CONFIDENTIAL

Client Report
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NATURAL HAZARD ASSESSMENT FOR THE TOWNSHIP OF FRANZ JOSEF GLACIER AND ITS ENVIRONS

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July 1998

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by

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EXECUTIVE SUMMARY

This report discusses the major natural hazards threatening the welfare of the community at Franz Josef Glacier. These include hazards caused by recent changes in the Waiho River, and those due to the proximity of the village to the Alpine Fault, one of the planet's major active geological boundaries.

The Callery/Waiho River system is discussed both as a natural system, and as one disturbed by human intervention. 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 now is poised to break out of its channel at one or more of a number of weak points along the river banks. The site which breaches first could be selected intentionally, to create an outcome that is less undesirable than might otherwise eventuate by chance. Such a choice will have to be made very soon if it is to be useful.

Most of the five likely break-out points on the left (south) bank potentially threaten half or more of the assets on that side of the river because a new river path there would cut a wide swath to the sea, following SH 6 and Docherty's Creek. There are two likely break-out points on the right (township) bank, but only the more northerly, the break-out of the Waiho River into the incised channel of the Tatare River above the Waiho Loop, leads the river from its present active channel. Continued maintenance of existing river-control works to keep pace with the present aggradation of the river channel will lead in the short term to the Tatare break-out

Any break-out towards Docherty's Creek may be reversible, as such break-outs have been reversed in the past. If Docherty's Creek is to be the preferred option for a new river course, the break-out may have to be assisted, because otherwise it is likely to be only temporary. Any break-out to the Tatare River would quickly become irreversible. All of the alternative break-out scenarios have potentially damaging and somewhat unpredictable outcomes: that to the Tatare is the least predictable, because such an event has never occurred before.

Break-out of the Waiho into the Tatare will induce rapid incision of the Waiho River across the portion of the fan above the Waiho Loop. This incision of up to 15 metres may extend upriver to above the village and highway bridge. If uncontrolled, it could lead to loss of the village oxidation ponds, the SH 6 bridge, and may undercut part of the village. Break-outs elsewhere may also induce river incision at the fan head, but the incision is unlikely to be as large.

The report considers the following options for future community management of the Waiho River:

- Hold the river in its present course;
- Let the river choose a new course (this is the do-nothing option);
- Choose a new course for the river;

- Make a new course;
- Choose where the river will not make a new course;
- Maintain the *status quo.*

The last two options may have similar outcomes because the actions of past management have been to prevent the river from taking potential new courses as progressive river aggradation has made them available. If the *status quo* is maintained, the river will not be held in its present course, in even the short term.

We feel that the hazard presented by the river should inherently be reducible (i.e. reversible) because it has been largely created by human use of the river's active flood plain, and the consequent need for engineering intervention. The engineering works in turn have led the problem to escalate to its current extreme form, and now other areas are threatened which were never endagered by the original threat.

The earthquake hazard stands in marked contrast to the river hazard, because this hazard is escalating through natural processes and cannot be reduced. The township straddles a major active fault which is expected soon to produce an earthquake greatly exceeding current building design standards. Analysis of available data on past movements of the Alpine Fault indicates a 10% probability that the next earthquake will strike within 5 years. It will be a Magnitude 8 earthquake, a Great Earthquake on world standards, and it will cause major damage throughout much of South Island, and perhaps beyond. The community at Franz Josef Glacier (and many communities elsewhere) will suffer extensive damage, injuries and some fatalities, and may be isolated from substantial outside assistance for several days or perhaps longer. An efficient and comprehensive local emergency response will be essential. Fuel tanks (petrol, diesel and LPG) within the central business area of the township currently are within the zone of expected deformation around the fault, and are extremely likely to rupture during the earthquake. Accidental ignition of the leaking fuel would cause a disastrous fire in the town centre. Even without fire, substantial damage to property in the township is largely unavoidable because of the extreme shaking intensity expected close to the fault: adequate earthquake insurance cover is likely to prove to be the most effective mitigation measure for this extreme event.

The earthquake and fault movement will also strongly affect river behaviour. Channels will be offset by about 8 metres horizontally and 3 metres vertically. River banks will collapse, especially those newly built up to keep pace with the aggrading river. As the river system sluices earthquake-triggered landslide deposits in the headwaters downstream, there will be massive, rapid aggradation at the fan head the like of which has not been seen in historic time. A well planned and frequently rehearsed emergency response which can evacuate the entire community to high ground is seen as the only practical mitigation available to minimise the outcome of this potential disaster.

CONTENTS

1.0 INTRODUCTION

This report is intended as a non-technical discussion document on natural hazards threatening the welfare of the community at Franz Josef Glacier. It discusses recent changes in the powerful Waiho River, and the community's proximity to the Alpine Fault, one of the planet's major active geological boundaries. The report examines past, present and possible future trends in the river's behaviour, and likely effects of an impending major earthquake. It considers how the community might mitigate the effects of the hazards on future village life.

The report has been prepared by The Institute of Geological & Nuclear Sciences Ltd (GNS) for the West Coast Regional Council. The consultants' brief for preparation of the report is given in Appendix 1.

The purpose of the assessment is to:

- Provide the Franz Josef Glacier community with an overview of the behaviour of the Waiho River, first as a natural system, and now as one influenced by human intervention.
- Identify, quantify and rank the natural hazards within the village and peripheral areas.
- Identify the standard of protection (structural and non-structural) from natural hazards (principally flood-induced) appropriate for the community.
- Assess the adequacy of existing protection and management to meet these standards.
- Identify some courses of action that the community could choose from that would enable them to avoid or mitigate the identified hazards.
- Identify the possible consequences of taking any (or none) of these actions.

This report:

- Provides a concise history of the development of the Waiho River alluvial fan, based on examination of historical records and geomorphic evidence.
- Identifies what could happen: the types and possible likely extents of hazardous events, based on examination of historical records and geomorphic evidence left by past occurrences, and how these hazards may now have been modified by engineering work.
- Identifies and quantifies the possible adverse effects of such hazardous events, to the extent of available evidence.
- Identifies what can be done to avoid or mitigate these effects, to levels which might be acceptable to the parties concerned (community and visitors, businesses and shareholders, DoC, Westland District Council, West Coast Regional Council, Transit NZ).

The study has involved scientists from The Institute of Geological & Nuclear Sciences Ltd, and Lincoln University. The report was written jointly by Dr Mauri McSaveney (GNS), and Dr Tim Davies (Department of Natural Resources Engineering, Lincoln U.). Information on seismicity and seismic hazards was compiled by Dr Kelvin Berryman of GNS.

Drs McSaveney and Davies inspected the area as part of this study between 7-24 April 1998.

1.1 Natural hazards and the Franz Josef Glacier Community

The Waiho River in fresh or flood has been, and always will be, a very powerful and dangerous river. Flooding and associated changes in bed level and channel location have frequently caused concern throughout the brief history of occupation of the area. Persistent river-bed-level rises over the past 60 years have expanded the areas at risk, and heightened the dangers, but these trends may be reversible. Because of the nature of the area, however, flooding, and its associated hazards of erosion, aggradation, and river-channel changes will always be serious threats to parts of the Franz Josef Glacier community.

The Waiho area has been settled for only about 120 years. This is too short an interval to provide a complete picture of the area's likely range of adverse natural events. Although the historical range of events has been alarming, the true range is likely to be far worse. Evidence of the true range is recorded in the landscape and the deposits underlying it.

To the detriment of general community safety, the focus of attention on natural hazards in the Waiho area has always been on the immediate threats presented by the Waiho River. This has resulted in the community centre developing close to the Alpine Fault - now recognised as one of the world's great faults. The Alpine Fault passes through the township: accumulated earth forces have the fault ready primed to explode into spectacular and destructive action. It can be likened to a time bomb that cannot be defused. We cannot know in advance when it will trigger, but we now know that the longer it goes without rupture, the worse will be the outcome. The next Alpine Fault earthquake, with an expected magnitude (M_w) of 8.0, is the most devastating natural event that the township is likely to experience. The earthquake and its consequences (infrastructure collapses, fires, landslides, floods, diseases, and financial ruin) seriously threaten the survival of the Franz Josef Glacier community. It is not the only community so threatened: some deaths are expected as far away as Christchurch (*The Press*, Saturday, 6 June 1998).

2.0 TECHNICAL BACKGROUND

2.1 Geomorphic Processes

2.1.1 Alluvial Fan

An alluvial fan is an area formed by deposition of sediment by a stream as it widens on leaving a confined channel in a narrow valley. Over long time intervals, the stream moves to and fro across the fan, dropping sediment as it goes. The deposited sediment aggrades the bed, forcing channel break-outs (technically called *avulsions* - the sudden switching of channel position) to occur. At the fan-head, aggradation can be very rapid if a large amount of sediment enters the river a short distance upstream. If sediment can be removed from the toe of the fan (by the sea or another river) the fan will build to an equilibrium profile. With such a profile, the combination of water flow and fan slope gives the river the power over the long term to transport enough sediment down the fan to the toe to balance the amount of sediment being supplied to the fan head. At equilibrium, the amounts of materials being delivered to the fan head, being shifted about on the fan surface, and being removed from the toe are each equal to one another over the long term. The incoming sediment, however, is not all transported directly through the fan system to the toe.

All parts of an alluvial fan can flood during high flows, but seldom simultaneously.

2.1.2 Braided vs. single-thread meandering river channels

Rivers flow in sinuous channels when the river banks are free to be shaped by the river. Under some conditions of slope, river flow and sediment load, a river will adopt a single sinuous (meandering) channel; with steeper slopes and higher sediment loads, it will form multiple channels which split and merge in a braided pattern. Over a limited range of slope and sediment load for a given water flow, the river may adopt either pattern and can be manipulated to switch from one to the other.

The Waiho River is braided over most of its length most of the time, but locally it maintains a single meandering channel. Precipitous rock slopes constrain the Callery River to a single-thread channel over most of its length.

In addition to these river forms, steep mountain torrents can form a series of pools and riffles, or occupy steep, straight, narrow, U-shaped channels cut in bed rock - these latter are carved by repeated powerful debris flows (see below). These are not to be confused with the very much larger U-shaped valleys cut by glaciers.

2.1.3 Debris Avalanche

A debris avalanche is the flow of debris consisting of water, rock, soil, and plant cover resulting from the collapse of the surficial mantle of loose, weathered material on a steep hill or mountain side, usually caused by heavy rain. The material in a debris avalanche flows very much like a fluid and can acquires a high velocity. Debris-avalanche scars are common on most steep, vegetated slopes in south Westland. They show clearly as vertical bare stripes on the slopes when the scars are fresh, and stripes of even-aged plants on older scars. Debris avalanches can be of almost any size, but small ones are much more common than large ones.

2.1.4 Debris Flow

During heavy rain, erosion of the land bordering stream channels can be so intense that very large quantities of sediment enter the stream, increasing the viscosity of the flow. This can alter the way in which sediment grains interact with each other. Instead of the flowing water carrying the sediment along with it as is normal, the water and sediment form an intimate mixture which flows very much like wet concrete. This is called a debris flow; it can easily be twice as dense as water, and can carry large boulders along on its surface. Such flows usually move as discrete surges, and so have greater flow depths than the corresponding uniform flow; large boulders tend to accumulate at the front of surges.

Debris flows often are generated by debris avalanches falling into narrow confined channels.

Debris-flow surges can move at high velocities (about 10 metres a second) and can be very destructive, scouring narrow channels deeply and growing in volume as a consequence. On leaving a narrow channel (for example, on arriving at a fan head), however, a surge can stop suddenly, forcing the next surge to divert around it and follow a different course down the fan.

Debris flows need a steep slope to develop, and do not occur on slopes of less than about 5 degrees (9%). If a debris flow enters a river it can dilute to form what is known technically as a hyper-concentrated flow - more like a moderately thick soup than wet concrete.

Debris-flow processes are very energetic and intense, and it is not normally possible to provide reliable protection against them by engineering. Debris flows are much more dangerous than most other alluvial-fan processes because they involve much greater volumes of sediment and therefore much more intense aggradation.

Debris flows occur frequently on the steep mountain slopes inland from the Alpine Fault. Rarely, materials of debris-flow character pass through the Callery Gorge, but more usually they are diluted to form hyper-concentrated flows by the large volume of water in the Callery Gorge during high flows.

Debris flows are only likely to be a problem at the Waiho fan head if a particularly large one is generated in the Callery Gorge during the break up of an earthquake-generated landslide dam, when there is likely to be a huge quantity of loose rock in the channel bottom to be picked up by the flood.

2.1.5 Rock Avalanche

A rock avalanche is the flow of rock debris resulting from the collapse of a steep mountainside or mountain summit, usually caused by an earthquake, or less commonly by heavy rain or glacial erosion. Although the debris may be dry, it flows much like a fluid. The debris can travel very fast over extraordinarily long distances. Little is understood about rock-avalanche motion, except that large rock avalanches for some reason go farther in proportion to their size than small ones.

A rock avalanche is very destructive and most things are obliterated when hit by one.

A rock avalanche could occur from any of the steep slopes between the Alpine Fault and the main divide. Countless rockfalls and some large rock avalanches are expected in the upper valleys of the Waiho, Callery and Tatare Rivers during the Alpine Fault earthquake. Although the rockfall sites are easily predicted from the distribution of historical rockfalls, sites of large rock avalanches are unpredictable because they are critically dependent on the amplification of the earthquake shaking within the steep mountain landscape, and so prediction would need unavailable information on the unique propagation of the particular earthquake's waves of shaking energy.

Only the slope immediately above the Franz Josef Glacier township poses a direct threat to the community from potential rock-avalanche run-out. There is a reasonable certainty that the slope above the township has not failed catastrophically in the time since expanded glaciers deposited the Waiho Loop moraine some 13,000 years ago (or we would see a characteristic scar on the slope and some evidence of its deposits), and hence it has survived through at least 50 major episodes of severe ground shaking. Although it **could** fail in the next great earthquake, there is very little likelihood that it **will** fail.

2.2 Relevant terms used in the Building Act (1991)

Erosion is the process of removal of land, usually by the action of running water. In the Waiho context, this is scour of river banks, and excavation of a new channel after a river break-out (*avulsion* - see below).

Avulsion is the switching of a river or individual channel from one course to another; the flow may create a new channel or use a previously abandoned one. This historically has been a major hazard on the Waiho River fan. It is the major immediate hazard at present on the Waiho Flats. In this report, we have used the term "break-out" in place of this technical term.

Alluvion is an obscure term which in the context of the act probably was intended to be the more common technical term *alluviation*, which is sediment deposition both in the stream channel or on adjacent land. Sediment deposition historically has been a major hazard on the Waiho River fan. The Resource Management Act (1991) uses the more obvious term *sedimentation* in identical context to the Building Act's *alluvion*. The movement of slugs of sediment through the channel system discussed in this report is by a combination of *alluviation* followed by *erosion*.

Falling debris in the Franz Josef Glacier context is rocks and trees falling from the steep slopes behind the township, and rockfalls and rock avalanches in the upper valleys. Falling debris historically is a major hazard in the upper Waiho Valley, but not **within** the township area, or elsewhere on the fan.

Subsidence occurs with ground-water abstraction in some areas, collapse of land over abandoned coal and gold mines, collapse into limestone caverns, collapse over buried melting ice, and differential compaction when soils liquefy during earthquakes. It is not a significant hazard away from the immediate area of the Franz Josef Glacier.

Inundation means flooding with water, either from flooded streams, or directly from heavy rain. As with *avulsion* and *alluviation*, this historically has been a major hazard in the area.

Slippage means landslides and could be interpreted to cover advancing glaciers which are not mentioned in the Building Act. These have not been problems within the township area, but the collapse of high terrace banks when undermined by the river are landslides.

