OTAGO ALLUVIAL FANS PROJECT

REPORT # 1205 - VERSION 2

OPUS

Otago Alluvial Fans Project

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Executive Summary

This report is a 2nd version of the original report produced in July 2007 and is a complementary document that helps put the Stage 3 Report, "Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago" into context. This report provides information on what was completed in Stage 1 of the project including background information regarding alluvial fans within Otago and their associated hazards.

An alluvial fan is an accumulation of river or stream (alluvial) sediments that form a sloping landform, shaped like an open fan or a segment of a cone. Alluvial fans typically occur near the boundary between hillslopes and valleys. They owe their origin to changes in the slope of natural drainage systems, for example where a steep gully merges onto a flatter valley floor. The gradient decrease and widening of the flood path where a gully meets a valley floor encourages the deposition of sediment. Over time, sediment accumulates to form a fan-shaped landform, with its apex at the gully mouth. Alluvial fans form on all scales, from a few tens of metres across, to several kilometres across.

Alluvial fans evolve and change through time, at time scales ranging from the geological (i.e. thousands of years) to the historical (years to centuries). The prime factors controlling the evolution are topographic (landscape) setting, climate, the size and geology of the catchment, and sometimes vegetation changes within catchments. Alluvial fans may evolve rapidly in short periods, with sediment deposition and the lateral displacement of streams during flooding, or may remain dormant or only intermittently active for long periods.

Alluvial fan flooding is a type of flood hazard that occurs only on fans and is characterised by flow-path uncertainty so great that the unpredictability must be considered in realistic assessments of flood risk or in the reliable mitigation of the hazard. Flooding on alluvial fans can be more damaging than other types of flooding because alluvial fans have steeper gradients than river floodplains. Water and entrained debris on alluvial fans can flow faster, and has a greater density, than is the case in river floodplains. A considerable amount of sedimentation may also occur in conjunction with alluvial fan floods. The principal hazards on alluvial fans are inundation by flood water, debris flow and debris flood deposits, channel migration, deposition and erosion. In terms of threat to life and destructive potential, debris flows are the greatest concern, however, depending on the characteristics and extent of development on an individual alluvial fan, the economic costs of each hazard will vary.

The Otago Regional Council commissioned Opus International Consultants and GNS Science to assess and report on the risk that alluvial fans pose to Otago communities. A regional assessment was carried out at 1:50,000 scale utilising previous geological mapping, aerial photo and map observations, and the combined local knowledge of the GNS Science-Opus project team. This report explains what alluvial fans are, exemplifies the different types of alluvial fan that occur in Otago, shows how alluvial fans can be identified, discusses the hazards posed to Otago communities from alluvial fans and outlines some of the ways that the risk can be mitigated. A Geographic Information System (GIS) map database was compiled, with 2197 separate fan areas identified and classified. There are 1970 km^2 of significant alluvial fan landforms in the Otago landscape, amounting to approximately 6% of the Otago land area.

The alluvial fans in Otago have been classified according to the type and activity of deposition processes that have formed a particular fan, because these criteria have the greatest bearing on the hazards present. The categories used are based on dominant processes interpreted on the fan, being either debris-dominated, floodwater-dominated or composite. A generalised map of these fans accompanies this report, using this classification scheme, but more detail can be obtained from the GIS dataset. The classification scheme is illustrated in this report with seven examples of alluvial fans from throughout Otago. The debris-dominated examples are the Pipson Creek fan and Mill Flat fan, in the Queenstown Lakes District area. The floodwater-dominated examples are the Milton fan in the Tokomairiro plain and the Pukeuri fan complex in North Otago. Composite fan examples where there is a combination of debris flow and floodwater flow processes include the North Roxburgh fan complex and the Stoney Creek fan in Wanaka. The Waikerikeri fan is introduced as an example of a large fan whose surface is for the most part old and inactive, but has been cut into by young active stream channels.

Much infrastructure and development is found on alluvial fans in Otago. These landforms form attractive places for development because they are elevated, scenic and have good drainage. Flooding processes including debris flows, sudden channelised flow, channel migration, and sheet flow will occur on a number of these fans and will not only be a threat to life but will also affect infrastructure. This could have significant consequences for Otago communities and steps are required to mitigate these hazards.

The first step to mitigating the hazards has been addressed by this assessment. Presently the public awareness of alluvial fan hazards is very low. Education is needed because fans are only intermittently active, and hazard definition and mitigation can be difficult. The identification of Otago's alluvial fans and the problems associated with them is the first stage of raising public awareness of the issues. This study provides a provisional classification of alluvial fan activity. Rather than defining site-specific hazards, the accompanying GIS dataset defines locations where alluvial fan-related hazards may exist, together with a prediction as to the nature of that hazard. The assessment is appropriate for regional scale planning and development purposes but should not be used as a substitute for site specific investigations and/or geotechnical engineering assessment for any project.

The next step in mitigation is to evaluate the risk on each fan. Site specific investigations and fieldwork are required to provide qualitative hazard evaluation, and identify the risk posed by alluvial fan hazards to infrastructure and human life. Where there is a low risk it may be appropriate for no further mitigation other than to be aware of the hazards. In high risk areas mitigation measures may include such steps as increasing public awareness, implementing a hazard warning system or a hazard management plan, better land use management, modifying infrastructure, installing engineering works, or hazard zoning.

Alluvial fans are going to continue to evolve, in response to natural processes including climate and earthquakes, with modulation by human factors such as changes in land-use and vegetation. For the present time we can expect increased human development on alluvial fans within the next 100 years. Human-induced changes are likely to be the most important influence on alluvial fan processes in the relatively short timescale of importance for land-use planning and management.

Contents

1 Introduction

This report is a 2nd version of the original report produced in July 2007 and is a complementary document that helps put the Stage 3 Report, “Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago” (Barrell et al., 2009) into context. This report provides information on what was completed in Stage 1 of the project including background information regarding alluvial fans within Otago and their associated hazards.

The Otago Regional Council commissioned Opus International Consultants Ltd (Opus) and the Institute of Geological and Nuclear Sciences Ltd. (GNS Science) to assess and report on the risk from alluvial fans that may impact on communities in Otago. This report describes the types and distribution of alluvial fans at a regional scale throughout Otago, discusses the hazards posed to Otago communities by the processes acting on alluvial fans, and outlines possible measures to mitigate the risks presented by active fans. Potential effects of climate change are also reviewed. The information collected in this project is expected to be supplied to Territorial Authorities for their use and will be distributed through the online Natural Hazards Database, hosted by the Otago Regional Council.

Alluvial fans (in this report, this term includes debris flow and debris flood fans –see glossary) have the potential to detrimentally affect many aspects of land occupation and use. The natural hazards associated with active fans include erosion, sedimentation from debris flows and sheet floods, and inundation by water (flooding). They are caused by natural processes, and typified by flow path uncertainty and widely variable flood hazard severity.

Following the Committee on Alluvial Fan Flooding (Schumn et al. 1996), the following definition is used for alluvial fan flooding:

“Alluvial fan flooding is a type of flood hazard that occurs only on fans. It is characterised by flow-path uncertainty so great that this uncertainty cannot be set aside in realistic assessments of flood risk or in the reliable mitigation of the hazard. An alluvial fan flooding hazard is indicated by three related criteria: a) flow path uncertainty below the hydrographic apex, b) abrupt deposition of sediment as a stream or debris flow loses its competence to carry material eroded from a steeper upstream source area, and c) an environment where the combination of sediment availability, slope and topography creates a hazardous condition for which elevation on fill will not reliably mitigate the risk”.

Alluvial fans provide attractive development sites due to their commanding views and general good subsoil drainage characteristics. However they can be hazardous areas both in terms of unpredictability and potential destructive flood waters or debris transport.

The infrequency of high-intensity rainfall events, presence of gentle slopes across the lower flanks, and often long time spans between severe events tend to create a sense of complacency regarding the hazardous nature of alluvial fans, and this causes risk to infrastructure and life. These “benign” factors also make it difficult to determine whether a fan is inactive, or is simply in a prolonged dormant phase (perhaps not active in historical times). Regardless of whether or not fans are designated as active, inactive or dormant, their very nature means that there is always a measure of unpredictability in terms of hazard and this should not be overlooked or ignored.

This report discusses in general terms the nature of flooding on alluvial fans in Otago. It outlines definitions of the various types of fans, the natural processes that occur on them, and methods for identifying them. It includes discussion on source material, triggers, consequences to communities and possibilities for mitigation. Some well-known examples are used to illustrate the different types of alluvial fans in Otago.

The report is accompanied by a Geographic Information System (GIS) dataset, which has been used to generate a map of alluvial fans in Otago (see Appendix 1). The regional dataset and map provide a provisional assessment of the alluvial fan hazard. It is an assessment at 1:50,000 scale based on previous geological mapping, remote aerial photo and map observations, and the combined local knowledge of the GNS Science-Opus project team. The assessment has identified there is 1970 km^2 of alluvial fans in the region, or approximately 6% of the Otago land area. Fans < 0.1 km^2 are typically too small to have been consistently recorded, although many are recorded. In other words, there may be small-size fans that exist in Otago which have yet to be recorded in the dataset, but require more detailed site-specific studies. We are confident that all alluvial fans larger than 0.5 km^2 have been identified, with boundary accuracies of either ±100 m or ±200 m.

Alluvial fans in Otago are landforms which have developed by repeated events over geological rather than human time frames (historical). This regional assessment provides an indication as to the nature of depositional processes involved in fan formation, being either debris-dominated or floodwater-dominated events, and whether or not these events are still likely to occur. A conservative "guilty until proven innocent" approach has been adopted, because alluvial fan processes have potential to cause considerable damage and loss of life.

All fans are considered active (i.e. hazardous) unless there is good reason to think otherwise. In a regional-scale assessment such as this, it is rarely possible to distinguish the presence or absence of activity over a geologically-short time period (e.g. the last several hundred years), on individual fans or specific parts of fans. As demonstrated by debris flood problems at Paekakariki from 2003 to 2006 (Hancox 2003), some alluvial fans that may have not been active historically (say for at least 150 years), can become active again, given suitable conditions, such as extreme rainfall intensity (Hancox 2006), landsliding or vegetation changes in the headwaters. Reactivated 'dormant' fans may then remain active for many years because of changed conditions (e.g., erosion gullies, landslide scars) within a catchment (Hancox et al. 2006). Clear evidence for long-term inactivity and/or the detailed nature of hazards faced is typically much more forthcoming in detailed site-specific assessments.

The assessment has divided alluvial fans into 2197 areas, of which 1526 are classified as active – i.e. that flooding, deposition and/or erosion are considered possible. 671 alluvial fans, or parts of fans, are now physically separated from the stream and catchment from which they were derived, and can now confidently be considered inactive. This study is the first phase of classifying alluvial fan activity in Otago and should be regarded as provisional. Rather than defining site-specific hazards, the accompanying GIS dataset defines locations where alluvial fan-related hazards may exist, together with a prediction as to the nature of that hazard. More detailed hazard assessments, with site specific investigations and fieldwork, are required to provide qualitative hazard evaluation defining the extent to which events can be expected, for example, during the next 100 years.

2 Definition of alluvial fans

An alluvial fan is a gently to steeply sloping landform, shaped like an open fan or a segment of a cone that radiates down slope from a point where the sediment transport capacity of a permanent or ephemeral stream rapidly decreases downstream because of increases in channel width, reductions in channel gradient, and other influences (Bull 1977, Rachocki & Church 1990). Alluvial fans are composed of sediments that may include boulders, gravel, sand, and mud (Rust & Koster 1984). The nature of the sediment reflects the rock and soil types within individual catchments. Alluvial fans generally form where a stream issues from a hillslope gully onto a plain or broad valley, where a tributary stream is near or at its junction with a main stream, or wherever a constriction in a valley abruptly ceases or the gradient of a stream suddenly decreases.

Individual alluvial fans that have coalesced along hill or mountain fronts to form a semi-continuous series of fans connected by aprons are referred to as a *fan complex*. (the terms *alluvial apron*, *coalesced fan*, *fan aprons* or *bajada* are also used internationally). While alluvial fan complexes do not have the instantly recognisable shape of individual fans, they are formed by, and are subject to, the same alluvial fan processes and hazards. A stylised alluvial fan system is illustrated in Figure 1.

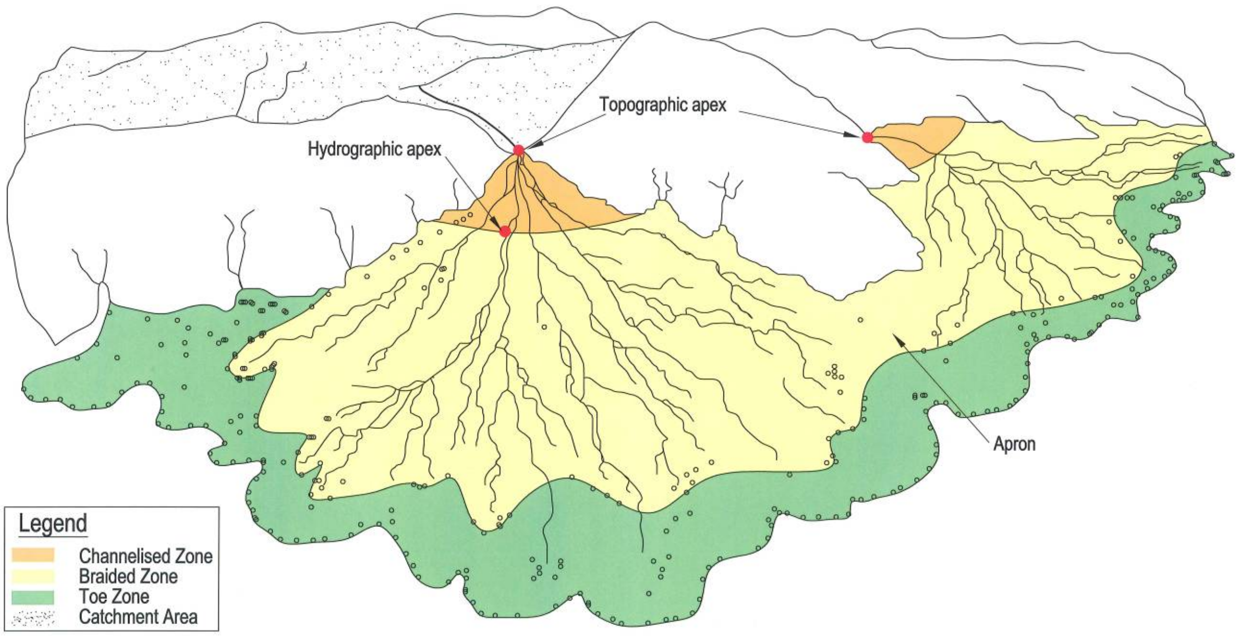

Figure 1: Idealised diagram of an alluvial fan.

There are four main parts to a typical alluvial fan (Figure 1).

Catchment area: The area in which precipitation (rain, snow etc) is collected before being carried downstream across the fan. While not strictly part of the fan as such, the catchment area plays an important role in initiating processes on the alluvial fan. Water collected in the catchment carries and discharges sediment on the fan surface, typically in association with storm events. The presence of instabilities such as landslides or soft erodable rock and the nature of vegetation and soils may enhance the supply of sediment from the catchment and delivery down and across alluvial fans.

Channelised zone: This zone is also termed the *fan head*. It is the region of highest elevation on the fan where streams are often incised into the fan surface. There are two important points of reference to the landform in Figure 1, the topographic apex and the hydrographic apex (Schumm et al. 1996). The topographic apex is the highest point of the fan surface; whereas the hydrographic apex refers to the point at which channelised streams merge out onto the fan surface (i.e. flows cease to be confined). On a fan that is not channelled the hydrographic apex coincides with the topographic apex.

The hydrographic apex is of considerable relevance to alluvial fan flooding because it is generally the point where flooding and/or deposition may begin on the fan (Schumm et al. 1996). The stream leaves the hydrographic apex via a channel or channels, at high velocity during floods. These channels may be re-occupied by successive flood events, may become eroded and more incised as the flood progresses. The hazards in this zone can be severe due to high velocity discharges of sediment and water.

