MORRIS, R.W. & ASSOCIATES. 1989: Cape Foulwind Port Feasibility Study, 1987-1988; Executive Summary. Unpublished Report for Milburn New Zealand Ltd. 29p.

MOYNIHAN, S. 1996: Buller District Council – Punakaiki Sea Erosion: Review of Proposed Remedial Works. Report Prepared by S. Moynihan, Works Consultancy Services, Wellington. 13p.

NEALE, D.M. 1989: Buller Coastal Hazard Assessment and Management Programme (CHAMP): Options Potentially Available for Managing Coastal Erosion and Flooding Hazards at Ganity-Ngakawau. Unpublished Report for the Department of Conservation and Buller County Council. 26p.

NEALE, D.M. 1996: Evidence on Behalf of the Director-General of Conservation, in the Matter of Coastal Permit, Application RC96/20, by the Buller District Council. 11p.

NEVINS, T.H.F. 1938: Erosion at Westport Aerodrome. Proceedings of the New Zealand Institute of Engineers, Vol. 24, Part 2, pp 487-497.

PFAHLERT, J.J. 1983: Coastal Dynamics and Sedimentation at Point Elizabeth, West Coast, South Island, New Zealand. Unpublished MSc Thesis, Geography Department, Canterbury University. 306p.

REID, S.J. & COLLEN, B. 1983: Analysis of Wave and Wind Reports from Ships in the Tasman Sea and New Zealand Areas. New Zealand Meteorological Service, Ministry of Transport, Wellington. 74p.

RIDGWAY, N. 1984: Tsunami Hazard in New Zealand. *In* Natural Hazards in New Zealand. Compiled by I.Spender and M.J. Crozier for the New Zealand National Commission for UNESCO, 1984. pp 375-382.

ROCHFORT, J. 1870: On Changes in the Hokitika River. Transactions of the New Zealand Institute, Vol. 3, pp 299-303 plus Maps.

SHARP, H.H. 1915: Erosion of the Sea Beach Fronting the Town of Hokitika and the Remedial Measures Adopted. Proceedings of the New Zealand Society of Engineers. pp 90-120.

SIMPSON, R.A., & FYSON, J.H. 1971: Westport Harbour Entrance. New Zealand Engineering, pp 266-271.

TODD, D.J. 2002: Punakaiki Development Plan: Coastal Issues. Report Prepared for Glasson Potts Fowler Ltd, by DTec Consulting Ltd, Christchurch. 22p.

VALENTINE, E.M., & MACKY, G.H. 1984: Sea Wave Climate at Ngakawau, Westport and Carter's Beach. Hydraulics Section, Central Laboratories, Ministry of Works and Development, Lower Hutt. Vol. 1. (32pp), Vol. 2. (Diagrams).

WESTLAND CATCHMENT BOARD. 1984: Hokitika Beach Front Sea Erosion. Greymouth. 15p plus Maps, Plans and Photographs.

WESTLAND CATCHMENT BOARD. 1986a: Okarito Township Proposed Flood and River Protection Scheme. 15p.

WESTLAND CATCHMENT BOARD. 1986b: Hokitika Beach Sea Erosion. Application for Assistance, Rock Groyne Proposal, September 1986. 28p.

5.0 EARTHQUAKE HAZARDS

5.1 Introduction

Of all the natural hazards in the West Coast Region, earthquake hazards present the single largest risk. This is due to the region's position across a major active plate boundary, the number of active faults in the region itself and surrounding regions, the inevitability of large scale earthquakes occurring, and the multiple effects of earthquakes, including ground shaking, liquefaction, land-sliding, river avulsion, tsunamis and fire outbreaks.

Numerous earthquakes have affected the region historically: the two largest and most famous cases being the 1929 Murchison Earthquake (M7.8, Dowrick and Smith 1990), and 1968 Inangahua Earthquake (M7.1, Adams *et al*. 1968). Both caused widespread destruction to property and were responsible for the loss of a number of lives; seventeen people died in the 1929 earthquake (including the Tasman District and northwest Nelson area), and 3 died in the 1968 earthquake. The scars on the landscape from both events are still obvious. These two earthquakes, and *all* others recorded historically, were associated with local faults, which are relatively small when compared to the Alpine Fault.

Earthquake hazards have been intensively investigated and much of the relevant research was reviewed in Benn (1992). The most significant studies since then have concentrated on prediction of the movement of the Alpine Fault, and faults in the Canterbury Region, (Pettinga *et al.* 1998, Yetton *et al.*1998, Stirling *et al.*1999). Yetton *et al*. (1998) suggested that the Alpine Fault ruptured about once every 250 - 260 years on average, with associated earthquakes of ~M8, and ground shaking intensities in the epicentral region of MM9-MM10.

5.2 Causes Of Earthquakes

The north-west corner of the South Island, and the South Westland/Fiordland area are two of the most seismically active areas in the country. The West Coast Region is particularly prone to earthquakes due to its location across the actively deforming boundary of the Indian and Pacific plates (e.g. see Benn 1992, Pettinga *et al*. 1998, Yetton *et al*. 1998 , Stirling *et al.* 1999). Relative movement across the plate boundary occurs within a deformation zone between 70-350km wide. On the West Coast, the Alpine Fault represents the surface expression of the plate boundary. At 650km long (Yetton *et al*., 1998), the Alpine Fault is a major fault in world scale terms, and extends the entire length of the region and beyond (from Milford Sound in the south-west to Blenheim in the north-east).

As well as the Alpine Fault, there are numerous other active faults in the region (Figure 2). These are concentrated in the northern section of the region in the Paparoa Tectonic Zone (PTZ) (Laird 1968, Suggate 1978), and in south Westland and Fiordland, in the South Westland Shear Zone (Suggate 1978). Faults from the Marlborough Fault Zone (MFZ) also extend into the region and connect with the Alpine Fault (Yang 1991, 1992, Pettinga *et al*. 1998, Stirling *et al*. 1999). All appear to have been active at some time in the Quaternary period (i.e. geologically very recently).

The main faults in the PTZ are the White Creek Fault, Inangahua-Glasgow Fault, Lower Buller Fault, Lyell Fault, Mt William Fault, and the Montgomerie Fault. The White Creek Fault was considered dormant until 1929 (Ferrar and Grange 1929), when displacement on the fault caused the M7.8 Murchison Earthquake (Dowrick and Smith 1990). Movement of the White Creek Fault during this earthquake was in the order of 5m vertically (Fyfe 1929) and 5m obliquely (Berryman 1980, see Section 5.3). Movement of several faults occurred during the Inanghua Earthquake (see effects section), although almost all of the identified surface rupture occurred on the Inangahua-Glasgow Fault. Lensen and Suggate (1968) stated that:

"In detail it appears the most, although not all, of the relative movement occurred across four of the five main faults in the area (White Creek, Glasgow, Lower Buller, and Lyell), the Mt William fault being the exception. Surface faulting however, was found at only one fault – the Glasgow Fault, although along a short section of the Lyell Fault a short surface break was observed".

Young (1963) and Laird (1968) recorded faulting of Quaternary gravels at the Montgomerie Fault, which indicated recent movement of the fault.

In South Westland, Suggate (1978) suggested a distinct zone of shear faulting in Tertiary rocks was probable, characterised by closely spaced faults, separating steeply dipping slices of Tertiary rocks – some late Tertiary in age. These features are not characteristic in North Westland and thus, the South Westland Shear Zone was proposed. Suggate noted that Late Quaternary deposits buried large areas of Tertiary rocks, and more research was required in the area to establish the exact nature and history of faulting.

For the South Island's West Coast (from Fiordland to North West Nelson), Smith and Berryman (1986) described Fiordland as the most seismically active area in the country even though large earthquakes generated in this area tended to produce low MM intensities. The Alpine Fault was noted for its low present and historical seismicity (see Section 5.5), and the

Paparoa/Buller area was distinguished by its compressive reverse faulting, folding, and large earthquakes in the twentieth century.

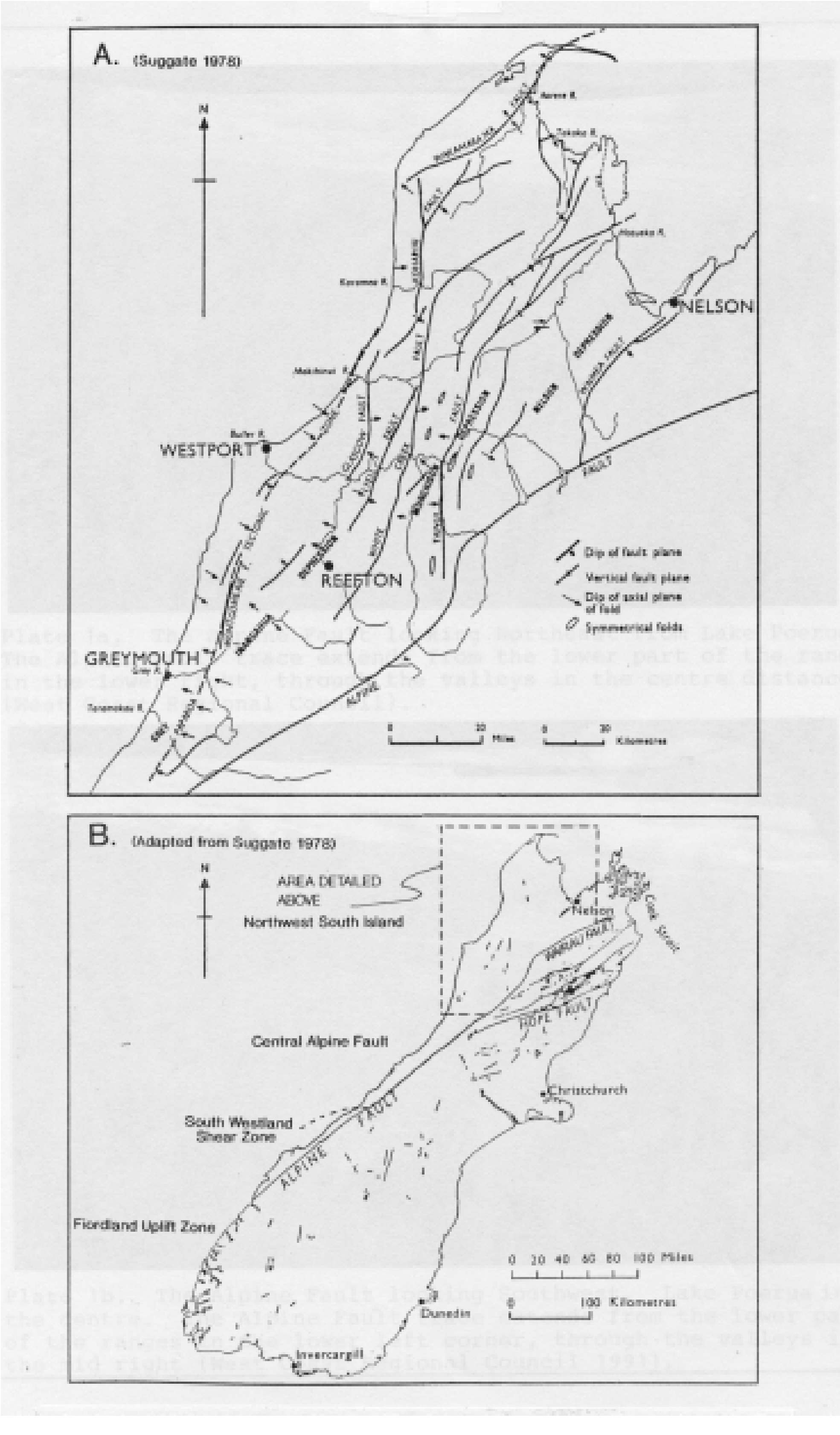


Figure 2: Major Faults, Folds, and Tectonic Zones of the West Coast

5.3 Effects Of Earthquakes

The regional effects of earthquakes are numerous and have been described in detail in Benn (1992) and more recently in Yetton *et al*. (1998). Earthquake effects and their general time scales in relation to the earthquake shock include:

- Ground shaking: Immediate.
- Surface rupture: Immediate.
- Liquefaction: Immediate.
- Landslides: Immediate - Moderate/Long Term
  Note: An earthquake can initially weaken slopes, and then subsequent trigger mechanisms may actually cause the slope to fail and slide. (See Chapter 3 & Appendix 3).
- Landslide dammed lakes: Immediate - Long Term.
  Note: Dams and lakes can form almost instantly, and fail in a few hours, or last thousands of years. (See Chapter 3 & Appendix 3).
- Tsunamis: Immediate - Short Term.
  Note: Near field tsunamis generated by local earthquakes will be felt within a matter of minutes (See Chapter 4).
- Seiches: Immediate.
- River avulsion and sedimentation, by landslides: Immediate - Long Term
  (See Chapter 1 and Appendices 1 & 3).
- Severing of engineering lifelines (roads, rail, water supplies, sewage pipes, telecommunication lines, powerlines): Immediate - Moderate Term.

The time scales mentioned above give an indication of the duration of the effects actually occurring, but the physical clean-up, repair work, and economic effects may last for many months, or years. The effects mentioned between numbers 4-8 above were discussed in detail in previous chapters, and hence only passing references are made to them in this chapter.