2.3 Hazard Frequency and Return Period

Natural hazards result when human activity is in conflict with dangerous but infrequently active natural processes. These processes are caused by weather, rivers and earthquakes acting on the landscape. They act in different intensities, and in different combinations at different times. A hazard event usually is measured by its magnitude. While we might know much about the conditions required for a hazard to occur, it is not usually possible to predict when a hazard will occur, or how big it will be. The frequency with which particular hazard events of known magnitude occur provides information from which the probability of their occurrence can be calculated. Information on the probability and magnitudes of particular hazards is necessary when communities plan to cope with or mitigate hazards.

Although a probability of occurrence can be estimated, **this does not allow us to predict when a given hazard will occur**; all we can know about a particular hazard is that:

- if it can occur, it will occur;
- if it is driven by the weather alone, it is as likely to occur next week as during any other

week in the future.

Some hazards "develop" over time; for example, once a debris avalanche has occurred at a site and a rock surface has been cleaned of loose debris, a long time has to elapse before enough loose debris accumulates on the slope to be able to form another debris avalanche - the longer the time between events, the more debris can accumulate, and the larger the next debris avalanche can be. Earthquakes caused by the movement of particular faults are hazards of this type. For these types of hazards, the probability of their occurrence changes over time. It can be very important to know just where in the hazard cycle the present moment might be - as with the Alpine Fault which is known to be approaching an imminent major rupture (Appendix 2).

It is important to realise that it only makes sense to quote a probability of occurrence of an event during a stipulated period of future time. There are a variety of ways of expressing these probabilities over time. For example, an event can be said to have a 0.01 probability of occurring in any year; this is the same as saying that it has a 1% probability of occurring in any year. Another way to express this is as the time period over which only one event is expected to occur: in this example 0.01 per year is one event per 100 years, hence the expression "a 100-year flood". It always **is possible** to get two "100-year" events just days, weeks or a few years apart, but it **is improbabl**e.

For most communities, the next 50 to 100 years is a sensible planning horizon. Although a "100-year" event sounds awfully rare, there is a 1-in-5 chance that it will occur during the next 20 years; about the same as throwing a six when rolling a die (1-in-6 chance). Are such risks acceptable? An event of 1% probability in a year will occur about once during the next 100 years, i.e. it is almost a certainty in that time and if a community is to last that long, its facilities must be able to survive such an event. Should community facilities be able to survive the 500-year event? These have a 1-in-5 chance of occurring in the next 100 years.

There are big events and small events; they can occur at any time. It is **often** impossible, **and usually uneconomic,** to engineer protection against big events. Where big events can occur, and protection is not possible, warning and evacuation systems can allow continued occupation of a site. Where such systems are not feasible (due to lack of warning time, for example), occupation of the site involves accepting a serious risk of death, and may not be sustainable in the long term. The next Alpine Fault earthquake may come into this latter category because effective warning is not likely, whereas Waiho River floods appear to belong to the former. It remains to be determined if warning is feasible for Callery River dam-break floods.

The event probabilities referred to above are effectively the same as the "risk" of the event occurring in a stated future period of time; e.g. an event with a 1% probability of occurrence in one year has a "1% risk" of happening in that time (risk here is used in a non-technical sense). The levels of risk usually thought to be acceptable vary with circumstances. Fell (1993) examines the risks usually thought to be acceptable in the context of landslides, and concludes that the highest level of risk that can be accepted is about 0.001 **in any one year**, this is about the same as the "1000-year" event. This is the case for "voluntary" risk, i.e. risk that people are fully aware they are taking, and choose to take. If the risk is "involuntary", i.e. the risk-takers are either unaware of, or are forced to take the risk (as a guest at a resort, or in a workplace) then the maximum acceptable event is the "100 000-year" event. Of course, the level of acceptable risk also depends on the expected outcome - as the likelihood of death, injury or financial loss decreases, so the level of acceptable risk increases.

These event probabilities can be illustrated by looking at the odds of winning Lotto. Where a win is choosing 6 numbers in any order from 40 numbers, the odds of winning are given by:

$$\text{Probability of winning} = 6/40 \times 5/39 \times 4/38 \times 3/37 \times 2/36 \times 1/35 = 0.00000026$$

At 50 cents per chance, a person would have to spend $370 a week to make their winning first prize in Lotto occur on average once each 100 years, $37/week for once each 1000 years, and 37 cents a week for once in 100 000 years! There is a 10% probability that the Alpine Fault will rupture within five years: to have such odds of winning Lotto, a person would have to spend $740 a week!

There are, unfortunately, several insurmountable problems with estimating the return periods or frequencies of events on the Waiho River. The first is that the quantities of water flowing in the river are unknown, so that it is not possible to determine how frequently a flow of a given magnitude occurs. The second problem is associated with location. A river on an alluvial fan is not a fixed feature, but moves about within and between storms. Sometimes a flood flow will split between many channels; sometimes it will be contained within just a few. At lower total river discharges, the number of active river channels commonly reduces. The discharge in any particular channel, however, need not reduce, and may even increase depending on how the flow splits between channels. Also, individual channels themselves grow and decay, and may move. There are probabilities associated with each of these, and the net probability of any particular combination of these probabilities is obtained by multiplying them together. Because probabilities are always less than 1.0, the probability of a particular combination of events happening is always less that of any one of them occurring (it is much easier to get one of the Lotto numbers right than to get all six of them right together!).

When a river can split into a number of different-sized channels, and these can go in any of a number of directions, the return period of a given flow at a given point on the fan surface is very different from the return period of the total river flow at the same flood peak. For example, a flood of one-year return period can occur in the flow at the SH 6 bridge, but there may be little, or even no water adjacent to the SH 6 stopbank by Canavan's Knob if the river happens at the time to be flowing mostly on the other side of the fan. Conversely, at normal river flow at the SH 6 bridge, a flow of relatively high return period can occur against the Franz Josef Glacier Hotel and oxidation-pond banks merely because the river happens to be largely flowing in a single channel against that bank, instead of splitting its flow between numerous braids.

A braided river on an alluvial fan may be able to safely pass a flood of a given total discharge in one particular braid configuration, but not be able to contain it in another configuration. This is particularly so if there are big differences in local fan geometry from one side of the river to the other, for example if there are artificial containment banks on only one side. In the Waiho River channel configuration of late April 1998, and using the conventional flood definition that a flood occurs when a river spills beyond its banks, there was a continuous flood on the right bank, 200 metres downstream of the oxidation ponds, because there the river was spilling over pasture in the process of creating a new channel.

The hazard of overtopping the Waiho River stopbanks needs a combination of high bed level with high river flow: the higher the bed level at the time, the smaller the high flow needed to cause overtopping. Both bed level and flow height have associated probabilities of occurrence, so the probability of a bank being overtopped is the product of the two probabilities. Of course, the probability of a particular bed level occurring during a flood changes over time: the probability of achieving a particular high bed level during a flood is much higher if the bed level already is high before the flood.

For these reasons, event probabilities stated in this report are neither precise nor very significant. They merely provide a guide to planning and design.

2.4 Building Act

Section 36 of the Building Act (1991) deals with limitations and restrictions on building consents for land subject to erosion, avulsion, alluvion, falling debris, subsidence, inundation or slippage, and the means whereby territorial authorities may limit their civil liability if buildings are damaged by these adverse events.

Section 36 provides that if the authority believes that a building site is likely to be subject to one or more of the above problems (or if the building itself might cause such problems) it can approve the building if it is satisfied that adequate provision has been or will be made to protect the land or building (or to restore any damage to the land or other property concerned), or it can issue a notification that it will not be under any civil liability if later the building suffers damage arising from any of the likely events.

The current issue at Franz Josef Glacier township involves the likelihood of erosion, avulsion, alluvion and inundation on the Waiho River fan, and whether existing protection works are adequate to make such events unlikely, or could be upgraded to make them unlikely.

Building codes (E1.3.2 and 1.3.3) related to surface water and drainage suggest that **likely** could be considered to be a 2% probability in any one year of an event occurring severe enough to cause flooding of the ground floor of the building. That is, damage to the ground floor is to be expected to occur on average only once in any 50-year period. For events likely to cause extensive structural damage, however, NZS4203 recommends probabilities of 0.2% (500-year return period) for wind and earthquake loading. Thus, the 2% probability event may be appropriate for some flooding events on the Waiho Fan - as with flooding by seepage through the stopbanks, but a 0.2% probability should be considered when there is a likelihood of significant structural damage - as with any building in the way of the Waiho in flood.

We note that there are no river-control works on the fan head of the Waiho River with a demonstrated capacity to withstand the 2% probability-per-year water-surface level delivered by this river system (and nobody yet knows what this level is!). Also, there is no possibility of engineering to provide protection from the 0.2% probability-per-year events because the magnitudes of these events defy our comprehension: there is no evidence of such extreme events occurring, because the landscape here is so young that it has not yet had the chance to experience and record such rare events!

Last, we note that the expected seismic loading from a Magnitude (M_w) 8.0 earthquake in the area greatly exceeds the accepted New Zealand earthquake building-design codes for all buildings except major hospitals (and national museums). At the expected level of shaking, it is reasonable to suppose that well constructed buildings will suffer structural damage, but they should not collapse.

2.5 Resources, Emergencies and Hazardous Substances

The Resource Management Act (1991) covers wider issues than buildings, and includes the provision for sustainability of resource use, including the sustainability of land uses, and the protection of the environment from unsustainable uses. It also includes the protection of outstanding natural features and landscapes from inappropriate subdivision, use and development. For hazard management at Franz Josef Glacier, consents are required to undertake or to change river-containment works, to alter landscapes, and to take or discharge water into streams or underground aquifers. Ground and surface waters must be protected from contamination, and records kept of known hazard occurrences (or likely occurrences) in the area.

The Resource Management Act also considers safe storage of hazardous materials, but the Hazardous Substances and New Organisms act replaces this part of the legislation.

New Emergency Management legislation places greater responsibility for emergency planning with the local community. This is not a central government abrogation of responsibility, but a recognition that the initial emergency response may be needed too quickly to be effectively delivered from afar, and at times and under conditions when it cannot be delivered from afar. At Franz Josef Glacier, across the river may at times be too far.

3.0 GEOMORPHIC BACKGROUND

3.1 Physical setting

The Waiho-Callery River system flows west from the main divide of the Southern Alps to the Tasman Sea (Fig. 3.1a, b). In this area, the divide is above 2500 metres, rising to over 3000 metres in several places. The permanent snowline is at about 1800 to 2000 metres, and glaciers mantle a significant part of the catchments at higher altitudes.

The Tasman Sea is 30 kilometres from the main divide, and the low-altitude alluvial fan of the Waiho-Callery system covers about half this distance. Slopes between the mountain front and the main divide are very steep, the result of geologically rapid uplift of the mountains.

The drainage system consists of the major catchments of the Callery and Waiho Rivers, together with the smaller ones of Tatare River and Docherty's Creek (Fig. 3.1) and a number of minor streams. The Callery River has the largest mountain catchment area; it is the major contributor of water and sediment into the Waiho River system. The Callery and Waiho join about 500 metres upstream of the township of Franz Josef Glacier, and flow to the sea across the alluvial fan of the Waiho Flats.

The Tatare emerges from the mountains 1.5 kilometres north-east of the Waiho, and flows across its incised fan to a gap in the forested Waiho Loop (Fig. 3.1b), a former glacier terminal moraine that is about 13 000 years old. A kilometre downstream of the Loop, it joins with the Waiho River. Docherty's Creek emerges from the mountains about 4 kilometres west of the Waiho-Callery confluence, and flows along the south-western side of the Waiho Flats before crossing to the other side to join the Waiho. Stony Creek flows into the eastern end of the Waiho Loop and joins the Tatare at its exit through the Loop. North of Stony Creek, a small creek drains around the outside of the Loop to Lake Pratt and the Tatare. Lake Pratt is dammed by a small fan of the Tatare where the river exits through the Loop. When the Tatare is in flood, drainage of Lake Pratt is reversed and silt-laden Tatare water enters Lake Pratt.

The water that powers the river system comes mostly from the prodigious precipitation in the mountain headwaters. Some runoff comes from the melting of snow and glacier ice, but most of the flood runoff comes directly from rain. The average annual precipitation in the upper headwaters is not known, but it is estimated to be at least 11,000 millimetres, based on a few scattered measurements. There are very strong variations in annual precipitation within the headwaters, with precipitation generally increasing inland. The zone of maximum precipitation probably lies roughly parallel to, and slightly west of, the main divide, but its precise location has not been determined by measurement. Local rainfall also varies markedly in individual storms. For large storms, the total depth of rain falling on the upper drainage basin may be two to three times greater than that recorded at the Franz Josef Glacier township rain gauge, west of the mountain front. Within the catchment, the highest intensities of rain that can fall over a short term (1-60 minutes) are not very different from place to place: maximum intensities are likely to be about 2 millimetres a minute. The much larger annual precipitation in the mountains arises because heavy rain is more frequent and lasts longer there, rather than from higher intensity rain when it is raining.

Intense storms are frequent in the area: at the township, storms producing 200 millimetres of rain in 24 hours occur about once a year; 600 millimetres over 3 days occur every few years. Precipitation often falls as rain up to 3500 metres altitude. In colder conditions, a substantial proportion of the precipitation falls as snow at higher altitudes. Much of the runoff generated in the upper catchment areas enters glacial drainage systems such as that of the Franz Josef Glacier.

The rocks in the river catchments southeast of the fault are mostly very highly metamorphosed rocks - schists and gneisses of various types, but there are some much less metamorphosed rocks including greywacke close to the main divide. The lowland fans are constructed of sediments, largely gravel and sand, eroded from the mountain catchments. The sediment forming the Tatare River (and Stony Creek) fan is very much finer than that forming the Callery-Waiho fan. The Waiho Loop is composed of very bouldery glacial moraine.

The Waiho River has deposited a huge alluvial fan where it exits from the mountains at a steep front formed by uplift along a major geological boundary, the Alpine Fault. This fault runs along the mountain front, and is widely accepted as the local boundary between two great moving plates of the world's crust. Here, the Pacific tectonic plate is in a sliding collision with the Australian plate. A steady differential movement of the plates of 30 millimetres a year is measured between the east and west coasts of New Zealand: most of this movement is being used to "wind up the spring" that drives the Alpine Fault.

The Southern Alps mark the crumpled edge of the Pacific plate, piling up against the Australian plate, and the Alpine Fault marks where the two plates slide past each other. Slip on the fault averages 25 to 30 millimetres a year over the long term, but no slip has occurred in historic time. There is evidence that the fault last moved in about 1717 AD (see Appendix 2). Since then, the rocks around the fault are thought to have already accumulated enough elastic strain energy to cause future movement of about 8 metres horizontally and 3 metres vertically, rupturing the fault along 400 kilometres of its length. This is enough stored energy for a Magnitude (M_w) 8.0 earthquake if it were to occur today (M_w refers to Moment Magnitude which more accurately measures the earthquake energy release than do other magnitude measures such as the now outdated Richter Magnitude, or the Local Magnitude, M_L, usually reported immediately after earthquakes).

Traces of past fault movement can be seen along the foot of the steep slopes to the northeast and southwest of the Waiho River. Across the fan heads of the Tatare River and Docherty's Creek, erosion and sediment deposition have obliterated the fault traces. Within the township of Franz Josef Glacier, a clear trace of the last movement on this fault crosses SH 6, where it can be seen as a marked rise in the main road between the service station and the DoC visitors' centre. This trace was never simply a clean sharp break in the landscape which has become rounded by erosion and road building. Although the fault trace has been modified within the town, it always was part break and part fold over a zone several tens of metres wide. The folding is the result of the propagation of a relatively sharp break in the underlying bedrock up through the overlying river gravels which form the old alluvial fan remnant on which the township is sited. Further folding of this zone are expected in the next rupture. Traces of the last movement are missing on the opposite side of the Waiho River, indicating that the river has trimmed these surfaces since the last fault movement (i.e. since 1717 AD). Further fault movement is a serious hazard in itself, and the effects of fault movement on river behaviour are also significant.