Braided zone: This is an area of topographical change, where the fan gradient decreases and a wider flatter area is encountered. Debris flows and floods lose velocity across this zone and start to deposit their sediment load (Jakob and Hungr 2005). Previous channels can be filled (aggraded), meaning the flows are no longer confined; the flows can spread out, jump into a nearby older channel, or erode a new channel in a process called avulsion. In some cases channels are so deeply incised that the chance of streams moving laterally across the fan is low. In other cases the possibility of avulsion is high, and channel switching with associated debris deposition and flooding in new pathways is unpredictable. This aspect needs to be well understood in determining the activity status of a fan and to mitigate risks to any development.

Toe zone: The lowest section on a fan, where the water leaves the braided zone. Flood waters move across lesser-gradient slopes as sheet floods (Schumm et al. 1996), described as shallow overland flow. Water may also infiltrate into the fan deposits. Stream velocities can still be high but decreasing, and finer grained sediment load is deposited. Sheet floods (described below) are common in the toe zone. Some fans lack a distinct toe zone, or the toe may be eroded by a main valley river (e.g. Figure 2).

Figure 2 illustrates a classical example of an alluvial fan system which has been built by debris flows and floods into the edge of Dart Valley, northwest Otago. The major streams running down the mountain (Scott Creek on the left) are confined above the topographic apex of the fan. They are very steep (including sections of waterfall) and transport sediment down-slope onto the deposition area at the base of the slope. Large boulders and coarse-gravel deposited by debris flows are found near the top of the fan, whereas in the toe zone the sediment is floodwater-deposited pebble to cobble gravel. Hazard to the road is mitigated by engineering of the channel above and below the bridge (not particularly visible in this photograph).

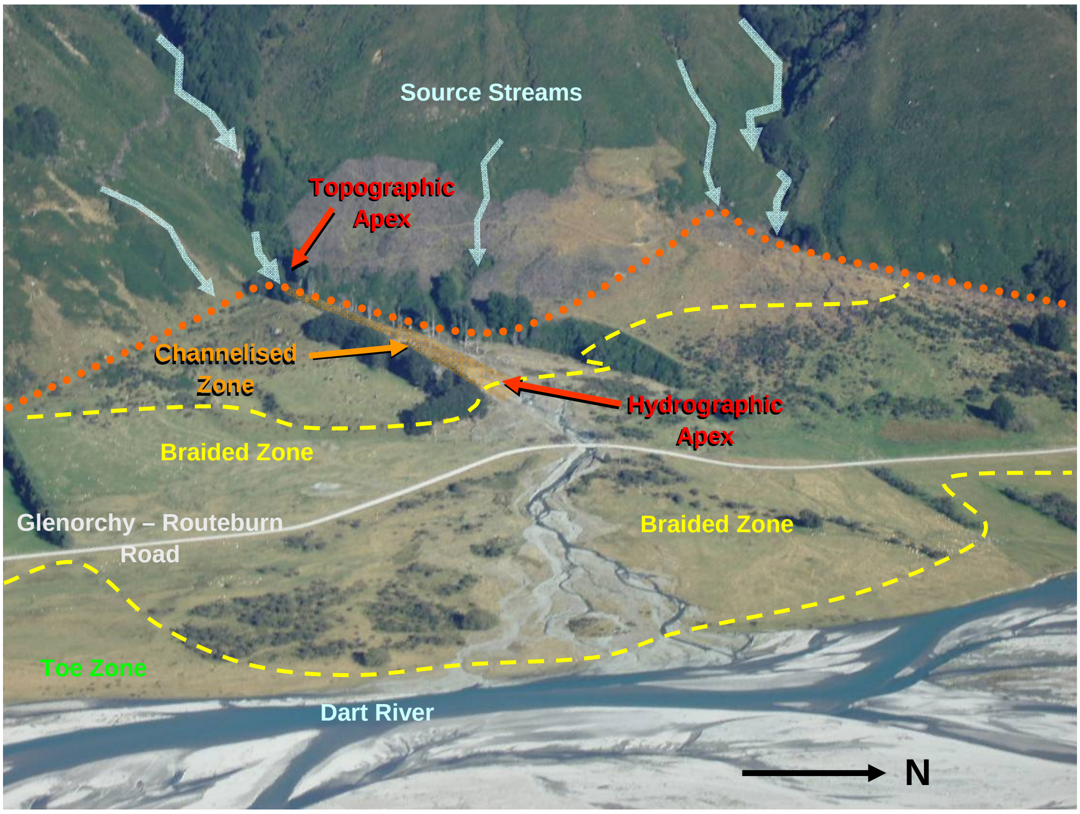

Figure 2: Annotated photograph of alluvial fans developed at the western edge of Dart Valley, where Scott Creek is crossed by the Routeburn road. Photograph taken 24/3/2007.

Alluvial fans in Otago are landforms which have developed during the Quaternary Period of geological time (spanning the past 1.8 million years). They are the result of multiple debris flows and/or floods, which may or may not still continue across the land surface today. Descriptions of the processes by which alluvial fans are formed are provided later in this report. Currently there is limited evidence of age (e.g. by numerical dating methods such as radiocarbon or luminescence) in some specific areas but not across the entire region. Accordingly we prefer to assign only the broadest inferences of age to the surfaces mapped. Without dating, we can only estimate ages using morphological criteria such as: heights of surfaces above modern streams; degree of preservation of 'palaeo' stream channels on the surfaces, and; the degree of dissection by minor streams or gullies. Increasing age of fan surfaces is indicated by reduced channel expression and increasingly deep or intensive dissection by gullies. Most of these geomorphological criteria, however, are only tentative indicators of age. In the accompanying GIS dataset each fan has been assigned a **relative age** attribute that reflects the approximate period during which the deposit accumulated (see Table 1).

Table 1: Relative age attributes recorded for fans in the GIS dataset and description of the period they represent.

RELATIVE AGE	DESCRIPTION
Young fans	possibly less than one hundred to 10,000 years old, perhaps up to 20,000 years old
Medium-age fans	from 10,000 years old up to a few tens of thousands of years old
Old fans	probably at least one hundred thousand years old
Very old fans	may be up to several hundreds of thousands of years old

3 Classification of alluvial fan activity

Assessing and defining the *activity* of alluvial fans is a crucial part of alluvial fan hazard assessment. At present, fans range from active to inactive, or there may be active and inactive portions on one fan or within a fan complex. *Active* alluvial fans are those where there is evidence of historically recent or ongoing flooding, erosional and/or depositional processes on the fan surface (e.g. bare gravel bars, transported logs, etc), or where there is clear potential for flood activity to occur in future. Inactive fans are those where these processes have clearly ceased, or are confined to the extent that erosion no longer takes place and sediment can no longer be deposited on the fan surface.

Clearly the time scale is a key issue for the definition of activity/inactivity. Fans are developed over geological (e.g. many thousands of years) rather than human (historical) time frames. Fans can go into prolonged periods of inactivity for decades (or longer), or become dormant, only to re-activate in the future due to unusually extreme events, or to regional environmental change (or both). Fans may become isolated from their feeder streams and therefore inactive due to downcutting; to tectonic (geological) uplift of the land; or to changes in sediment supply in the catchment. New fans may evolve as a result of stream capture, landsliding, or changes in catchment vegetation.

For the purposes of this work, we distinguish between active and inactive fans in a temporal sense by defining that a fan will only be regarded as inactive if it does not, in its present form, pose any further threat to infrastructure, development or life, **perhaps within a time period of 100 years** (a time frame integral to the Building Act – derived from statistical data on past events to estimate a return time for certain type of events, such as floods). If active processes are currently occurring on a fan, or on part of a fan, it is classed as active. Most classification of fans has been carried out remotely, based at 1:50,000 scale on geological and geomorphological observations using maps and aerial photographs. In greater detail it is possible that fan processes of < $0.1km^2$ may be active on larger inactive fans; fan processes < $0.1km^2$ are typically too small to be consistently recorded in this assessment and may have gone unnoticed.

An active (cf. inactive) classification indicates that flooding, deposition and/or erosion are **possible** within the next 100 years in the area defined by a particular fan polygon in the GIS dataset. A conservative “guilty until proven innocent” approach has been adopted during the assessment process. Unless there is clear evidence to prove otherwise (e.g. abandonment of a fan surface from its catchment, with entrenchment of the streams significantly below a fan surface), alluvial fans are all regarded as having the potential for continued, or renewed activity within the next 100 years. Of the 2197 fan areas, 671 are regarded as inactive. It is important to emphasise that evidence for the absence of activity is not always forthcoming in regional-scale assessments such as this based on remote observations. Evidence for the absence of activity, on individual fans or specific parts of fans, is much more likely to be found by detailed site-specific investigations. These areas can then be more confidently assigned as inactive and the potential hazard dismissed.

In summary, this study is the first phase of classifying alluvial fan activity in Otago and should be regarded as provisional. The dataset outlines locations where there is **likely to be an alluvial fan-related hazard to look for within time periods of up to 100 years.** More detailed hazard assessment and qualitative risk evaluation will require site specific investigations with fieldwork.

4 Nature of flood hazards on alluvial fans

Flood-hazards on alluvial fans can be more damaging than floods in many other environments, because water and debris travel at higher flow velocities and densities, and considerable amounts of sedimentation occur in addition to inundation by floodwater. The flow path uncertainty, sediment content and lack of topographic confinement distinguish alluvial fan flooding from more predictable river flooding.

The principal hazards (see Figure 3 below and definitions in the Glossary at the back) are:

- Debris flow – deposition and impact force
- Debris flood – sediment laden flood water, slow burial by gravel (Figure 3)
- Inundation by flood water – channelised or sheet flow
- Channel migration - deposition, erosion and scour
- Deposition and erosion

Flooding on alluvial fans typically begins near the hydrographic apex which is the highest point at which stream flow is still confined. From here, floods can then travel down channels as debris flows, or spread out as debris floods and sheet flows (unstable flow path flooding), where they are characterised by relatively shallow flows travelling at high velocities and carrying large amounts of sediment or debris. Often such events occur with little warning. Flood events can arrive suddenly as channelised flows, or sudden channel migration may give rise to sheet flow flooding across the entire fan. They may also occur over several hours at the height of a rainstorm.

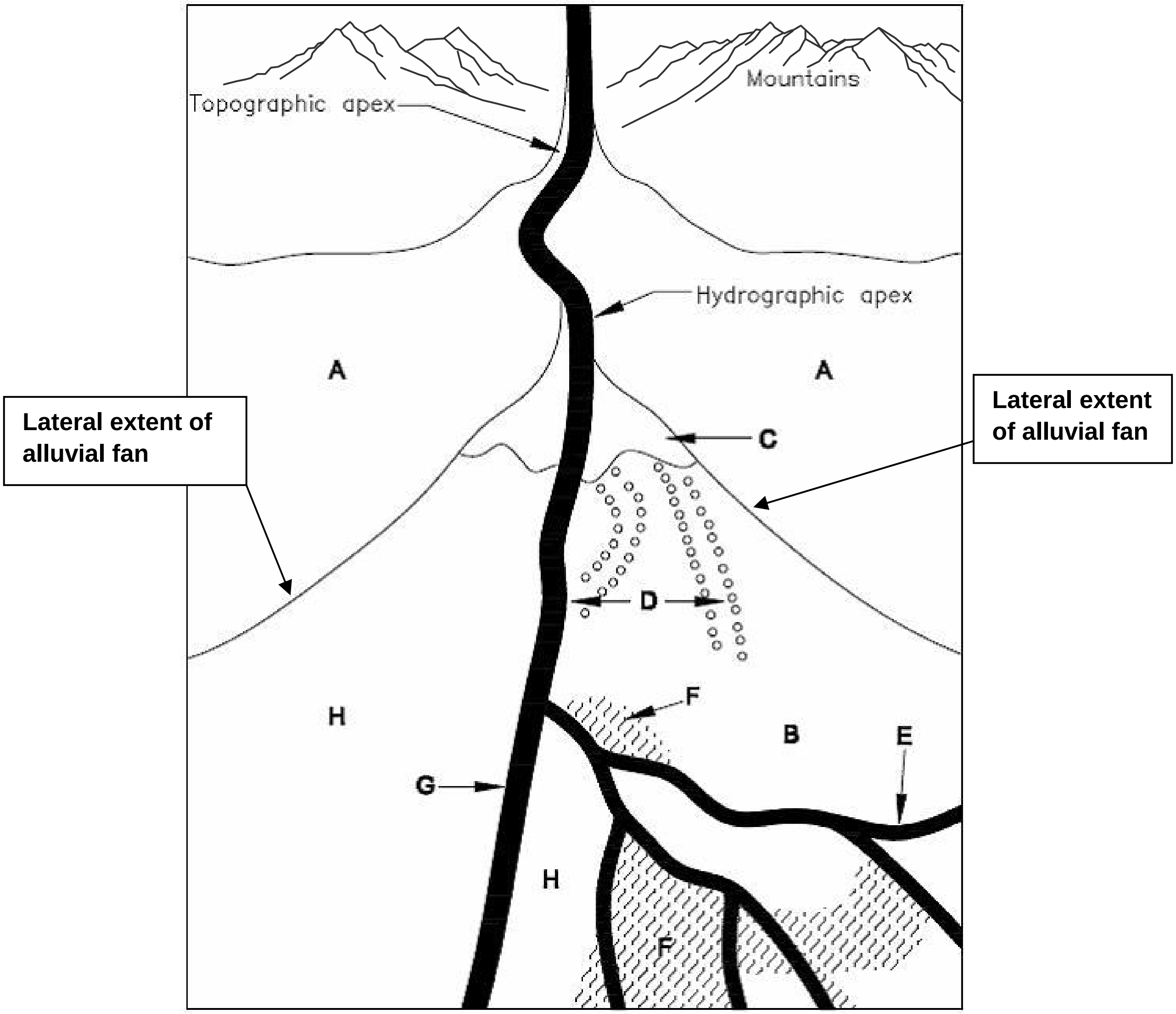

Figure 3: Main features of alluvial fan showing possible hazards. Note hazards are unpredictable, and not all fans have same hazards

A	**Old fan surface no longer affected by flows**
B	**Main fan deposition area (alluvial flows/debris flows)**
C	**Channelised zone – subject to high velocity confined channel flooding and debris flows**
D	**Abandoned channels where previous main channel used to flow**
E	**Distributary channel – channelised flooding**
F	**Areas subject to inundation, sheet flow and debris floods**
G	**Main channel – debris flows**
H	**Surface susceptible to over-bank flooding from main channel or distributary channels – deposition, debris floods, inundation**

4.1 Debris flows and debris floods

Generally the most hazardous events on alluvial fans are debris flows which have considerable destructive potential (Jakob & Hungr 2005). Debris flows involve dense viscous mixtures of water, mud, sand, gravel, with entrained boulders and, commonly, woody debris. Debris flows normally arrive at high velocity (up to 10m/s), as a semi-cohesive slurry, not unlike mixed concrete and a viscosity about 10 000 times greater than water. Individual flows may involve thousands of cubic metres of material. The flows usually move in surges, characterised by boulder fronts, either as a single pulse, or as several successive pulses separated by pulses of floodwater flow. The main surge is water-borne debris often containing gravel and large boulders and the after flow is dilute sediment-filled water such as a debris flood.

Apart from the destructive potential of the debris itself, debris flows are more dangerous than floods because they travel faster than normal flood water, they can increase their volume in transit as they absorb more flood water and entrain debris in their path. They can fill existing channels with sediment causing flood water draining from the sediment to reach areas not normally reached by flood. In the aftermath of an event, debris remains a permanent feature on the fan surface, and clean-up work usually requires major earthworks and repairs.