5.3.1 Surface Rupture

Berryman (1984a) noted that a good correlation existed in New Zealand between surface rupture (faulting) and shallow earthquakes equalling M7 or greater. It was also observed by Berryman that a good correlation existed between surface rupture and felt intensities of greater than MM9. However, examples of surface rupture have occurred with earthquakes of less than M7. These include the 1929 Arthur's Pass earthquake (M6.9, Rynn 1975, M7.1, Dowrick 1991, Yang 1992), the 1983 localised earthquake swarm of M3-M4 on the Kaiapo Fault (north Taupo Fault Zone, Berryman 1983), and the Edgecumbe earthquake in 1987 (M6.3, DSIR 1987).

Notable West Coast examples of surface rupture include the 1929 Murchison Earthquake (M7.8) and the 1968 Inangahua Earthquake (M7.1). Respective felt intensities of these earthquakes in the epicentre regions were MM9 and MM10. Surface rupture on the White Creek Fault during the Murchison Earthquake was 4.5m vertical where the fault crosses the Buller Gorge Road (now SH6) (Ferrar & Grange 1929, Fyfe 1929, Hendersen 1932, Bastings 1933). Maximum uplift of 4.9m occurred about 503m east of the fault, and was recorded by Fyfe (1929). The uplifted block tilted gradually to the east, with the tilt becoming non–existent at about 19.5km from the fault. Hendersen (1937) detected the fault trace displacement for 8km, and Berryman (1980) recorded 2.1m of sinistral horizontal movement and 3.1m vertical movement at a fence crossing the fault scarp.

During the Inangahua Earthquake, surface rupture was recorded on the Glasgow-Inangahua Fault, and the Rotokohu Fault traces. Maximum displacement on the Glasgow-Inangahua Fault was near the railway lines at Inangahua. Lensen & Otway (1971) recorded 190mm of sinistral displacement, 400mm of vertical displacement, and a shortening component of 270mm (i.e. high angle reverse faulting as in the Murchison Earthquake). Maximum uplift occurred 4km east of Inangahua, and an area of at least 1 000km^2 was uplifted by an average of 1m. The Rotokohu Fault traces were formed during the Inangahua Earthquake, and were formed by slippage of bedding planes (bedding plane faults) in underlying Tertiary sediments. All were up-thrown to the south- east, with maximum vertical and dextral displacements reaching 1m on some traces: 400mm of thrusting was indicated by compressional rolls on the ground surface (Lensen & Otway 1971).

Although no movement of the Alpine Fault has been recorded historically, geological evidence suggests that individual dextral movements associated with large-scale earthquakes are in the order of about 8m horizontal (Hull & Berryman 1986, Yetton *et al*. 1998). The most recent earthquake on the Alpine fault occurred in 1717AD, with an associated minimum rupture length of 375km, from Milford Sound to the Haupiri River (Yetton *et al*. 1998). This rupture may actually be up to 450km in length (see Section 5.5).

5.3.2 Liquefaction

Liquefaction occurs as a result of ground shaking, when pore fluids in fine grained sediments are prohibited from escaping, hence the sediments become saturated, lose their strength and behave like a fluid – that is, the sediments flow. Liquefaction is commonly associated with geologically young sediments, especially those less than 10 000 years old, deposited in low energy environments such as lagoons, estuaries and artificially reclaimed ground. Bell (1994) also noted a high ground water table was necessary for liquefaction to occur. Fairless and Berrill (1984) noted that with the exception of the 1895 Taupo Earthquake (greater than M6, in pumice soils which have unique properties), all cases of liquefaction in New Zealand have occurred in earthquakes of at least greater than M6.9. However, liquefaction occurred in the 1913 Westport (Fairless & Berrill 1984), which was assigned a magnitude of greater than M5 by Eiby (1968), although the exact magnitude is not known. Liquefaction was also recorded in the January 1991, M6 Westport earthquake (Benn 1992). Keefer (1984) suggested that M5 might be the minimum magnitude required for liquefaction to occur. For New Zealand, Hancox *et al*. (1998) claimed that MM7 was the minimum shaking intensity threshold for sand boils, and MM8 was for lateral spreads. They also noted that both might occur at one intensity level less, in highly susceptible materials.

With the region's main settlements being established on river mouth/estuarine deposits, and reclaimed lagoons, there is a considerable risk of damage by liquefaction during earthquakes. Fairless & Berrill (1984) commented that *"...it is now recognised that liquefaction is a fairly common seismic effect and one with great potential for destruction"*.

Liquefaction causes damage by water ejection (like a high pressure fountain), sand boils, settlement of sediments, landslides on moderate slopes, foundation failures, and floatation of light structures. Numerous examples of liquefaction have been reported on the West Coast (Fairless & Berrill 1984, Berrill *et al*. 1987a, 1987b, Adlam 1988, Berrill *et al.* 1988, Benn

1992). The most damaging case, described by Berrill *et al*. (1988), occurred during the Inangahua Earthquake: At 10A Romilly St, Westport, a sand boil under the house had sufficient force to lift the house, rotate it, and leave it skewered on it's foundations. The house had to be demolished. Appendix 4 summarises liquefaction cases recorded in Benn (1992).

As can be seen from Appendix 4, most cases of liquefaction have been recorded in the Buller District, being coincidental with earthquake epicentres in the district. However, if earthquakes are generated elsewhere in the region, it can be expected that reported liquefaction cases would also increase from those areas. Berrill *et al*. (1988) noted that liquefaction becomes more sporadic with increased epicentral distances, and all West Coast examples have been recorded from level or near level ground.

Benn (1992) noted that:

"Widespread liquefaction is possible on the West Coast, given the geologically young, near level flood plains of many river valleys. The most extensive flood plains (potentially the highest liquefaction risk) occur in the Grey and Inangahua river valleys, the Buller and Karamea river flood plains, and in the valleys of the Arahura, Hokitika, Wanganui and Poerua Rivers.

All of these floodplains have been intensively settled and developed. Hence, because all the major West Coast settlements are located on river flats (e.g. Inangahua, Murchison, Reefton) or at river mouths in a lagoonal environment (e.g. Greymouth, Westport, Karamea, Hokitika, Okarito), the potential for liquefaction damage is high"

Potential liquefaction sites can be determined to a certain degree by basic soil identification, and scientific soil and pore pressure tests, although Fairless & Berrill (1984) noted that predictions of liquefaction potential are far from reliable due to the mechanics of liquefaction not being fully understood. However they did state that *"If we ask whether liquefaction would have been predicted at Three Channel Flat* (Inangahua area, Buller Gorge) *given the soil properties found, the answer is definitely yes"*.

Benn (1992) suggested that locating potential liquefiable sites should be considered important, especially in areas of intense development or proposed development. Fairless & Berrill (1984) concluded that Three Channel Flat and Kilkenny park in Westport would be interesting to investigate further because of their recorded liquefaction, as would the Grey River site if it could be located more precisely. This was suggested: *"…to establish soil properties there and to check the results of various predictive liquefaction models against the known occurrence of liquefaction"*.

Identifying potential liquefaction sites and creating hazard maps was one of the main hazard priorities expressed by the three District Councils, when interviewed for this project (See Chapter 7).

5.3.3 Seiches in Lakes

Landslides falling into lakes, or disturbances of the lake floor by submarine slides or fault ruptures, can cause waves in the order of tens of metres high (Hawley 1984). Two such reported cases occurred during the 1929 Murchison earthquake, when it was reported from Lake Rotoroa (now in the Tasman District):

"Lake Rotoroa rocked from side to sided like a huge basin of water being tipped out. Half an hour after the main shake, the water receded from the hotel shore and exposed the lake bed for 50 yards. It then came back in a series of large waves. The bridge over the Gowan River at the lake was torn from its piles and banks of the river and was hurled upstream by the Gowan waters, which were temporarily flowing back into the lake. The water then returned back to its normal course" (Greymouth Evening Star 20/06/29, *in* Benn 1992).

The same edition of the paper also reported: *"Lake Moana (Brunner) sank down in the middle then came up like a typhoon"*. Lake margins were flooded. It is assumed that these two seiches were generated from submarine disturbances, as no contemporary reports or observations of landslides falling directly into either lake have been found.

Benn (1992) noted that since there are numerous deep lakes in the region, located in steep sided glacial trench valleys, landslides into lakes and seiches are a potential threat throughout the region. At Lake Brunner and Lake Kaniere there is a threat to the substantial settlement and development around their shores, However, development is not intense around many of the other smaller lakes in the region. Yetton *et al*. (1998) stated that: *"In general lake seiches are more likely to cause damage during an Alpine Fault earthquake than are tsunami"*. This was based on the proximity of the lakes to the Alpine Fault trace, and it was noted that Lake Brunner and Lake Kaniere were 7km and 500m from the fault respectively, and both have steep peaks on their shorelines, elevated at more than 1000m above the lake levels. Yetton *et al.* also noted the potential effects of seiches on individual lakes throughout the region.

5.4 Earthquake Magnitude, Intensity and Frequency

5.4.1 Earthquake Magnitude

An earthquake's magnitude (M) is instrumentally recorded and measures the amount of energy (Ergs) released in an earthquake at its source. The magnitude is measured on a logarithmic scale, with the amount of released energy increasing about 32 times for each unit of increase in magnitude. Table 5 shows the comparison.

Table 5. Comparison of Difference in Magnitude and Radiated Energy for any Two Earthquakes. (after Ziony 1995).

Difference in Magnitude	Number of Ergs (Energy Released)	Difference in Radiated Energy
5	20×10^{13}	32 000 000
4	6×10^{11}	1 000 000
3	2×10^{10}	32 000
2	6×10^{8}	1 000
1	2×10^{7}	32 (31.6)
0.1	6×10^{5}	1.4

To date the largest magnitude earthquake centred, and recorded, on the West Coast, is the 1929 Murchison Earthquake at M7.8 (Dowrick & Smith 1990). The second largest was the 1968 Inangahua Earthquake at M7.1 (Adams *et al*. 1968). Based on geological evidence of pre-historical events, Yetton *et al* (1998) and Pettinga *et al*. (1998) predict that the next Alpine Fault rupture is likely to produce an earthquake of M8 ± 0.25, and will be larger than any other earthquake that has occurred in the last 100 years.

The range of magnitudes presented in Table 6 below, for the Toaroha River Event (1717AD) (see Section 5.5) is due to the possibility of two rupture lengths, of 375km based on trenching evidence, and 450km based on tree ring evidence: For 375km of rupture length, Wells & Coppersmith (1994) suggested an associated earthquake of M8 ± 0.15, whilst Anderson *et al*. (1996) suggested M8 ± 0.26 for the same distance. For 450km of rupture, Wells & Coppersmith (1994) predicted an earthquake of M8.15 ± 0.2, and for the same rupture, Anderson *et al* (1996) predicted M8.05 ± 0.26.

5.4.2 Earthquake Intensity

In relation to hazards, earthquake intensity (MM) is more relevant than magnitude. The intensity of an earthquake is the measure of the *felt effects* at the earth's surface, and these vary according to proximity to the epicentre, local geology and engineered structures (Cowan & Pettinga 1990). Eiby (1966) devised a Modified Mercalli Scale (New Zealand version) for measuring such intensities. The scale ranges from MM1, where the shock is usually unfelt by humans, to MM12, where damage to structures is virtually total and large rock masses are displaced. The full scale is shown in Eiby (1966), Benn (1992), Pettinga *et al*. (1998).

The highest MM intensity recorded on the West Coast is MM10, in both the Murchison Earthquake (Adams 1981, Berrill *et al*.1988), and the Inangahua Earthquake (Adams *et al*. 1968, Adams 1981). Table 6 shows estimated MM intensities (and magnitudes) from Yetton *et al*. (1998), for the two most recent Alpine Fault earthquakes (see Section 5.5), and the most likely intensities to be expected at various locations in the next Alpine Fault event.

Table 6. Predicted Intensities for the Two Most Recent Alpine Fault Earthquakes and the Most Likely Modal Intensity as a Guide to the Next Event (After Yetton *et al*. 1998).

Location	Predicted Intensities (MM Units)					
	Crane Creek Event		Toaroha River Event		Modal Intensity	
	Date	*M*	*Date*	*M*	*Date*	*M*
	1625 AD	**>7.8**	**1717 AD**	**~8(.05)±0.26**	**<2100AD?**	**8±0.25**
Otira	=9		=9		=9	
Franz Josef	=9		=9		=9	
Hokitika	9		8		8-9	
Greymouth	8		8		8	
Westport	7		7		7	
Reefton	8		7		7-8	

Yetton *et al*. (1998) produced isoseismal models, from which the data in Table 6 were extracted, and stated that an area of MM10 closest to the fault trace was likely in previous events (and predicted events), but was not shown on their isoseismal models due to the possible influence of local fault effects.

5.4.3 Earthquake Frequency

Benn (1992) summarised the work of a number of researchers, who investigated the return periods (frequencies) for fault movements in the region, including that of the Alpine Fault. At that time, based on the work of Adams (1980) and Hull & Berryman (1986) it was thought that the Alpine Fault ruptured about once every 500 years on average. However, recent research has radically changed this thinking. A variety of independent research lines now indicate that the Alpine Fault ruptures on average, about once every 250-260 years. Bull (1996) used lichenometric dating of large rockfalls and determined that Alpine Fault earthquakes had occurred in 1748AD, 1489AD, 1226AD and possibly 967AD (all ± 10 years). The implied recurrence interval was 261 ± 14 years. Cooper & Norris (1990) used ^{14}C dating of sag pond material from near the fault scarp in South Westland, and tree dating methods. They suggested large Alpine Fault earthquakes had occurred somewhere between 1650AD and 1725AD, and possibly around 1980 ± 60 BP.