3.2 The Waiho River as a natural system

The Waiho-Callery River drainage network is developed in one of the planet's more actively changing landscapes. A very young mountain range - the Southern Alps - has been thrust high into the moisture-laden Roaring Forties, so the drainage system has to cope with the rapid runoff of huge amounts of water, in which is mixed large amounts of eroded sediment. Most fine sediment (silt and sand called wash load and suspended-sediment load) moves continuously in suspension at the same speed as the water. The rest of the sediment load moves discontinuously, along the bed (bed-material load) much more slowly than the speed of the water. Therein lies the essence of why the Waiho River has been so difficult to manage successfully.

The Waiho-Callery River drainage network functions in the landscape as a conduit for both water and sediment. In any river system, the active channel system evolves to handle the amounts of water that flow during frequently occurring events that are large enough to scour and shape channels. When rain delivers more water than the channels can handle, the river overflows its banks and is said to be in flood. Sediment movement complicates this picture by locally partly filling the channel system. When more sediment is delivered than the flow can move, the water leaves some sediment behind in the channel. The bed is raised, and so less water is needed to cause the river to overflow its banks. So much sediment can be left behind that the river sometimes creates a new channel to bypass a clogged portion of channel.

Sediment is injected into the river system during storms, by landslides, debris flows, and bank collapse. The injections are at irregular intervals, and a single injection can be of almost any size, from something quickly and easily whisked away by the river in flood, to something much larger that may take many large floods to clear. Each sediment injection is moved through the system entirely by river flow. The irregular injections create pulses or slugs of sediment which move through the system much more slowly than the pulses of water called floods. The speed of movement of any particular slug through the river system depends on details of the path it takes (particularly in a widely braided river), on the frequency and size of water flows that can move sediment, and on the slope of the bed the slug creates as it moves. As a slug of sediment passes a particular reach of the river, it is seen as aggradation as the slug approaches the reach, and degradation as it leaves. That is, rises and falls in river bed level at any spot indicate the passage of slugs of sediment. The falls in bed level occur when locally the river is carrying less sediment than it is capable of carrying, and it is able pick up new sediment by eroding its bed and banks.

In the Waiho-Callery River system, large slugs of sediment are generated in several ways. Some are flushed out from beneath the Franz Josef Glacier by changes in the subglacial drainage (accompanied by ice bursts or ice floods). Some occur when large sections of high terraces of gravel collapse, and some when debris avalanches fall into the Callery River gorge, or into any of the steep tributaries. These happen mostly in storms: the larger the storm (and flood), the larger and more numerous are the likely slugs. Larger slugs of sediment also are formed when faster-moving slugs catch up with slower-moving ones during their passage through the river system.

The maximum height of a gravel slug that can pass through a particular river reach is tightly limited by the height of the channel banks, because these limit the height at which the water spills out and no longer is available to move sediment along the channel. This limit to the height of the water surface, in turn limits the height to which the river can build its bed by piling up sediment.

The Waiho-Callery system is dynamic: huge quantities of sediment are continually eroded from uplifting mountains and deposited on the flatter land at the mountain front on the alluvial fan. The toe of the fan currently is maintained in a constant position and elevation by the sea. Over thousands of years, the movement of water and sediment have adjusted the slope of the fan surface so that the fluctuating supply of water is able to carry the fluctuating supply of sediment to the sea. The occasional oversupplies of sediment (such as might result from severe ground shaking during fault movements or from severe storms) cause short-term steepening, and hence aggradation, of the fan surface; this steeper slope allows the available water to flow more rapidly and move the sediment, and when the sediment is gone, the slope reverts to normal. Similarly, sediment-supply deficits, or water surpluses, cause episodes of degradation (and lessen the slope). In the long term, the system achieves an equilibrium: the fan surface is episodically changing, with local, temporary episodes of aggradation and degradation as the river moves constantly across the fan, eroding the existing surface and replacing it with fresh sediment, on a time scale of a thousand years or so.

The township of Franz Josef Glacier is sited at the head of the Waiho River alluvial fan, and straddles the most recent trace of the Alpine Fault movement. The community has developed in this location because of the site's historical safety from flooding, and proximity to a relatively safe, short and stable river crossing.

The principal area that has been the settled is the gently-sloping surfaces of alluvial fans, deposited where steep tributary streams issue from narrow confining valleys onto a wide, relatively flat valley floor - the Waiho Flats. The fans have been deposited on the floor of the glacially scoured Waiho valley since glacier ice receded from the mountain front about 10,000 years ago. The reach of the Waiho causing severe difficulties for the community is at the fan head, and includes the section of riverbed between the highway bridge and the confluence of the Callery and Waiho rivers (referred to in this report as the “transfer reach”), where aggradation and associated bank scour are occurring. The elevation of this reach is determined by the water and sediment inputs to the fan from upstream, together with the position and elevation of the fan toe. The latter is the ocean and is fixed in the long term. Before the land was cleared for settlement and agriculture, the fan surface oscillated about a grade, with a long-term equilibrium between the water and sediment inputs. Two other factors influence the behaviour of the Waiho-Callery fan: periodic uplift of the mountain front and fan head at the Alpine Fault, and river-training works erected over the past 60 or so years.

We now discuss the components of the system in turn; starting with the catchments that supply water and sediment, then looking at the fan system starting at the sea and working back up to the fan head. This gives a background to developing an understanding of the fan-head behaviour which has caused the river-management problems in recent decades.

3.3 The upper Waiho catchment

3.3.1 Description

The catchment of the upper Waiho River is 7700 hectares in area, 1300 hectares (18%) of which are covered by the Franz Josef Glacier and its tributary glaciers. The Franz Josef Glacier descends to an altitude of about 200 metres and to within 5 kilometres of the Waiho-Callery confluence. Only about 1550 hectares of the catchment area contributes water and sediment directly to the river, while the remaining 5150 hectares deliver water and sediment to the glacier drainage system.

The rock-walled valley of the Waiho is relatively wide (about 500 metres) for 2.5 kilometres downstream from the glacier terminus; this area stores much of the sediment delivered by the subglacial drainage system, and further reduces the catchment area delivering water and sediment directly to the river. The river is usually incised in the upper part of this reach, but changes course frequently as sediment is delivered to it from beneath the Franz Josef Glacier. Further downstream, the river is often braided.

The final 2.5 kilometres of the course of the upper Waiho to the Callery confluence runs through a low gorge in moraine deposits, and here the river is mostly in a single channel.

The Waiho River is always coloured grey by substantial quantities of fine glacial flour.

3.3.2 Water and Sediment Delivery

Precipitation can occur as rain up to an altitude of 3,500 metres, but in cold weather, much of the precipitation falls as snow above about 1000 metres. Most of the runoff generated by rain at high altitudes and by melting of snow and ice enters glacial drainage systems such as that of the Franz Josef Glacier. Little is known about these drainage systems, but runoff over the glacier surface is insignificant compared with water movement within and under the glaciers.

Sediment is generated both by erosion by glacial plucking and grinding at the base of the glacier, and by subaerial erosion, including rockfalls and large landslides. Most of the debris produced by subaerial erosion falls onto the glacier and is incorporated into the glacial system. The subglacial drainage system is the source of all of the sediment delivered to the river flowing from beneath the glacier. Little is known about sediment transfer within the glacier. However, the drainage system in and under the glacier flows in pressurised conduits rather than in open channels. The ability of a given flow of water to transport sediment is much greater in such a system.

The glacier is presently advancing, and brings more sediment to the Waiho than the river can remove, with the result that the upper valley is rapidly aggrading. For example, it aggraded 10 metres in a large flood in December 1965, and about 3 metres in a moderate storm in February 1997. Temporary blockage or changes in the subglacial drainage system create floods that expel large pulses of sediment: one such event in December 1995 deposited about 250,000 cubic metres of sediment, much of it as very large boulders, in the upper Waiho valley (Turnbull, 1998). Such floods are known as "Jokullhlaups" (an Icelandic term) or "glacier bursts". These very large water flows last for a short time as the subglacial drainage depressurises. They contain huge quantities of broken ice, and invariably much sediment.

Sediment delivery along the Waiho to the Callery confluence takes place at the transport capacity of the Waiho River; this is limited by the flow rate and slope of the river. During the periods when the glacier has been retreating, the floor of the upper valley has usually been incised, indicating a much lower rate of sediment supply from the glacier. Because of the sediment storage capacity of the upper Waiho valley, however, the sediment supply to the confluence with the Callery responds only slowly to sediment delivery from the glacier.

3.4 The Callery catchment

3.4.1 Description

The Callery catchment is larger (9200 hectares) than the Waiho, and contains a larger area of ice (1700 hectares; about 18%). The three major glaciers (Callery, Burton and Spencer), however, terminate above about 1000 metres elevation. About 3000 hectares of the catchment delivers water and sediment directly to the river; and thus the effect of glaciers on the delivery of water and sediment is less than in the Waiho catchment. A small lake in the upper Callery prevents the transport of coarse sediment from the area above it.

The main feature of the Callery is the 10-kilometre long Callery Gorge which forms the lower reach of the catchment. This has long (up to 2 000 metres), steep (up to a grade of 60%) sides, and the river for much of the reach runs in a narrow, deeply incised, rock-bound channel. The average bed slope of this reach is about 2.5%.

3.4.2 Water and Sediment Delivery

In the Callery catchment, a much greater proportion of the water and sediment generated by storms is delivered directly to the river than is the case in the Waiho. The area above the gorge delivers water and sediment to the river in much the same way as for the upper Waiho.

Runoff and sediment move very rapidly through the Callery Gorge from a 3000-hectare area. Very little sediment can be stored in it because of the gorge is steep and narrow. Any temporary accumulation of sediment in the channel causes local steepening of the water surface and is moved through the gorge as a coherent slug; these tend to accumulate into larger, moving sediment bodies as they migrate downstream. Thus sediment can be delivered from the lower end of the gorge into the Waiho at a very high rate during some floods, while during other floods with similar water flows, the sediment-delivery rate may be much lower.

The Callery Gorge is so narrow that it can easily be blocked by a landslide large enough to form a temporary dam. A landslide in the 1930s blocked the river for about a day. The dam failed when it was overtopped, and released a surge of water and sediment down the gorge to the confluence with the Waiho. Such dam-break floods are a significant hazard on the Waiho fan: we can expect at least one large landslide of about a million cubic metres to occur each 50 years (in addition to those generated by earthquakes on the Alpine Fault). Landslides this big are capable of holding back enough water to generate flood discharges of thousands of cubic metres per second, compared with the estimated "hundred-year" flood of about 2000 cubic metres per second in the combined Callery-Waiho system (Davies and Scott, 1997).

3.5 Other catchments

The Tatare River catchment has an area of approximately 3000 hectares and is largely unglaciated. It is physiographically similar to the lower Callery, being deeply gorged. It delivers both water and sediment very rapidly to its fan.

The catchment of Docherty's Creek is about 1500 hectares in area and is of lower relief than the other main watersheds.

Both of these catchments are capable of being blocked by large landslides, but there is no historical record of this happening in either river.

3.6 The Lower Fan (the Waiho Flats)

The area of flat land between Canavan's Knob and the sea is known as the Waiho Flats.

3.6.1 Description

The lower fan has little topographic variation; the valley is an infilled glacial valley, and channels of the Waiho River have flowed over all points in the valley over the past few centuries. At present, the Waiho River follows the north-eastern edge of the valley, this being a slight topographic low. Docherty's Creek follows the other side of the valley before crossing to join the Waiho six kilometres from the sea.

Where the Waiho crosses the Waiho Loop it is redirected to the right by Eatwell's (formerly Milton's) stopbank, and flows down a steeper sub-fan to the north-east side of the valley. It is there joined by the Tatare which has cut through the Loop farther east.

3.6.2 Processes

The base level of the lower fan is fixed by sea level: the fan extends beyond the moraine headlands only for short periods following floods that quickly build a delta into the sea before the sediment is whipped away by aggressive marine erosion and the northerly along-shore drift. The extent to which the delta builds between episodes of marine erosion is a clear indication of the prodigious quantity of gravel that the Waiho is able to carry to the sea.

Sea level has been more-or-less constant for the last six thousand years. It is unlikely that the lower fan has aggraded or degraded much since the fan accumulated to span the gap between the headlands. In effect, all the sediment delivered to the lower fan is carried to the sea and disappears from the system. This implies that the whole fan system, including the upper fan, has been in dynamic equilibrium for some time - probably for thousands of years.

3.7 The Upper Fan

The upper fan is the reach from the lower end of the transfer reach to the Waiho Loop.

3.7.1 Description

In this reach the active river bed widens and the river switches its course frequently during high flows. Along the true left (south) bank, the river is flanked by control banks to downstream of Canavan's Knob. It is constrained to flow due north around the downstream side of the Waiho Loop by Eatwell’s stopbank. On the true right (north) bank, the river is discouraged from widening by banks along the frontage of the heliport area (formerly the airstrip), Franz Josef Glacier Hotel and the oxidation ponds. Downstream of the oxidation ponds the river is presently widening rapidly.

3.7.2 Processes

This part of the system behaves as a typical alluvial fan (Zarn and Davies, 1994), but with its base level fixed by the behaviour of the lower fan. The river channels vary their positions on the fan surface rapidly and unpredictably, though there is evidence for an underlying oscillation, from one side of the fan to the other. At present the river is prevented from re-occupying the fan surface from the Holiday Park to Docherty's Creek by stopbanks along the south-west side of the river from the Callery confluence to Canavan's Knob. Until the present, the Waiho has been prevented from breaking out into the Tatare because the latter's fan crest was at a higher level than that of the Waiho. The Tatare has cut into its fan and is no longer building up the fan surface. The Waiho fan surface has now reached the same elevation as the Tatare fan crest and is rapidly encroaching on it. The break-out of the Waiho into the lower Tatare may occur in the near future.

Confinement of the river bed to the central part of the fan has resulted in a general increase in aggradation over past decades. The river bed thus is now above the level of the ground outside the stopbanks over most of the upper fan, and at or above the limit of aggradation in recent centuries as indicated by the river's encroachment onto the surface of the Tatare Fan for the first time, and its burial of a terrace dated to about 1850 by Mosley (1983).

3.8 The Transfer Reach

Between the Callery-Waiho confluence and the fan head of the Waiho is a short (0.5 - 1.0

kilometres) reach in which the river is confined by high terraces on the north and by the glacier access road on the south. Since this reach is at present unable to widen easily, and since its behaviour causes some of the most urgent hazards, it is treated separately from the Waiho fan, although in geomorphic terms the distinction does not exist.

3.8.1 Description

This is a short, straight reach of alluvial river that receives water and sediment from the Callery and the upper Waiho. Much of the uppermost reach is occupied by a low fan that the Callery has built at the point where it emerges from its gorge; this has recently forced the Waiho against its western bank at the top of the reach. There is a lot of relief across the river bed (sometimes up to four metres), and it is noticeable that the coarsest sediments are found towards the north bank and emanate from the Callery gorge. The whole length of the west bank of the reach is protected with stub groynes and a raised gravel bank; the east bank has a few stub groynes to prevent erosion of the high terrace, and high-standard rock armouring along the downstream half of this bank. Half way along this reach is the SH 6 bridge, the abutments of which reduce the river width somewhat.

3.8.2 Water and Sediment Motion

Water and sediment are supplied to this reach by the Callery and Waiho Rivers.