The amount of material carried depends on the size of the rainfall event, particularly the intensity, and the amount of available sediment in the catchment, the nature of land-use and vegetation cover, and the stream network below the hydrographic apex. The nature of the hazard can potentially be enhanced by strong earthquake shaking that causes landslides or debris avalanches in the catchment and thereby increases the available sediment. Earthquakes do not have to cause landslides to add to the sediment load. Even gentle shakes may loosen slopes and increase erosion, producing sediment.

In some cases after landslide and intense rain, channel damming can occur. If a large channel dam is able to form, a severe flood hazard can result when there is a breach and stored water and debris is released (e.g. Hancox et al. 2005).

Debris flows are also very powerful erosion forces which can sculpt out deep channels, severely scouring the sides even in bedrock. During these processes they are capable of entraining sediment from previous events and uprooting vegetation which adds to the debris load.

When movement of the main debris flow event slows and stops, and this is normally on slopes less than about 5° or 6°, a debris flood can spread downstream from the debris flow. This is a hyperconcentrated flow, more viscous than normal sediment-laden floodwater and so has a higher density. There is still potential for a debris flood to pick up and move boulders, so the problems of widespread deposition can continue as well as the inundation hazard. Thus, while the problem of the debris flow may have subsided, sediment-laden flood water still poses a hazard (see previous discussion). However, debris floods also occur (probably more commonly) without a debris flow having occurred. It is likely that debris flood deposition is the main sedimentation process on most alluvial fans.

4.2 Inundation by floodwater

Sudden channelised floods can occur because the relief of some basins is such that precipitation is transported efficiently, concentrated and then accelerated in discrete channels down slope onto the fan. The bowl shape typical of many small to medium size alluvial fan source basins causes the coordinated arrival of flow through the channelised zone of the fan, maximising the flood peak.

Where existing channels are almost imperceptible floods can spread over large areas of the fan surface as sheet flow. Sheet flow flooding occurs when a flow is no longer confined in the channels on the fan and has a tendency to spread laterally across the fan like a sheet. This can occur when flows leave existing channels or in areas where distributary channels join together causing flow to merge over broad areas. As the flow spreads out and moves towards lower relief, the velocity decreases and low bars of sand and gravel are deposited. Although the depth and velocity of the flow is low, inundation by turbid waters can still be very destructive.

4.3 Channel migration and scour

In cases where existing channels are not deeply incised, flows may be subject to lateral migration and sudden relocation during the course of a flood.

A fan is composed of loosely compacted sediment, including boulders, gravel, sand and mud. During flooding, some fans may experience rapid channel widening due to the channel bank collapsing. In other situations fans may experience rapid scouring or infilling causing the channel to change direction by tens of metres in a single flood event. Where aggradation is most intense the channel may migrate across the fan or distributary channels may develop, shifting the centre of active sedimentation across or along the fan.

The migration of flows during and after floods means that it is difficult to predict the areas on a fan that will be subject to flooding. It is difficult to assess this when reviewing previous flooding events because of the potential for flows to migrate across the fan with little warning.

4.4 Deposition and erosion episodes

It is these aspects which most distinguish the hazards posed by alluvial fans from river-flood processes. Deposition continues to take place on all active alluvial fans and as the channel migrates across the fan through a process known as avulsion, the area where deposition is occurring will also shift across the fan. It also means that over time, the topography across the fan will change permanently as more sediment is deposited or erosion takes place. Often, sediments deposited during the peak of a flood will be progressively removed by erosion over several hours or days as a flood wanes (usually indicated by channels and terraces formed in the recent deposits).

Just as material can be deposited at random, shifting channels may cause erosion of parts of previously stable parts of the fan surface. The long term changes on a fan are therefore not necessarily due just to deposition. The rates at which these processes occur will depend on the size and frequency of storm events, as well as other environmental aspects of a particular fan.

Overall deposition and erosion can be caused by an event of any size, however, the size and type of flooding which occurs depends on rainfall intensity, relief and degree to which existing channel incision has occurred across the fan surface.

4.5 Hazard relativity

Debris flows are more dangerous than floodwater because: (1) they travel faster; and (2) debris flow sediments can choke and fill up the stream channel and allow floodwater to spill out over areas previously above flood levels.

In a water-dominated flood event, the huge mass of rushing water carries fine sediment suspended in it, and coarse sediment is dragged along by the rush of water. The bulk of the sediment moves more slowly than the bulk of the water. While flood water-dominated events may cause less structural damage, they generally occur more frequently on alluvial fans than do debris flows.

Debris flows generally cause structural damage to buildings in their paths, unlike the ‘inconvenience’ that attends inundation by floodwater and associated sediment. Hence, debris flows should be considered in the same context as other structurally damaging hazards such as earthquakes and strong wind. On debris fans there is always the potential for a debris flow to occur during a flood event, so measures should be designed to cope with this possibility.

The hazard posed is ultimately dependent on the nature of the process and the return period, both of which generally require an in-depth detailed study of specific fans. In terms of destructive potential and threat to life, sheet flood hazard could be regarded as lower risk than debris flow events, but in terms of economic cost the hazards can be equivalent (over a given time period there may be more water floods to deal with). Whichever way the hazard is viewed, active alluvial fans pose an unpredictable, and ever-changing, hazard with the potential to affect life, development and infrastructure.

5 Classification of alluvial fans by process

Natural processes operating on alluvial fans are complex, and may change over time. There are numerous classification schemes within the international literature on alluvial fans, based on features such as fan slope, morphology and or sedimentation (e.g. Bull 1977, Rust & Koster 1984, Schumm et al. 1996, Rachocki & Church 1990). For this report and accompanying GIS, we focussed on trying to define the dominant processes and depositional mechanisms, because these have the greatest bearing on the hazard faced in the area.

All (active) fans are subject to flooding; it is only when heavy rainfall and/or landsliding in the catchment 'chokes' the incoming stream with sediment that debris flows and debris floods occur. In nature, most fans are, to some degree, composites of both types of events, with debris flows in the upper steeper reaches, grading through debris floods to sheet flood deposits on the fan fringes. Fans in this study have been classified (Table 2 and GIS database) based on a prediction as to areas where fans are **debris-dominated** (debris flows and debris floods are more likely to occur), as distinguished from **floodwater-dominated** areas (where water-dominated flooding is more likely). A **composite** category was applied where the processes cannot be separated due to the scale of mapping or where fans appear to be subject to both processes.

Sediment deposited on alluvial fans is derived from the upstream catchment, and carried downstream during flood events. As the channel gradient decreases down the fan, the capacity of the stream to transport its sediment decreases and the sediment is deposited, with a tendency for coarser material near the head of the fan and progressively finer material towards the toe. Deposits resulting from debris flows can be recognised because they are composed of poorly sorted mixtures of mud, gravel and boulders, and generally lack internal stratification and imbrication (alignment). Floodwater-deposited alluvial fan sediments (gravels, sand, and mud) are more evenly sorted in size, commonly stratified and imbricated.

In general the greatest risk of debris flow deposition is towards the head of the fan, whereas out towards the toe, where slopes are very gentle, debris floods and sheet flooding processes dominate. Examples in Otago and from around the world suggest that debris flows slow considerably on slopes less than about 5° or 6°, although such a definition needs to be used with caution because of the ever-changing deposition and erosion activity which takes place on the fan surface. Also, very large volume debris flows are capable of running out over low-gradient surfaces for great distances, which may be indicated by the distribution of old deposits.

Our classification of the dominant process is based on a combination of: the slope of the fan, size of the stream, distance from the topographic fan apex (note that hydrographic apex is relevant only to active fans), together with any information available as to the nature of sediments on the fan (based on local knowledge). Debris flow processes generally occur within the vicinity of the fan apex in areas where slopes are greater than 5°. Debris floods are an intermediate stage, where debris flows may spread out from channels, but still carry large amounts of fine to coarse debris. Debris-dominated fans are steeper than floodwater-dominated fans, they tend to be associated with smaller streams and are more likely to occur where catchments contain landslides, have greater changes in elevation and are subject to higher rainfall.

Table 2: Attributes describing the activity and dominant depositional processes in the GIS dataset.

PROVISIONAL ACTIVITY STATUS	DOMINANT PROCESS	CODE	MAP COLOUR
Active - flooding, deposition and/or erosion are considered possible within the next 100 years	Debris fans: debris flows and debris floods	AD	Dark Orange
	Floodwater fans: sheet floods, channel floods carrying sediment, gradational to debris floods	AF	Mid-orange
	Composite fans – debris or flood water dominated (processes cannot be separated in regional scale assessment due uncertainty in nature of process, or insufficient size of fan on maps)	AC	Yellow
Inactive - clear evidence for the absence of activity	Debris fans	ID	Dark green
	Flood water fans	IF	Mid green
	Composite fans – debris or floodwater, or uncertain	IC	Light green

6 Otago examples

The Otago region in the South Island of New Zealand has a diversity of alluvial fan settings, from linear mountain fronts such as the north-west and north-east trending ranges of Central Otago, to low-gradient major valleys like the Waitaki valley and the Taieri basin. This diversity, together with variations in climate, rates and styles of tectonism, source area (catchment) rock-types, vegetation, land use, geology and topography, means there is range of mechanisms by which fans form. Most of the fans identified in Otago are not the classical fan shape but are formed from multiple sources on one side of a valley, or are coalesced from both sides. In other cases they are channelised or confined along valley systems, or built out as small fans over river terraces to form complex fans. In this study, alluvial fans have been classified as to whether the processes that built the alluvial fans are still active or inactive; and whether the fan is built predominantly from processes that are debris-dominated or floodwater-dominated. This section of the report illustrates some representative examples of alluvial fans and alluvial fan processes in Otago. A comparison between these fans, together with maps generated at 1:50,000 scale from the GIS dataset, are presented in Appendix 2 at the rear of this report.

Debris fans are predominant in the Alpine regions of Otago, but also occur along the steeper slopes beneath many Central Otago ranges, and in the landslide-prone gullies of coastal Otago, such as on Otago Peninsula. Alpine catchments are steeper and have greater change in elevation than the coastal regions. Nearly all alpine catchments are within schist rocks, and many contain extensive areas that are subject to slope instability. Unstable schist slopes are easily eroded and produce sediment that ranges from fine-grained material through to large boulders. Debris flows and floods are the dominant process, but most fans also have sheet flood-prone lower reaches.

In the alpine region of the Queenstown Lakes District, high-intensity rainfall is more common and flood events more frequent (Tait et al. 2001). Debris flows in this area have recently been responsible for loss of life (e.g. McSaveney & Glassey 2002) as well as causing widespread local damage (e.g. McSaveney 1995; McSaveney & Davies 2005). In the Central Otago examples, although the region is relatively dry in terms of annual precipitation it does experience intense localised rainfall events or cloud bursts (locally known as 'thunder plumps') (Tait et al. 2001). The streams that feed these fans may be relatively small, but intense rainfalls have triggered some substantial flood events carrying large amounts of sediment.

Floodwater-dominated fans are mostly found in coastal and North Otago, and over much of Central Otago. They tend to be associated with catchments in relatively low altitude regions with shallow gradients through the channelised and braided zones. Catchment geology is more varied east of the Taieri and in North Otago, where Tertiary and Cretaceous deposits (between about 100 million and 2 million years old) including mudstone, limestone, and sandstone are common (Forsyth 2001). Loess (wind-deposited silt and fine sand, mobilised from river floodplains) is also abundant in coastal Otago. Slopes within catchments and on fans are shallower, so flood flow velocities are lower and fan shape is less pronounced with long run outs which may merge almost imperceptible with valley floors. Fine grained sediment can be carried long distances and deposited over large areas to merge into river and stream terraces. Debris flows, if they occur, are generally confined to the uppermost parts of these fans.

Pipson Creek fan

The Pipson Creek fan lies at the western flank of the McKerrow Range just north of Makarora township (Figures 4, 5). It is one of the most spectacular examples of an active debris fan in Otago and is currently the subject of studies and risk assessments by both the Otago Regional Council and Transit NZ.

Figure 4: Photograph showing debris flow clean up work on SH6 at Pipson Creek. Photograph taken 10th March 2004.

The catchment rises from 400 m to 2000 m covering an area of approximately 3.5 km^2, the majority of which is an alpine environment. Active landslides and rockfalls occur on the valley sides in the lower part of the catchment. The combination of unstable slopes, steep topography and high rainfall contribute to debris flow activity with an unusually high frequency. Pipson Creek has formed a symmetrical semicircular fan with a stream which aggrades and degrades at varying rates. The distal portions of the fan are actively eroded by the Makarora River. Debris flow and debris flood deposits dominate the upper parts of the fan, with downstream run-out flood zones such as Millionaires Flat typified by silty sheet flood deposits. Deposits from larger debris flows reach right out to the Makarora River.

The beech forest covering much of the braided zone and toe zone of the fan consists of trees of similar age suggesting that they grew together after the previous forest was destroyed. This may have been the result of a historic debris flow of considerable size (Petellar et al. 2007), or could reflect a period of intense flow activity, maybe triggered by landsliding following a major earthquake, or simply reflect a succession of high-intensity rainstorms.

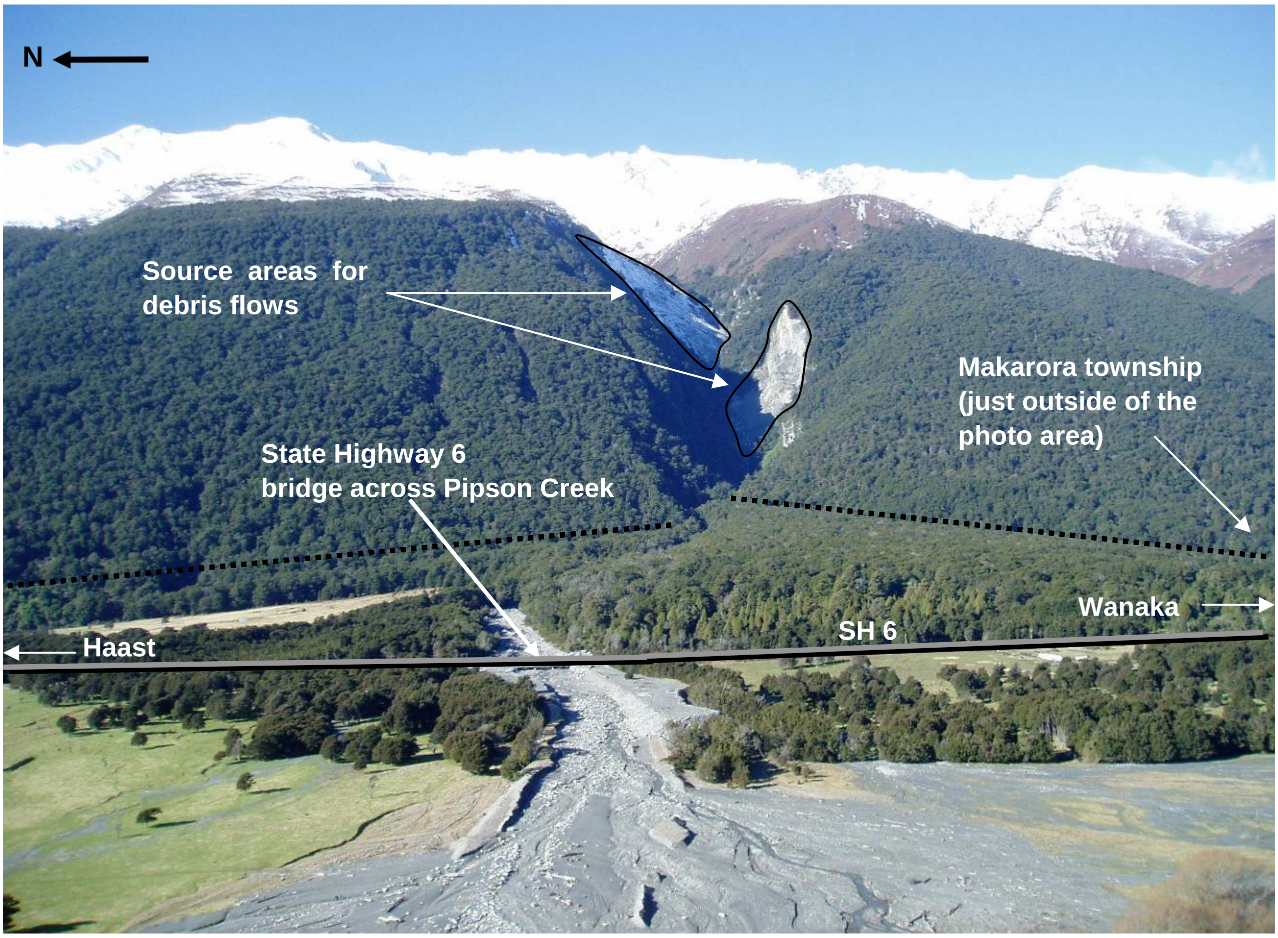

Figure 5: Photograph looking southeast across the Pipson Creek fan, 21 April 2005

In terms of present development and infrastructure, the Pipson Creek fan is a major concern. Makarora township and airstrip lie on the south side of the fan, and the fan is crossed by State Highway 6, the only route to the West Coast from Otago. The fan has been differentiated into two areas in the accompanying GIS dataset, with one area characterised by active debris-dominated processes at the head of the fan, and an area of floodwater-dominated processes at the toe (see map Appendix 2).