Yetton *et al*. (1998) produced four lines of independent evidence for which the results were very constant with each other (see research section). Based on this evidence, Yetton *et al*. inferred earthquake dates of 1717AD, 1620AD ± 10 years, 1425AD ± 15 years. Other earthquakes inferred with decreasing reliability, were estimated to have occurred around 1200AD, 940AD, 600AD, 25BC (based on the evidence of a number of researchers (see Yetton *et al*. 1998, pp 85-86). As the four independent lines of evidence are consistent with each other, the fault rupture dates of Yetton *et al*. are the most reliable produced to date. It was also noted that some intermediate timed events have probably occurred but have not yet been recognised. Yetton *et al*. stated:

"The implied pattern of earthquake occurrences is not regular but averages around 200 years and varies from 100 years to at least 280 years, which is the lapsed time since the last earthquake. Probability estimates can be made using the record of earthquake recurrence

derived from a combined analysis of earthquake timing on other plate boundary faults around the world".

These calculated earthquake probabilities are presented in Table 7, which shows there is a very high probability of an Alpine Fault earthquake occurring in the next 50 to 100 years.

Table 7. Probability Estimates for the Next Alpine Fault Earthquake on the Central Section of the Alpine Fault (Yetton *et al*. 1998).

Years Hence	Probability of an Earthquake Event (%)	
	Average	Range
5	10	6-14
15	27	12-26
20	35	20-45
30	45	30-60
40	55	40-70
50	65	50-75
70	75	60-90
100	85	75-95

For other faults in the region, the return periods presented in Benn (1992) are still valid until further research is undertaken to determine otherwise. Table 8 presents the mean return periods for various earthquake intensities, from all these other potential sources of earthquakes

Table 8. Mean Return Periods for Various Intensities at Selected Locations

Location	Earthquake Intensity MMVI	MMVII	MMVIII	MMIX
	Mean Return Period (Years)			
Nelson	5	16	56	200
Westport	8	26	91	330
Greymouth	10	34	110	410
Otira	9	31	100	370
Arthur's Pass	9	31	100	370
Mt Cook	14	48	170	600
Queenstown	12	54	250	1100
Milford Sound	12	62	330	1800

Note: Arthur's Pass/Otira data from Paterson (1996). All other sites from Smith (1990)

5.5 Earthquake Research

Much research has been undertaken on earthquakes and fault movement in the West Coast Region and the relevant surrounding areas of Canterbury, Marlborough, and Fiordland. Benn (1992), reviewed the then current earthquake research, and the most relevant to the West Coast is noted below:

Murchison Earthquake: Bastings (1933), Ferrar & Grange (1929), Fyfe (1929), Hendersen (1932, 1937), Berryman (1980) gave measurements of fault movement and described general earthquake damage and effects. Fairless & Berrill (1984), Berrill *et.al* (1987a,), Berrill *et al*. (1988), identified and discussed sites of liquefaction.

Inangahua Earthquake: Adams *et al* (1968), Lensen & Suggate (1968), Lensen & Otway (1971), Lensen (1976), reported on earth-shift and earth deformation. Fairless & Berrill (1984), Adlam (1988), Berrill *et al.* (1987a, b), and Berrill *et al.* (1988) reported on liquefaction sites.

Alpine Fault and Regional Tectonics: Adams (1980) and Hull & Berryman (1986) reported on palaeo-seismicity of the Alpine Fault. Berryman (1979,1984a, 1984b), Suggate (1965, 1978), Walcott (1979a, 1979b) reported on South Island (and New Zealand) tectonism and seismicity. Laird (1968) described the Paparoa Tectonic Zone and faults within it, and Young (1963) described Late Pleistocene faulting near Blackball.

Seismicity Modelling and Earthquake Frequency: Eiby (1968, 1970, 1971, 1975, 1978), Peek *et al*. (1980), Smith (1978, 1990) and Smith & Berryman (1983, 1986), describe historical earthquakes and present seismic frequency models for New Zealand.

Since 1992, several reports have been produced that have changed and improved the general understanding of the Alpine Fault and other fault failures, and associated earthquakes.

Cooper & Norris (1990), used ^{14}C dating on material from sag ponds near the Alpine Fault scarp, in South Westland, and estimated the age of damaged trees (based on circumference rather than the more reliable ring counting method). It was assumed that earthquake shaking damaged these trees. Using this evidence, they concluded that the most recent large Alpine Fault Earthquake occurred between 1650AD and 1725AD, with another possible event at around 1980 ± 60 yrs before present. Yetton *et al*. (1998) noted that whilst the tree dating method of Cooper & Norris was not the most accurate, their results of earthquake timing were the most reliable so far published, as the results were based on a direct investigation of the Alpine Fault.

Bull (1996) dated large rockfalls in the Southern Alps by lichenometry (based on the assumption of uniform growth rates of the lichen *Rhizocarpon rhizocarpous*). At altitudes between 400m and 600m the lichen is deemed to grow at the same uniform rate of ~0.17mm/yr regardless of substrate type, microclimates or aspect. Bull stated this method was very accurate and within a tolerance of ± 10 years. He identified four size modes (43mm, 84mm, 125mm and a less distinctive mode of 166mm), and inferred that these were the results of Alpine Fault earthquakes in 1748AD, 1489AD, 1226AD and possibly 967AD. The recurrence interval was 261 ± 14years.

There are two potential problems with Bull's analysis. The first is that all of Bull's sample sites were east of the Alpine Fault, the closest being 18km away, and most were over 25km away. The second, is that dating landslides is indirect evidence of earthquakes as the fault line itself is not investigated, and very large landslides can occur in the Southern Alps as a result of rainfall or other aseismic mechanisms (e.g. see Chapter 3, Appendix 3, Hovius *et al.* 1997, Yetton *et al*. 1998).

Yetton *et al*. (1998), have produced the most detailed and reliable account on the history of movement and earthquakes on the Alpine Fault to date. They used four independent sources of information to determine past fault ruptures and associated earthquake events, magnitudes and frequencies. The sources of information used were:

1. Data obtained from 5 trenches, and pit excavations at five locations on the central Alpine Fault between Hokitika and the Ahaura River.
2. ^{14}C dating of organic material in older sheared strata, and younger overlying strata (landslides and terraces)
3. Forest age structures (regeneration patterns, determined by ring counts on large numbers of trees)
4. Tree ring analysis (trees that survive an earthquake are quite often damaged and this shows up in their growth rings, providing a very accurate way to determine the timing of earthquake events.

The report described in detail the geophysical aspects of the Alpine Fault, and each fault rupture event was identified, including the earthquake date, estimated magnitude, fault rupture length, isoseimal maps for the two most recent events and comparisons of earthquake timing to that presented in other research. The authors also present a substantial list of the likely effects of the next earthquake, including locations of strong shaking, highway severing, land sliding, liquefaction, and seiches among other things. Other general effects are also described. The main findings of Yetton *et al*. were:

- The Alpine Fault moves by sudden ruptures of several metres displacement and not by aseismic creep, as proposed by previous researchers (e.g. Walcott 1979a, b).
- Expected movement in the next earthquake is: dextral horizonatal offset varying from around 1.8 ± 1m in the north to around 8 ± 2m further south, and a vertical component of 0.5 - 1.5m.
- A total of 7 fault ruptures in around 2 000 years were identified (3 most recent and definite examples based on evidence of Yetton *et al.*(1998); older, less certain events based on combined results from other researchers).
- Events and dates of occurrence were: Toaroha River Event 1717AD, Crane Creek Event 1620AD ± 10yrs, Geologist Creek Event 1425AD ± 15yrs. Estimated magnitudes range from greater than M7.8 – M8.15 ± 0.2. Less certain events were: Murial Creek Event 1220AD ± 50yrs, Roundtop Event 960AD ± 50yrs, Waitaha River Event 595 ± 60yrs, and the John O'Groates Event BC 25 ± 90yrs.
- From the most reliable method of determination (comparison to other plate boundary faults), the probability of an Alpine Fault earthquake occurring in the next 50 years is 65% ± 15, and in 100 years is 85% ± 10.
- Likely magnitude is around M8 ± 0.25.
- Predicted shaking intensities of greater than MM9 are likely in the Southern Alps, and shaking will be strong in most West Coast towns.

- Next fault rupture will most likely be in the central section of the Alpine Fault between Haast and Inchbonnie. The rupture could extend into Milford Sound. The northern extent of faulting past the Ahaura River/Haupiri area is difficult to determine. Rupture was limited to this area in the previous two earthquakes (near where the Hope and Clarence splay faults intersect the Alpine Fault).
- Landslide dams will form in many of the West Coast river valleys.
- Seiches are likely on many West Coast lakes.
- Aggradation and avulsion are likely in the upper reaches of river channels near the epicentre, and may affect populated areas at river mouths later on.
- Liquefaction will occur at a number of sites.

McSaveney & Davies (1998) considered the effects of an Alpine Fault earthquake in their assessment of natural hazards in the Franz Josef area. They used the estimated magnitude and probabilities of Yetton *et al*. (1998) in their assessment, but disagree with Yetton *et a*l. on predicted MM intensities for the township. McSaveney & Davies considered felt intensities of MM10 or greater will affect the town and surrounding area. This was based on the fact that the town is located right on the surface trace of the fault. Predicted effects in the area include severe damage to houses and contents, minor subsidence in some areas that may rupture lifelines (water, sewer, power. telephone, road), snow and ice avalanches, and landslides in the mountains. These mass movements may form landslide dams and lakes (See Chapter 3, Appendix 3).

Yang (1991) examined the geology and rates of movement on the Kakapo Fault (in the MFZ). This fault was divided into four sections, with the southern most being called the Arthur's Pass-Alpine Fault Section. Based on the total dextral displacement, and rates of movement (of terraces and streams on the Canterbury side of the Main Divide), the fault was identified as being very young (~ 250ka), and very active. Slip rates between were between 6-12mm/yr, with a total displacement of 4m in 444 years occurring (9mm/yr average).

Yang (1992) then mapped landslides (from aerial photographs) around the Kakapo Fault in the Arthur's Pass area. Analysis of the distribution and density of the landslides inferred that the 1929 Arthur's Pass Earthquake (M7.1, Dowrick, 1991) was centred on the Kakapo Fault. This earthquake caused considerable damage on the West Coast from Otira to Reefton, and from Greymouth to Westport (see Benn 1992). Until Yang's (1992) work, the epicentre of the earthquake was uncertain. As Yang noted, the epicentre was poorly located from seismograph records at the time; Speight (1933) defined an *area* of strongest shaking and was unaware of the existence of the Kakapo Fault, and Gutenberg & Richter (1954) located the epicentre about 5km from the Alpine Fault. More recent New Zealand researchers also presented different locations. Yang (1992) also produced geological evidence for a M7.4 earthquake occurring on the Kakapo Fault about 500 years ago, and concluded that the Kakapo Fault was *"one of the most active faults in the region, and therefore a possible source of the Arthur's Pass earthquake"*.

Pettinga *et al*. (1998), and Stirling *et.al*. (1999), examined earthquake hazards in the Canterbury Region. These two studies described the active faults in Canterbury (particularly those of the MFZ), and presented details of historical earthquakes that had affected Canterbury, and surrounding regions, including the West Coast. They also presented results from the Alpine Fault research undertaken by Yetton *et al*. (1998). The relevance of these two reports to this study, is that the West Coast could be affected by earthquakes generated from Canterbury or Marlborough, and that major faults of the MFZ transgress Marlborough-

Canterbury and into the West Coast Region, terminating at the Alpine Fault (e.g. Awatere Fault, Clarence Fault, Hope Fault, Kakapo Fault). Pettinga *et al.* (1998) noted that the MFZ was the most active earth deformation zone in Canterbury, and that the Taramakau –Hope River section of the Hope Fault *"…to date remains the only documented example of surface rupture associated with a large earthquake on any of the major Marlborough faults"*. This section of the Hope fault ruptured during the 1888 North Canterbury earthquake (M7-7.3, MM9 in the epicentral region, Cowan 1991). The earthquake was felt strongly in Buller and Westland (down to Hokitika), with minor damage occurring throughout the area (mainly chimneys, windows and crockery, Cowen 1989, 1991, Pettinga *et al*. 1998, Stirling *et al*. 1999).

5.6 Knowledge and Information Gaps

The West Coast's history of earthquakes and fault ruptures have been intensively studied because their effects extend beyond the regional boundary, and thus they have inter-regional and national significance. Therefore as far as West Coast hazard knowledge is concerned, earthquakes are well catered for in terms of information. Nonetheless, there are still many gaps in the knowledge and information pertaining to earthquake hazards. Many of these gaps are of geological and academic interest, but for practical hazard planning and management purposes the following should be considered (in order of priority):

- Potential/historical liquefaction identification and mapping in the main centres.
- Engineering lifelines risk analysis
- Northern section Alpine Fault research

5.6.1 Potential/Historical Liquefaction Identification and Mapping in the Main Centres

Benn (1992) recorded this as a top information priority, and discussions with the District Councils (see Chapter 8), established that councils still consider this a high priority. Yetton *et al.* (1998) recorded that very little, if any, investigations of foundation conditions had been undertaken in Greymouth or Hokitika (where they identified a high risk of liquefaction occurring during a large earthquake). This work could be undertaken by:

- WCRC and district council staff: Basic soil maps could be constructed, identifying broad categories of soils such as lagoon sediments, reclaimed land/landfill, floodplain deposits etc. The WDC are about to start such a project themselves (Rob Daniel & Richard Cotton (WDC, pers.comm.)