Flow of the Waiho into the transfer reach increases quickly following the onset of rain. Its sediment contribution is determined by the water flow rate and the river slope at the confluence. Flow from the Callery rises faster following the onset of rain, and the peak flow rate may be much greater than that from the Waiho. Its sediment contribution will also vary with water flow and slope, but given the much steeper slope of the Callery, the sediment concentration will be higher during high flows. In addition, the arrival of a "slug" or "pulse" of sediment at the exit from the Callery Gorge will result in a very large sediment delivery.

The supply of water and sediment to the transfer reach varies considerably during the course of a storm, and between storms, depending on events in the upstream catchments. In general, the flow rates and water volumes, as well as sediment input rates and volumes, will be higher from the Callery. It appears unlikely, therefore, that storm rainfall can be used reliably to predict river-bed behaviour in the system. Recent experience bears this out. In May 1997 a storm of 387 mm of rain in one day caused minor changes in the area immediately below the Franz Josef Glacier terminus, but had no effect elsewhere, whereas in February 1998 a storm with 195 mm in one day caused several metres of aggradation in the upper valley, significant aggradation in the Waiho reach above the confluence (a most unusual occurrence) and rapid sediment buildup in the transfer reach.

Transfer of sediment through this section depends on the slope of the reach. This is determined by the river bed levels at the ends of the reach. At present the slope is lower than that upstream and downstream, due to aggradation downstream; however aggradation of the Callery fan might soon change this. At present, the reach is aggrading, indicating inadequacy of sediment transport capacity through the reach. The reach has also become wide enough for channels to meander during high flows, lowering the channel gradient and increasing the probability of bank erosion. In order to induce degradation in this reach, either the sediment inputs from the Callery and Waiho have to decrease, or the course of the Waiho on the fan must change in a way that causes degradation to migrate headwards into the reach, or both.

3.10 Past Behaviour of the Callery-Waiho Fan System

3.10.1 Ancient history

As recently as 16,000 to 18,000 years ago, the glaciers of the southwestern Southern Alps extended beyond the present coastline. A coalesced Waiho-Callery-Tatare Glacier carved a broad, deep valley across the coastal lowland now occupied by the Waiho Flats. As this glacier retreated, the river draining from it began to fill in the valley with sediment. It seems likely that the infilling was rapid enough that, as the glacier retreated from the coast and sea level rose with the worldwide melting of glaciers, the valley was always filled with enough sediment to prevent incursion of the sea into the valley (that is, the valley probably never became a fiord - as did the Haast valley).

By about 13,000 years ago, the Callery-Waiho Glacier had retreated to behind Canavan's Knob and the knob became forested. The glacier then advanced again, destroying the forest and extending beyond the mountain front as a lobe on the coastal lowland. The edge of the glacier lobe is outlined by the Waiho Loop, which is a glacier moraine deposit. When the glacier receded from the Loop, the glacier-fed Waiho and Tatare rivers began delivering sediment to the upper fan area. At this time, ground level was at least 100 metres lower than at present, and sea level was much lower. On its western side, the Loop probably extended farther to the south than at present, but this is now buried or eroded. The isolated hillock known as Rata Knoll was once part of the formerly more continuous Waiho Loop.

Because the Loop then formed a more complete obstacle, the Tatare (probably assisted by the Waiho in the early stages) rapidly filled in the area upstream of the Loop. This area soon became higher than the Waiho fan in order that it could drain west to the Waiho. The Tatare eventually built up its fan to the level of a low point of the Loop; it then cut through this about a thousand years ago, forming a substantial waterfall on the downstream side, and rapidly cut the gap down in stages. The downcutting caused the Tatare to become incised into its fan. The establishment of a new course through the Loop stopped further aggradation of the upper Tatare fan surface. It is likely that prior to the cut through the Loop, the Loop was filled in almost entirely by the Tatare fan. There is no evidence that the Waiho has ever flowed into the Tatare above the Loop (except recently during small overflows in high flood).

While the Tatare was infilling the Loop, the Waiho was aggrading its fan farther towards the outer sea coast, keeping pace with the rising sea until sea level stabilised about 6000 years ago. This long-term aggradation ceased once sea level stopped rising. That the fan surface has changed little in level for some time is shown by the presence of shallowly buried old soils close the south end of the Waiho Loop on either side of the Waiho.

It is likely that for much of the last 10,000 years the Waiho flowed south of Rata Knoll; the Tatare fan extended across to the Knoll and blocked north-easterly migration of the Waiho. For much of this time, the Waiho has generally alternated between flowing on either side of Canavan's Knob, and has buried or eroded any former extent of the Loop moraine.

At some relatively recent time, however, and possibly as a result of a large sediment input or fault movement (or both) causing unusual aggradation of the upper fan, the Waiho channel shifted to the east of Canavan's Knob and onto the Tatare fan surface; where it found an exit from the Loop through a low point between Rata Knoll and the present end of the Waiho Loop. This event may have induced a nick-point and caused incision of the Waiho channel back through the system, much as the Tatare did when it cut its present exit through the Loop.

Since the Waiho Loop formed about 13,000 years ago, there probably have been more than fifty uplift movements on the Alpine Fault, amounting in total to perhaps 150 metres of uplift of the ground south-east of the fault. Each of these movements would have had a complex effect on the river system. Massive amounts of sediment would tumble into the Callery and Waiho from earthquake-induced landslides and other erosion. On the other hand, fault movement would also induce substantial degradation of the Callery-Waiho system east of the fault. The immediate impact of fault movement on the transfer reach would be to uplift it, causing incision to extend upstream. Very soon, however, a massive wave of sediment would come down both the Callery and the Waiho, causing massive aggradation in the transfer reach and the development of a steep sub-fan on top of the upper fan area. Once the large volume of earthquake-induced sediment had largely moved downriver, incision of the aggradation surfaces would begin, eroding downward within the transfer reach to a very low level due to the uplift that reach had experienced. The last time that this sequence was initiated appears to have been in 1717AD. An understanding of the process rates in the response sequence of the catchment-fan system to episodic uplift is not yet available, and awaits further investigation.

3.10.2 Modern history

The earliest known descriptions of the Waiho area date from the mid-1800s when Julius von Haast visited the glacier. Early photographs of the area date from about 1870. A few written records of the river system come from gold-mining tales of the 1880s (Hewitt 1965). Since then, reports have been more frequent, as more tourists began to visit the area and hotels and roads became established. However, the exact behaviour of the river system cannot be reconstructed accurately prior to the first aerial photographs in 1948.

From the mid 1800s, and until the mid 1890s, the Waiho River below the Callery confluence was deeply incised - so much so that the locality and township was known as Waiho Gorge. Mosley (1983) noted a "high" terrace on the true left of the river just above the SH 6 bridge that was covered by vegetation 110-120 years old (estimated by Dr Peter Wardle). Dr Mosley attributed this terrace to an aggradation event in the river in the 1850s. This terrace and its plant cover have been lost in the recent aggradation of the river channel, so its age can not be verified. Downstream, the surface on which the earliest hotel (and later the earliest airstrip) was built, was the active channel when the area was first visited in the 1860s.

Peter Graham reports in his autobiography (Hewitt 1965) that miners found the richest gold deposits in the Waiho Gorge at the contact between recent river sediments and the underlying moraine material at the base of the Waiho channel, indicating that the river then was incised to its maximum depth since glaciers had passed through. It is not known if or to what extent miners might have encouraged the Waiho to degrade below its natural level of the time when gold was first discovered. Their ability to affect long-term changes in the bed level appear to have been limited, because Peter Graham reports that the bed rose in an “Old Man” flood in the mid 1890s, and the moraine interface was never again accessible to miners. A photograph of the first car fording the Waiho below a footbridge in the 1910s shows a deeply incised channel with huge boulders, but a rock gabion in place to control the location of the river crossing, indicating significant sediment movement and channel instability. Photographs of the construction of the first road bridge in 1927 show that the deeply incised channel with huge boulders persisted for many decades. At about this time, however, there are also reports indicating that the river was aggrading. For example, the original hotel was moved from its low terrace site (the former "airstrip" terrace) because of flooding. In the 1930s there was concern that sediment coming down the river was causing problems (flooding of the airstrip). The first "permanent" Waiho river-control works were erected in the 1930s to keep the river off this terrace.

Air photos of 1948 show a bed with large boulders prominent in the Waiho River channel above the highway bridge, but they also show active bars of recent gravel. Bars are absent from 1927 and 1930s photos. This evidence indicates that aggradation was well under way by 1948, having begun much earlier; but it was to be another 20 years before it began to be a problem at the bridge. The lower terraces downstream look as if they were being increasingly used by the river during floods, and there are bank protection works visible on the true right bank opposite the Holiday Park site and on the true left bank immediately upstream of Canavan's Knob. It was thought (Mosley 1983) that the proglacial lake that existed in the Waiho valley in the 1930s and 1940s had a significant effect in modulating aggradation at the bridge. Recognition of aggradation on the upper fan in the 1890s and 1930s, and appreciation that the Callery probably supplies much more than half of the sediment, however, reduces this emphasis.

The upper Waiho River area has been visited almost daily since before the turn of the 20th century, and so its behaviour is well observed and easily documented. The Callery on the other hand is remote and rarely visited. Its behaviour is largely unknown. It is a mistake to confuse lack of information with lack of importance, or lack of effect.

Since 1948, aggradation of the upper fan has continued. Each set of air photos shows the active bed wider than the previous one (and also more and more control banks to contain the river). The contrast between the river planform in 1948 and that fifty years later is astonishing. The upper fan surface has now aggraded to the extent that the Waiho could soon easily break into the Tatare for the first time ever.

It is likely that the recent behaviour of the river on its upper fan has been greatly affected by control works. In the absence of control, the expected behaviour of the river would be to oscillate between deep degradation, as in the late 1880s, perhaps in response to fault movement, and aggradation to the level of the "high" terrace - that is, to a level somewhat below its present level. We know that the 1880s incision upstream of the bridge has never been exceeded, because the moraine below the base of the recent gravels has never again been exposed. The "high" terrace level has never been exceeded naturally by aggradation either because that would allow a break-out to the Tatare, which has never occurred.

During the periods between fault movements, one would expect the transfer reach and upper fan to show behaviour resulting from recovery from the uplift event and also from the occurrence of large storms (and also the occasional landslide dam-break flood from the Callery Gorge as occurred in the 1930s). This behaviour would be an oscillation between episodes of mild aggradation and degradation with up-to-4 metres change in bed level.

In summary, the behaviour of the transfer reach and upper fan results from the influence of water and sediment inputs from upstream and the fixed position of the fan toe. The response of the system to tectonic uplift every few centuries is unclear and may also be a factor in its present behaviour.

4.0 CONTROL WORKS

4.1 Right Bank

4.1.1 Spur groynes between the Callery Junction and SH 6 Bridge

Works here include two short spur groynes faced with interlocked heavy rock. The aim of these groynes is to deflect river flow from the base of the high terrace and so prevent further scour and loss of terrace edge, where this could threaten the right-bank (northern) approach to the SH 6 bridge and the Waiho River frontage of the Franz Josef Glacier township. The works are of a high standard, and have not suffered damage since installation in 1996. They do not extend the full length of the high terrace edge to the Callery junction and so do not stop the river from gaining large quantities of sediment locally. Sediment eroded by undercutting of the high terrace here contributes directly to further aggradation of the river bed both here and further down stream. Continued aggradation will negate the protection afforded by these works. There is potential for these groynes to be outflanked by erosion in the long term.

4.1.2 Scour protection for the SH 6 Bridge approach and the Church

The 280 metre length of bank from upstream of the SH 6 bridge to the downstream edge of the terrace upon which the Anglican Church is sited is protected by an embankment (15,200 cubic metres) faced with interlocked heavy rock (18,887 tonnes). The rock is deeply trenched (originally 5 metres) in the river bed to accommodate future scour. The aim of the bank is to protect the bridge approach and DoC and church property from future scour and erosion, and so protect the remainder of the township area. The works here are to high standard, and have not suffered damage since they were installed in 1996. Continued aggradation of the river bed in this reach will ultimately negate the protection, but there is space for further additions to the height of the bank, which does not yet reach the full height of the terrace edge.

4.1.3 Heliport (formerly Airstrip) stopbank

This section of the right bank of the Waiho River has the longest history of river-control works in the area. The former airstrip required protection from episodic flooding from the 1930s onwards. This is not surprising because this area was the active river channel in the 1860s, and the original Waiho Gorge Hotel had to be moved from this area in 1911 because of the repeated threat of flooding.

At various times there has been a stopbank up to a kilometre long along this section of bank to "prevent" the river from overflowing onto the former airstrip, where it also threatens the western frontage of the village, the Franz Josef Glacier Hotel and the oxidation ponds. The efficacy of the protection can be shown by the frequency with which the bank was been damaged : between 1968 and 1998, it was breached or damaged on average every 3 years, although it has been designed and built to contain floods of much larger return period. The airstrip now is abandoned and destroyed.

Because control works have been here longer than at any other site in the upper fan area, and because they have not performed as intended according to their design, we strongly suspect that these works initiated the continuing aggradation problem on the upper fan. Certainly, this stopbank has been a key player in the developing aggradation problem: without this stopbank in place, the river bed would not have built to its current level beneath the SH 6 bridge or beside the Holiday Park area in the last 60 years.

4.1.4 Stopbanks protecting the Franz Josef Glacier Hotel and Oxidation Ponds

Local residents warned of the possible dangers of erosion of this area at the time the site was proposed for development as a hotel in 1957. They warned that its frontage to an "abandoned" Waiho channel had been severely eroded in about 1911 and again about 1937. Their warnings were ignored for 10 years, but the threat was officially recognised in 1968 when the Airstrip protection works were upgraded to protect the hotel site. In 1985, fill and rock rip rap were required to directly protect the frontage of the Franz Josef Glacier Hotel and oxidation ponds.

Since 1985, there has been river-bed aggradation along this frontage. Aggradation is now such that, on 23 April 1998, water from the Waiho River during normal flow was passing through the bank (probably via unfloodgated stormwater outflows) and ponding in drainage depressions in the hotel lawn. Some of this grey, silt-laden Waiho water was draining back to the Waiho north of the oxidation ponds, indicating a potential for the bank to be outflanked.

We assessed the standard of protection offered by this bank to be good enough to protect structures behind it from scour in events up to about 5-year recurrence interval, but it will not prevent flooding of the hotel site during freshes while most of the flow is in this direction. The oxidation ponds are unprotected from scour of their northern flanks if ever much water leaks through the banks along the hotel frontage.

4.1.5 The unprotected frontage to the Greens' property

There are no protection works fronting the Greens' property to the north and west of the oxidation ponds. The lie of the land in this area is due to ancient deposition of the Tatare River fan, and so in earlier times there has been no likelihood of the Waiho River taking this route onto other properties. Over the last 60 years, every attempt by the river to break out into new courses in other directions has been strongly opposed with river-control works. The river has been repeatedly directed against this bank by spur groynes deflecting the river away from other banks. From 1965 to 1998, up to 250 metres width was lost from about 2 kilometres of river frontage on this property (about 90% of its former area). Loss of much of the remaining farm area, and a break-out of the Waiho River through the adjacent farm to the Tatare River is now an immediate prospect. On 23 April 1998, continuing bank scour was occurring at normal flow because a major channel of the river was adjacent to this bank. The free-board of the bank above normal flow was a mere 30 centimetres.

At the bed levels and flow configuration of late April 1998, floodwater from the Waiho River could enter the Tatare River above its gorge through the Waiho Loop during flows as small as are likely to occur several times each year. When these flows initiate scour in their fall to the Tatare, the Waiho River will quickly adopt a new, and potentially irreversible, course change of far-reaching consequences.