North Roxburgh fans

Coalesced alluvial fan complexes are developed all along the base of the Old Man Range, from Roxburgh northwards (Figure 6). They are formed by a series of streams which appear small and insignificant under normal flow conditions. Mitchell Creek 1km north of Roxburgh, for example, is less than a metre wide under normal flow and is incised several metres into the fan surface (see Figure 7A). However, during floods it is capable of carrying debris that includes large boulders (Figure 7B). Development on these fans includes houses, farm buildings, an orchard, and it is crossed by State Highway 8.

Figure 6: Photograph of alluvial fans developed beside the Clutha River at the foot of the Old Man Range. Roxburgh has been developed on one of these fans. (Photo 19 Dec 1981).

Figure 7A: Mitchell Creek under normal flow conditions.

Figure 7B: Large boulders transported and deposited by Mitchell Creek during a flood in the 1970s.

Photographs taken 21 March 2007

The fans slope between 7° and 20°. Their catchment areas rise from 160 m at the valley floor to more than 1000 m elevation on the Old Man Range, and are vegetated with tussock, matagouri and briar. Large areas of these slopes have been affected by landsliding. The landslide debris includes large schist blocks, which according to locals may have been dislodged by the streams during floods (which erode the toe of the landslide debris), and deposited on the fans by debris flows and debris floods. Stream avulsion has occurred from time to time during high-intensity localised rainfall events in the catchment. The Clutha River removes material from the toe of some of the fans, which helps to maintain fan gradient and channel flow. The fan complex is classified as active, composite debris- and floodwater-dominated, fan in the accompanying GIS (see also Appendix maps).

According to locals, sheet floods also occurred on the fan during storms in the 1970s and early 1980s. Since then, some engineering mitigation works have been carried out. The works involved enlarging the stream channels to contain more flood water, and thus reduce the risk of sheet flooding. More recently, willow trees have been removed from some of the stream beds and banks to maintain the channel and reduce the risk of trees collapsing into and being carried by the stream. Such woody debris can exacerbate flooding by forming dams or blocking culverts.

Also, a subdivision called Quail Haven has recently been constructed on this alluvial fan complex. As part of the planning process Opus undertook a site specific assessment to investigate geotechnical and hydrological issues at this site (Harwood, 2004). Three creeks were identified as flowing onto the fan surface in the vicinity of the subdivision. Flooding and debris were identified as hazards to the subdivision with three creeks (Mitchell Creek, Berry Creek, and Quail Creek) identified as problematic. In order to mitigate the flooding hazard posed to the subdivision a number of recommendations were made in the Opus report, and these now form part of the conditions for the resource consent for the Quail Haven subdivision. Included in these recommendations were deflection berms, increased culvert sizes, enlarged channels lined with rocks, and a programme of regular maintenance work to enhance the debris-catching ability of the collector drains.

Stoney Creek fan

The Stoney Creek fan lies west of Wanaka township, below Mt Alpha (Figure 8). Its 1.7 km^2 catchment rises from 400 m to 1300 m, and about three-quarters of this has been affected by landsliding; while the remainder is either *in-situ* schist or schist colluvium.

Stoney Creek transports fine-grained material during smaller floods but during large floods debris flows containing coarse gravel and large boulders up to a couple of metres in diameter, are commonly sourced from the catchment. The stream currently occupies the central area of the fan and although some reaches are incised by up to 2 m, stream avulsion is frequent.

The drainage divide between Stoney Creek and neighbouring Waterfall Creek is not well defined near the range crest. There is potential for a further 0.3 km^2 of the adjacent Waterfall Creek catchment to be captured, as the landslides move and change the drainage pattern, which would increase the amount of floodwater discharging across the Stoney Creek fan.

Until recently the Stoney Creek was farmland, but subdivisions have now been established. Two severe rainstorm events in 1999 and 2004 caused flood damage. In both cases the stream left its channel and deposited debris flow and debris flood material across Studholme Rd and Mt Aspiring Rd. The storm in 2004 was assessed as being smaller than a 1 in 50 year event, and similar (or larger) floods are expected to occur in future. Stoney Creek is classified as an active, composite debris- and floodwater-dominated fan. Debris traps, tree planting, flood protection works, and an overflow channel have now been put in place, which aim to mitigate the hazard to properties in lower Stoney Creek by increasing the capacity of the channel and reducing the risk of the channel becoming blocked with sediment.

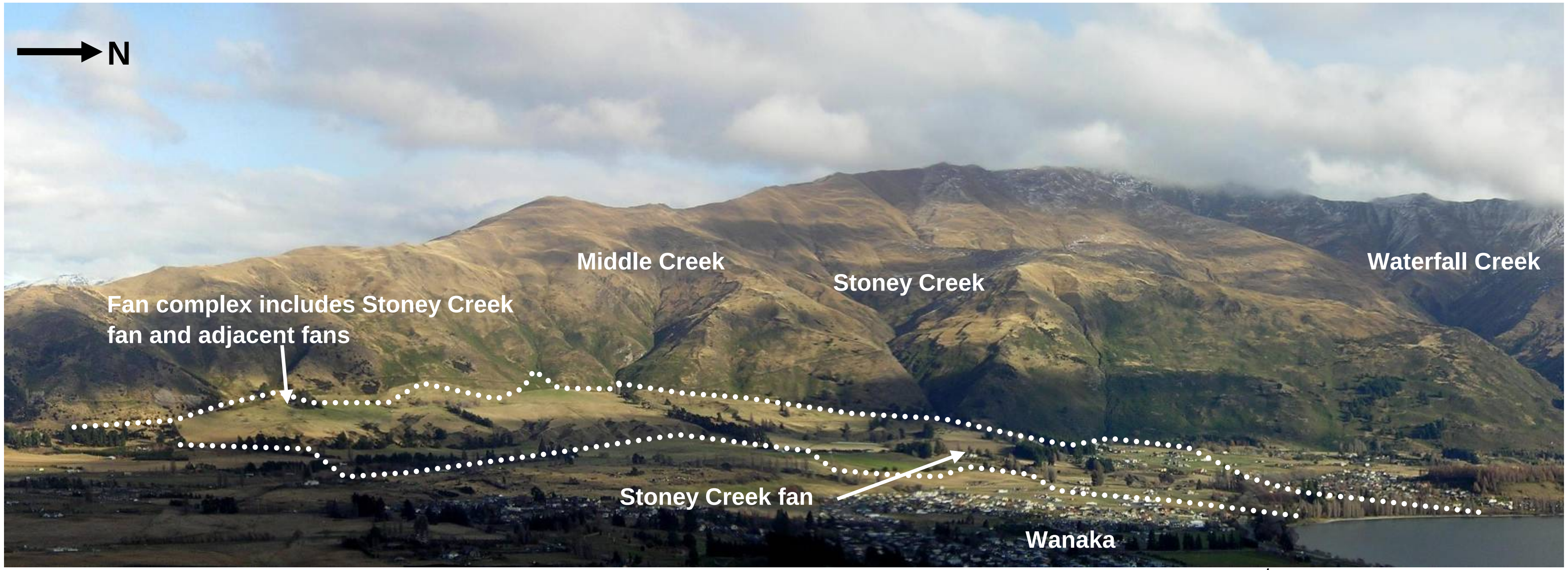

Figure 8: Photograph showing Stoney Creek alluvial fan with Lake Wanaka in the foreground. 1st July 2006

Mill Flat fan

The Mill Flat fan is located at Paradise, 17 km north of Glenorchy. The catchment is approximately 4 km^2, ranging from 460 to 1840 m, composed of *in-situ* schist and scree slopes immediately below the ridge crest (Figure 9). At the fan head a confined channel slopes between 7° and 16° and the area is covered in beech forest at least 100 years old. The toe of the fan has a gradient of less than 5°, is in pasture and is actively eroded by the Dart River. Most of the material on the fan is fine to coarse schist gravel, but there are also boulders up to 2 m in diameter, and woody debris (entire trees) deposited across the middle and upper reaches of the fan. A number of abandoned channels can be seen in the bush across the fan and attest to its activity (Figure 10). The fan has been differentiated in the accompanying GIS into active debris-dominated and active floodwater-dominated areas.

Figure 9: Photograph showing Mill Flat fan, 22nd March 2007

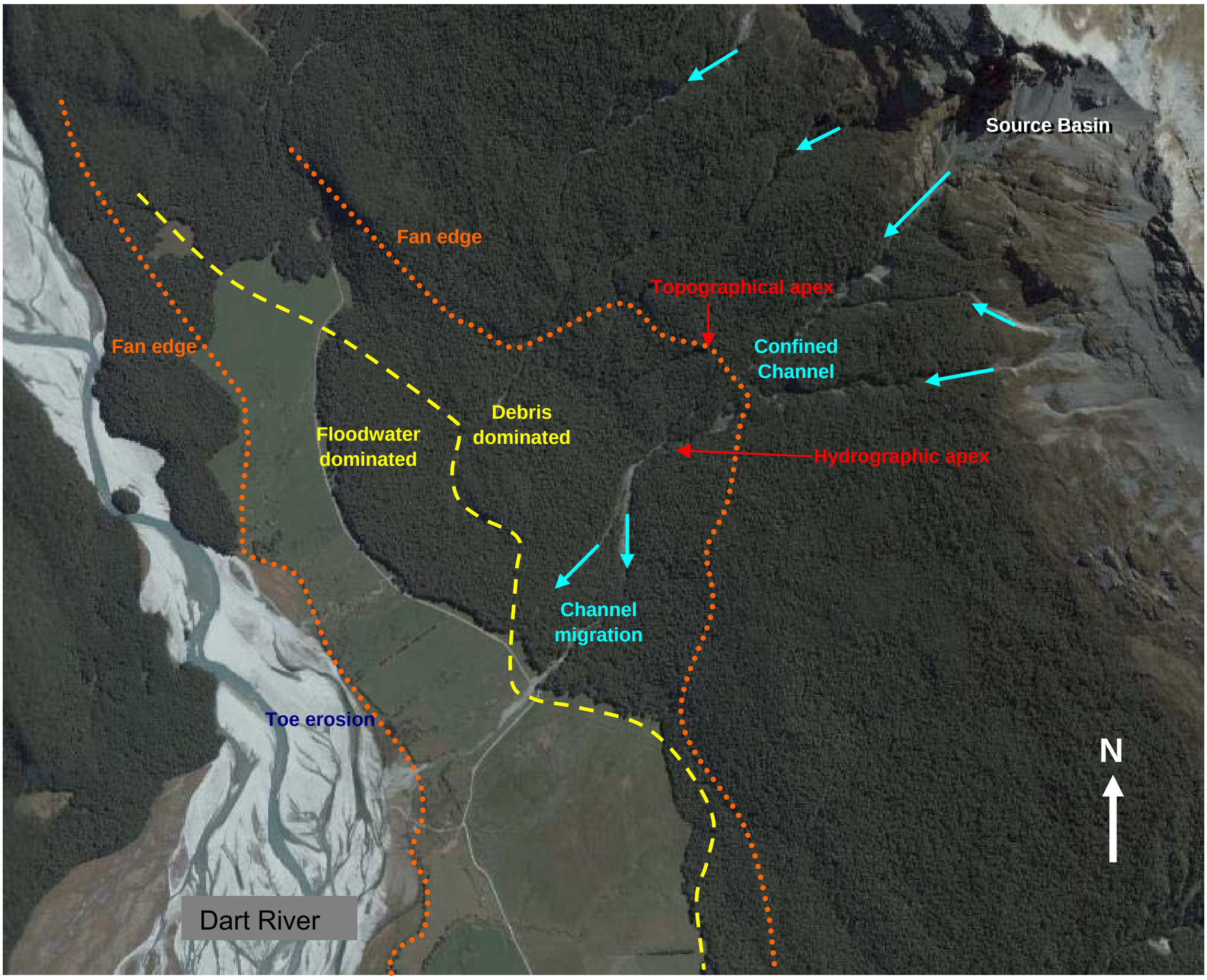

Figure 10 – Aerial photograph of Mill Flat fan near Paradise

Milton fan

Immediately east of Milton the Narrowdale Stream drains the hills of the Otago Coast Forest and flows out onto the Tokomairiro Plain (Figure 11). The Milton fan is a broad fan with incised channels formed across the plain by Narrowdale Stream. Its catchment has low to moderate relief and rises in elevation from 100 m to 400 m, with an area of approximately 20 km^2 . Rock formations in the catchment are low grade Otago Schist and Henley Breccia with no known landslides of any significance.

The fan has an area of approximately 11km^2 and is relatively a young geological feature, probably forming within the past 24,000 years (Bishop 1994, Bishop & Turnbull 1996). The upper reaches are gently sloping (10°) and the lower part of the fan is much shallower (<5°) and becomes even more gentle towards the toe of the fan. Due to the incised channels much of this fan is thought to be inactive with flooding activity thought to only occur in the vicinity of the main stream channels.

Infrastructure in the area of the fan considered to be active includes 20 farm buildings and dwellings and some sealed and unsealed roads. In the areas regarded as inactive there is State Highway 1, areas of Milton township and approximately 300 other farm buildings and dwellings.

The degree of soil development on fans indicates in broad terms the time since the fan surfaces were last active (e.g. growOtago 2004). Much of this fan surface has well developed soils, supporting the conclusion that large areas of this fan are inactive. While the fan is distinct as a geomorphological feature, and therefore an alluvial fan related hazard thought to exist, relatively little is known about the long-term flooding activity and formation processes. It exemplifies a fan where it is not entirely clear where the flooding hazard has flow path uncertainty (i.e. alluvial fan flooding) compared with flow path predictability (normal stream/river flooding). Further work and site specific investigations are necessary to quantify the potential hazard.