- Post Graduate University Students, Probably in Engineering or Engineering Geology: Good practical subject for a thesis investigation, and a good opportunity for WCRC to obtain detailed documentation. For example, see Adlam (1988).

- Consultants: Would produce very detailed maps and accompanying reports. Consultant use depends on financial resources, and urgency (priority) councils allocate to this hazard.

5.6.2 Engineering Lifeline Risk Analysis

Using information from soil mapping above, combined with other relevant hazard maps and information, vulnerable points in essential services could be identified. This information was considered necessary and of high priority by the Westland and Grey district councils (Rob Daniel WDC, Mel Sutherland GDC, pers.comm; Chapter 8). Yetton *et al*. (1998) suggested this be done for Greymouth and Hokitika, and probably for smaller towns that will be worst affected by an Alpine Fault earthquake (namely Franz Josef, Fox Glacier, Otira etc). This type of project would be most suited to a combination of local authorities and consultants:

- WCRC and District Council staff: Provide infrastructure asset information (location maps, plans, construction details etc).

- Consultants: Gather similar information from the private sector (eg Tranzrail, Transit NZ Ltd, power companies, telecommunication companies.) Collate information, compile maps, and reports.

5.6.3 Northern Section Alpine Fault Research

Relatively little is known about the northern section of the Alpine Fault between the Ahuara River and Blenheim compared to the sections further south. This section of the fault is most likely to have major effects in the Buller District. However, this is currently being addressed in an investigation by Yetton (in preparation), to which the WCRC has contributed to, over the past two years (Helen Rouse, WCRC, pers. comm.). Yetton has been investigating the section of the Alpine Fault between Springs Junction and Tophouse Saddle.

It is appropriate to note that apart from liquefaction maps and lifeline information, the general consensus amongst the district councils was that they had enough earthquake hazard information for planning and emergency management purposes.

5.7 Summary

Of all natural hazards, earthquakes present the largest threat to the West Coast Region. This is due to the multiple effects of earthquakes, including ground shaking, landslides, landslide dams and lakes, tsunamis, seiches, liquefaction, river avulsion and sedimentation, and the severing of critical infrastructure. The West Coast straddles an active plate boundary, and is prone to earthquakes due to the number of active faults (and folds) in the region. The Alpine Fault, now recognised as one of the world's great faults, runs the entire length of the region and beyond, and represents the plate boundary at the ground surface. The north-west corner of the South Island (including Buller District), and the south-west corner (South Westland and Fiordland) are two of the most seismically active areas in the country.

Major historical earthquakes in the last 100 years have originated in the Buller District: the largest two being the 1929 Murchison Earthquake (M7.8) and the 1968 Inangahua Earthquake (M7.1). These were centred on the White Creek Fault and Inangahua-Glasgow fault respectively. Both earthquakes caused extensive physical, economic and social damage in the region and beyond: The damage took many months to repair and landscape scars are still clearly evident today. Seventeen people were killed in the Murchison Earthquake and three were killed in the Inangahua Earthquake. The low death tolls were due to the earthquakes being centred in remote areas.

Much more significant damage could occur with a rupture of the Alpine Fault. The most recent predictions indicated that there is about a 65% probability of this occurring in the next 50 years, and about an 85% probability of occurrence in the next 100 years. Such a rupture is predicted to produce an earthquake of around M8, and felt intensities of at least MM9, and possibly up to MM12 (the scale maximum). With these intensities, severe damage can be expected to communities and infrastructure, and to the landscape.

To assist in hazard planning and emergency management, more information needs to be collected in certain areas. This includes identifying and mapping areas of historical and potential liquefaction, lifeline studies and better defining the characteristics and rupture history of the northern section of the Alpine Fault.

5.8 Earthquake References

ADAMS, J. 1980: Palaeoseismicity of the Alpine Fault Seismic Gap, New Zealand. Geology, Vol. 3, pp 72-76.

ADAMS, J. 1981: Earthquake Dammed Lakes in New Zealand. Geology, Vol. 3, pp 215-219.

ADAMS, J., EIBY, G. A., & LOWRY, M. A. 1968: Inangahua Earthquake –Preliminary Seismological Report. *In* Preliminary Reports on the Inangahua Earthquake, New Zealand, May 1968. DSIR Research Bulletin 193, pp 7–16.

ADLAM, R. J. 1988: Engineering Geological Documentation of Seismic Liquefaction Resulting from the 1968, Inangahua Earthquake, West Coast, New Zealand. Unpublished MSc Thesis (Engineering Geology), Canterbury University.

ANDERSON, H., WESNOUSKY, S. G., & STIRLING, M. W. 1996: Earthquake Size as a Function of Fault Slip Rate. Bulletin of the Seismological Society of America, Vol. 86, pp 683 - 690.

BASTINGS, L. 1933: Some Seismological Aspects of the Buller Earthquake, 1929, June 16-17. New Zealand Journal of Science and Technology, Vol. 18, pp 396-409.

BELL, D. H. 1994: Landslide Hazards. *In* Natural Hazards in Canterbury. Canterbury Regional Council. Report 94 (19). pp55-76.

BENN, J. L. 1992: A Review of Earthquake Hazards on the West Coast. The West Coast Regional Council, Greymouth. 62p.

BERRILL, J .B., ADLAM, R. J., OOI, E. T. C., & FORAY, P. Y. 1987a: Seismic Liquefaction in the Buller: Preliminary Results. Pacific Conference in Earthquake Engineering, Wairaki, New Zealand, August 1987. Vol. 3, pp 13–24.

BERRILL, J .B., ADLAM, R. J., OOI, E. T. C., & FORAY, P. Y. 1987b: Seismic Liquefaction in the Inangahua, New Zealand Earthquakes. Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin. pp587-590.

BERRILL, J. B., BIENVENY, V. C., & CALLAGHAN, M. W. 1988: Liquefaction in the Buller Region in the 1929 and 1968 Earthquakes. Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 21 (3), pp 174-189.

BERRYMAN, K. R. 1979: Active Faulting and Derived PHS Directions in the South Island, New Zealand. *In* The Origins of the Southern Alps (edited by Walcott, R.I and Cresswell, M.M.). The Royal Society of New Zealand Bulletin 18, pp 29-34.

BERRYMAN, K. R. 1980: Late Quaternary Movement on the White Creek Fault, South Island, New Zealand. New Zealand Journal of Geology and Geophysics, Vol. 23 (1), pp 93-101.

BERRYMAN, K. R. 1983: Late Quaternary Tectonics in New Zealand. *In* Walcott, R. I. (Editor), An Introduction to the Recent Crustal Movements of New Zealand. Royal Society of New Zealand Miscellaneous Series 7, pp91-107.

BERRYMAN, K. R. 1984a: Active Folding and Faulting. *In* Natuaral Hazards in New Zealand (Edited by Spenden, I. and Crozier, M). New Zealand Commission for UNESCO, pp 302-331.

BERRYMAN, K. R. 1984b: Late Quaternary Tectonics in New Zealand. *In* Recent Crustal Movement of New Zealand (Edted by Walcott, R.I.). Royal Society of New Zealand Miscellaneous Series 7, pp 91-107.

BULL, W. B. 1996: Prehistorical Earthquakes on the Alpine Fault, New Zealand. New Zealand Journal of Geophysical Research, Vol. 101, pp 6037-6050.

COOPER, A. F. & NORRIS, R. J. 1990: Estimates for the Timing of the Last Coseismic Displacement on the Alpine Fault, Northern Fiordland, New Zealand. New Zealand Journal of Geology and Geophysics, Vol. 33, pp 303-307.

COWAN, H. A. 1989: An Evaluation of the Late Quaternary Displacements and Seismic Hazard Associated with the Hope and Kakapo Faults, Amuri District, North Canterbury. Unpublished Msc Thesis, Engineering Geology, University of Canterbury.

COWAN, H. A. 1991: The North Canterbury Earthquake of 1 September 1888. Journal of the Royal Society of New Zealand, Vol. 21, pp1 –12.

COWAN, H. A. & PETTINGA, J .R. 1990: Seismic Hazards in the Canterbury Civil Defence Region. *In* Analysis of Natural Hazards in the Canterbury Civil Defence Region. Canterbury Regional Council, Christchurch. pp115-142.

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH (DSIR) 1987: Earthquake. *In* Resource Research, No. 8. DSIR Publishing, Wellington. 4p.

DOWRICK, D.J. 1991: Magnitude Reassessment of New Zealand Earthquakes. Earthquake Engineering and Structural Dynamics, Vol. 20, pp 577-596.

DOWRICK, D. J., & SMITH, E. G. C. (1990): Surface Wave Magnitudes of Some New Zealand Earthquakes 1901 – 1988. Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 24, pp210–224.

EIBY, G. A. 1966: The Modified Mercalli Scale of Earthquake Intensity and its Use in New Zealand. New Zealand Journal of Geology and Geophysics, Vol. 9 (1-2), pp 122 –129.

EIBY, G. A. 1968: Annotated List of New Zealand Earthquakes. New Zealand Journal of Geology and Geophysics, Vol. 11 (3), pp 630-647.

EIBY, G. A. 1970: Seismic Regions of the South Island of New Zealand. Transactions of the Royal Society of New Zealand; Earth Sciences, Vol. 8 (2), pp 29-39.

EIBY, G. A. 1971: The Frequency of Earthquake Occurrence in New Zealand. Journal of the Royal Society of New Zealand, Vol. 1 (1), pp 55-72.

EIBY, G. A. 1975: Seismology in New Zealand. Geophysical Surveys, Vol. 2. pp 55-72.

EIBY, G. A. 1978: The Milford Sound Earthquake of 1976, May 4. Bulletin of the New Zealand National Society for Earthquake Engineering. Vol. 11 (3), pp191-192.

FAIRLESS, G. J. & BERRILL, J. B. 1984: Liquefaction During Historic Earthquakes in New Zealand. Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 4 (4), pp 280-291.

FERRAR, H. T., & GRANGE, L. I. 1929: Geological Reconnaissance in the Murchison Area. The New Zealand Journal of Science and Technology, Vol. 11 (3), pp 185-190.

FYFE, H.E. 1929: Movement on the White Creek Fault, New Zealand, During the Murchison Earthquake of 17th June 1929. The New Zealand Journal of Science and Technology, Vol. 11 (3), pp 192-197.

GREYMOUTH EVENING STAR 1929: Extract 20/06/1929.

GUTENBURG, B., & RICHTER, C.F. 1954: Seismicity of the Earth and Other Associated Phenomena (Second Edition). Princeton University Press.

HANCOX, G.T, PERRIN, N.D., & DELLOW, G.D. 1998: Historical Earthquake-Induced Landsliding in New Zealand. Geological Society of New Zealand/New Zealand Geophysical Society, 1998 Joint Conference, 30 November –3 December: Programme and Abstracts. Edited by Basset, K.N. & Nobes D.C. Geological Society of New Zealand, Wellington. p105.

HAWLEY, J.G. 1984: Slope Stability in New Zealand. *In* Natural Hazards In New Zealand New Zealand Commission for U.N.E.S.C.O. (Edited by Spenden, I., and Crozier, M.J.), pp 88-133.

HENDERSEN, J. 1932: Earthquakes in New Zealand. New Zealand Journal of Science and Technology, Vol. 14 (3), pp 129-139.

HENDERSEN, J. 1937: The West Nelson Earthquakes of 1929. New Zealand Journal of Science and Technology, Vol. 19 (2), pp 66-143.

HOVIUS, N., STARK, C.P., & ALLEN, P.A. 1997: Sediment Flux from a Mountain Belt Derived by Landslide Mapping. Geology, Vol. 25 (3), pp 231-234.

HULL A. .G. & BERRYMAN, K.R. 1986: Holocene Tectonism in the Region of the Alpine Fault at Lake McKerrow, Fiordland, New Zealand. Royal Society of New Zealand Bulletin, Vol 23, pp317-331.

KEEFER, D.K. 1984: Landslides Caused by Earthquakes. Geological Society of America Bulletin. Vol. 95, pp 1288-1290.

LAIRD, M.G. 1968: The Paparoa Tectonic Zone. New Zealand Journal of Geology and Geophysics, Vol. 11 (2), pp 435-454.

LENSEN, G. J. 1976: Earth Deformation in Relation to Town Planning. Bulletin of the International Association of Engineering Geology No.14, pp 241- 247.

LENSEN, G. J. & OTWAY, P. M. 1971: Earthshift and Post- Earthshift Deformation Associated with the May 1968 Inangahua Earthquake. *In* Recent Crustal Movements. Royal Society of New Zealand, Bulletin 9, pp 107-116.

LENSEN, G. J. & SUGGATE, R. P. 1968: Inangahua Earthquake–Preliminary Reports on the Inangahua Earthquake, New Zealand. DSIR Bulletin 193, pp 17-36.

McSAVENEY, M.J. & DAVIES, T. R. H. 1998: Natural Hazard Assessment for the Township of Franz Josef Glacier and its Environs. Report prepared for the West Coast Regional Council by the Institute of Geological and Nuclear Sciences Ltd (McSaveney), and Department of Natural Resources Engineering, Lincoln (Davies). Client Report 44714b.10. 52p.

PATERSON, B.R. 1996: Slope Stability Along State Highway 73 Through Arthur's Pass, South Island, New Zealand. New Zealand Journal of Geology and Geophysics, Vol. 39, pp 339-351.