4.2 Left Bank

4.2.1 The raised glacier access road and stopbank upstream of the SH 6 Bridge

By April of 1985 continued aggradation and bank scour of the river channel adjacent to the glacier access road above the SH 6 bridge made it inevitable that the road be raised. This work was completed in 1988, when the raised road was reinforced on the river side with about 9000 tonnes of rock rip rap. The road was raised further in 1996 and again in 1998. There is a proposal that it, and the bridge, be raised a further five metres.

4.2.2 The Holiday Park Stopbank

River-control works first became necessary along the river frontage of the Holiday Park in 1978. The works were enlarged or repaired in 1980, 1991, 1996, and 1998 in response to continuing aggradation of the river. Part of this bank is armoured with heavy rock: the rest is protected from scour by stub groynes.

4.2.3 SH 6 stopbank between the Holiday Park and Canavan's Knob

The first works here were built immediately upstream of Canavan's Knob not long before 1948. Stopbanks were built to stop the river breaking out along the highway. A larger, longer bank was in place in 1965 to inhibit erosion of State Highway 6. This bank was breached in the late 1970s, and in March 1982, when some floodwater spilled to Docherty's Creek. Subsequently the river has significantly aggraded adjacent to this bank, so that the river bed now stands at or above the road level along this reach. In 1998, in response to floodwater spilling around the end of the Holiday Park bank, the SH 6 bank was extended south to overlap with the Holiday Park bank (while still allowing outflow of stormwater drainage). At the same time, the bank was raised to allow for aggradation of the river bed. As now constructed, there is no road verge between SH 6 and the stopbank wall along some sections. The outer wall is at the angle of repose for tipped gravel, and loose gravel can roll onto the highway. On its inside, the bank is protected from scour by stub groynes.

4.2.4 Stopbank protecting the upper Waiho Flats at Canavan's Knob

A short section of stopbank is present downstream of Canavan's Knob. Its high standard of construction dates it to the mid 1980s. It ties to a low terrace at its upstream end. It appears to be intended to inhibit erosion of the continuation of the low terrace downstream. It acts to deflect flow away from the left bank (towards the unprotected right bank).

When inspected in April 1998, significant aggradation had occurred at the upstream end of the bank. During a recent (1998) flood flow, a small portion of the flow against Canavan's Knob had outflanked the bank because aggradation upstream had overwhelmed the low terrace to which the bank was tied at its upstream end. This water flowed parallel to the stopbank to re-enter the Waiho above Rata Knoll. It now is possible for normal flows of the Waiho to outflank this stopbank should the river again return to this section of the fan. In future floods, this could lead to further loss of land between Canavan's Knob and Rata Knoll.

4.2.5 Eatwell's (Milton's) Stopbank

The Eatwell's (formerly Milton's) stopbank prevents break-outs of the Waiho River immediately downstream of Rata Knoll across farmland and the Waiho Flats airstrip into Docherty's Creek. The first works of about 950 metres in length were not in place at the time of the first aerial photography in 1948, but were well established at the time of aerial photography in 1965. The history of damage prior to 1982 is not known in detail, but damage is likely to have been considerable, because the bank destroyed in 1982 was curved and significantly narrowed the river channel, whereas the bank in place in 1965 was straight and approximately on line with the present bank. The stopbank was overwhelmed and washed away in the flood of 11/12 March 1982. When the bank was reinstated, it was set back 100 metres to allow a greater river width, and the radius of curvature was increased from 230 to 350 metres to lessen the effect of scour. The bank height was also raised by a metre to prevent overtopping. The river face of the bank was faced with large rocks to inhibit scour.

The Eatwell's bank was in sound condition in April 1998, and does not appear to have been damaged significantly since it was reinstated after 1982. The bank is a significant constriction on flood flows, however, so that in large floods, water is impounded above the Waiho Loop. This in turn inhibits the movement of gravel into the reach, causing aggradation up stream.

4.2.6 Other Stopbanks

In the lowest reaches of the Waiho River, within a few kilometres of the sea, there are other stopbanks to inhibit bank erosion (and loss of farm and forest land) and to keep Docherty's Creek and the Waiho River within their lower channels. The adequacy of these banks was not considered in this study.

4.3 Docherty's Creek Works

We did not closely inspect all the control works along Docherty's Creek, but none is intended to contain flows such as will be experienced if the Waiho River breaks out into this channel.

4.4 Effect of River Control Works

The Waiho has an intrinsic tendency to shift laterally across its fan from time to time through a combination of local aggradation and bank erosion: to prevent this occurring requires very robust control works. Control works in the form of bank-erosion protection and stopbanks, designed to prevent widening of the river bed, have been used on the Waiho system for six decades. There have been rare spectacular failures: a long central bank erected in 1980 to move the river into a narrow bed against the south-west bank downstream of the motor camp was destroyed in 1984, and no trace of it now remains. When the nature of the river is considered, the works have provided the community with a useful measure of protection from the threat of flooding, but there is an underlying escalating trend in the area threatened by severe flood damage: this we attribute to presence of the works themselves for reasons discussed below.

Preventing the lateral movement of the river has led to changes in its behaviour: these changes are those to be expected from principles of fluvial geomorphology. The longitudinal section of the river from above the fan head to the coast (Figure 4.1) reveals two reaches where locally elevated riverbed replaces the otherwise smooth profile: in the vicinity of the end of the Loop and in the transfer reach. These are both places where the lateral movement of the river bed has been thwarted by control works - Eatwell's stopbank has been in place in some form for about 40 years, and there were bank-erosion-protection works in place below the bridge in the 1930s. More recently, increasingly robust control banks have been constructed to protect the bridge and airstrip, along the whole west side of the river from the Callery confluence to Canavan's Knob, and along the east bank to protect the Franz Josef Glacier Hotel and oxidation ponds. The result of these works has been to restrict the river to the same half to one kilometre wide area of bed for the last few decades, when its natural behaviour would have been to move to occupy different areas during this period.

We believe that the control works have caused the long-term aggradation, because:

- Large bed-level changes of about 4 metres are normal for the Waiho and had been occurring at least since the area was visited in about 1865. It follows that the river always has been passing very large quantities of sediment. The bed level did not start to rise consistently until about the 1930s.

- Very few other south Westland rivers have shown such a consistent pattern of bed-level rise since the 1930s. Those that do have rising bed levels, invariably have some form of control works in place, because control is needed to reduce damaging break outs across farmland, or to constrain water to pass under existing bridges which are costly to relocate or replace. Such control works in turn restrict the area where aggradation can occur, and so lead to more and larger control works. With time, this can lead a river to threaten areas of land that may not originally have been threatened.

- The Fox River at Fox Glacier has shown no equivalent behaviour to the Waiho despite the similarities in behaviour of the Franz Josef and Fox Glaciers. The Fox River is sufficiently incised in its fan head that control measures have never been necessary to restrain the river in its channel. If climate change were the cause of the Waiho behaviour, we would expect to see similar behaviour occurring more widely.

- The river formerly was in dynamic equilibrium which now has been disturbed by the training works, and it is now attempting to reach a new equilibrium, but is being thwarted by repeated stopbank modification. It is evident from community's response to the present river behaviour, that the new equlibrium profile in the transfer reach would be unacceptable to the community.

- The consistent trend in bed-level rise in the Waiho River transfer reach and upper fan coincides in time and space with the construction of control works. The level of the crests of the stopbanks have always been raised to keep them above the flood level. The Waiho River bed has now reached elevations never before achieved on the fan.

- It is self-evident that if the control works were now to be built lower than the bed level, the active bed level would lower as a direct response.
- It is known that break-outs of the Waiho River are caused by sediment slugs which raise the bed up to the height of the surrounding land. Without stopbanks, the river would break out into a new channel and so limit the buildup of bed level. Construction of stopbanks has raised the elevation to which slugs can build up the bed, and the bed level has risen accoringly. Therefore the river-control works must be considered to be the cause of the present level of aggradation.

It is known that reducing the ability of a braided river to achieve the width it would naturally adopt will result in increased aggradation (Davies and Lee, 1988), and preliminary laboratory experiments suggest that this would also be the case with alluvial fans.

Never-the-less, short-term aggradation episodes of up to 4 metres amplitude at the highway bridge are natural and normal in the Waiho River. It is the inability of the past control works to efficiently cope with these natural fluctuations which appear to have led to the present acutely serious river hazard.

Control works do not have to lead to persistent aggradation: elsewhere in this report we discuss a future option of control which potentially could lead to problems associated with extreme degradation. There are many examples elsewhere where no marked changes in bed levels occur in association with protection works.

5.0 HYDROLOGICAL HAZARDS

5.1 Landslide Dam-break Flood

Davies and Scott (1997) made a preliminary assessment of the possibility of floods caused by a landslide dam-break within the Callery Gorge. They concluded that such events were indeed possible, and reported a record of one such event in the 1930s. They also identified some potential landslide sites and estimated the size of the likely peak discharge from such events. Landslides of the order of one million cubic metres have the potential to generate peak discharges of the order of a thousand cubic metres per second. There is geomorphic evidence, in the form of landslide scars, that much larger landslides than this have occurred in the past. The Callery thus threatens the facilities along the Waiho with destruction. No effective protection works are feasible against the larger possible failures.

Such events, especially the larger landslides, are likely to be generated in earthquakes, in which case their probability of occurrence may be similar to that of large earthquakes (a 10% probability of occurring within 5 years!).

Independent of the earthquake event is the probability of a large landslide due to rainfall. Hovius et al. (1997) show that the probability of rainfall-generated landslides west of the Southern Alps follows a power law trend. Their data, gathered from aerial photographs, indicate that the probability of a one-million-cubic-metre (10 hectare area) landslide is about 0.03 per year, or one every 30 years or so on average; a 50-million-cubic-metre landslide would occur on average every 500 years or so. This means that about 3 times per 100 years, a dam-break flood with flows of the order of a 1000 cubic metres per second can be expected to occur. The 1930s event reported seems to have been of this size.

5.2 Glacier Burst

Glaciers like the Franz Josef have tunnels and cavities within the ice. Normally these do not flow full, but during heavy, prolonged rain they carry a large volume of water. If a blockage should occur, due either to ice-tunnel collapse, or sediment accumulation (for example in a section of tunnel sloping uphill), then high pressure can very rapidly build within the subglacial drainage system. The blockage can then blow out and then release a large volume of water very quickly, carrying with it a high concentration of sediment and much broken ice.

Glacier bursts are a serious hazard in the upper valley; water overflowed Champness Rock to a height of about 10 metres during one minor burst in March 1998, and in the December 1995 flood, 250 000 cubic metres of sediment was deposited very rapidly in the upper valley to form a deposit 5 metres deep and about 1 kilometre long. Anyone in the upper valley during such an event could easily be killed. An even larger event occurred in 1965.

Large glacier bursts have been recorded from the Franz Josef Glacier, at intervals of a few years to tens of years. However, the glacier is now in the sixteenth year of an advance, and is advancing over the wide sediment-filled bed of the upper Waiho valley. This situation is occurring for the first time in the glacier's recorded history. It is therefore possible that the frequency and magnitude of glacier bursts in the future could differ from that in the past. It would be prudent to recognise, in management of access to the upper valley during heavy rain, that there is potential for flash floods carrying large quantities of sediment.

The larger glacier bursts have been accompanied by aggradation in the transfer reach (e.g. in December 1965), but there is no information on the magnitude of river flows caused by them.

5.3 Catchment erosion and sediment delivery

On air photos of 1981, there are many more erosion scars in the headwaters of the Tatare and Callery catchments than were present in 1965. There are also substantial areas of sediment on the riverbeds in these two steep, narrow catchments in 1981 that were not there in 1965 and are not present today (aerial reconnaissance). This suggests that between 1965 and 1981 there was a large storm that mobilised a lot of hillslope sediment and delivered it to the stream channels. One possibility is a 3-day storm in March 1979 that produced 750 mm of rain at Franz Josef Glacier township.

In 1965, the Tatare River flowed to the Waiho Loop as a narrow, sinuous meandering channel in its incised arroyo. By 1981, its sinuosity had decreased markedly and it was much wider; and by 1985 it was very braided and had been laterally unstable for some time. Today the Tatare River is still braided but its bed is narrower and it appears to be incising itself into recent deposits. The Tatare River has thus responded to a severe erosion event by an aggradation-degradation episode within a 20-year period.

It is likely that the Callery and Waiho Rivers also received a major injection of sediment from the 1979 storm, and responded similarly. Hence some of the aggradation in the transfer reach and upper fan of the Waiho River over the last two decades is probably due to increased sediment input from the Callery and Waiho headwaters.

5.4 Flooding

The basic cause of flood hazards is human behaviour - we occupy land over which the river, as part of its natural behaviour, tends to flow from time to time. However, a community is now established in the vicinity of the river, so we must deal with the existing situation.

A flood hazard is related to the water surface elevation of the river. This in turn is the result of two factors: the flow rate of the river and the bed cross-section. Flow rate is determined by precipitation and flow processes in the river system upstream. The river bed cross-section is determined by the rate of supply of sediment to the reach in comparison with the sediment transport capacity of the flow. The elevation of the riverbed significantly affects the water surface elevation at a given flow rate. At the Franz Josef Glacier township, the main cause of the developing flood hazard has been the increase in elevation of the river bed. This has been going on since the 1890s, originally in response to natural processes, but more recently in response to the very control measures that have been implemented to reduce the flood hazard.

A storm of February 17 1998 allows an estimate to be made of the present flood hazard in quantitative terms. This storm delivered 195 mm of rain to Franz Josef Glacier township, a moderate fall by local standards and one that would be exceeded about every one to two years on average. During the storm, water levels rose to the extent that properties immediately to the west of the river were evacuated, and emergency top-ups were placed on several of the stopbanks. These indicate that the limits of the capability of the protection works have been reached. It is therefore concluded that the present flood hazard is such that about once a year, there is a serious threat to the facilities on the west side of the river.

During the February 1998 storm, there was no need to reinforce the east bank protection. Above the "heliport" (formerly "airstrip") stopbank, the east bank protection is of a higher standard than elsewhere, but the banks protecting the Franz Josef Glacier Hotel and oxidation ponds are not. If the river during that flood had flowed mostly to its east side rather than to its west, these banks would have been seriously threatened. There is no way of knowing where the river will attack during the next flood; therefore it is concluded that, during an event of the magnitude of the annual flood, all protection works except those on the east bank above the former airstrip may be threatened with failure.

Thus, floods are likely to cause serious damage at any of the susceptible locations every year, except on the east bank above the "heliport" stopbank.

The facilities on the east bank above the "heliport" stopbank (the northern bridge approaches and the church) are safe from overtopping during an annual flood at present bed levels. Depending on the behaviour of the river, however, the northern bridge approaches could be outflanked by erosion, because the high gravel bank upstream of the approach is only lightly protected. In a larger flood (say a five-year event), however, the higher-standard protection may be threatened, mostly by severe aggradation of the bed and burial of the works.

In general terms, the flood hazard is greater now than it has ever been, because of the unprecedented present elevation of the river bed.

Sediment delivery from the Franz Josef Glacier to its proglacial valley during its present advance may be greater than in the past, but the rate at which the Waiho River is transporting this to the flood-susceptible reaches downstream has not increased commensurably. There is no evidence that sediment delivery from the Callery system is, or has in the recent past been other than normal. In the near future, therefore, there is no indication that changes in the water and sediment delivery to the problem reaches could ameliorate the situation.

6.0 BREAK-OUT SCENARIOS

Six break-out scenarios are considered the most likely to occur in the near future, as a result of high flows overtopping or breaking through the stopbanks, or causing the Waiho River to break out laterally to the Tatare River. The high flows will be accompanied by high sediment loads and may be associated with substantial bed aggradation which will allow break-outs to occur at lower high flows than might otherwise be needed to cause a channel shift.