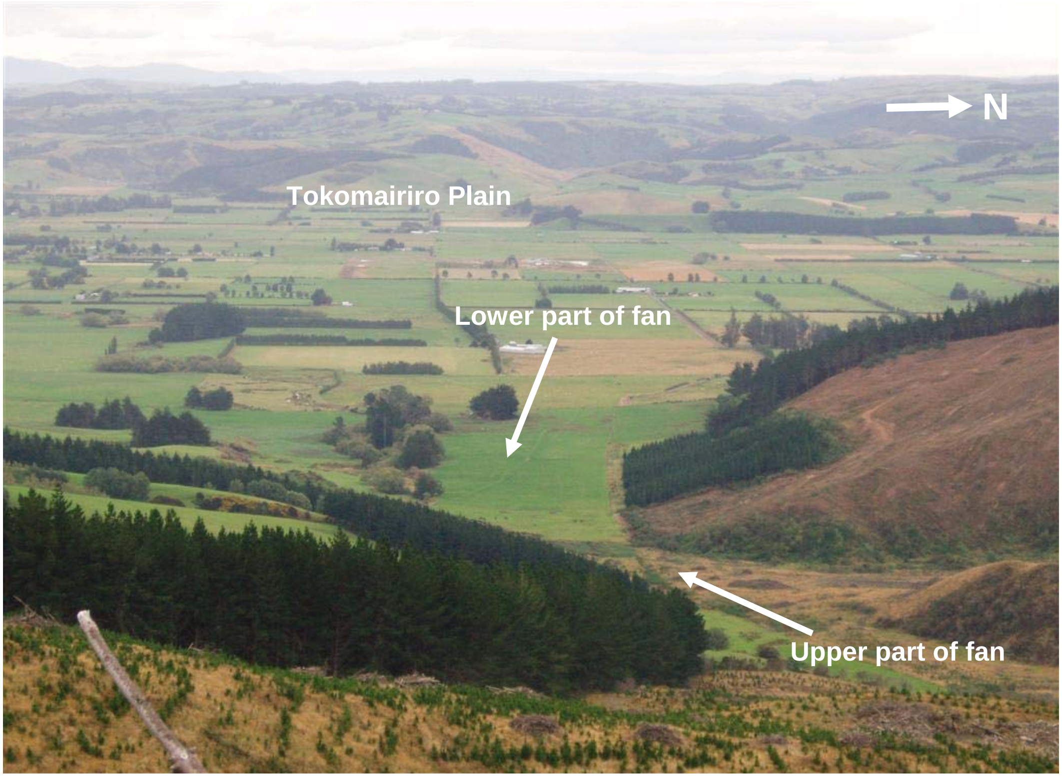

Figure 11: Photograph looking down the Milton fan towards the Tokomairiro Plain. Note the subdued nature of the upper and lower reaches of the fan. Photograph taken 21st March 2007.

Pukeuri fan complex

The Pukeuri fan complex lies north of Oamaru and comprises a series of low angle fans that have coalesced along the southwestern margin of the river terraces that form the Lower Waitaki Plain (Figure 12). These fans lie along the edge of an inactive fault scarp and all are young features. The fan complex has a collective area of approximately 31km^2 and is composed largely of sand, silt and some clay. Individual fans are subtle geomorphological features, but clearly recognised in the field or in stereo aerial photographs.

The catchment for this fan complex consists of short gullies draining the North Otago downlands, whose geology comprises Cretaceous and Tertiary sedimentary rocks, blanketed by thick deposits of silty and clayey wind-blown loess. Erosion of the loess is an important source of sediment for the fan complex, and erosion of the sedimentary rocks provides additional fine-grained sediments for the fan complex. Shallow landslides and tunnel gullying of loess is common in these catchments.

These fans are active features that are floodwater-dominated, although flooding evidence is quickly covered up due to the growth of vegetation and farming activities. It is likely that only parts of the fans remain active and this is displayed by the presence of both well developed and recent soils found on the fan surface (growOtago 2004).

The fan complex is crossed by State Highway 1, State Highway 83 and numerous sealed and unsealed roads. Additionally some areas of northern Oamaru and approximately 300 farm building and dwellings are located on the fan complex. However, despite the subtle fan morphology that can be easily identified and the development that has occurred on these fans, little is known about the long-term fan history other than the occasional rainstorm event.

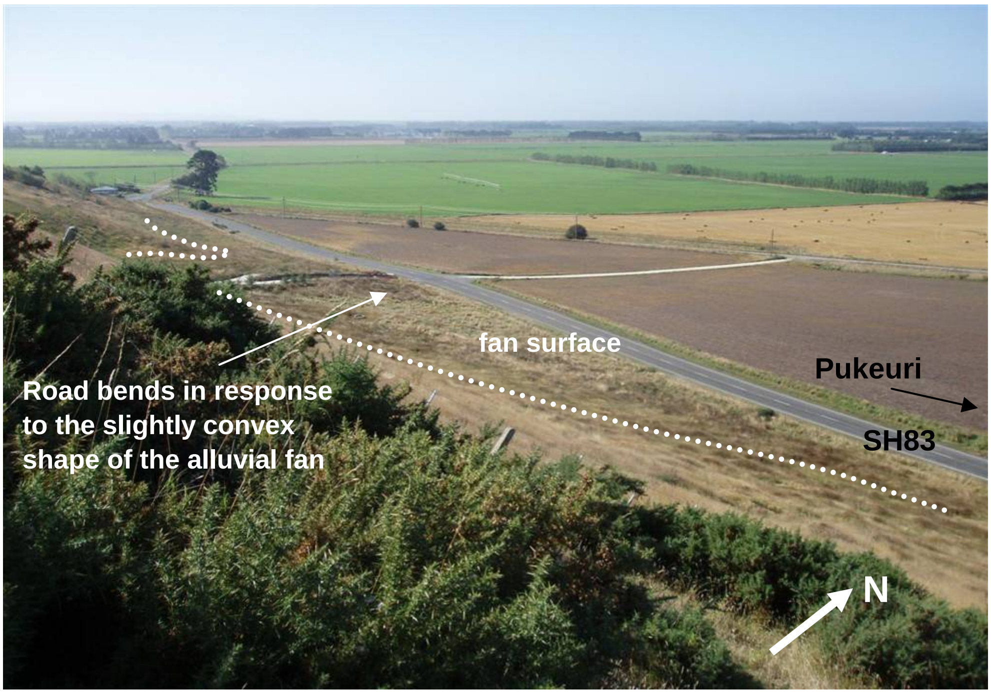

Figure 12: One of the individual fans that make up the Pukeuri fan complex north of Oamaru. The morphological features of these fans is quite subtle, the fan surface above is only very slightly convex and has a very low gradient. Photograph taken, 23rd March 2007

Waikerikeri fan complex

The Waikerikeri fan complex extends out from the south-east foot of the Dunstan Mountains (Figure 13), and is part of an even larger set of coalesced fans along the entire western edge of Manuherikea Valley. The fan complex contains a range of very old, old, medium, and young fan surfaces. Most of the older fan surfaces are now abandoned above active younger channels. The history of the fan over the past 350,000 years has been complicated by tectonic deformation associated with the Dunstan Fault

The Waikerikeri fan complex is fed by second and third order streams which drain a 26 km^2 area of the Dunstan Mountains. This catchment ranges in height between 1600m and 350m and contains numerous landslides in schist rock.

The fan surface has several components. The Waikerikeri valley forms the main active fan channel and is incised into an older fan surface. When this channel reaches Muttontown on the Clyde flats it spreads out into a classical fan morphology, however, at this point the main channel is still incised into the fan. The hazard arises from the presence of small first order streams that have developed across the lower regions of the fan. These are young features which have the potential for continued alluvial fan activity.

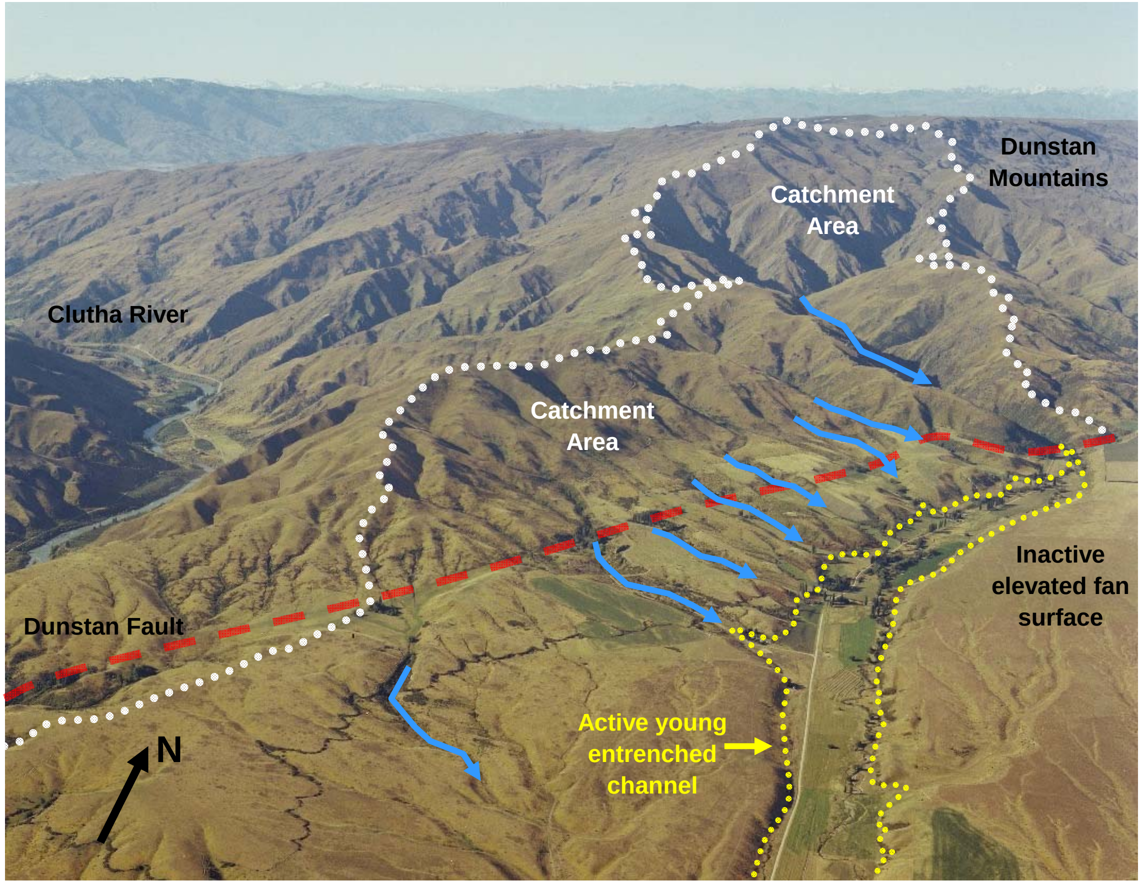

Figure 13: The upper area of the Waikerikeri fan complex along the southeast foot of the Dunstan Mountains. The Dunstan Fault can be seen in the foreground cutting across and offsetting an old surface of the fan. The Clutha River (now Lake Dunstan) is on the left. Photograph, D.L. Homer 3954/16, Jan 1983.

7 Identifying and mapping of alluvial fans

7.1 Methods

In their simplest form alluvial fans are easily recognisable as conical or fan shaped accumulations of sediment defined by morphology and surface topography. Fans are typically identified on a regional scale by using topographic maps and aerial photographs. Fans typically form where there is a topographical break and many appear on topographic maps as a triangular shape with radiating contours. Topographic maps and digital elevation models are useful for defining slope and catchment of fans (Figure 14).

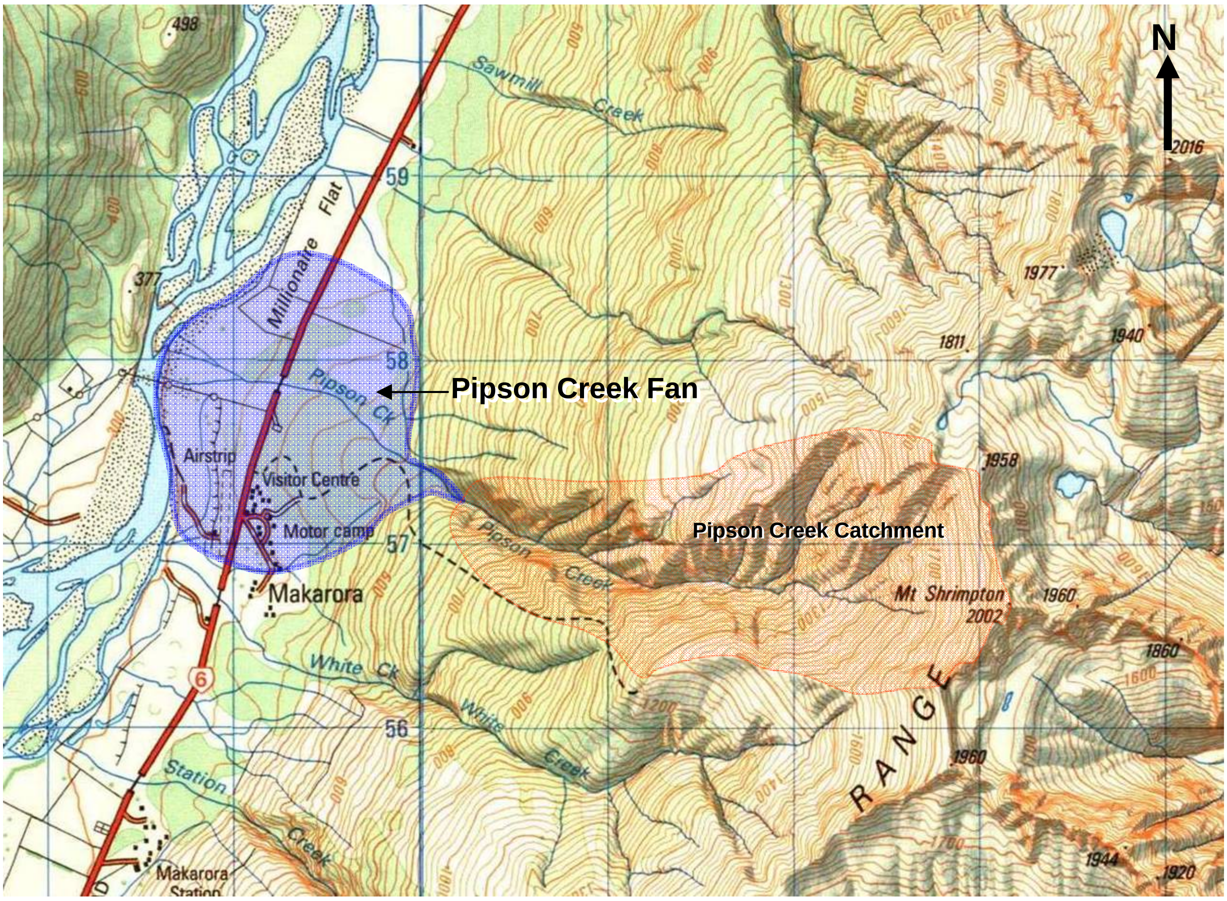

Figure 14: Topographic Map (expanded from original 1:50,000 scale, NZMS 260 series) showing the identification of the Pipson Creek fan at Makarora

Aerial photographs commonly show more subtle features such as active channels and subtle changes in relief (seen using stereo pairs) that are not always evident on topographic maps (e.g. Figure 10). Lines can be used to "map" or define the area of the alluvial fan on a topographic map. Their accuracy of fan definition depends on whether the map is of local (e.g. 1:1000-1:10,000) or regional (1:50,000 to 1:250,000) scale. Difficulties may arise in fan identification when transported sediment extends down-valley over large but narrow areas, or where fans accumulate from several sources and the fan shapes start to merge laterally. The distinction between areas with flow path uncertainty vs flow path predictability is not always clear.

The processes responsible for fan building can be assessed remotely from changes in slope, size of streams (stream-order), the shape and nature of channels and surface deposits. However, it takes field observations of distribution of sediment, and the size of the sediment, across individual fans for confirmation of processes, and identification of hazards which may be present on fans. Fine grained sediment on gently sloping terrain indicates those parts of the fan where water inundation and sedimentation from sheet floods dominate, with only occasional risk of debris flows and floods after extreme events. On steeper terrain with a greater proportion of coarser grained debris (gravel and boulders) with or without trees a higher likelihood of debris flows and debris floods can be inferred. On lower fan slopes, evidence for debris flows may be buried under fine grained material. A common method of assessing the degree of activity on fans is to look at soil development, and the degree to which paleosols (old surficial soil layers) have been buried (e.g. growOtago 2004).

The geological setting of fans influences sedimentary content and fan size. Fans sourced from greywacke catchments may be debris-flow or debris-flood dominated, but the debris is c.50-200 mm clasts, with a few larger boulders. While rock hardness is relevant, rock fracture spacing in the in-situ rock mass, and the presence of landsliding are more influential factors in determining the clast size in debris flows. Expert and local knowledge of geology, landforms and history of events in the area is required to assess possible risks in this regard to the nature of debris.