PEEK, R, DARRILL, J .B., & DAVIS, R. O. 1980: A Seismicity Model for New Zealand. Bulletin of the National Society for Earthquake Engineering, Vol.13, pp355-365.

PETTINGA, J. R., CHAMBERLAIN, C. G., YETTON, M. D., VAN DISSEN, R. J., & DOWNES, G. 1998: Earthquake Hazard and Assessment Study, Stage 1: Earthquake Source Identification and Characterisation. Report Prepared for the Canterbury Regional Council, Rivers and Coastal Resources, and Hazards Sections. 121p plus Appendices.

RYNN, J. M. W. 1975: Seismotectonics of the Arthur's Pass Region, South Island, New Zealand, and Regional Variations in TS/TP. Unpublished PhD. Thesis, Columbia University, New York.

SMITH, W. D. 1978: Earthquake Risk in New Zealand; Statistical Estimates. New Zealand Journal of Geology and Geophysics, Vol. 21 (3), pp 313-327.

SMITH, W. D. 1990: Earthquake Hazard in New Zealand: Some implications from the Edgecumbe Earthquake, March 1987. Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 23, (3) pp 211-219.

SMITH, W. D. & BERRYMAN, K. R. (1983): Revised Estimates of Earthquake Hazard in New Zealand. Bulletin of the National Society for Earthquake Engineering, Vol. 16 (4), pp 259- 272.

SMITH, W. D. & BERRYMAN, K. R. (1986): Earthquake Hazards in New Zealand; Inferences from Seismology and Geology. Royal Society of New Zealand Bulletin, Vol. 4, pp 173-182.

SPEIGHT, R. 1933: The Arthur's Pass Earthquake of 9th March, 1929. New Zealand journal of Science and Technology , Vol. 15, pp173-182.

STIRLING, M., YETTON, M. D., PETTINGA, J. R., BERRYMAN, K., & DOWNES, G. (1999): Probabistic Seismic Hazard Assessment and Earthquake Hazard Scenarios for the Canterbury Region, and Historic Earthquakes in Christhchurch: Stage 1 (Part B), of Canterbury Regional Council's Earthquake Hazard and Risk Assessment Study. Report Prepared for the Canterbury Regional Council, Christchurch. 79p plus Appendices.

SUGGATE, R. P. 1965: Late Pleistocene Geology of the Northern Part of the South Island, New Zealand. NewZealand Geological Survey Bulletin (77), 91p.

SUGGATE, R. P. 1978: The Kaikoura Orogeny. *In* The Geology of New Zealand, Vol 2, pp 671-701. New Zealand Geological Survey, DSIR, Wellington.

WALCOTT, R.I. 1979a: Plate Motion and Shear Strain Rates in the Vicinity of the Southern Alps. *In* The Origin of the Southern Alps (Edited by Walcott, R. I., & Cresswell, M. M.). Royal Society of New Zealand Bulletin, Vol. 18, pp 5-12.

WALCOTT, R.I. 1979b: New Zealand Earthquakes and Plate Tectonic Theory. Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 12, (3), pp 87-93.

WELLS, D. L. & COPPERSMITH, K. J. 1994: New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. Bulletin of the Seismological Society of America, Vol. 84, pp 974-1002.

WHITEHOUSE, I. & GRIFFITHS, G. A. 1983: Frequency and Hazard of Large Rock Avalanches in the Central Southern Alps, New Zealand. Geology, Vol. 11, pp 331-334.

YANG, J. S. 1991: The Kakapo Fault – A Major Active Dextral Fault in the Central North Canterbury – Buller Regions of New Zealand. New Zealand Journal Of Geology and Geophysics, Vol. 34, pp 137-143.

YANG, J.S. 1992: Landslide Mapping and Major Earthquakes on the Kakapo Fault, South Island New Zealand. Journal of the Royal Society of New Zealand, Vol. 22(3), pp 205-212.

YETTON, M. D., WELLS, A., TRAYLEN, N. J., 1998: The Probability and Consequences of the Next Alpine Fault Earthquake. EQC Research Report 95/19. Prepared by Geotech Consulting Ltd, Christchurch. 161p.

YOUNG, D. J. 1963: A Faulted and Tilted Late Pleistocene Terrace Near Blackball. New Zealand Journal of Geology and Geophysics, Vol. 6, pp 721-724.

ZIONY, J. I. (1985): Evaluating Earthquake Hazards in the Los Angeles Region–An Earth Science Perspective. U.S. Geological Survey Professional Paper 1360. U.S. government Printing Office.

6.0 CLIMATIC HAZARDS

6.1 Introduction

The previous chapters have dealt with the more obvious natural hazards in the region. However, there are several other hazards recognised by the WCRC that need consideration at some stage in the future. Most of these relate to climatic hazards. Scattered references are made to some of these in reports on main hazards. There are relatively few published works that deal with climatic hazards in the West Coast Region, either relating to the region alone (e.g. Hessell 1982), or as part of broader surveys of specific hazard agents (e.g. Tomlinson and Nicol 1976). There are numerous newspaper reports of atmospheric and related hazards that could be analysed in a manner similar to that employed by Benn (1990) for flooding, though this would be a large undertaking. However, as an indication of what could be done, searches were carried out for these types of reports relating to the West Coast region in an electronic database of INL newspapers over the last five years (Appendix 5).

In the following sections of this chapter, the information on causes, effects, magnitude, frequency and past research for each type of hazard is presented together in one section on that hazard.

6.2 Heavy Rainfall

The existence of very heavy orographic rainfall in the West Coast area has been known for some time but the details of the distribution were not clearly elucidated until Ministry of Works scientists established profiles of rain gauges perpendicular to the main divide in the 1970s. The major finding of these studies was the identification of a zone of very high precipitation just to the west of the main divide (Chinn 1979, Griffiths & McSaveney 1983). At the same time, the earlier work of Robertson (1969) on extreme value analysis of high intensity rainfalls for the country, was extended by Tomlinson (1980). As an example his maps show that for the high precipitation zone just to the west of the central Southern Alps, the 24-hour, 5-year return period rainfall is over 640 mm, far greater than any other part of the country. Whitehouse *et al*. (1985) provided more detail for the central Southern Alps and provided graphs for estimating short period extreme rainfalls from M.A.P. data.

More recently, the processes involved in these very high rainfalls have been the focus of the SALPEX study (Wratt *et al*. 1996) and papers are still being published using the measurements made during the experiment (Ibbitt *et al*. 2000, Revell *et al*. 2002). Because the effects of heavy rainfalls are considered elsewhere in this review under floods and landslides, no further discussion is included here, except to note that in view of the difficulty of obtaining precipitation measurements at suitable resolution, either numerical modelling should be used (Stainer & Auer 1997) or run-off itself be used as the best measure of precipitation amounts (Ibbitt *et al*. 2000). However, there is little doubt that the West Coast Region is afflicted by a higher frequency of severe storm phenomena than most other parts of New Zealand, and the effects of these are discussed in the following sections.

6.3 Hailstorms

As indicated by Sturman & Tapper (1996), hailstorms along with thunder, lightning, violent updraughts and downdraughts, and in extreme cases, tornadoes, are typical of an unstable atmosphere in which temperature decreases rapidly with height. Consequently, they are often found in convective cloud cells following the passage of a cold front (Brenstrum 1998). On the West Coast, their formation is enhanced by orographic uplift.

Using newspaper reports, Neale (1977) documented 444 hailstorms throughout New Zealand from 1924 to 1973. Steiner (1989) extended this study to include 118 storms up to 1986 and also examined hail reports from 38 climate stations. The climate station reports revealed that Hokitika Airport had a similar frequency of hail occurrence to Dunedin and Waiouru and that only Invercargill exceeded this frequency. However, the West Coast Region featured less frequently in the newspaper reports with only 17 of the total of 662 considered. This is a complicated function of low population density, lack of susceptible agricultural and horticultural activities and the fact that the climate station data are probably dominated by occurrences of small sized hail. Both Neale and Steiner showed that the 'western hail region' was characterised by low frequencies of hail in autumn and high frequencies in winter and spring.

Three references to hail were found in the INL database over the last five years (Appendix 5); one to the effect of hail on loss of white heron chicks near Whataroa (The Press 27/02/2001), one to hail associated with a tornado at Hokitika (The Press 08/09/2000) and one to a possible hailstorm influence on the loss of a light plane near Haast (The Dominion 11/11/1997).

6.4 Thunderstorms and Lightning Strike

Tomlinson (1976) and Revell (1984) analysed the occurrence of thunderstorms throughout New Zealand. Tomlinson noted that by world standards, the frequency of thunderstorms in New Zealand is low. However, the frequency of thunder days is larger on the West Coast than elsewhere in the country. Most of the region can expect 20 thunder-days/year whereas almost all the remainder of the country has less than 15. The average number of thunder days at Hokitika and Westport is 20.5 and 17.0 respectively: This is more than any of the other 23 stations analysed by Tomlinson (1976). There is no clear seasonal trend in thunder occurrence.

Tomlinson (1976) recorded 11 fatalities from lightning strike throughout New Zealand between 1919 and 1975, one of which occurred in Hokitika on 22 February 1937.

Cooper (2000) outlined the cause of lightning (tri-polar storm clouds), and noted that such storm clouds often occur off the West Coast, and lightning strikes are seen out to sea, although they were uncommon on land. However, although no detailed analysis has been made, historical records indicate that lightning strikes are common on land, and cause a considerable amount of damage in the region (Cowie 1957, Benn 1990, Appendix 1). From Appendix 1 it can be seen that direct lightning strikes caused considerable damage on at least five occasions between February 1990 and March 1995. Most of this damage was to power supplies (the Dillmanstown Power Station being directly hit on two occasions), although the most serious damage was at the Snowflake Ice cream factory at Coal Creek, which burnt down as a result of a lightning strike.

Rob Daniel (WDC, pers. comm.) noted that lightning strikes were relatively common at the new Hokitika water supply plant, and at telecommunication masts. He said that Telecom did not bother with lightning conductors or other protection methods, due to the frequency of strikes at their masts (i.e. it was cheaper to take the risk and repair damage, than to pay for lightning protection). An example of these types of effects, from the INL database, indicated that in a storm in September 2000 (The Press 12/09/2000, Appendix 5), there had been 200 telephone outages and over 900 customers between Arahura and Franz Josef had been without power for up to six hours on occasions.

The district councils considered lightning strike hazards as low priority (See Chapter 7).

6.5 Strong Winds and Tornadoes

Gale force winds and tornadoes have caused considerable damage in the region and are reasonably frequent occurrences. Numerous cases of damage caused by strong winds are referred to in Cowie (1957), Benn (1990) and Appendices 1 & 5, inferring that strong winds are commonly associated with storms that cause flood events. However there are numerous cases reported where strong winds occur by themselves. Examples of wind damage that can occur are presented in Appendix 1, for 8-12 January 1994, 1-2 October 1996, 29 March 1998, where power and telephone lines were cut by falling trees and poles, roofs were blown off, windows smashed, and small buildings were demolished. Although not as marked as the north west fohn effect to the east of the main divide of the Southern Alps, some synoptic situations may give rise to very strong south east winds. For example, Coulter (1965) reported the uprooting of mature trees in the Waiho Valley by such a wind. Doran (1979) recorded similar effects from a strong south-easterly wind in November1975 which *"killed young stock, brought down trees, unroofed a house and several sheds, and blew the NZR[1] bus off the road"*. Ryan (1984) and Russell (1987, 1989) identified turbulence and downdrafts in the region as a hazard to aircraft.

Tornadoes are also a relatively common occurrence in the region, and can cause considerable damage (Rob Daniel, pers. comm., Appendices 1& 5). Seelye (1945) and Tomlinson & Nicol (1976) compiled information on tornadoes reports throughout New Zealand. Seelye (1945) recorded 162 reports from 1919 to 1944, and Tomlinson & Nicol (1976) recorded 236 reports from 1961 to 1975. Tomlinson & Nicol (1976) noted that although the greatest number of reports came from the northern and western parts of the North Island, this probably reflected high population density there. Consequently, their identification of Buller and north Westland as areas of common occurrence suggested significant numbers in the region. Twenty-seven West Coast region tornadoes were included in the list given by Tomlinson and Nicol (1976), and it is clear that the seasonal and diurnal distribution of tornadoes in the West Coast Region is different to that of the country as a whole. Table 9 shows that whereas the seasonal distribution for the country is relatively even, the West Coast Region frequencies are greatest in winter.