In each case, the exact path followed by the river when it breaks out is difficult to predict; in general the water will flow perpendicular to the topographic contours, but local drainage paths, vegetation and minor topographic detail not visible on maps will influence the flow path in the early stages. Sediment build-up, and ease of scour of the land along the flow path will also influence the flow as the new channel becomes established.

6.1 Break-out through the true left bank above the SH 6 bridge

This would cause water to flow north parallel to the Glacier Access Road until it entered the Holiday Park at the bend in SH 6. Much of the water in the new channel would flow north-west through the Holiday Park and re-enter the present bed of the Waiho at the downstream end of the stopbank protecting the Holiday Park. Some of the water, however, could flow west, following old channels through the forest until it entered Wombat Creek, which would lead it to Docherty’s Creek. The flow would then follow Docherty’s Creek to its present confluence with the Waiho. The extra water and sediment added to Docherty’s Creek would cause it to change its course, particularly in the vicinity of the end of Gibbs Road. At the lower end of Docherty's Creek, break out into the coastal forest or Neils Creek could occur.

This break-out is likely to occur. The Waiho bed is at present aggrading rapidly above the SH 6 bridge, its left bank protection there is not strongly armoured, and the energetic flow and sediment deposition at the Callery-Waiho confluence place a powerful channel against this bank. A break-out could occur by overtopping and washout or by direct erosion. Once the river was out of the old channel, the SH 6 bridge approach works would tend to keep it on a new course. The diversion could be reversed during low flows with little difficulty. A large proportion (33 to 66%) of the Waiho flow could be involved in this break-out, because the river is very mobile at this section and usually flows in one channel.

Taking into account division of flow at the Holiday Park, initially as much as a quarter of the Waiho flow might enter Docherty’s Creek. If the break-out were not rapidly contained, however, this could quickly increase to half of the flow. It is unlikely that a channel to Wombat Creek would degrade significantly because the gradient to there is about the same as in the present bed. In its passage through the kilometre of bush west of SH 6, the developing new channel is likely to aggrade, but if the river were to become established in Wombat Creek, headward-cutting through the aggraded new channels would be likely.

This break-out could be inhibited by filling the depression between the raised glacier-access road and the terrace on which Lake Wombat sits. Alternatively, it could be prevented from continuing to Docherty's Creek by extending the SH 6 stopbank above Canavan's Knob along the west side of the Holiday Park to tie in to the high ground at the south of SH 6. The flooding would then be limited to the left bank Holiday Park area and areas upstream. Such a stopbank extension is needed to minimise the damage area in Section 6.2 (below).

6.2 Break-out through the Holiday Park

This would result from failure of the true left bank below the SH 6 bridge. The outcome would be similar to that in Section 6.1,- Waiho water and sediment in Docherty's Creek.

This break-out is quite likely to occur. The Waiho River narrows at the SH 6 bridge, and the line of the north bank above the bridge, ending in the north bridge abutment, sometimes directs the main channel directly at the Holiday Park stopbank. This bank has moderate rock armouring, but is not as strong as that on the north bank, and could not long withstand direct attack. Once the bank is breached, emergency repair work may be difficult, and the break could enlarge rapidly due to the fall from the riverbed to the lower ground outside the bank. A substantial portion of the total river flow could be quickly captured by this breach.

Some of this water would flow back into the Waiho at the north end of the Holiday Park: extension of the SH 6 stopbank could make all of the break-out water do this.

6.3 Break-out across SH 6 south of Canavan's Knob

This would result from overtopping or breaching of the bank beside SH 6. Over about 500 metres, the river often flows hard against this bank. The river bed is slightly above road level for much of this distance. The bank is augmented by stub groynes, but otherwise has no rock protection and historically has not resisted direct attack by a main channel for long. Again, emergency repair would difficult in a major event, and so an initial breach will enlarge rapidly to take a substantial proportion of the flow. The river bed here is very wide, so direct attack on the bank can easily occur - more easily than in a narrower reach.

Following such a breach, water would probably follow the road as well as moving west through the trees. Depending on the location of the breach, water and sediment would eventually reach either or both of Wombat Creek (through the trees) or Gibbs Creek (via SH 6), and thence to Docherty's Creek.

This break-out has occurred historically, and has been reversed by repair of the stopbank. Past break-outs here have not led to incision of the river bed and rapid capture of larger flows. This probably is because the slope of the land away from the river is very similar to the gradient of the river itself. Hence, a permanent channel change at this reach is unlikely to have any effect on river behaviour upstream.

6.4 Break-out between Canavan's Knob and Rata Knoll

6.4.1 Immediately north of Canavan's Knob

An old stopbank north of Canavan’s Knob is not tied in to the high ground of the Knob, and the river has outflanked it in recent high flows. A break-out through the trees here has already begun due to recent aggradation. When this new channel is active, water flows due west from Canavan’s Knob, then north-west to rejoin the Waiho River at Rata Knoll. If it becomes fully developed as a major channel, aggradation of its bed could cause it to break out further, to join Docherty’s Creek in the vicinity of the end of Gibbs Road.

It is unlikely that this break-out will develop rapidly or take a large portion of the Waiho flow; it must develop through forest and there is little difference in elevation between the river bed and the forest floor. It seems unlikely that a main channel will access this spot in the lee of Canavan’s Knob. Being hidden from sight, however, it has developed unnoticed and could become a major flow path unexpectedly at some future time unless monitored.

6.4.2 South-east of Rata Knoll

Immediately north of the old stopbank referred to in 6.4.1 (above), river-bed levels are such that a break-out is possible due west. Further north, closer to Rata Knoll, a 1-metre-high terrace prevents a break-out with present river levels. This break-out would lead water south of Rata Knoll, then in a north-westerly direction into recent flood channels now blocked off by Eatwell’s Stopbank; these channels run across Gibbs Road, then parallel to Waiho Flats Road and eventually into Docherty’s Creek. This break-out would take some time to become established, as a low terrace has to be surmounted at the outset, and since a measure of aggradation is needed to accomplish this it is less likely to occur than other break-outs. Direct impingement by a major channel could however quickly accomplish such aggradation. Once water and sediment entered the recent flood channels in quantity, the watercourse would become well established. The result would be inundation of a considerable area of the Waiho Flats to the east of Waiho Flats Road.

Access to the break-out site in flood would not be too difficult if this were the only area threatened; if the danger were recognised in time, it would be relatively easy to prevent or reverse the development of this break-out.

6.5 Break-out at Eatwell's (Milton’s) Stopbank

This bank was built to prevent break-out at the outside of the right-hand bend of the river past the end of the Waiho Loop. This point appears to act as the apex of a sub-fan, and recent channels radiate from it over the quadrant from west to north.

Through reconstruction after past failures, Eatwell’s stopbank now is one of the better constructed banks on the Waiho, and the river presently shows no sign of threatening to overtop or breach it (probably because aggradation here seems to have been minimal since 1948). It ties in to Rata Knoll and so cannot be outflanked to the south, and it continues far enough north to make outflanking at the downstream end of little significance.

To break out here, the Waiho would have to aggrade so much that other break-outs (e.g. 6.4.2) would probably occur first; hence this break-out is classed as “unlikely”. Its consequences would be widespread inundation both west and east of Waiho Flats Road, extending as far as the confluence of the Waiho with Docherty’s Creek; once it occurred it would be difficult to prevent from developing because the circumstances needed to initiate it are so severe.

6.6 Break-out into the Tatare River

This threatens to occur in the near future, because the Waiho bed is very close to the level of the Tatare fan surface to the north of the oxidation ponds (and exceeds this level locally). Between June 1997 and March 1998, the north bank of the Waiho eroded more than 200 metres towards the Tatare, a kilometre below the oxidation ponds. A further 500 metres of erosion will bring the Waiho to the edge of the 15-metre-high Tatare terrace. The height difference now is so low that a major flood could easily cross the "divide" and accomplish the break out. There are no river control works in place to prevent this.

The consequence of this event will be rapid headward erosion of a nick-point (waterfall) in the Waiho system. Once established this course will be impossible to reverse, because the fine-grained Tatare gravels that underlie both the Tatare and Waiho river beds in this area will be easily eroded by the Waiho. As it erodes headward, the mini-gorge thus created will capture an increasing proportion of the flow of the Waiho. The extent to which this gorge will widen cannot easily be predicted, but it is relevant that the Tatare, having experienced just such a nick-point recession after it broke through the Waiho Loop about a thousand years ago, now flows in an active bed about 200 m wide, in a gorge about 500 m wide. The larger Waiho could presumably develop a wider gorge. There is no obvious reason for the headward erosion to cease before it reaches the Waiho-Callery confluence, nor for the depth of the primary incision to reduce significantly on the way (at least until it encounters the large lag boulders that were visible in the bed of the Waiho about a century ago). In due course, however, the sediment eroded from the gorge will tend to re-aggrade the bed downstream. The headward incision could threaten the present riverside facilities at Franz Josef Glacier township with undercutting and collapse. A large volume of eroded sediment will be moved into the Tatare, and will accumulate downstream of the gorge through the Waiho Loop. The bed of the Tatare would then aggrade upstream as its base level is raised. Lake Pratt may be filled with sediment, and unless action is taken to prevent it, Waiho-Tatare water could at some future time flow into Lake Mapourika, and thence to Okarito.

If action were taken before this Tatare break-out occurs, it could be prevented by a 5-kilometre-long stopbank along the present north bank of the Waiho from the Franz Josef Hotel to the Waiho Loop. Given the present tendency of the river to erode the north bank, a bank of the height and standard of the Eatwell's stopbank would appear to be needed.

7.0 OPTIONS FOR FUTURE MANAGEMENT OF THE WAIHO RIVER

Here we consider the family of options that the community might choose from for future management of the Waiho river system. We do not consider capital costs of implementing these options, or the likely damage from choosing a particular one or not choosing one.

7.1 Hold the river on its present course

This option requires continued maintenance and repair of existing stopbanks and the urgent construction of about five kilometres of new, high-grade stopbank along the Green's frontage from the oxidation ponds to the Waiho Loop. To be truly effective, it also requires urgent upgrading of existing stopbanking on both banks from the Callery Junction to Canavan's Knob on the left bank and the oxidation ponds on the right. The upgrading, however, is to an unknown higher standard. Because of the extreme likelihood of structural damage to buildings on the left (south) bank in the event of river break-out there, stopbanks should be designed to higher standards than needed to protect from the flood of 2% probability in a year, but there will still be need for emergency evacuation of people from the southern bank.

Bigger, higher stopbanks will lead in the short term to a further need for even bigger, higher stopbanks. Within about 10-15 years, stopbanking would be needed to keep either the Callery or Waiho, or both, out of the central township area.

If repairable failures are accepted, this option is sustainable at high cost, but probably only until the Alpine Fault earthquake, when most high stopbanks will collapse along much of their length, and the upper fan head all may be overwhelmed by floodwater, gravel or both.

Advocates of part or all of this option are reminded that on current knowledge, the earthquake is more likely to occur in the next 20 years than is the 2%-probability flood.

New, bigger and better stopbanks require Resource Consents and capital to invest.

7.2 Let the river choose a new course (the do-nothing option)

This option simply stops maintenance of existing works until the river breaks out somewhere. There is no cost (except to those who suffer damage as a consequence) until the river makes its choice. Break-out into the Tatare is the most likely, because the Waiho River can accomplish this incrementally even at normal flow by slowly whittling away at the low bank.

There is, however, a risk that unmaintained stopbanks on the left bank will fail first. Failure there is most likely first in the left-bank reach above SH 6. This will have the same outcome to the Holiday Park area as a direct breach through the Holiday Park stopbank. Floodwater would probably re-enter the Waiho River at the lower end of the Holiday Park around the end of the stopbank. The expected outcome of such a break out is destruction of the Glacier Motel and Holiday Park, and possible destruction of the southern approach to the SH 6 bridge and Glacier Access Road. Any local degradation of the Waiho River bed around the stopbank breach is likely to be temporary, because the potential storage area for gravel in the Holiday Park area is small. It might fill in one or two floods. Waiho water would initially return to the Waiho immediately downstream of the Holiday Park, but as this channel filled with gravel, a further break out down SH 6 towards Docherty's Creek would be inevitable in the short term.

No Resource Consent or capital is needed to implement this option

7.3 Choose a new course for the river

Rather than take a chance on letting the river make the choice of a new course, a new course could be chosen for it. This would require first selection of one of several options for a new course, second obtaining a resource consent to implement the preferred option, and third, construction of the new channel with any new protection works that might be needed.

This option perhaps demands less capital than several of the other options, but obtaining a

Resource Consent for at least one potentially viable channel option could be difficult because the long-term outcome of developing it is not readily predictable.

This option has a safety advantage - the timing of the breakout can be known in advance, and the breakout water can be controlled (to some extent) while a new course is established.

A new channel to the Tatare would be very easily constructed and is likely to lead to reversal of the current trend of continued aggradation at the fan head, but the long term outcome is not clear, and the extent of potential degradation could itself become a problem. That is, it is very likely to solve the present problems, but it is likely to lead to other problems, some of which might be worse than the present ones.

There are several options for new courses to Docherty's Creek. All are longer courses than a new route to the Tatare. None are likely to lead to degradation problems. Some may not solve the present aggradation problems. Because of the width that will be needed for the new course, there is little possibility that a course in this direction could be developed without substantial disruption of the local community on the southern bank.

7.4 Make a new course for the river

This option is a variant on Option 7.3, but takes a more pro-active approach on channel selection by creating a course that would not otherwise be available to the river.

For much the same capital cost required to fully implement a new course to and through Docherty's Creek, a deep channel could be cut directly through the Waiho Loop at a point close to where there is maximum height difference between the Waiho fan surfaces on either side of the Loop.

This option would have the same desirable effects of upstream channel degradation as could be achieved with a river break-out to the Tatare, but with fewer undesirable "side effects". It has some advantages over a Tatare break-out: it maximises the potential drop across the Waiho Loop, and hence could maximise the potential degradation at the fan head; it allows more space to be created between the oxidation ponds and the river channel (the river could be shepherded to incise immediately adjacent to Canavan's Knob, well clear of the ponds). This option leaves the Tatare gorge through the Waiho Loop untouched, and keeps the Tatare river flow to help clear the toe of the Waiho fan below the Loop between major floods (as it does today). This may help keep open the Lake Pratt drainage to the Waiho, and minimise the potential for diversion of the Waiho into Lake Mapourika and the Okarito drainage.

A cut through the Waiho Loop minimises the Waiho River encroaching onto "new" territory. Degradation at the fan head to the level of 1890, however, would destroy the present highway bridge and could bring other problems as the newly deepened channel adjusts by widening.

7.5 Choose where the river will not make a new course

This option has the same intended outcome as Option 7.3, but it requires no Resource Consent or channel construction. Stopbanks are strengthened where it is desirable to prevent a river break-out, and nothing is done, or stopbanks are deliberately weakened where a new course would be desirable, or less destructive. For this option, the timing of the break-out is unpredictable, and the route of the new course is less readily controlled (or may be uncontrollable). If the choice is to prevent break-outs at the locations of existing stopbanks, this option becomes the option of maintaining the *status quo* (section 7.6 below).