7.2 The GIS mapping of this study

Alluvial fans in Otago have been previously identified by numerous geological and geomorphological maps. As part of this project, the location and characteristics of Otago's alluvial fans have been documented in a Geographic Information System (GIS) database developed by GNS Science. This database has been compiled from a variety of studies carried out since the early 1990's, with some limited re-evaluation for this project, and is based on plotting alluvial fans on 1:50,000 topographic base maps. It includes mostly published and some unpublished observations made at either 1:50 000 or 1:250,000 scale for the QMAP (**Q**uarter-million-scale **MAP**; Nathan 1993, GNS 2007) Geological Map of New Zealand completed by GNS Science, or other more-detailed local studies.

Compilation of previous mapping and re-evaluation has identified 2197 alluvial fans, including coalesced fan complexes or parts of fans, which make up 1970 km^2 or approximately 6% of the Otago land area. They range from small (< 1 km^2) fans associated with individual streams, to large (max 47 km^2) fan complexes that are formed by interaction of multiple streams. We are confident that all alluvial fans larger than 0.5 km^2 have been identified. Although numerous small fans have been included in the dataset, it is not possible to record all of the smallest fans or active versus inactive areas in a regional-scale study. Due to the scale of mapping, features smaller than 0.1 km^2 may have been left out of the dataset and would need to be recorded by more detailed investigations.

The alluvial fan GIS database contains details (data attributes) outlining the **source** of each fan area defined, including the scale at which the information was derived and captured, and a comment on how the accuracy of lines in the dataset translates to the precision on the ground (see Table 3).

Table 3: Outline of attributes describing of the sources of fan information in the GIS dataset.

SOURCE	DATA ORIGIN (see reference list)	SCALE	ACCURACY
GNS_QMAP18_2000_Turnbull	Turnbull (2000)	250000	±200 m
GNS_QMAP19_2001_Forsyth	Forsyth (2001)	250000	±200 m
GNS_QMAP20_2003_Turnbull Allibone	Turnbull & Allibone (2003)	250000	±200 m
GNS_QMAP21_1996_Bishop Turnbull	Bishop & Turnbull (1996)	250000	±200 m
GNS_SciRep_94/39_Barrell et al.	Barrell et al. (1994)	50000	±100 m
GNS_SciRep_98/11_Barrell et al.	Barrell et al. (1998)	50000	±100 m
GNS_SciRep_99/15_Barrell et al.	Barrell et al. (1999)	50000	±100 m
GNS_new_2006_QMAP & Commercial	New information derived by combining observations from maps compiled for published QMAPs, updated with observations for unpublished commercial client contracts.	50000	±100 m
GNS_new_2007_QMAP and Qtown map	New information derived by combining observations from Turnbull (2000) with Barrell et al (1994).	50000	±100 m
GNS_new_2007_QMAP record sheet	New information extracted from maps (record sheets) compiled for published QMAPs	50000	±100 m
GNS_new_2007_QMAP14_unpub	New information extracted from maps (record sheets) compiled for QMAP Haast (in preparation)	50000	±100 m

8 Fan evolution

Alluvial fans are constantly evolving through geological (and historical) time. They are formed and affected by a number of inter-related processes which change over time and cause the fans to evolve. Tectonic activity (faulting, folding and uplift) creates, alters or maintains the relief necessary for alluvial fans to form, but although this activity operates on a geological timescale of thousands to millions of years, it is a major factor in understanding fan evolution.

The prime factors involved in fan construction and evolution are:

1. topographic (tectonic) setting, with steeper hills or mountains above an apex point which marks the change in gradient onto a shallower fan deposition zone
2. the size of the catchment above the apex, affecting run-off rates and volumes
3. channel avulsion, giving rise to flow path uncertainty
4. climate, especially rainfall intensity and storm event frequency
5. the geology of the catchment (the sediment source) – including erodability, rock hardness and defects, presence of landslides etc
6. the vegetation within a catchment can affect rainfall runoff rates, which in turn influences erosion potential in susceptible unconsolidated deposits.

Long-term climate change over the past 30,000 years is a fundamental driving force behind fan aggradation and entrenchment. In the alpine areas of Otago, glacial troughs left after ice retreat at the end of the last ice age have since been infilled within sediment and provide accumulation areas for alluvial fan formation. The adjacent mountains contain the catchments from which streams emerge, and source areas for fan sediment. In many, glacial retreat has also induced large-scale (tens of km^2 or greater) landsliding in these catchments. Many alpine valleys have merged fan aprons. However, short-term climate change such as the present “global warming” probably has only secondary influence on fan construction and evolution, if any influence at all (see section below). Other secondary factors include erosion of the fan toe by rivers, seas or lakes; and sediment availability.

Fan construction involves two main processes; (i) sediment deposition from debris flows, debris floods and sheet floods; and (ii) stream avulsion. Sediment is deposited as the transporting currents lose velocity at lower gradients; the locus of deposition changes as stream channels migrate back and forth across the fan. As one part of the fan gains height from aggradation the stream will shift across the fan and start depositing material elsewhere on the fan.

Avulsion is the lateral displacement of the stream from its main course across a fan or floodplain. Channels may shift several metres laterally during a single event, or a completely new channel may develop. Avulsion is more likely to occur on the outer fan fringes of a fan where the channels are less deeply incised. Avulsion occurs during flood events when:

- the channels can no longer contain the volume of flood water, which overtops banks and sheet flow occurs
- the channel moves sideways or breaks out due to rapid scouring of the banks
- distributary channels develop due to intense aggradation
- debris flow deposits redirect the flow to other channels or parts of the fan due to the rapid aggradation that has occurred in the channel originally occupied by the flow.

9 Consequences of alluvial fan processes on existing settlements and lifelines

Alluvial fans can form attractive elevated and scenic places for development with good drainage characteristics. However, where there are existing settlements and lifelines on fans or where new development is proposed there can be risk of inundation and sedimentation damage from debris flow, channel migration, sheet flow, sudden channelised flooding, and sudden erosion.

Unlike river flooding the problems come from not only water inundation but also the sedimentation component. Sedimentation has an immediate effect during the actual event, but also has long term effects by permanently changing the shape, features and elevations of the fan. This means that the nature of the hazard can actually change with time. An area subject to existing channel or migratory channel problems today could be an area subject to severe sheet flow risk in the future.

As previously discussed, one of the greatest hazards is debris flows, which have the potential for transporting and depositing large amounts of debris, including boulders. The flow from such events can create substantial impact force threatening life, and causing damage to infrastructure and buildings. There will also be significant clean up cost in the aftermath of such an event. Alternatively, damage to infrastructure may occur from the flow of turbid, sediment laden waters and deposition when sudden channelised flooding, channel migration or sheet flows occur.

9.1 Sudden channelised flow

Sudden channelised flooding is a particular problem on alluvial fans because the bowl shape of the source basins causes the coordinated arrival of flow maximising the flood peak. Essentially these are short lived floods with a short time to flood peak. This means there is little warning of the flood arrival after intense rain.

In deeply incised channels some level of predictability maybe possible relative to the flow volume based on catchment size and hydraulic characteristics. However during intense rain events, severe erosion can occur in the catchment and this will increase the sediment load entrained in the flow. The consequences of sudden channelised floods in existing channels can be drainage course and culvert blocking, or bridge waterway blocking caused by excessive debris accumulation. In extreme cases the infrastructure can be damaged by the sudden arrival of the flow in excess of the design. Additional maintenance is needed to clear such structures and this has to be carried out promptly in case a second flow arrives when the consequences could be even more severe. Second waves can mean overtopping or channel migration, discussed in the next section.

9.2 Channel migration

Channel migration can occur in a variety of ways and rates. Causes can be sudden infilling re-directing flow, sudden scour and slumping in existing channels, or a more gradual process of erosion leading to a trend of movement which may be accelerated in flood.

Deposition, erosion and scour can cause the channel to change direction without warning and in extreme cases by up to tens of metres in a single flood event. Migration may also occur much more slowly where channel aggradation causes the formation of completely new channels. This makes it difficult to predict the areas on a fan at risk and needs to be viewed with caution when for example trying to determine 'safe' areas of a fan for hazard zoning purposes.

One of the greatest risks here is to existing buildings which may not have been affected since they were built. Flows may remain within certain channels for long periods, until there is a severe event, possibly unprecedented; the channel may infill and change direction onto or towards the property. The ensuing deluge of flood water and or sediment clearly presents a hazard, potentially causing damage to the building, and in extreme cases destruction.

Channel migration is also a problem for roads and highways. Existing channels maybe culverted or bridged, but again, a sudden shift will lead to inundation of other parts of the road surface by either water or debris causing surface damage, obstructions on the road capable of causing traffic accidents (especially at night on quiet routes) or loss of traction and aqua-plaining.

Channel migration on fans, across areas not recently affected, must always be considered as a possibility, unless natural changes (for example very deep entrenchment) or engineering works are constructed to control stream flows. However, such issues cannot be identified or addressed at a regional scale and generally require site specific investigations.

9.3 Sheet flow and debris floods

Where sheet flow of floodwater occurs, the depth and velocity maybe lower than inside existing or new channels but the associated inundation by turbid waters can still be destructive. Water-dominated sheet floods are transitional to debris floods, in which sediment is deposited across areas which are grazed for instance, over road surfaces or around developed sections.

Other types of infrastructure which can be affected by any of the above include power lines and even underground services. Power lines are vulnerable to impact forces on the poles and in extreme cases erosion may cause underground services to become damaged.

A further difficulty is that after an event emergency response may be hampered because the lifelines to a settlement including power and road access may be cut. When this happens reinstatement will be a slow process. In remote areas of Otago the disruptions may go unnoticed or unreported for several hours further delaying the response and increasing the risk to motorists and residents. Where damage has occurred to a road, bridge, or culvert, the road may be impassable and therefore dangerous, especially for motorists travelling at night.

Services may need to be repaired and restored. Roads need to be cleared of sediment and damage needs to be repaired. This may include repairing the base course where erosion has occurred, resurfacing the road, replacing culverts, and repairing bridges. Power lines and underground services will also need to be repaired or replaced.

Unlike river or lake flooding events, sheet and debris floods on alluvial fans are commonly accompanied by large amounts of debris. During an alluvial fan event in the 1990s a house near Roxburgh became inundated; when the flood water receded the house was filled with rocks up to the level of the window sills (see also Paekakariki motels, Hancox 2003). If large quantities of debris have to be removed, remediation can become very expensive. Not only is there earthworks involved in removing the material but a site has to be found where this material can be dumped. This has been a particular problem at Pipson Creek, near Makarora on State Highway 8, where after debris floods on two occasions in recent years several thousand cubic metres of debris, has had to be cleared from the state highway and channels upstream and downstream and carted to dump site after clean up. This causes severe disruption, loss of service and unexpected maintenance costs for regulatory authorities such as Transit NZ.

10 Possible mitigation approaches for alluvial fan hazards

The first step in the mitigation of alluvial fan hazards, and one which this study addresses, is to identify the location of alluvial fans and disseminate this knowledge to the regional and district councils. Presently one of the difficult challenges is how to increase public awareness of the hazards.

A provisional indication of where alluvial fan-related hazards may exist is provided by this study, together with a prediction as to the nature of these hazards. More detailed hazard assessments, with site specific investigations and fieldwork, are required to provide qualitative hazard evaluation defining the extent to which events can be expected, for example, during the next 100 years at individual locations. Site investigations will be essential to confirm which parts of a particular alluvial fan are subject to, or free from, hazard. Strategies for evaluating the risk and mitigation options may then follow.

Risk is typically assessed by combining the likelihood of an event(s) occurring, with the consequences that will result (e.g. Australian Geomechanics Society 2000). Risk levels for individual fans vary across the Otago region, and will be different for various affected parties (e.g. public vs organisations). Detailed assessments will be required to establish the risk level associated with both the types of alluvial fan hazards and human activities on individual fans. Planning decisions will then be required to determine what risk level is acceptable and when mitigation measures are required. In low risk situations it may be appropriate to do nothing and live with the risk.

Mitigation measures can range from simply increased awareness and vigilance during storm events through to regulation by hazard zoning (such as prohibition of development in some areas) or engineering measures such as defensive structures, walls or storage basins. Further details of options in general terms are discussed below, but this list is based on the most commonly adopted measures and in many cases a combination could be required.

10.1 Increasing public awareness

The initial course of action following completion of this study is to compare the location and activity status of alluvial fans relative to where people live, and to decide which areas are in need of further, more-detailed, site assessment.

The second course of action is to compare the information with what is contained within the District Plans and transfer to territorial Local Authorities for inclusion in hazard registers. In some cases modification or update of the District Plans will be required incorporating this new work.

The third course will be the inclusion of the information in the Otago Regional Council’s own hazard register, which again may trigger further in depth studies as part of hazard assessment where development is proposed.

Enhancing public awareness can have both positive and negative results. It is our recommendation that this regional assessment such is not suitable for identifying hazards at an individual property scale. Information should not, for example, be used on LIM (Land Information Memorandum) reports until site specific studies have identified problems on specific fans. To do so from a regional study such as this could unintentionally and unnecessarily disadvantage many existing homeowners. If a council does this retrospectively, after having approved a subdivision or building, the home owner might consider the council responsible for any effects on property value as a result of identifying a potential hazard on a LIM report. However, the fan mapping is quite suitable for regional planning purposes, as a guide to where alluvial fan hazards should be considered, or assessments might be undertaken in future planning and development at District or Regional level.

10.2 Hazard warning system

Warnings can be anything from motorist signs on the roadside warning of flood hazard or debris on the road through to rain gauging, video closed circuit television monitoring of flow sites and debris accumulation measurement. Such warning systems are helpful in protecting life but generally do little to protect existing development or infrastructure.

High intensity rainfall events can be monitored by remote catchment monitoring of the intensity and period of rainfall. Rainfall intensity trigger values can be established (with some uncertainty) from previous events or determined from site specific studies. Regional tracking of weather conditions and storms is also useful in this approach. Weather radar is probably potentially the most useful way of seeing rainfall intensity distribution in near real time, but coverage of the country is at present somewhat limited, with little coverage in Otago (MetService currently have plans to upgrade this coverage across the country).

A word of caution is needed for where remote catchment monitoring is the sole means of hazard warning. Storm events affecting catchments releasing debris flows can be very localised and so detection requires reliable local coverage (see above re weather radar). Telemetric links can be used for continuous monitoring but these have to be maintained, and obviously must be working at the time of the event. There also has to be some way of getting the information back to the affected area and informing people in time – which can be a costly ongoing process.

10.3 Hazard management plan

Within the overall context of a site hazard management plan, emergency response to alluvial fan activity, flooding/debris flow can be incorporated. This would include the warning system measures in place, distribution of information and response actions or evacuation.

10.4 Management by enlarging and clearing stream channels

In some cases efforts to maintain flood waters within established channels provides an effective means of controlling events. Proactive work in this area in many cases will provide added security but should only be used with the following cautions in mind. As stated in other parts of the report, the nature of alluvial fan hazard is uncertain and unpredictable, so whilst maintaining channels based on previous events may work in most cases contingency needs to be built into the management regime and the work is best carried out under the direction of practitioners who understand the processes on the particular fan being managed in this way.

10.5 Land use management and vegetation control

Vegetation and land use, particularly in the catchment area, have variable effects on catchment stability and erosion, and hence alluvial fan flooding processes. Some species of trees, for example, can enhance slope stability with root strength and by maintaining lower ground water levels, and other vegetation can be effective in reducing runoff and infiltration rates. Alternatively, some trees may decrease slope stability, for example by increasing the weight on the slope making failure more likely, then adding to the load carried in a debris flow. Trees may become a real hazard by blocking culverts and bridge underpasses etc.

Mitigation of alluvial fan flood hazard by controlling vegetation or land use requires planning on a case by case basis. Importantly, land use management and vegetation are important causative-mitigative factors that people can have an influence on, just as people can mitigate the vulnerability of people & development in the flood path, by combinations of avoidance and structural engineering.