Table 9. Seasonal Distribution of Tornado Occurrence in New Zealand and the West Coast Region

	Summer	Autumn	Winter	Spring
All New Zealand (%) 1961-75	24	25	28	24
West Coast (%) 1961-75	13	25	46	17

The diurnal frequency for the whole country shows a pronounced maximum in the early afternoon whereas the West Coast Region tornadoes are more evenly spread throughout the day except for the very early morning when none have been recorded (Figure 3). As there has been no specific search for historical records, determining the frequency or return periods for such events is impossible until such information is gathered. It was previously mentioned in

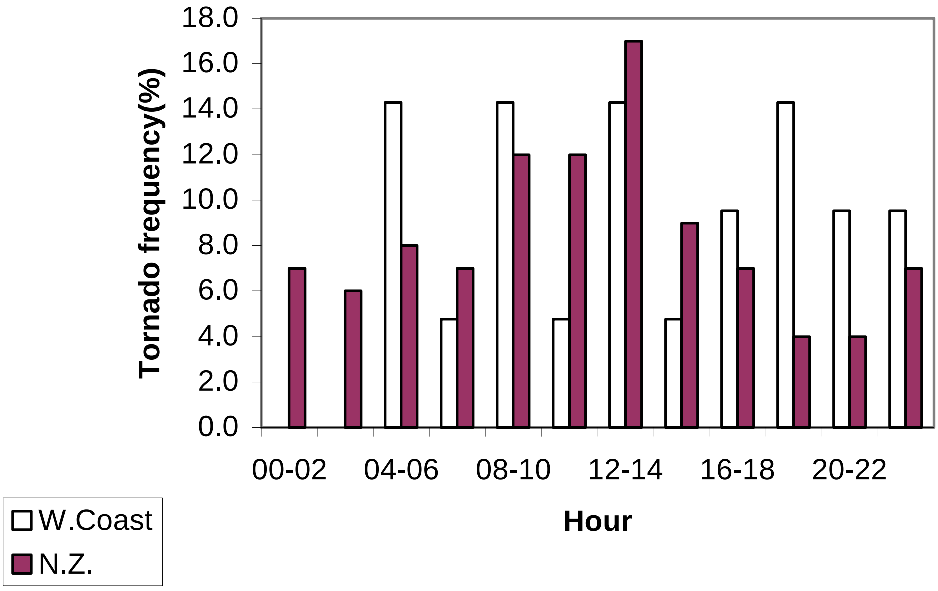
[1] NZR =New Zealand Railways.

Chapter 4, that with global warming, an increase in the occurrence and frequency of strong westerly winds associated with El Nino weather patterns could be expected for the West Coast Region.

District Council staff general felt high winds and tornados fell into the mid-lower range of priority for research (Chapter 7).

INL reports included reference to tornado occurrence in March 2001, January 2000 (water spouts) and March 1998 (The Press 28/03/2001, 26/01/2000, 16/03/1998, Appendix 5).

Figure 3. Diurnal Distribution for New Zealand (n=236) and West Coast (n=24) Tornados for 1961-75.



Note: Three West Coast tornadoes are not included in the above diagram as the times of occurrence were not presented by Tomlinson & Nicol (1976).

6.6 Snow and Ice

Very little information about snow and ice hazards has been unearthed. Hessell (1982) commented on snowline elevations and observed that snowfalls at sea level are extremely rare north of Haast. There have undoubtedly been some snow avalanche fatalities associated with climbing and tramping at high elevation, for example, a fatality in County Stream in the headwaters of the Waitaha River, reported by Irwin *et al*.(2002). Newspaper reports over the last five years were mainly confined to road accidents and articles relating to the safety on the Otira viaduct during snow and ice conditions.

6.7 Drought

Despite the extremely high average annual rainfall in the region, droughts are relatively common (in terms of hazards and inconvenience caused). This is partly a result of the fact that drought is not directly a function of average amounts of rainfall because systems making use of the water become adjusted to the amount available. Thus drought is best defined by some measure of the negative departure from the average conditions – or water that is not available when it is expected to be. One of the earliest droughts in New Zealand's European history was recorded from the West Coast, when in 1867, water supplies to gold mines ran dry, due to a lack of rain (May 1962). Based on meteorological records, Hessell (1982) indicated that dry spells are rare in Westland, especially in the south. Table 10 compares the average number of dry spells (defined as periods of 15 days or more without rain) of West Coast locations to other sites from New Zealand

Table 10. Frequencies of Dry Spells at Selected Stations (Hessell 1982).
(A) = No Rain for at Least 15 Days. (B) = Not More Than 1mm/day for at Least 15 Days

	A, B.	No. of Years	Longest Period (Days)	No. Per Year
Rotoiti	A	30	29	0.8
	B	30	33	1.3
Westport	A	17	19	0.2
	B	17	23	0.6
Hokitika	A	103	29	0.4
	B	103	29	0.6
Haast	A	25	20	0.2
	B	25	25	0.3
Milford	A	45	20	0.3
	B	45	20	0.4
Puyseger Point	A	60	15	0.0
	B	60	16	0.1
Christchurch	A	29	25	0.9
	B	29	45	3.0
Auckland	A	107	39	0.6
	B	107	40	1.2

Hessell (1982) also noted that synoptic conditions with a "blocking" (and relatively stationary) anticyclone to the east of the South Island produced dry spells such as the one which resulted in no rain at Hokitika between 5th and 25th January 1971. Doran (1979) noted a similar occurrence at Whataroa in December 1974 – January 1975, with 21 days of no rain.

Some of the effects of drought in the region are:

- Residents in parts of Greymouth (and other locations) not on reticulated water supplies, often have to get water trucked in, as home water tanks run dry. In extreme cases, such as in March to July 2001, drought conditions caused the contamination of the whole Greymouth town water supply: Low rainfall led to very low flows in the Grey River. This in turn led to a salt-water wedge entering the river and contaminating the town water supply intake area.

- Low river flows can lead to river mouth blockages and subsequent backwater flooding as described in Chapters 2 and 4.
- Long dry periods increase the risk of natural forest and bush fires. Cooper (2000) noted that *"Within the Buller District, naturally triggered fires commonly occur in areas where forest undergrowth becomes dry and humidity is low, or where the brush covering becomes tinder dry in the summer months"*.
- As river and stream flows reduce, increased pressure on water resource allocation occurs. This is particularly true for the dairy and mining industries that use large quantities of water.

No specific information search or analysis has been undertaken, so the magnitude and frequency of drought occurrence are unknown at this stage.

Five drought references are made in the INL database (The Press 19/02/2002, 21/08/2001, 26/03/2001,13/03/2001, The Dominion 09/03/2001, Appendix 5).

Staff at both the BDC and WDC considered drought hazard a low priority, whilst Mel Sutherland (GDC) thought that salt water contamination (resulting from dry periods and low river and ground water levels), was of current concern (see Chapter 7).

6.8 Wildfires

Most studies of regional fire hazard in New Zealand place the West Coast Region in a low hazard class because of ample rainfall, high humidity and a relative lack of strong winds during dry periods (Kerr & Hunter 1986, Pearce 1996). However, as shown in the drought section, some synoptic situations can give rise to long dry spells that may lead to significant fire danger. Consequently scrub and bush fires may pose significant problems in some years. For example, Arnold (1994) noted that in 1886:

"*At Greymouth the Grey River Argus of 11 January told of fires on that coast where none had been seen before, far from any settlement. The masters of coasters reported the smoke of bush fires all along the coast between Nelson and Greymouth.*"

Cooper (2000) noted that in the Buller District during 1998, 57 fires were notified, with most of these occurring in the Charleston and Whitehorse areas. Cooper stated:

"Historic documentation of fires has not been included in the WCRC Hazards Register due to the sheer volume of data (held by Alan Flux at the Greymouth Fire Station). This data needs to be included at a later date, as it may be possible to predict areas that are most at risk".

Attempts were made during this project to obtain the information but it was not readily available at the time of writing. Mel Sutherland of the GDC (pers.comm.) thought that there was an increasing risk of rural fire hazards (maybe accidentally started), due to an increased development of rural lifestyle blocks. That is because development is encroaching into natural bush-clad areas.

INL reports referred to bush and scrub fires in March 2002, February 2002, January 2000, December 1998 and January 1997 (The Press 28/03/2002, 19/02/2002, 21/01/2000, 01/12/1998, 07/01/1997, see Appendix 5).

The main effects of natural fires are probably to the rural landscape (forests, scrub etc), although in some locations, houses, power and telephone pole/lines may be at risk (for example, the lower bush-clad slopes in Greymouth)

Fire information is obtainable from various sources (NZ Fire Service, District Councils, Dept. of Conservation), and efforts should be made to obtain it, to help identify areas prone to fire hazards and to assist in emergency management.

6.9 Knowledge and Information Gaps

As very little information exists for most of these hazards, any information gathered would be of a baseline nature, and would help define hazard location, magnitude and frequency. Priority should be given to wind, fire, lightning, and drought hazards, as these regularly cause structural damage, cut essential services and present risks to public health. As mentioned, information on these hazards is scarce although some does exist. Searches of newspapers, weather reports and general West Coast history books would be obvious places to begin. Dependent on resources, initial searches could be done by:

- Students and/or consultants: Such searches are labour intensive and local councils would probably not want to commit so much of their staff time to such an exercise.

6.10 Climate References

ARNOLD, R. 1994: New Zealand's Burning. Victoria University Press, Wellington. 319p.

BENN, J. L. 1990: A Chronology of Flooding on the West Coast, South Island, New Zealand. The West Coast Regional Council, Greymouth. 159p

BRENSTRUM, E. 1998: The New Zealand Weather Book: Nelson, Craig Potton Publishing.

CHINN, T. 1979: How Wet is the Wettest of the Wet West Coast? New Zealand Alpine Journal, Vol.32, pp 85-87.

COOPER. L. L. 2000: Geotechnical Hazard Analysis, Management and the Development of Hazreg for the Buller District. MSc Thesis, Department of Geological Sciences, University of Canterbury. Vol. 1 (205p), Vol. 2 (Appendices).

COULTER, J. D. 1965: The Weather of Westland National Park. *In* Westland National Park. Westland National Park Board.

COWIE, C. A. 1957: Floods in New Zealand, 1920-1953, With Some Notes On Earlier Floods. New Zealand Conservation and Rivers Control Council, Wellington. 239p.

DORAN, J. A. 1979: Whataroa, South Westland: A Centennial Report. Prepared for the Whataroa District Schools Committee. 105p.

GRIFFITHS, G. A., & McSAVENEY, M. J. 1983: Distribution of Mean Annual Precipitation Across Some Steepland Regions of New Zealand. New Zealand Journal of Science, Vol. 26, pp 197-209.

HESSELL, J. W. D. 1982: The Climate and Weather of Westland, New Zealand Meteorological Service. Miscellaneous Publication 115, 44p.

IBBITT, R. P., HENDERSON, R. D., COPELAND, J., & WRATT, D. S. 2000: Simulating Mountain Runoff with Meso-Scale Weather Model Rainfall Estimates: A New Zealand Experience. Journal of Hydrology, Vol. 239, pp. 19–32.

IRWIN, D., MacQUEEN, W., & OWENS, I. F. 2002: Avalanche Accidents in Aotearoa-New Zealand. New Zealand Mountain Safety Council. In Print.

KERR, I. G. C. & HUNTER, G. 1986: A Review of Fire Management in Rural New Zealand. Journal of the Tussock Grasslands and Mountain Lands Institute. Vol. 43, pp 1-14.

MAY, P. R. 1962: The West Coast Gold Rushes. Pegasus Press, Christchurch. 587p.

NEALE, A. A. 1977: A Climatology of Severe Hailstorms in New Zealand. New Zealand Meteorological Service Technical Note 230. Wellington. 22pp.

PEARCE, G. 1996: Fire Technology Transfer Note No. 10, Forest Research Institute and National Rural Fire Association. 32p.

***REVELL, C. G. 1984**:* Annual and Diurnal Variation of Thunderstorms in New Zealand and Outlying Islands. New Zealand Meteorological Service., Science Report 3 . Wellington. 35pp.

REVELL, M. J., COPELAND, J. H., LARSEN, H. R. & WRATT, D. S. 2002: Barrier Jets around the Southern Alps of New Zealand and their Potential to Enhance Alpine Rainfall. Atmospheric Research, Vol. 61, pp 277–298.

ROBERTSON, N.G. 1969: The Frequency of High Intensity Rainfalls in New Zealand. New Zealand Meteorological Service Miscellaneous Publication 118. 53p plus Appendices.

RUSSELL, P. G. 1987: Interacting Multi-Scale Wind Systems in Westland National Park, New Zealand. Unpublished MSc Thesis, Geography Department, University of Canterbury. 204p plus Maps.

RUSSELL, P. G. 1989: Spatial and Tempoaral Analysis of the Complex Wind Regime of Westland National Park. Proceedings of the 15th New Zealand Geographical Society Conference, pp 246-253.

RYAN, A.P. 1984: Flying Weather: Manual of New Zealand Aviation Climatology. New Zealand Meteorological Service. 120p.

SEELYE, C. J. 1945: Tornadoes in New Zealand. New Zealand Journal of Science and Technology, Vol. 27, pp166-174.

STAINER, R. & AUER, A. 1997: How Does the MetService Forecast and Communicate Weather Information? Tephra, Vol 16, pp. 38-54.

STEINER, J. T. 1989: New Zealand Hailstorms. New Zealand Journal of Geology and Geophysics, Vol. 32, pp 279-292.

STURMAN, A .P. & TAPPER, N .J. 1996: The Climate of New Zealand and Australia. Oxford University Press, Melbourne.

THE DOMINION. 1997-2001: Extracts from11/11/1997, 09/03/2001.

THE PRESS. 1997-2002: Extracts from 07/01/1997, 16/03/1998, 01/12/1998, 21/01/2000, 26/01/2000, 08/09/2000, 12/09/2000, 27/02/2001, 13/03/2001, 26/03/2001, 21/08/2001, 19/02/2002, 28/03/2002.

TOMLINSON, A. I, 1976: Frequency of Thunderstorms in New Zealand. NewZealand Meteorological Service. Meteorological Office Note 82. Reprint of New Zealand Journal of Science, Vol.19, pp 319-325.

TOMLINSON, A. I. 1980: The Frequency of High Intensity Rainfalls in New Zealand Part 1., National Water and Soil Organisation, Technical Note 19. 36p.

TOMLINSON, A. I. & NICOL, B. 1976: Tornado Reports in New Zealand 1961-1975: Technical. Note 229. New Zealand Meteorological Service, Wellington.