7.6 Maintain the *status quo*

This option continues to manage existing river-control works as they have been managed in the recent past, but with no new work. That is, repair or replace banks as they are damaged or destroyed, and add to their height as the bed rises. The expected outcome is relatively easily predicted in its early stages. Ongoing costs in the short term (one to two years) are likely to be similar to those over the past ten years (but the parties on whom the costs fall may change). Substantial repair work is likely to be required several times each year. There is about a 1-in-2 chance that Waiho floodwater will enter the Holiday Park area in any year, and a 1-in-3 chance that the heliport bank will be damaged or circumvented in any year. Buildings on the Franz Josef Glacier Hotel site are likely to suffer flooding of the ground floor several times a year, and there is a 1-in-5 chance each year that the adjacent stopbank or that adjacent to the oxidation ponds will be breached. The SH 6 stopbank upstream of Canavan's Knob is less substantial, but still has perhaps a 1-in-5 chance of being scoured through in any year, which would allow floodwater to temporarily enter Docherty's Creek.

In the very short term, within the next few years or less, the *status quo* option will lead directly to break-out of the Waiho into the Tatare downstream of the oxidation ponds.

This option requires no change to existing resource consents. It does require a well rehearsed emergency evacuation procedure for the settlements on the left bank of the Waiho River.

7.7 Consider the whole hazard picture

In choosing how to manage problems with the Waiho River in the future, it is important to remember that there are three independent hazard types to be concerned with: normal flooding; dam-break flooding; and the earthquake. Any management strategy (choice of options) must be able to cope with each of these, and with any pair of them in combination. It is not sufficient to consider each in isolation.

8.0 GENERAL HAZARDS TO THE COMMUNITY

In addition to the hazards associated with the river, the community at Franz Josef Glacier also is exposed to the hazards associated with earthquakes, storms (wind and rain), landslides, transport accidents (road and air), fire, terrorism (bomb and arson threats), and hazardous chemical emergencies. Of these, the earthquake hazard, which may also include accidents, fires, hazardous chemicals, flooding and landslides, is by far the most dangerous, and most far-reaching in its effects. When (if) the community is able to solve the problems with the river, there will still be left the even greater problem of how to ensure that the community survives the impending Alpine Fault earthquake relatively intact. The community faces little choice with the earthquake: the choice is to be prepared, or to be unprepared. Individuals, however, may choose to leave the area before it strikes. There can be no useful advance warning of when this, or any other, earthquake will strike.

8.1 Effects of earthquakes

New Zealand's most significant fault line, the Alpine Fault, which marks the boundary between two great tectonic plates moving relative to each other at 30 to 40 millimetres per year, passes through the township of Franz Josef Glacier. Appendix 2 summarises the available knowledge on past and likely future movements of the fault. On the basis of past geological record, the Alpine Fault is expected to cause a severe earthquake of Magnitude ca. 8.0 in the near future. It has an estimated 10% chance of occurring within the next five years (Yetton et al. 1998). This earthquake will be very destructive in south Westland, and particularly destructive at Franz Josef Glacier.

The lack of a historical record of strong earthquakes thus is not a reason for complacency. With an expectation for movement on the Alpine Fault soon, the area is much more dangerous than Wellington with respect to large earthquakes. Yetton et al. (1998) analyse the likely effects of the next Alpine Fault earthquake, but they present a broad overview that may be misleading to people in south Westland. Because of the uncertainties in modeling very high shaking intensities, Dr Yetton and his colleagues did not portray the likely distribution of very severe ground shaking (Modified Mercalli Earthquake Intensity scales MM10 to MM12) in the next Alpine Fault earthquake, and so limited their estimate for Franz Josef Glacier township to MM9 **or greater**. Because it is centred on the surface fault-rupture trace, the community centre at Franz Josef Glacier is likely to experience an earthquake of shaking intensity **MM10 OR GREATER**. Few, if any, structures in the township will be undamaged in this earthquake: some will be seriously damaged by this shaking intensity alone.

Most buildings in the area are single-story, wood-frame structures, and **most** should survive - shaken, stirred, but generally not "trashed". Building contents, however, are very likely to be "trashed". In the space of seconds to a few minutes, the land surface, and everything firmly attached to it will move by more than the dimensions of the average room. Everything unattached will be thrown violently about - refrigerators, freezers, pianos, water beds and people included. Diving under a table or a desk may be feasible early in the onset of shaking, but once there, you will have to stay with it for some minutes in its wild, erratic waltz around the room. Controlled movement during the most severe shaking will be impossible.

The likely earthquake loading will exceed the current earthquake design code (by more than ten times, in terms of energy applied in the shaking). It is uneconomic to require all buildings to exceed the code.

In the Alpine Fault earthquake, there will be minor subsidence of many areas of alluvial gravels, especially of artificial fill material. This may rupture water and sewer lines. There also are likely to be a great many rock-falls and landslides, as was demonstrated in the 1994 and 1995 Arthur's Pass earthquakes. If in winter, there are likely to be many snow avalanches from mountain slopes, and in any season, many ice avalanches. The main concern to the village area is if landslides or snow avalanches in the drainage basins of any of the rivers are large enough to temporarily dam their flow. Break-out flooding from rupture of landslide-dammed lakes can be catastrophic at most scales from small streams to large rivers. It is to be hoped that any earthquake-induced landslide dam does not form during heavy rain, and that there will be time to evacuate threatened areas (and a safe place to evacuate to). No other useful mitigation strategy is possible.

All services are likely to be lost to the township for days to weeks. There will be no reticulated water supply, no sewer, no electricity, and no telephone line. Ground access to the village is likely to be lost for weeks if bridges are destroyed. Where SH 6 crosses steep slopes, there will be countless slips on the road, and the carriageway will have fallen away in many places. For the expected magnitude of earthquake, medical services throughout much of South Island will be damaged or overloaded.

8.2 Decreasing the community's vulnerability to earthquakes

A severely damaging earthquake at Franz Josef Glacier is inevitable. On our current knowledge, the Alpine Fault is by far the most likely site of New Zealand's next major earthquake. No other geological structure (that the earthquake community knows about) in New Zealand has as great as a 10% chance of giving a Magnitude 8.0 earthquake within 5 years. At Franz Josef Glacier (and elsewhere in south Westland), it will damage many buildings and their contents. It will damage community infrastructure, and it will cause some fatalities. There is evidence of earthquake unpreparedness. The lifelines most vulnerable to earthquake damage are water supplies for fire control, and communication and evacuation routes for medical care.

The water tanks for town supply at Franz Josef Glacier are perched on a vulnerable site and are seriously endangered in a large earthquake when water for fire control will be critical to save lives. In addition to the possible loss of the tanks, the water main will rupture because it crosses the fault. A very different design of water main would be required to cope with the expected 8-metre slip of the fault. Such designs are more appropriate for gas mains, where the escaping gas would be a major hazard in itself. There is need to make provision for an alternative water supply for fighting fires. There will be a 3-metre high scarp between the Fire Service Depot and the rest of the town, so alternative water supplies will have to be independent of road transport.

There will be injuries in the community. Loss of telephone communications within and outside the community area will severely hamper the distribution of medical aid. Evacuation of the more severely injured will be a priority. Overland routes all are likely to be closed by losses of bridges, their approaches, and the road carriage-way on steep slopes. Helicopters and light aircraft will be essential to evacuate the seriously injured. The severity of the shaking over a large area of South Island may stretch the limits of New Zealand's resources to respond quickly to all places in need.

We inspected few homes or work places for earthquake preparedness. A level of general unpreparedness is apparent. A number of simple strategies can be easily implemented to greatly reduce damage in the inevitable earthquake. For example:

- Paint cans can be stored at or close to ground level where they will not fall far enough to burst open.
- Open shelves can have a raised lip across the front to inhibit shelf contents from "walking" off the shelf in a shake.
- Wood stoves can be strongly anchored in place.
- Hot-water cylinders and header tanks can be tied (strongly) to the internal bracing of the house.

- Bedroom ornaments and bookshelves can be placed so that nothing can fall on a bed.
- Ornaments can be removed from places where they could fall on seating, or on hard surfaces (such as stone fireplaces).
- Valued ornaments can be attached to shelves or walls with "blue tack" or restraining wires.
- Televisions, microwave ovens, computers and the like can be anchored in place.
- File drawers can be kept locked when not in use.
- Freestanding shelves such as book cases can be secured in place by screws into adjacent timber framing.
- No one should work adjacent to, or below large panes of unreinforced glass.

Some of these measures are likely to be of only limited value in a Magnitude 8 earthquake. For this, the most practical measure is to ensure that property is adequately insured against earthquake loss. Because there will be some deaths as a result of this earthquake, through people being unavoidably in the wrong place at the wrong time, the prudent resident will have written their will and lodged it with agencies outside the local community long before the earthquake strikes.

It is a community responsibility to ensure that it has on hand appropriate resources to provide a useful emergency response. It could be days before help comes from outside. This will be too late for fires, many injuries, or if total evacuation of the fan-head area is needed.

With the Alpine Fault "spring" already well wound and set to trigger, perhaps the most frightening statistic about the impending earthquake, until it occurs, is that the most likely day for the next rupture is **TODAY**, and if the fault does not rupture today, then the next most likely day is tomorrow and so on. The time for action to mitigate potential damage is **NOW**.

8.3 Security of hazardous chemicals

In any community there are a number of hazardous chemicals. The most abundant in the Franz Josef Glacier area are fuels (petrol, diesel, Avgas, Jet A1, and LPG), and the most vulnerable are those in the storage tanks at the petrol station because of their extreme proximity to the Alpine Fault. All fuel storage tanks are somewhat vulnerable in a large earthquake, but rupture of petrol tanks in the township centre is very likely because they are buried within the zone expected to be strongly deformed during the fault rupture. Accidental ignition of leaking petrol vapour would cause a disastrous fire in the community's "central business district" (compounded by the presence of LPG tanks that could also rupture in the shaking).

Diesel, Avgas and Jet A1 will be essential commodities after the earthquake. There is need for a community emergency response team to know where all the supplies are, and need to take precautions to prevent their destruction in the earthquake or subsequent fires.

For the earthquake, there is need to store other hazardous chemicals at floor level to prevent their containers rupturing when they fall, but for the floods, they need to be safely above ground level to avoid being washed away.

8.4 Protection of essential services

The oxidation ponds are an essential service in the operation of the township. They may be the most used structures on the fan, and certainly are the most undervalued community resource. In view of their high replacement value, they are currently exposed to an unacceptably high risk of damage from flooding, scour or river break-out. We assess the present level of protection as adequate to protect the ponds from an event of about five-year recurrence interval if the main channel were against the bank. This assessment does not take account of the likelihood of substantial aggradation against this bank in the near future. It also does not take account of the likelihood of a break-out of the Waiho into the Tatare. If such an event were to occur while the main channel of the Waiho was near the oxidation ponds, it is likely that ponds would be lost in the resulting channel widening as the new course became established. They deserve a higher standard of protection than is currently supplied. Earlier, the ponds were afforded greater protection through the control works in place to protect the now-destroyed airstrip.

The ponds are not constructed to survive the likely ground shaking of the Alpine Fault earthquake. But after this event, there would be little waste water to dispose of, and little likelihood of an intact sewer main either.

Other essential services include water for fire fighting, the SH 6 bridge which provides the community link across the Waiho, and local helicopters and other light aircraft, and their pilots and fuel supplies for emergency medical evacuation. These services will be needed immediately following the Alpine Fault earthquake. There is little that can be done to protect the highway bridge, but its present temporary construction makes it easily repaired. The township water supply probably can not be economically protected from the earthquake. Water for fire fighting will have to be obtained from elsewhere and delivered to the fires by pump, truck, or monsoon bucket.

The remoteness of south Westland in the event that the highway is substantially destroyed puts a special value on light aircraft. They, their fuel supplies, and their necessary ancillary services, deserve careful thought as to their earthquake-safe siting and storage. The more of them that are available locally, the faster emergency medical evacuation can take place.

One essential service not presently endangered by flood or earthquake is the community rubbish dump. The existing facility, however, may lack the capacity to cope with the load that will be generated by the Alpine Fault earthquake.

Electricity and telephone communications are not listed here as essential services because they will always be vulnerable to storm damage and they are certain to be destroyed in the earthquake. Radio and satellite telephone communication will be all that will be available.

9.0 FURTHER WORK

In preparing this report, we were mindful of a number of gaps in knowledge which limited the quality of advice which we could give. Some of these gaps will be easily filled in future work, while others may always remain gaps.

We have presented some testable hypotheses about:

- the effects of stopbanks on aggradation in the Waiho River;
- the consequences of a break-out of the Waiho into the Tatare;
- the effects of a cut through the Waiho Loop;
- the effects of movement of the Alpine Fault on river behaviour at the fan head.

These hypotheses are most easily tested in laboratory-scale physical models.

The recognised hazard of a dam-break flood from the Callery River can be mitigated either by relocation of the community or by provision of an adequate warning system. It remains to be determined if it feasible to establish and maintain a system which compares flows of the Waiho and Callery Rivers and sounds a warning if the Callery River level drops unexpectedly. Such a warning system may be needed for the welfare of the entire community, not just for the part of it on the south bank at the fan head.

The amounts of water and sediment being carried by the Waiho-Callery River system is not currently known although much engineering work has been carried out in the past which required these data. Either the quantities should be measured, or only engineering work that does not require these data for design should be carried out. If either of these tasks were easily carried out, they would have been undertaken long ago.

Any likely break-out of the Waiho River will have far-reaching environmental effects. In order that they can be monitored, and mitigated where this is desirable or practical, there is need for information on the present environments likely to be affected.

Our analysis of the behaviour of the Waiho River system has used results from a number of on-going geological studies. Further work on the Alpine Fault is likely to refine the detail on the history of fault movement, but it is not likely to alter the general conclusion that a major earthquake is imminent. Work in progress on the evolutionary history of the Tatare River fan will provide accurate information of the timing of major events there, but there is no immediate prospect for equivalent information on the Waiho River fan.

There is urgent need to prepare for the earthquake. A part of this should be an appropriate emergency response plan, and verification that this can be implemented. Preparations should not await resolution of the flooding problems.

10.0 FUTURE REVIEW OF THIS NATURAL HAZARD ASSESSMENT

This hazard assessment should be reviewed after the occurrence of a natural hazard which causes serious damage to the community infrastructure or after 10 years, whichever is the sooner. Such reviews should be repeated on a similar schedule.

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APPENDIX 1: CONSULTANTS' BRIEF

The report will include these points:

- Overview of the Waiho as a natural system whose behaviour over history has shown us.......
- Overview of human interventions and their implications.
- Assessment of the hazards (earthquakes, flooding, aggradation, avulsions, etc.) including prioritisation.
- Assessment of the adequacy of existing protection.

The report is intended for the community hence it must be written accordingly.

Through mutual agreement these terms of reference may be varied as information is gained during the assessment work.

APPENDIX 2 - PROBABILITY ESTIMATES FOR RUPTURE OF THE CENTRAL SECTION OF THE ALPINE FAULT

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Introduction

Two approaches are commonly used to estimate the probability that a large earthquake will occur in the future in a given area. The return period of rare large earthquakes can be estimated from the records of smaller magnitude earthquakes in the area, using a frequency-magnitude relationship of earthquake occurrence (Gutenberg and Richter, 1949). A more direct approach uses available geological evidence to determine the timing and size of earthquakes that have caused rupture of the fault surface in the past; it is presumed that these events will occur again in the future.

In New Zealand, the historical record of seismicity is short (ca. 150 years at most), and through most of that period there have been surprisingly few earthquakes occurring on or near the central section of the Alpine Fault. This has led to the concept of a seismic gap along this section of the fault (Adams, 1980). However since the New Zealand national seismograph network was upgraded in the late 1980's the lack of seismicity has been less obvious (Figure A1). This has led to the speculation that the earlier record has not been as complete as once thought, or that the number of earthquakes occurring, even of small and medium magnitudes, may vary over time (Anderson and Webb, 1994). Because the historical record of seismicity is brief, it cannot be confidently extrapolated to estimate the return time of the large, surface-rupturing earthquakes.