10.6 Modifying or strengthening infrastructure

In some cases improvements to the design or strengthening of existing infrastructure can reduce the risk of damage from alluvial fan activity. This may include simple measures like increasing culvert sizes at critical locations through to more robust measures such as strengthening bridges to be able to withstand debris impact forces.

The success of such measures depends on being able to establish the design force and/or event size, and again this comes with a degree of unpredictability. What also needs to be kept in mind is the debris clean up post event. A suitable, consented place has to be located where sediment can be dumped and this in itself can impose large loads on existing infrastructure affecting existing road pavements and bridges etc.

10.7 Defensive structures and storage basins

In extreme cases, construction of defensive measures may be needed to assist in mitigating the hazard to critical sites. Measures can range from deflective berms or bunds to collection areas or storage basins.

Deflection berms are banks that are positioned on areas of the fan to redirect flow away from important infrastructure or development on the fan. The berms can be constructed from a variety of material including soil, rock, timber or concrete. Positioning of such defensives requires a thorough appreciation of the nature of the hazard and the investment required for construction should be backed up with sound engineering and risk advice to determine the number of berms, their location, orientation and the size necessary to protect the important parts of the fan.

Storage basins are used to contain sediment (rather than water) and control of debris flows. They have a low gradient to encourage deposition, and are often used in combination with debris racks or debris detention outflow structures to allow screening of material and the passage of water during normal flow conditions. Basins need to be designed to cater for the design flow and require regular inspection, maintenance and clearing of debris after each event so there is capacity to contain future flows.

10.8 Building regulation and hazard zoning

In some extreme cases, where for instance the perceived hazard is so great and mitigation measures are not able to reduce risk to tolerable or acceptable levels, it may be necessary to zone areas and prohibit development, especially residential. This is possible for proposed new developments but does not help existing ones. For existing developments consideration could be given toward relocating infrastructure and buildings away from the high risk areas of a fan, either completely off the fan or to areas where suitable mitigation measures are possible.

11 Impacts of climate change on alluvial fan processes in Otago

As part of this project, the Otago Regional Council requested that potential effects of climate change on Otago alluvial fans should be considered. According to the Ministry for the Environment (2007), climate scientists currently expect the Earth's average temperature will increase by between 1.4 and 5.8°C this century. In New Zealand, average temperatures are projected to increase about 1°C by the 2030s and about 2 to 3°C by the 2080s.

A more "El Nino-type" climate is predicted for the future, with more westerly winds increasing rainfall in the west of Otago and decreasing rainfall in the east, compared with the current climate (Tait et al. 2001). Data extracted from Wratt et al. (2004) exemplify the extent average temperatures might increase, the relative increase in the total precipitation in the west cf. east, and the extent of the uncertainties in these climate change predictions (Tables 4 and 5 below). Translating these predictions, with their considerable assumptions and uncertainties, into defensible conclusions on alluvial fan behaviour is not straightforward, although some hypotheses can be developed.

Table 4: Projected seasonal and annual increases of temperature for the Otago region (°C). Data from Wratt et al. (2004)

Season	1990 – 2030	1990 - 2080
Summer	-0.2 to 1.2	-0.1 to 2.7
Autumn	0.0 to 1.1	0.4 to 3.3
Winter	0.2 to 1.8	0.7 to 3.5
Spring	0.0 to 1.2	0.2 to 3.0
Annual	0.1 to 1.3	0.4 to 3.1

Table 5: Projected change in the percentage of seasonal and annual precipitation in the Otago region (%). Data from Wratt et al. (2004)

	Dunedin		Queenstown	
Season	2030	2080	2030	2080
Summer	-7 to +8	+1 to +34	-14 to +11	+ 3 to +46
Autumn	-2 to +3	-9 to +46	- 3 to +18	- 5 to +21
Winter	-7 to +15	-5 to +30	-12 to +59	-22 to +129
Spring	-4 to +11	-2 to +16	-11 to +23	-15 to +45
Annual	-2 to +6	+2 to +14	- 4 to +22	+ 2 to +57

Long-term erosion of South Island landscape is, in a generalised way, directly related to total precipitation. Much higher rates of erosion and total rainfall are observed in the west compared with the east (Adams 1980; Griffiths 1981; Hicks et al. 1996). Forecasted warmer, wetter climate in the future might therefore be expected to result in increased erosion, which in turn could mean increased sediment supply from catchments to the fans. It might be reasonably concluded, that alluvial fan activity, in a general sense, should increase with the predicted climate change.

However it is the intensity of severe rain storm events and increased storminess, not the total amounts of precipitation, that affect short-term activity on alluvial fans and the frequency of flooding events. While there are some predictions that climate change may result in more frequent heavy rainfall events (Ministry for the Environment 2007), it is not yet possible to develop reasonable models predicting which fans in Otago will be impacted by these storms in the next 100 years, and to what extent. Nor would it be possible to attribute any particular debris-flow or alluvial fan flooding event that does occur to be “climate change related” as distinct from the normal “sequence of sporadic processes” on that alluvial fan. Quantifying the effects of climate change may therefore be irrelevant relative to improving the definition of the actual hazard.

In considering the possible effects of climate change on alluvial fans, we suggest that:

1. It is difficult to predict which of the existing fans will be affected, and to what degree by climate change, particularly over time periods of 100 years important to quantitative hazard assessment.

2. The overwhelmingly important factor in alluvial fan hazards is landscape (geomorphic) setting. Fans exist because of gradient contrasts in drainage systems - without a change in gradient, or gully issuing into a valley, they don't form. Catchment processes affect sediment flux, which is influenced primarily by environment factors such as precipitation events, slope instability, vegetation cover/land-use.

3. It is changes in the rainfall intensity or storm frequency that may be brought about by climate change which will most affect alluvial fan activity, rather than annual rainfall trends. And this possible effect (consequence) of climate change is essentially unquantifiable with our current state of knowledge.

4. Rather than trying to predict and plan on the effects of uncertain climate change, it may be more prudent to allow for periodic hazard reassessments. For example, sites which may not require protection or other forms of mitigation today, may require such in the future.

5. Effects of climate change need to be kept in context with the other dynamic forces acting on fans, for example land use change may have just as much an impact.

12 Glossary

Abandoned Channel	A drainage channel along which runoff no longer occurs.
Aggradation	The accumulation of sediment on a surface leading to a rise in the ground level.
Alluvial Fan	A gently to steeply sloping landform, shaped like an open fan or a segment of a cone that radiates down slope from a point which where the sediment transport capacity of a permanent or ephemeral stream rapidly decreases downstream because of increases in channel width, reductions in channel gradient, or other influences.
Anastomosing	Pertaining to a network of branching and rejoining features e.g. an anastomosing river channel which separates from the main stream to flow parallel, then rejoins the main stream.
Apron	Merging of two or more alluvial fans.
Avulsion	Avulsion is the switching of a stream or individual channel from one course to another (often called a stream break-out); the flow may create a new channel or use a previously abandoned one.
Bajadas	Extensive, gently sloping plain of unconsolidated sediment accumulated along the base of a mountain range. Formed by the lateral coalescence of a series of separate but confluent alluvial fans, and having an undulating character due to the convexities of the component fans.
Base Course	A road pavement layer immediately below the finished road surface.
Braided Area	Area where sediments are deposited by numerous streams that may over time meander across the surface. This is generally a wide gently sloping area.
Briar	Type of hardy rose plant common in central Otago.
Catchment	The area from which a surface water system derives its water.
Channelised Zone	Region near the head of an alluvial fan where stream flow is constricted by channel(s).
Debris	Mass of loose unconsolidated material, can include silt, sand gravel, boulders and vegetation

Debris avalanche	A very rapid, to extremely rapid (5–~20 m/s, 15–60 km/hr), shallow flow of partially or fully water-saturated debris on a steep slope, without confinement in an established channel. Thin slabs of rock which detach from the slope together with all topsoil, cover soil and vegetation. They can initiate debris flows when they reach streams or channels in flood.
Debris flow	A mass movement (often classified as a type of landslide) involving rapid (5–10 m/s, 15–30 km/hr) flow of debris containing coarse grained, saturated, material confined in a steep channel and running out on to low-gradient fans and valley floors, often resulting from high intensity rainfall.. Because of their high velocity (speeds faster than a human can run are common), high density (like wet concrete), and entrained boulders, such flows are highly destructive and dangerous.
Debris flood	A debris flood is a very rapid (up to ~5 m/s), surging flow of water, heavily charged with debris (gravel, sand, and silt), in a steep channel. A debris flood is not a landslide, but is a mass-transport phenomenon with destructiveness similar to that of water, but less than debris flows. Objects impacted by debris floods are surrounded or buried by flood debris but are often largely undamaged. This is often the most common fan-building process on an 'alluvial fan'. Debris flows and debris floods can occur during the same flood, with the latter often occurring in the initial and waning stages of an event.
Dendritic	A drainage pattern similar to the shape of a tree, where many small streams stem from one main river upstream.
Distal	The furthest position from the source area at which sediment from the source can still be found.
Distributary Channel	A natural stream channel that branches off the main channel and may or may not rejoin it.
Entrenchment	The process of a stream eroding the stream bed to create a deeper stream channel
Fan Apex	Highest point on a fan where the stream enters the fan.
Fluvial	Related to water. In contrast to a debris flow which is sediment dominated a fluvial flow is water dominated.
GIS	A geographic information system (GIS) is a system for capturing, storing, analyzing and managing data and associated attributes which are spatially referenced to the earth. In the strictest sense, it is a computer system capable of integrating, storing, editing, analyzing, sharing, and displaying geographically-referenced information.
Hydrographic Apex	Highest point on a fan at which the stream flow is confined to a single channel.

Hyperconcentrated Flow	Flows of water so highly charged with sand and silt that its turbulence is damped out and flow appears smooth and oily. Normal small-scale surface choppiness and splashes of water are missing; capable of higher velocities and moving larger boulders than equivalent flows of water.
Incised	Said of a stream or channel that has been downcut or entrenched into a surface.
Inundation	To be covered or flooded.
Lithology	The description of a macroscopic feature of a rock, or physical characteristics of a rock.
Matagouri	Type of hardy plant common in central Otago.
Morphology	The external structure form, and arrangement of rocks in relation to the development of landforms; the shape of the Earth's surface.
Precipitation	Rain, snow or hail. Events where water falls from the sky.
Quaternary	A geological sub-era that covers approximately the last 1.8 Ma.
Runoff	That part of precipitation (rainfall, snow etc) that appears in surface streams. May be divided into terms such as direct runoff or base runoff; surface runoff, storm seepage and groundwater runoff.
Sediment Load	The material that is moved or carried by natural transporting agent, such as a stream, a glacier, the wind or waves, tides and currents. Commonly referring to the quantity or amount of such material at any given time.
Sheet flow	An overland flow of water taking the form of a thin, continuous film over a relatively smooth surface and not concentrated into channels.
Source Basin	Area above an alluvial fan that sediment deposits originate from.
Stratigraphic	The correlation of time and space information for stratified rocks which relate to the origins of the rocks.
Tectonism	Deformation of the earths crust through earthquake processes
Tertiary deposits	Sedimentary deposits from a geological sub-era which began 65 Ma ago and lasted until1.8Ma.
Toe Zone	Base of an alluvial fan.
Turbid	Similar to turbulent though turbid relates to density differentials relating to density of sediments in a medium.
Topographic apex	The head or highest point on an alluvial fan.

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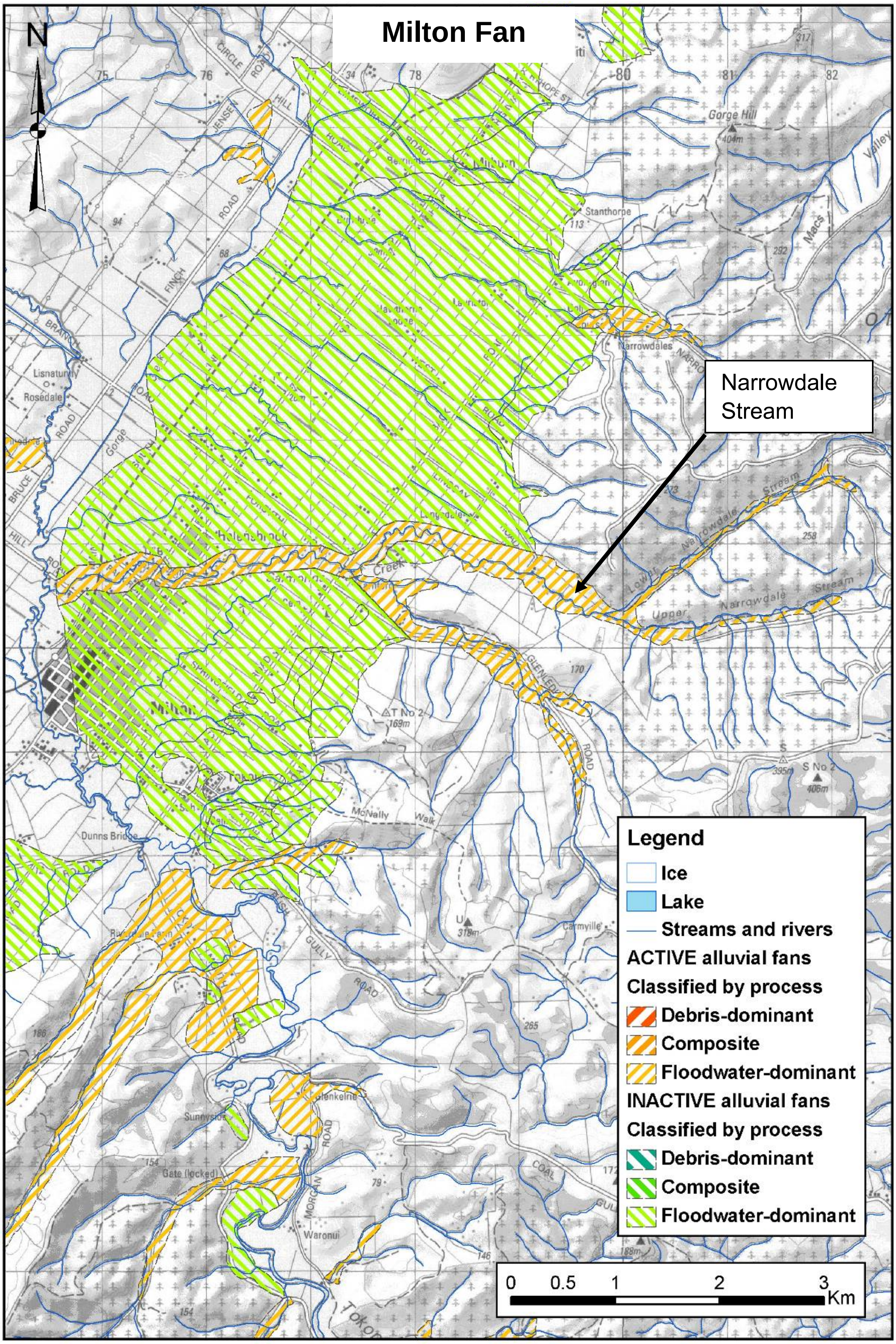
The report was written by James Grindley and Philip Woodmansey (OPUS), Simon Cox and Ian Turnbull (GNS Science). Sue Scott, James Grindley and Philip Woodmansey (OPUS) shared their experience of specific localities, engineering solutions and other mitigation approaches appropriate for alluvial fan hazards in Otago. Technical reviews of the report and GIS dataset were provided by Graham Hancox, David Barrell (GNS Science), Rhys Owen and Philip Woodmansey (OPUS).