WHITEHOUSE, I. E. 1985: The Frequency of High-Intensity Rainfalls in the Central Southern Alps, New Zealand. Journal of the Royal Society of New Zealand, Vol. 15, pp 213-226.

WRATT, D. S., RIDLEY, R N, SINCLAIR,M. R., LARSEN,H., THOMPSON, S. M., HENDERSON, R., AUSTIN, G. L., BRADLEY, S. G., AUER, A., STURMAN, A. P., OWENS, I. F., FITZHARRIS, B. B., RYAN, B. F., & GAYET, J-F. 1996: The New Zealand Southern Alps Experiment. Bulletin of the American Meteorological Society, Vol. 77, pp 683-692.

7.0. NATURAL HAZARD AWARNESS AND INFORMATION FLOWS

7.1 Introduction

An effective way to avoid or reduce the effects of hazards, is to increase the public awareness of such events by keeping them well informed and up to date with new information, legislation and council/civil defence plans. An aware public can lead to fewer adverse impacts by way of more informed planning and development decisions being made in relation to hazardous zones.

This chapter discusses the current state of hazard awareness on the West Coast, and ways of improving information flows to increase the level of hazard awareness and education in the community.

7.2 Hazard Awareness and Information Flow Research

Following the GNS report of McSaveney & Davies (1998) assessing the physical aspects of hazards in the Franz Josef area, the GNS published two reports on public awareness and attitudes to hazards in the same area (Gough *et al*. 1999, Gough 2001). The main aims of these social studies were to evaluate the effectiveness of adding qualitative information to scientific data, in assessing natural hazards and risks.

Gough *et al*. (1999) interviewed 25 local people with the objectives of measuring the community's understanding and preparedness of natural hazards, to determine if the community was provided with adequate information, and to ascertain opinions about local authority hazard planning/management. The main findings were:

- Long term residents were more aware of local hazards than short-medium term residents.
- People were more aware of flood hazards than earthquake hazards (or other hazards), and this was their main concern.
- Floods, but not earthquakes, had directly affected many people.
- People were aware of the earthquake hazard but felt there was little they could do about it.
- Short term river problems were seen as manageable, longer term ones were less so.
- Rural people accepted the effects of flooding – town people thought money/engineering would solve the problems.
- The community was sceptical about councils and 'experts', as local knowledge was rarely considered in hazard planning and management.
- McSaveney and Davies (1998) report was considered by many to be *"over the top"*, *"negative"* and used *"alarmist language"*.

In a follow up report, Gough (2001) focussed on changes in awareness, preparedness and understanding of natural hazards, since the 1999 report. She interviewed 14 people (11 re-interviewed from the prior study) and found that:

- People had become more aware of local hazards although it was uncertain if their attitude had changed.
- Some people still thought the community was insufficiently prepared for a major disaster.
- A rift had developed between residents on the north and south banks of the Waiho River.
- Most individuals believed that they were better prepared for natural hazards than in 1999 (personally and business wise).
- Information problems remained. Many (especially businesses) were not informed of meetings or meetings were at inconvenient times etc. Nearly all respondents wanted more direct contact with the regional and district councils (besides meetings, people wanted mail-outs to every letter box and post box in the community).

These reports were complimented by that of Gough (2002), comparing the results of the two previous studies to a similar situation in Mt Cook village (comparing attitudes and awareness in two remote communities with similar hazards). Here she found comparable results in that flood hazard awareness dominated over earthquake hazard. The main difference found was that because Mt Cook had a less transient population, it was a tighter community than Franz Josef, and thus, the general level of hazard awareness was higher. The implications of this study are that similar results may be found on the West Coast between close-knit communities and more disparate ones.

Although not examined in detail, similar themes to the above studies emerged from field notes, taken during interviews for the WCRC flood hazard map projects. Generally speaking, long-term residents had a better idea of flood hazards than recent arrivals. Long-term residents often had quite detailed records of flood events that had affected them, such as photographs, newspaper clippings, and flood level marks (nails, paint etc) on buildings. It is also apparent that rural people accepted living on a flood plain and the consequences of being flooded; where possible, many tried to keep assets away form known flood zones. Conversely, many urban people in the main centres expected *someone* to do *something* about the local flood problem.

Burney (2001) assessed the effectiveness of hazard information flows between the WCRC and the GDC, focussing on earthquake hazard information. The objectives of the report were to assess earthquake hazard, to review existing information collected and used by the councils, and to look at how the information was communicated between the two councils. The study was based on a search of existing information and interviews with Helen Rouse (WCRC Environmental Information Manager) and Martin Kennedy (GDC Environment Services Manager), and with staff of Environment Canterbury and the Wellington Regional Council. These latter two councils were approached to compare how large councils proceed with information flows.

Burney found the following similarities existed between the WCRC and the GDC.

- Both councils received hazard information irregularly from outside sources (consultants in most cases).
- The information received was usually in hard copy form and limited in scope by project briefs, time and financial resources.
- Consultant reports were often very technical and not in a format ready for easy use by the councils.
- Both councils updated their information databases and libraries as they received new information.
- Both councils acknowledged that the information flow between them could be improved, and were making efforts to do so.
- Hazard information had many applications for both councils, such as in processing resource consents, hazard and emergency planning, Civil Defence, building permits, LIMs[1], and PIMs[2].

Burney recommended numerous ways of improving information flows, suggesting ways to improve the type of information received, how hazard information was gathered, stored, and dispersed, and how hazard education could be improved. If Burney's recommendations are implemented, there are wider ranging implications in improving information flows in general between the WCRC, the three District Councils, and the wider community.

[1] Land Information Memorandums.

[2] Public Information Memorandums.

7.3 District Councils and WCRC Hazard Awareness and Information Flows

To establish some idea of hazard awareness and hazard information amongst West Coast local authorities, Helen Rouse (WCRC) asked appropriate staff members of the three District Councils to rank the hazards in order of concern. A questionnaire was also sent relating to hazard information flows between the WCRC and the district councils. These sources of information were backed up by discussions during production of the current report. The following general comments/replies were made.

7.3.1 Buller District Council

Terry Archer: Manager Regulatory Services.
For council meeting papers of 14 March 2002, Archer (2002) produced a list of hazards that needed further investigation, to help fulfil the council's obligations under Section 26 of the Building Act, and Section 35 of the RMA. Based on the list sent by the WCRC, Archer (2002) prioritised hazards in terms of funding and time frames for further research, as shown in Table 11 below.

Table 11: Proposed Hazard Research Priorities of the Buller District Council

Hazard	Approx. $	Annual Plan
Westport Gasworks	200 000	2002/3
Westport Flood Mapping	35 000	2002/3
Punakaiki Rockfall/Flooding	10 000	2002/3
Karamea Flood Mapping	40 000	2003/4
Reefton Flood Mapping	25 000	2004/5
Ngakawau Coastal Erosion	5 000	2004/5
Global Warming/Sea Level Rise	50 000	2005/6
Contaminated Sites	Unknown	Unknown

Note: Gasworks & Contaminated Sites are anthropogenic hazards and are not considered in this report.

Archer (BDC, pers. comm.) was concerned about the cost of getting flood probability maps produced (Stage 2 of the flood hazard project discussed in Chapter 2), and the size of the hazard zones for Punakaiki, as defined in Cooper's (2000) thesis (discussed in chapters 2 and 3). The BDC considered Cooper's zones as excessive, and if incorporated in District Plans, would restrict development by limiting the issuing of building permits and resource consents: effectively Cooper zones the whole village as hazardous and every property would have to be tagged with LIMs and PIMs.

Archer stated the BDC would prefer to receive hazard information in the form of non technical reports with easy to follow hazard maps, in both hard copy and electronic versions. BDC expected to receive most of its hazard information from the WCRC, and to a lesser extent from outside organizations such as GNS. The council gratefully received information from any source that was willing to provide cheaply or free of charge.

The main general comments from Archer's reply to the information questionnaire were:

- Information was received from various sources and in various formats.
- Information was collated onto a hazard register.
- Generally not enough hazard information is available.
- Finance was the main restriction on gathering hazard information.
- No protocols exist for checking information.
- The WCRC & BDC should jointly provide hazard information for the district.
- Hazard information was used for consents, LIMs, PIMs, asset and emergency/Civil Defence Management.
- Vulnerability analysis and risk assessments would be useful.
- Information flows between the WCRC and BDC could be improved.
- There is a need to gather useful information: *"It makes little sense in gathering information simply for the sake of gathering information"*.

Gary Murphy: Operations Manager
Murphy identified river flooding, coastal erosion, and earthquakes as the main hazards affecting the Buller District. However, these were in no particular order. Other hazards such as sea level rise and volcanic ash were given low priority. The remaining hazards were not given any ranking. The main points from Murphy's reply to the hazard information questionnaire were:

- The BDC received technical information (maps and reports) when it is commissioned and it was usually in a suitable format.
- Sufficient hazard information was available for the region but not the district.
- The WCRC and BDC should hazard provide information for district.
- Lack of co-ordination between authorities and agencies existed. This lead to financial resources being split.
- Some checks were done on the backgrounds of report authors and data sources, and peer review was undertaken if necessary.
- A lack of expertise existed in some areas.
- He would prefer to receive information in summary reports and maps.
- Vulnerability analysis and risk assessment would be useful.
- Information flows between the councils could be improved.

7.3.2 Grey District Council

Mel Sutherland: Assets Manager
Sutherland indicated that the circulated list of hazards was comprehensive and he assumed that hazards associated with earthquakes would be included in any future earthquake research (i.e. liquefaction, surface rupture, slope stability etc). Some hazards not identified by the WCRC needed considering such as groundwater contamination by saltwater. This was a direct response to the recent salt wedge contamination of the town's water supply. Also, more attention needed to be paid to riverbed aggradation and channel positions. Again these affect the town water supply. Rural fire hazards appeared to be on the increase as more rural lifestyle blocks were being developed. Sutherland also noted there was a need to develop and research a parallel list of anthropogenic hazards.

Sutherland and the council's GIS staff member sent a combined reply to the information questionnaire. General comments from that were:

- GDC relied on the WCRC and GNS for hazard information, and generally, there was not enough of it.
- Flood probability maps were of high priority.
- Hazard expertise was not a problem, but limited resources and public complacency were.
- Hazard information the GDC received was used in many applications.
- No protocols existed for information quality checks.
- Information flow between GDC and WCRC could be improved (making some advances)
- A co-ordinated resource/information sharing approach needed to be developed.

Sutherland also identified the following gaps in hazard knowledge.

- The lack of flood probability/recurrence maps need to be rectified.
- The relationship between snowmelt, river discharge and stage was little understood.
- Coastal hazards affecting the Cobden - Rapahoe area needed further investigation.

7.3.3 Westland District Council

Rob Daniel: Operations Manager
In response to the WCRC list, hazards were ranked as follows:

- Floods (river): High.
- Floods (coastal): High and/or Low (dependent on location and effects).
- Earthquake: High/Medium.
- Landslide (and dambreak): High.
- Coastal Erosion: Medium.
- Weather Hazards: Medium.
- Drought: Low.
- Volcanic Ash: Low.
- Tornado: Low.
- Fire: Low.
- Biological Disease Epidemic: Low.

Daniel raised the flowing points:

- Flooding was the top priority hazard.
- There was a real need for flood probability maps and accurate flood level information.
- More general hazard knowledge was needed for the purpose of LIMs and PIMs.
- There was a general lack of information and hazard maps for all hazards.
- There was a definite need for earthquake lifeline studies.
- Tornados, lightning and hail were common and caused considerable damage, but little known about likely areas of occurrence or frequency.
- Soil/liquefaction maps were needed (WDC about to compile some very basic ones).
- WDC regularly surveys the Hokitika coastal cross sections, as part of the proposed groyne expansion programme.
- As an outsider, he noted Greymouth was not sufficiently prepared for a super-design flood (one that overtops the floodwall).

Richard Simpson: Planning Manager
Simpson ranked the hazard list (from highest to lowest) thus:

- Floods – River.
- Earthquake.
- Floods – Coastal.
- Landslide (and dambreak hazards).
- Coastal Erosion.
- Fire – Rural.
- Fire – Urban.
- Tsunami.
- Weather (extreme temperatures, wind, snow).
- Tornado.
- Sea Level Change.
- Drought.
- Biological Disease Epidemic.

Simpson (pers. comm.) said river floods were the most important hazard issue affecting the WDC. He also said that the potential performance of many of the district's stopbanks were of concern. This was due to the age of the banks and that bed levels and positions had changed considerably since many of the banks were constructed. Simpson gave little regard to earthquakes as he thought little could be done to plan against a large magnitude event. Sea level rise was considered a problem of national importance and probably beyond the WDC dealing with it alone. Other hazards appeared to have relatively little weight far as WDC planning was concerned.

For hazard information, Simpson relied on the WCRC and GNS, and basically anyone else who could provide relevant information. He personally found technical reports most useful; if well written he could visualise the concepts/issues being discussed. He did concede that maps were also useful for planning purposes, but in the first instance he would prefer reports. Some criticism was directed at the WCRC in relation to information flows, where he found the WCRC was often slow at responding to requests for hazard information.

7.3.4 The West Coast Regional Council

Hazard information collected by the WCRC has been discussed in detail in other chapters of the report, but are collectively summarised here.