Large plate-boundary faults such as the Alpine Fault and the San Andreas Fault in California have high average rates of movement, but it has been shown that in most places movement is not occurring continuously. Rather, the stress applied accumulates over a long period - several decades to several hundred years - until friction on the fault plane is overcome and the elastic strain is released in a major earthquake. This concept of an earthquake "cycle" means that the fault has some sort of "memory" of its rupture history. Studies of many faults have shown that the faults show recurring patterns of rupture, with the return period of rupture having mean and standard deviation estimates.

If future movement on the fault were unrelated the previous movements, (i.e. the fault had no "memory"), then the likelihood of future rupture would be random, and the probability would follow a Poisson statistical distribution. If the fault had a very good "memory", then the return period would be very regular with only a small standard deviation about the mean, and the probability would be best estimated from a sharply peaked log-normal distribution (Figure A2). In this latter case the elapsed time since the last event is an important consideration.

Recurrence of large earthquakes on the Alpine fault

Evidence of single displacements of 6-8 m dextral slip and up to 3 m of vertical slip have been found at many points along the northern and southern sections of the Alpine Fault (e.g. Wellman, 1953; Berryman, 1979; Hull and Berryman, 1986; Berryman et al., 1992), but data have been lacking from the central section of the fault, and little is known of the timing of events. Cooper and Norris (1990) produced evidence for the most recent rupture on the South

Westland section of the fault in the range of 1650-1720 AD.

Yetton et al. (1998) have recently compiled all existing, as well as a substantial amount of new information, from the northern and central sections of the fault. Much of the data are indirect, coming from growth patterns in forests, aggradation in rivers that are presumed to be related to earthquakes, and dating of landslides over wide regions. As well as the indirect data, some direct information of the timing of fault rupture has been obtained from radiocarbon dating of displaced units observed in trench exposures of faults.

In summary (including work in progress in the Waitaha Valley by Wright et al., 1997), the most recent movement the Alpine Fault seems to have occurred around 1717 AD, and involved an approximately 400-kilometre-long rupture with about 8 metres of dextral slip in the southwest, decreasing to perhaps 6 metres in North Westland (Figure A3). The previous rupture was in about 1625 AD and its extent is currently known from north and central Westland. This event may be a single rupture of at least 250 km length or two smaller events that were closely spaced in time. Another event in about 1425 AD has been recognised, also from north and central Westland (Figure A3). Two further events, inferred from sediment pulses into sag ponds along the fault scarp, from widespread occurrences of landslides and river aggradation events, and from lichenometry measurements on rockfalls by Bull (1996), are estimated by Yetton et al. (1998) at 1220 AD ± 50 years, and 940 AD ± 50 years.

The available information on timing of ruptures on the Alpine Fault, including the elapsed time since the last one in 1717 AD, indicates that the time between ruptures varies from 92 years (1625 to 1717) to about 280 years (940 to 1220, and 1717 to present). There is thus considerable variability about the average recurrence interval of 211 years. The variability may in part reflect the incompleteness of available data. It is uncertain if the identified events represent the rupture of the whole length of the fault in a single event, or represent closely spaced events rupturing only part of the fault. In addition, only the most recent event has been dated in South Westland. Current work in the Haast area by the Institute of Geological and Nuclear Sciences and Otago University will refine the timing of the last three events in South Westland.

Probability estimates

For this study, probability estimates are presented for 100 year and 500 year return periods. The 100-year time frame is chosen because flood hazard is commonly estimated at this return period, and the 500-year return period is the level of hazard encapsulated in 1992 New Zealand seismic resistant design code (NZS4203), and in the Building Act (1991).

The Poisson model

The simplest model for estimating the probability of rupture of the Alpine Fault is the Poisson model. This model, however, assumes random fault (earthquake) behaviour, and thus the elapsed time has no effect on the probability of a future event. Based on this assumption, the probability of an earthquake occurring the day after the previous earthquake is the same as the probability of an earthquake occurring after several hundred years of inactivity.

To calculate the Poisson probability for the Alpine Fault for 100 and 500 years, all that is required is the average recurrence interval for movement on the fault. The date of the last event is not relevant. If the event record shown in Figure A3 is accepted, the probability can be calculated simply from:

$$P_N = 1 - \exp(-t/t_r)$$

where P_N is the probability over the time period; t = time period in years; and t_r = the average recurrence interval (in this case 211 years, based on the recurrence interval of the last five events and the lapsed time since 1717 AD).

P_N for 100 years = approximately 38%

P_N for 500 years = approximately 99%

The Poisson model does not take into account the concept of earthquake cycles, or elastic strain accumulation. The pattern of repeated large earthquakes on a fault suggests that some period of time is required for strain to accumulate after an earthquake before the fault is capable of producing another large earthquake. Poisson models tend to overestimate the probability of an earthquake soon after a previous earthquake, but seriously underestimate the probability of fault movement after considerable elapsed time (280 years for the Alpine Fault). Thus the probability for Alpine Fault movement calculated by this method is too low and substantially underestimates the true probability

Conditional probability

If rates of elastic strain accumulation, fault strength, and frictional considerations influence the recurrence of large earthquakes on a fault, then the elapsed time since the last event and some measure of the variability in periodicity, and perhaps the variation in the size of slip, are required parameters for estimating the probability of future occurrence.

The small number of data sets that contain recurrence intervals of active fault rupture strongly limits our ability to estimate the probability density distribution. Each fault would take thousands of years to define the full variation of recurrence interval which it could possibly exhibit. Nishenko and Buland (1987) proposed combining recurrence histories of as many examples as possible of a particular class of faults (for example, plate boundary faults such as the Alpine Fault); this compilation would then be large enough to make some meaningful deductions about variability in fault behaviour. This substitution of space for time is widely used in geology, seismology, geomorphology and hydrology when time ranges of events are large. In this way Nishenko and Buland (1987) obtained a data set of 40-80 recurrence intervals by combining the past 2-4 earthquakes from 20 similar faults. They developed statistical fits to the variability in the recurrence parameter, and derived a standard deviation about the mean of 0.21. In other words the maximum variation was up to around 75% of mean recurrence interval.

Yetton et al. (1998) extended the approach of Nishenko and Buland (1987) by updating their data. They have added an improved Pallet Creek paleoearthquake history from the San Andreas Fault (Sieh et al., 1989) and data from recent investigations of other segments of the San Andreas such as Wrightwood (Fumal et al., 1993; Biasi and Weldon, 1994); Phelan Creek (Sims, 1994) and Indio (Sieh, 1984). Yetton et al. (1998) also added the three most recent events identified on the Alpine Fault. In total Yetton et al. (1998) added 16 new recurrence intervals to the 54 in the original Nishenko and Buland dataset and recalculated the critical parameters in their method. The revised standard deviation about the mean recurrence is 0.34.

By adopting this wider standard deviation proposed by Yetton et al. (1998), a conditional probability of 75-95% (average 85%) was calculated for the 100-year period from 1998. For the 500-year return period, the probability is close to 100% because the elapsed time will be more than twice the maximum interval between events. Yetton et al. also report the time window within which there is a 90% chance that the next movement of the Alpine Fault will occur. Using all available data from the Alpine Fault, this interval is 1782 AD - 2014 AD. There was about an 80% chance that rupture would occur by 1998AD, but it did not. This does not mean, however, that there is now a 90% chance of it occurring in the next 16 years to 2014AD. As time passes, the time to the 90% chance of rupture occurring also drifts, but at less than a year for every year that passes. In 1782AD, there was a 90% chance that the fault would rupture within 232 years: in 1998, there is a 90% chance that it will rupture within the next 140 years (28% chance by 2014 AD, or 16% within 10 years).

A further indication that we are approaching the time of the next fault rupture is to use information on the amount of displacement during a single event. The largest single-event displacements reported for the Alpine Fault are in the range of 8-9 metres (Berryman et al., 1992; Sutherland and Norris, 1995). Such measurements are relatively common for the South Westland section of the fault. In North Westland, single-event displacements of 6-8 metres have been reported from the Hokitika and Otira areas, and from further north (Berryman, 1975; Berryman et al., 1992; Yetton et al., 1998). Dividing these single-event displacements by the 25-30 mm/yr average horizontal slip rate measured along the fault indicates it would take 200-360 years to produce 6-9 metres of potential slip. This compares with the time since the last event of 280 years. Alternatively one could say that 7 to 8.4 metres of potential slip have accumulated since the last movement of the Alpine Fault.

Uncertainties

The above analysis is an aggressive approach to estimating the conditional probability of rupture of the Alpine Fault within the next 100 years. It uses data that have not been widely reviewed (e.g. Yetton et al., 1998), with little direct dating from the actual fault. Work in progress at Haast should improve the dating of past rupture events in that area, and this may allow us to better define to the length of fault rupture for the 1625 AD and 1425 AD events.

This analysis assumed a model of fault behaviour where recurrence interval of rupture is a fundamental parameter. The available data however suggest that the intervals between fault movements are sometimes short (i.e. several earthquakes closely spaced in time) and sometimes widely spaced. This impression from the Alpine Fault is also seen on well-studied active faults in other parts of the world, where fault ruptures commonly appear to be grouped into “clusters” separated by longer-than-average “gaps” (e.g. Grant and Sieh, 1994; McCalpin and Nishenko, 1996). At present this variability is merged into a single standard deviation on the mean recurrence interval, but this may obscure a characteristic of large earthquakes on active faults. The current period since the last rupture of the Alpine Fault in 1717 AD (281 years) is longer than other inferred times between movements, which may imply that the next Alpine Fault event will involve rupture of the whole fault from South Westland to North Westland, as the 1717 AD event appears to have done.

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APPENDIX 3: ABOUT THE AUTHORS

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BSc (Hons), University of Canterbury - Geology (1966)
PhD, The Ohio State University - Geology (1975)

1992-96	Geomorphological research and consultancy, Institute of Geological & Nuclear Sciences Ltd
1988-92	Steepland geomorphological research and consultancy, DSIR Geology & Geophysics.
1976-88	Research in alpine hydrology and erosion processes, Water & Soil Directorate, Ministry of Works & Development.
1967-1976	Research Associate, Institute of Polar Studies, Columbus, Ohio. Glaciological, and geomorphological research in Alaska, and Antarctica.

Present research/professional specialties

Engineering and steepland geomorphology, Quaternary geology, dating of geomorphic surfaces, steepland hydrology, natural-hazard assessment, urban land-use capability assessment, environmental-impact assessment, erosion processes, rheology of earth materials, landslide kinematics, scientific editing.

Recent research and consultancy projects include:

- *Catastrophic landslides in New Zealand*
  Project leader of a 4-year research project funded by the Foundation for Research, Science & Technology investigating the mechanics of catastrophic landsliding in New Zealand.
- *Seismic hazard assessment for British Gas liquified natural gas processing plant, Pipavav, India*
  Investigation of site and surroundings for evidence of fault activity, as subconsultant with Dames & Moore, Seattle, for British Gas Co Ltd.
- *Seismic hazard assessment for liquified natural gas storage tanks, Dahbol Power Project, India*
  Investigation of site and surroundings for evidence of fault activity, as subconsultant with Dames & Moore, Seattle, for Dahbol Power Company India.
- *Terraces of the lower Waitaki River*
  Investigation of terrace profiles and ages along the lower Waitaki River for ECNZ.
- *Reservoir rim stability: Matahina Dam*
  Investigation of landslides and landslide potential at Lake Matahina on the Rangitaiki River as subconsultant with Woodward Clyde (NZ) Ltd for ECNZ.
- *Mount Cook/Aoraki Village: Natural Hazard Assessment*
  Geotechnical investigation for slope-stability, debris-flow, flooding and earthquake

hazards, review of performance of existing protection work, recommendation of further protection options for Department of Conservation, and Mount Cook Village Development Steering Committee.

- *Learning for geological design failures in roads*
  Project leader of a 2-year research project funded by the Foundation for Research, Science & Technology investigating roading design failures involving geological problems
- *Bridge losses at Waterfall Creek, SH 6 at Lake Wanaka*
  Geotechnical and project-management investigation of the causes of the succession of bridge losses at Waterfall Creek, SH 6 for the Foundation for Research, Science & Technology in the project *Learning from geological design failures in roads*.
- *Quaternary geology of the Rangitata Fan, Canterbury Plains*
  Leader of a research project funded by the Foundation for Research, Science & Technology investigating the development of the southern Canterbury Plains.
- *A 7000-year record of great earthquakes from Turakirae Head, Wellington*
  Investigation of the sequence of raised beaches along the south Wellington coast for EQC.
- *Geomorphic overview of lower Clutha River Valley*
  Review of geomorphology of the lower Clutha Valley in relation to future power development for Contact Energy Ltd.
- *Clyde Power Station Reservoir:- Cromwell Gorge, Right Bank: geomorphological evaluation for slope stability*
  Geotechnical investigation for slope-stability of the right bank of the Clutha River through the Cromwell Gorge for ECNZ.
- *Environmental impact assessment for snow-making at Mt Hutt*
  Project leader of multidisciplinary study assessing the potential environmental impacts of snow making at Mt Hutt skifield for Leisureland Corporation Ltd.
- *Snow tussocks and water yield: a review of the evidence*
  Hydrological appraisal of the effects of snow tussock on water yield in Otago for Central Otago Runholder's Association.
- *Glentanner Park development: appraisal for flood protection*
  An appraisal of flood protection for campground development at Glentanner prepared for Truebridge Callender Beach Ltd, Wellington.

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BSc(Hons) University of Southampton - Civil Engineering (1966)
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PhD University of Southampton - Civil Engineering (1973)

1975-98	Natural Resources Engineering, Lincoln University; Lecturer - Reader
1970-75	Dept of Civil Engineering, Sunderland Polytechnic, UK; Lecturer - Senior Lecturer
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Present research/professional specialties

Gravel-bed river processes, engineering and management, river meandering, alluvial channel bedforms, erosion processes and management, debris flow dynamics and hazard mitigation, flood hydrology and flood-plain management, physical modelling of geomorphic processes, rock avalanche dynamics and modelling, natural hazard identification and assessment.

Recent research and consultancy projects include:

- *Catastrophic landslides in New Zealand*
  Co-investigator in a 4-year research project funded by the Foundation for Research, Science & Technology investigating the mechanics of catastrophic landsliding in New Zealand.
- *Mount Cook/Aoraki Village: Natural Hazard Assessment*
  Geotechnical investigation for slope-stability, debris-flow, flooding and earthquake hazards, review of performance of existing protection work, recommendation of further protection options for Department of Conservation, and Mount Cook Village Development Steering Committee.
- *Franz Josef glacier access road - security of road-end facilities*
  Fluvial geomorphic investigation of river processes and aggradation in the upper Waiho valley; recommendation for resiting of car parks and information kiosk for Department of Conservation.
- *Report on the Waitaki Flood of December 1995*
  Hydrologic study of rainfall and flood generation in the upper Waitaki valley and the decisions and processes that led to flooding in the lower Waitaki valley for the Waitaki Flood Damage Committee.
- *Long-term management of facilities on an active alluvial fan - Waiho River fan, Westland, New Zealand.*
  Journal of Hydrology (New Zealand) Vol 36 No.2 1997, pp 127-145
- *Dambreak flood hazard from the Callery River, Westland, New Zealand*
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- *Using hydroscience and hydrotechnical engineering to reduce debris-flow hazards.*
  Proceedings, First International Conference Debris Flow Hazards Mitigation; ASCE,

San Francisco, 1997, 787-810.

- *Dynamically similar small-scale debris flow models*
  Proceedings, International Workshop on Floods and Inundations related to Large Earth Movements, Trento, Italy, 1995, A12
- *Rock avalanche runout - preliminary model studies.*
  Proceedings, International Symposium on Rapid Landslide Motion, Disaster Prevention Research Institute, Kyoto University, Japan, 1995.