River flood and aggradation hazards have been monitored since the days of the Westland Catchment Board (set up in 1947 and abandoned with the formation of the WCRC in 1990). This has involved monitoring river discharges and levels and surveying river cross-sections to determine bed levels and positions. Much of this work has been related to river protection scheme design. The WCRC still undertakes such monitoring. Similar types of monitoring were common in the 1980s where coastal erosion and sea flooding hazards were prevalent, such as at Hokitika, Okarito, and Punakaiki-Pororari. During the 1990s a series of hazard reports and hazard maps were produced by the WCRC, dealing with river floods, coastal hazards and earthquake hazards. Anthropogenic hazards such as dam failures and potentially contaminated sites were also investigated.

In dispersing this information, the WCRC provided copies to the three District Councils, the Ministry for the Environment (Wellington and Christchurch), and the Ministry of Civil Defence, Christchurch). Copies of are kept at the WCRC office for public consultation, and for sale at minimal cost (to recover production costs).

However, it is recognised that more information is needed for Civil Defence/emergency planning, and general planning and management purpose; hence this report. Rouse (pers. comm.) stated that the WCRC has numerous scientific and technical reports, but the information needs to be reduced into a more user-friendly format. Part of the problem in the past has been that the WCRC has not specified project outcomes clearly enough in project briefs. From her perspective, the WCRC lacked useful maps covering a range of hazards, noting flood probability maps and soil/liquefaction maps in particular. There were also large gaps in the coastal hazard knowledge (e.g. tsunami models, sediment budgets etc).

7.4 Gaps in Knowledge and Information

The analysis of information flows, public awareness and attitudes towards naturals hazards is a very new concept when applied to the West Coast Region and therefore information from most of the region is non-existent. If similar projects to those of Burney (2001), Gough *et al*. (1999), and Gough (2001, 2002) were to be undertaken in the future, they would be most suited to:

- Post Graduate Thesis/Honours Students: Geography (Human or Physical), Applied Science (Environmental Management Studies, Resource Management Studies). Expanding on the above reports would be a good thesis study, providing the WCRC with good, low cost information.

- Consultants: Probably only justified if the WCRC required the information urgently.

7.5 Summary

Having a better understanding of public hazard awareness on a regional scale could lead to better flows of information (e.g. targeting specific groups with relevant information), as discussed by Burney (2001). Combining the results from community awareness surveys with improved hazard information flows, could lead to reduced hazard risk and impacts: If the community is more aware of hazards by being better informed, it follows that better planning and management decisions will be made in relation to hazardous zones. This in turn would lead to reduced damage and social upheaval. In this light it may well be worth extending the research of Gough *et al*. (1999), Gough (2001, 2002) and Burney (2001). The WCRC and the District Councils should consider the recommendations made by Burney to improve information flows.

The main differences in awareness found by Gough *et al*. (1999) and Gough (2001, 2002), were between long and short-term residents, and between urban and rural communities. Similar themes were inferred from WCRC flood hazard map field notes compiled in the 1990s.

From a variety of sources it could be seen that local authorities in the region are quite well aware of hazards that affect their particular area of jurisdiction, although all requested further hazard information. The three District Councils relied heavily upon the WCRC to provide hazard information. However, the GDC was obtaining more hazard information, in GIS format, from other organisations (Mel Sutherland, GDC, pers. comm.). Staff from all councils identified hazards that required further research, and these have been discussed in detail in previous chapters.

Flooding was universally accepted as the hazard requiring more research and information (probability maps, historical hazard maps, and flood depth information). Earthquake hazards required further research in regards to potential liquefaction maps, and engineering lifeline studies. Coastal hazards and the probability and effects of tsunami were also of concern and require further investigation. Differences in awareness were detected between the three District Councils and subtle differences existed between staff members of the same organizations (e.g. between planning and engineering staff). All three District Councils thought the WCRC could do better in providing information, although it was accepted that this is improving, and resources were limited. Generally, all councils wanted hazard information that was simple, non technical, and accompanied by hazard maps. Both hard and electronic copies would be accepted – hard copies for libraries, and electronic copies for manipulation and reproduction

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7.6 Hazard Awareness and Information References

ARCHER, T. (2002): Hazards Requiring Investigation. Report for the Planning and Regulatory Services Committee for the Meeting of 14 March 2002. 2p.

BURNEY, T. (2001): Information Transfer for Management of Natural Hazards: Case Study of Earthquake Hazard Information and Management Within the West Coast Regional Council and Between the Grey District Council. M. App. Sci. (Enviro. Man.) Dissertation, Lincoln University, Lincoln. 50p.

COOPER. L.L. 2000: Geotechnical Hazard Analysis, Management and the Development of Hazreg for the Buller District. MSc Thesis, Department of Geological Sciences, University of Canterbury. Vol 1 (205p), Vol 2 (Appendices).

GOUGH, J., JOHNSTON, D., & McSAVENEY, M.J. (1999): Community Response to Natural Hazard Risk at Franz Josef. Institute of Geological and Nuclear Science, Lower Hutt. Report 99/10. 35p.

GOUGH, J. (2001): Changes in Understanding, Awareness and Preperedness for Natural Hazard Risk in Franz Josef Glacier. Institute of Geological and Nuclear Science, Lower Hutt. Report 2001/22. 19p

GOUGH, J. (2002): Perceptions of Risk from Natural Hazards in Two Remote New Zealand Communities. The Australasian Journal of Disaster and Trauma Studies. Vol 2, 14p.

McSAVENEY, M.J. & DAVIES, T. R. H. 1998: Natural Hazard Assessment for the Township of Franz Josef Glacier and its Environs. Report Prepared for the West Coast Regional Council, Client Report 44714b.10. 52p.

8.0 INFORMATION GAP PRIORITIES

The previous chapters have identified numerous of gaps in the current knowledge and information pertaining to a variety of hazards. In each chapter, these were prioritised in order of importance for further research relating to that specific hazard. This chapter goes one stage further and prioritises *all* of the identified knowledge and information gaps requiring further research. It should be noted that some of the individual research priorities from each chapter, have been grouped together in the overall priorities set out below. For example, Priority 2 groups liquefaction mapping and engineering lifeline identification together.

The priority order was based on:

- Frequency of events.
- Historical and potential damage of events, including injury and loss of life.
- Gaps in hazard knowledge and information identified from the literature search.
- The needs of the needs of the WCRC to mange natural hazards.
- Responses from questionnaires and discussions with the three District Councils and the WCRC.
- Consultation amongst the authors.

Thus the order differs from that presented in the Regional Monitoring Strategy (WCRC 1998). It is also appreciated that the order of priority may change as new information and/or resources become available, or as significant hazard events occur.

In light of the information presented above, and in addition to the hazard information it already collects, it is recommended that the WCRC should gather subsequent hazard information in the following order of priority:

1. Waiho River Aggradation Monitoring.
2. Liquefaction Mapping & Identification of engineering lifelines affected by liquefaction.
3. Rainfall Forecasting & Flood Probability Mapping.
4. Rainfall Monitoring. Especially South Westland high altitude sites.
5. Landslide Inventory. Develop the inventory started in this report.
6. Coastal Database. Collect coastal erosion & accretion rates for further analysis.
7. Historical Flood Mapping. Update existing maps. Cover catchments not yet mapped.
8. Coastal Wave/Sea Level Data. From NIWA, observations and published reports.
9. Landslide Mapping. Basic; based on WCRC inventory and GNS database.
10. Worst Case Scenario Floods. For the major catchments and areas of concentrated population /assets.
11. Historical Coastal Inundation/Sea Flooding Event Inventory.
12. Historical Coastal Sea Flood Mapping. Based on inventory information.
13. Predictive Coastal Modelling. Shoreline stability, storm surge, tsunami.
14. Flood Process Investigations. River mouth blockages, backwater effects etc.
15. Landslide Processes. Rainfall-slope relationship etc.
16. Coastal Processes: Sediment transport, river mouth dynamics etc.

17. Climate Related Hazards. Snow/ice, drought, wind, fire etc. As mentioned in Chapter 6, priority should be given to wind, fire, lightning, and drought hazards, as these regularly cause structural damage, cut essential services and present risks to public health.

9.0 SUMMARY, MAIN FINDINGS AND RECOMMENDATIONS

9.1 Summary

This report, prepared for the WCRC, has examined natural hazards in the West Coast Region. The aims of the report were to summarise current hazard literature relevant to the region, identify gaps in hazard knowledge and information, and provide a comprehensive reference list. The objective of the project was to provide a report that is a useful guideline for future information collection, and for hazard and emergency planning and management. Specifically examined were:

1. River flooding and aggradation hazards.
2. Landslides and landslide dam hazards.
3. Coastal hazards (stability, storm surge, tsunami, sea level rise).
4. Earthquakes hazards (ground shaking, surface rupture, liquefaction, seiches).
5. Climatic hazards (strong wind, tornadoes, hail, snow, ice, droughts, wildfires).
6. Hazard awareness and information flows.

Each hazard was discussed in terms of causes, effects magnitude, frequency, and a literature review. Many gaps in hazard knowledge and information were identified, as were ways of filling those gaps. An order of priority for information collection was then presented.

9.2 Main Findings

The main findings of the investigation are:

- The West Coast Region is affected by all natural hazards except active volcanism (discounting the remote possibility of ash fallout from a North Island event).

- The hazards result from the region's position across an actively deforming plate boundary, which controls the very steep, unstable topography, and the extreme climatic conditions.

- A number of distinctive physical features combine to make the region unique in New Zealand in terms of hazard monitoring, data collection, planning and management. These include:
  - being one of the wettest places on earth, if not the wettest;
  - the West Coast rivers have the largest recorded flood discharges in New Zealand;
  - the Alpine Fault, one of the world's major active faults, runs the entire length of the region and beyond;
  - major glaciers (Fox and Franz Josef) extend to very low altitudes;
  - local geography and topography make the region the longest and steepest in the country; and
  - many communities are isolated and remote.

- Hazards in the region are not usually mutually exclusive, and often more than one hazard occurs during significant events. For example, high rainfall is commonly associated with flooding and landslide hazards: Landslides in turn, can cause a flooding hazard by damming river channels. Multiple hazards can be associated with large magnitude earthquakes (ground shaking, tsunamis, seiches, liquefaction, landslides, surface rupture) etc.

- River flooding, landslides, earthquakes, snow avalanches, lightning strike and hail have all been recorded as causing loss of life in the region. River flooding has probably caused the most deaths, followed by landslides. Other hazards such as road ice may have contributed to accidents, injuries or loss of life, but this was not investigated as part of this study.

- Hazards occur over a variety of time scales resulting in varying effectiveness of planning and management techniques. For example coastal erosion and sea level rise are gradual and predictable, thus allowing time for planning against their effects, and sufficient warning times to remove people and assets from affected areas. In contrast earthquakes, landslides and tsunamis (near-field) are instantaneous, providing little or no warning time and are thus very hard to plan for, and manage.

- River floods are the most frequent hazard and have caused the most damage. This is due to all the region's main settlements being located on very active flood plains. All have suffered to some extent in historical times.

- Earthquakes (especially those associated with the Alpine Fault) have the potential to cause the most severe damage during a single event.

- The region's historical earthquakes have been centred on relatively small faults when compared to the Alpine Fault. The Alpine Fault has not generated a large magnitude earthquake in European times. Recent research indicates the Alpine Fault ruptures about every 250-260 years with associated earthquakes of around M8 and intensities of MM10-12 in the epicentral region. The last Alpine Fault earthquake was in 1717AD.

- Research for this report has identified rainfall induced landslides as a major, frequent occurring hazard. Landslides in the region are most commonly associated with intense/prolonged rainfalls (and thus flood events), and have caused considerable damage. The most common damage has been to transport routes throughout the region.

- River flooding/aggradation, coastal stability, earthquakes and landslides (earthquake generated) have been the most researched of the region's hazards, although many knowledge/information gaps still exist and much of the existing information requires updating. Very little is known about the other hazards in the region.

- Given the WCRC's limited resources, acceptable ways of encouraging financial support need to be identified, so as the WCRC can effectively and efficiently carry out it's statutory obligations in relation to natural hazard and emergency planning.

9.3 Recommendations

In consideration of the information presented in this report, the following recommendations are made:

1) The WCRC and other authorities in the region with responsibilities in natural hazard and emergency planning and management, use this document as a basis for developing and improving service delivery, information gathering, and monitoring techniques.

2) Further research and information collection should be undertaken for all natural hazards, as resources allow, and preferably in the prioritised order presented in Chapter 8.

3) The WCRC, the three district councils and the West Coast Engineering Lifelines Group, will have input into discussing and agreeing with the priority order, as outlined in Initiative 4 of the WCRC Strategic Directions document (see Chapter 1).

4) The WCRC should keep abreast of national and international developments regarding natural hazard planning, management and monitoring techniques.

5) The hazard inventory databases developed in this report and other WCRC reports, should be updated as new information becomes available, or after the occurrence of significant events.

6) The information priorities identified in Chapter 8, should be reviewed after 5 years, or after the occurrence of significant events.

7) The WCRC should pool resources with other relevant organisations in regards to natural hazard research and information collection. This would eliminate duplication of effort, and spread the financial and logistical resources involved.

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DISCLAIMER

This report has been prepared for the benefit of West Coast Regional Council with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

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APPENDICES

APPENDIX 1

Flood Events 24th April 1990 – 27th June 2002

APPENDIX 2

Glacier Burst Events

APPENDIX 3

Chronological History of Landslide Events in the West coast Region
5th November 1867 – 27th June 2002

APPENDIX 4

Liquefaction Events

APPENDIX 5

Selection of INL Database Reports on Climatic Hazards