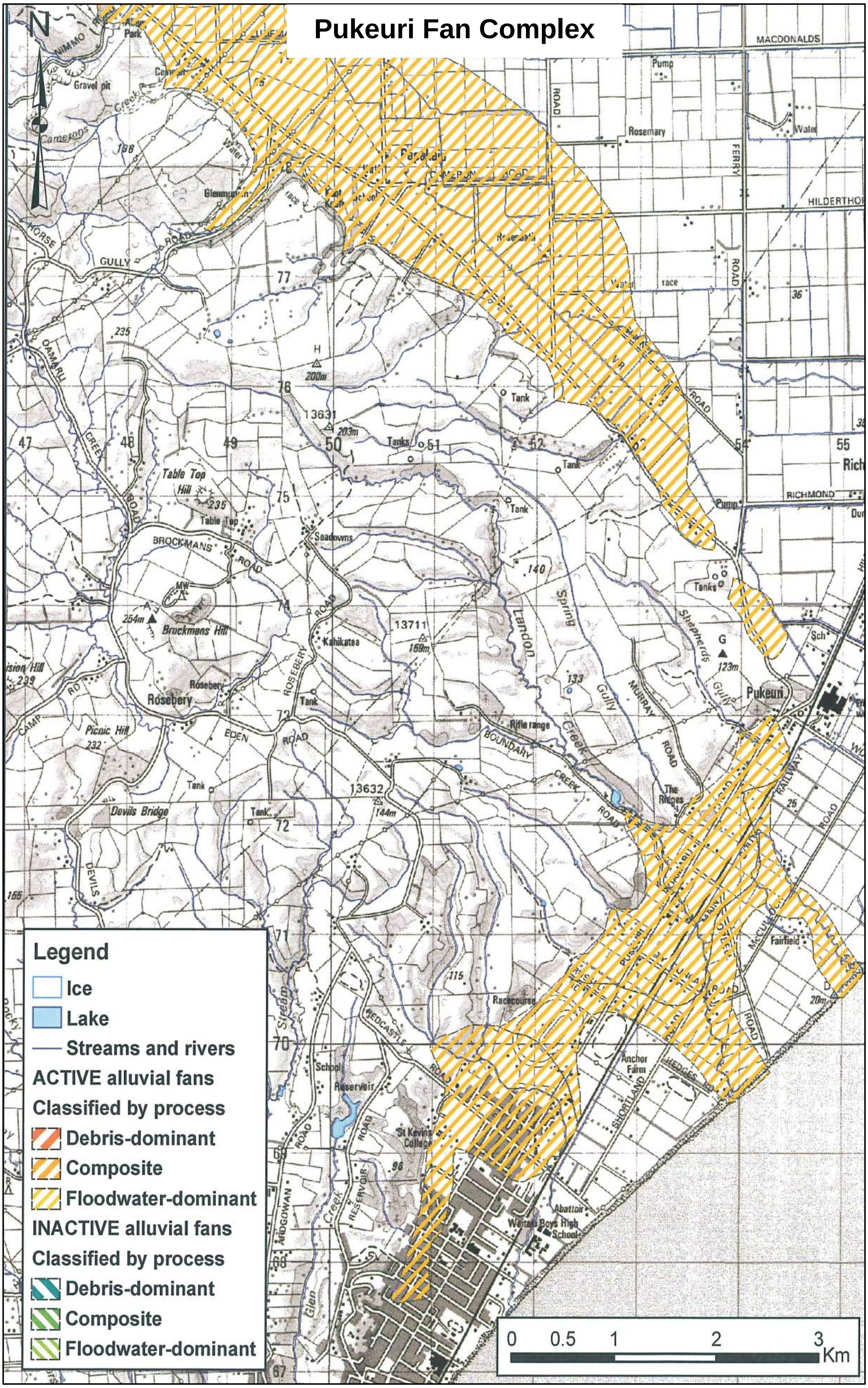
Appendix 1 – Map of Alluvial Fans in Otago

Map Pocket Here

Appendix 2 – Comparison between Otago Alluvial Fan Examples

	Milton	Pukeuri	Waikerikeri	North Roxburgh	Stoney Creek	Mill Flat	Pipson Creek
General							
Location	Fan immediately east of Milton	Fans developed along the margin of the Waitaki River Flood Plain	Southeast foot of the Dunstan Ranges	Fan Complex at base of Old Man Range	Western outskirts of Wanaka	Well defined fan just north of Paradise.	Fan at base of Mckerrow Range
Catchment							
Area	20 km^2	20 km^2	26 km^2	19 km^2	1.8 km^2	10 km^2	3.5 km^2
Δ height	300 m	200 m	1200 m	800 m	900 m	1300 m	1600 m
Stream Order	3rd Order	2nd, 3rd and 4th Order	1st and 3rd Order	1st and 2nd Order	1st Order	2nd Order	2nd Order
Slope	Moderate to steep	Moderate	Steep	Moderate to very steep	Steep to very steep	Very Steep	Very Steep
Landslides	No significant landslides	No significant landslides	Landslides Present	Numerous Landslides	Landslides Present	Landslides, steep cliffs, rockfall all present.	Landslides Present
Geology	Low grade Haast Schist, Henley Breccia	North Otago Tertiary sequence	Haast Schist	Haast Schist	Haast Schist	Low grade Haast schist (soft)	Haast Schist
Vegetation	Otago Coast Forest (pine forest)	Farmland	Tussock, Matagouri	Tussock, Matagouri	Tussock, Matagouri	Native forest, tussock and bare ground.	Tussock, native bush, bare mountain areas
Fan Deposit							
Type	Individual Fan	Fan Complex	Fan Complex	Fan Complex	Individual Fan	Individual Fan	Individual Fan
Area	11 km^2	77 km^2	26 km^2	2.2 km^2	1.2 km^2	4 km^2	1.7 km^2
Age	Young	Young	Very old to Young	Young	Young	Young	Young
Δ height	50 m	30 m	200 m	80 m	220 m	100 m	100 m
Slope	Gentle	Gentle	Moderate to gentle	Moderate to gentle	Moderate to gentle	Moderate to gentle	Moderate to gentle
Activity / Processes							
Dominant Process	Floodwater dominated	Floodwater dominated	Floodwater dominated	Composite - dominated by both debris and floodwater process	Composite – dominated by both debris and floodwater process	Debris flow at the head of the fan, floodwater process in areas less than 5° slope.	Subdivided into debris and floodwater dominated areas.
Soil Development	Well Developed Soil	Both well developed and recent soils	Both well developed and recent soils	Recent and well developed soils	Recent soil	Recent and gley soils	Recent soil
Infrastructure							
Buildings	• Between 300 and 20 buildings. • Part of Milton.	• 300 buildings • Part of Northern Oamaru	• 100 buildings	• Parts of Roxburgh • 100 buildings	• Parts of Western Wanaka	• DoC estate	• Makarora township
Roading	• Both sealed and unsealed roads	• State Highway 1 • State Highway 83 • Other sealed and unsealed roads	• Sealed and unsealed roads.	• State Highway 8 • Other sealed roads	• Sealed roads	• One dirt road	• State Highway 6
Other	-	• Railway	-	• Power transmission lines	-	-	-
Mitigation							
Likely Mitigation	Site specific investigation to determine active areas.	• Improve Channel Definition	• Site specific investigation to determine active areas	• Channel enhancement • Clearing of trees	• Site specific assessment likely to recommend mitigation measures.	• Maintenance of ford in dirt road	• Clear State Highway bridge
Comments							
	Little known about fan history other than the occasional rainstorm event.	Little known about fan history other than the occasional rainstorm event.	Contains young active channels incised into old inactive fan surfaces.	Site specific assessment has already occurred on parts of this fan complex.	Site specific assessment currently underway.	Covered in large forest indicating little activity in last 200 to 300 years.	Highly studied, probably the most well know example in Otago.


Milton Fan
N
Narrowdale Stream
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3 Km


Pukeuri Fan Complex
N
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3 Km
Pukeuri
Rosebery
Table Top Hill
Brockmans Hill
Picnic Hill
Devils Bridge
Racecourse
St Kevins College
Waitaki Boys High School
Anchor Farm
Fairfield
Abattoir
Reservoir
School
RICHMOND
MACDONALDS
HILDERTHO
Rosemary
Pump
Tank
Tanks
Seadowns
Kahikatea
Landon
Spring
Gully
Creek
Shepherds
The Ridges
Rifle range
BOUNDARY
CREEK
ROAD
EDEN
BROCKMANS
OAMARU
GULLY
HORSE
CAMP
DEVILS
ROSEBERY
MURRAY
SHORTLAND
HEDGES
RAILWAY
FERRY
Glen
Stream
Creek
RESERVOIR
ARDGOWAN
REDCASTLE
Gravel pit
Camerons
13631
13711
13632
200m
203m
159m
144m
254m
123m
235
140
133
115
96
36
20m
47
48
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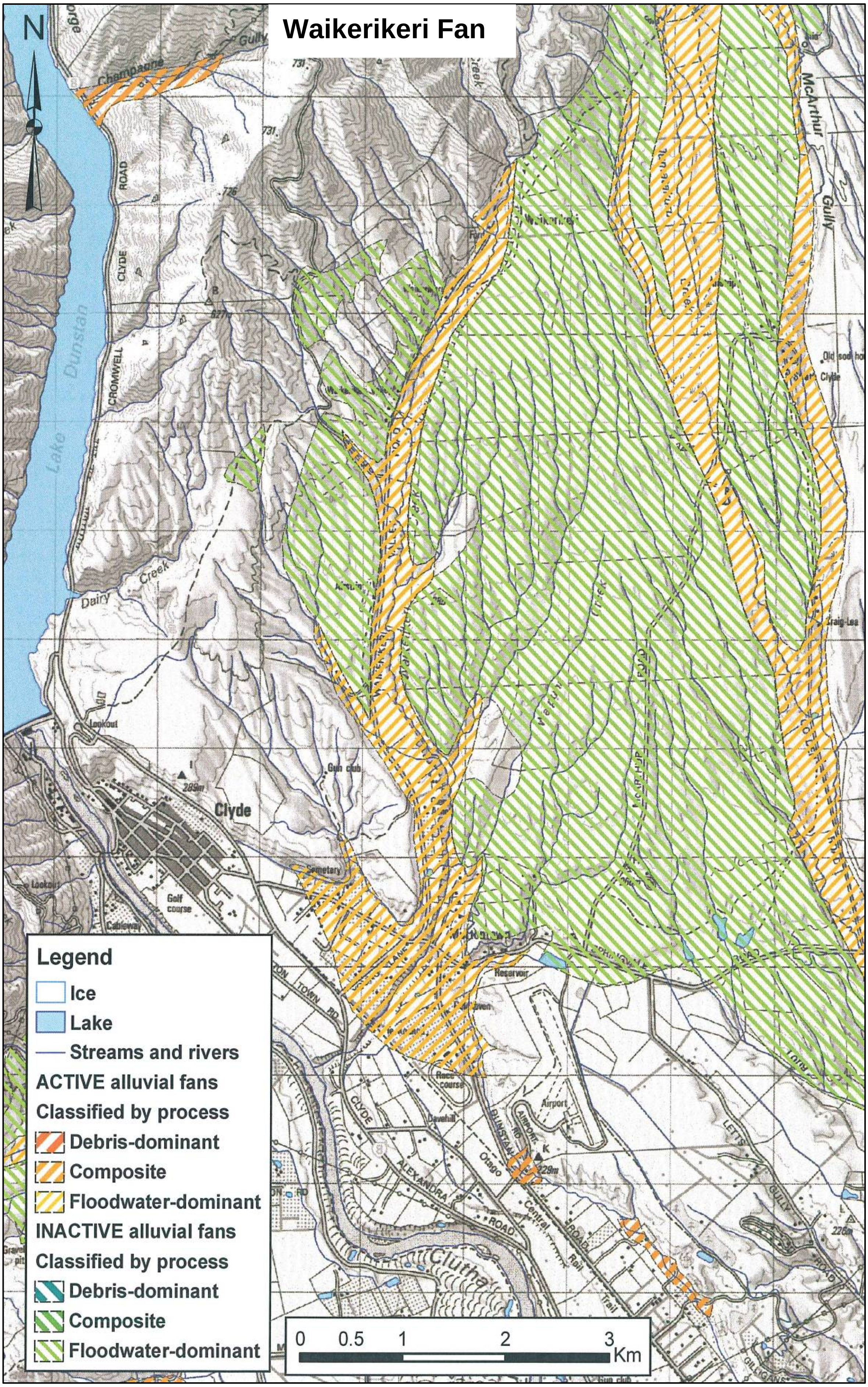
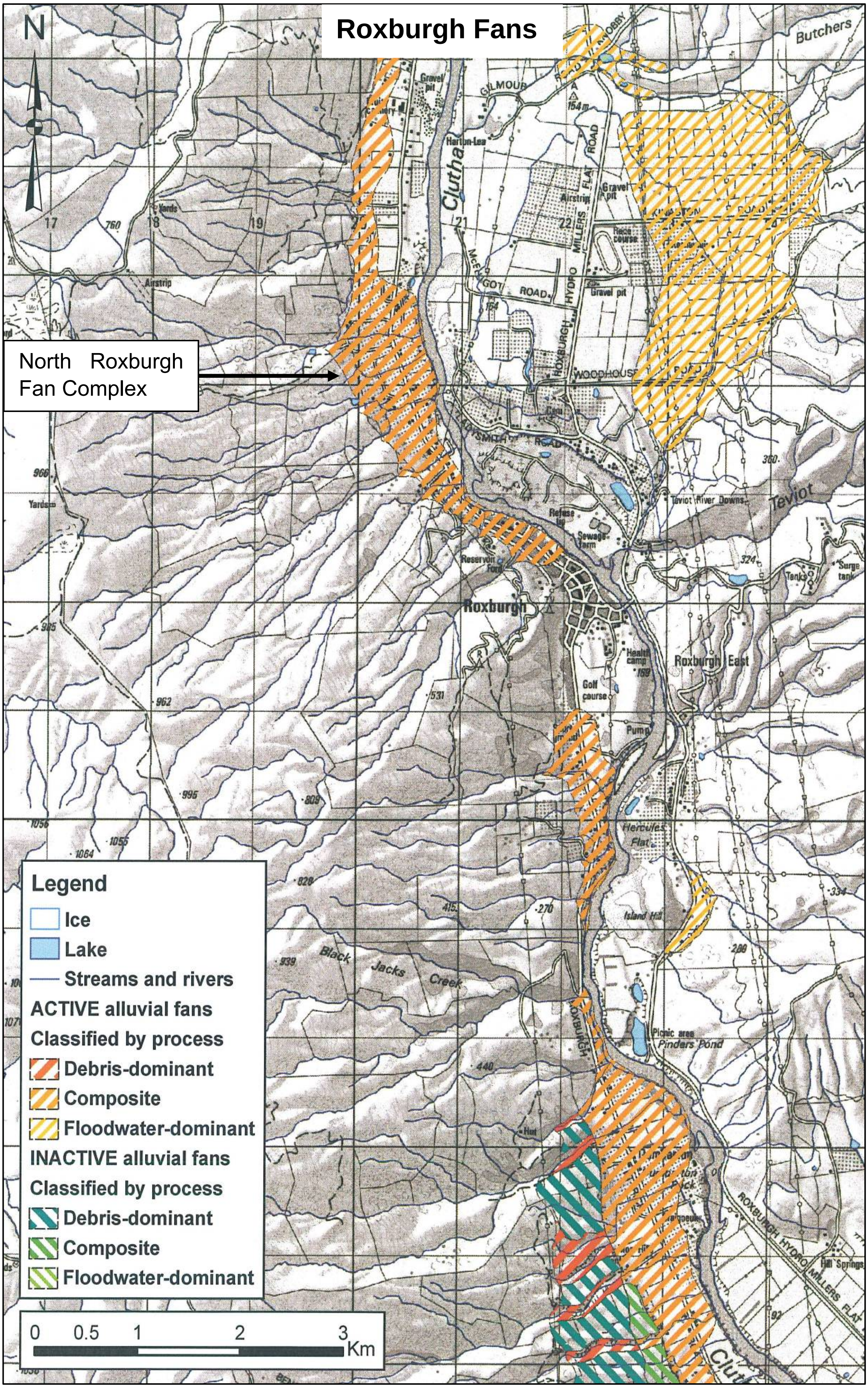
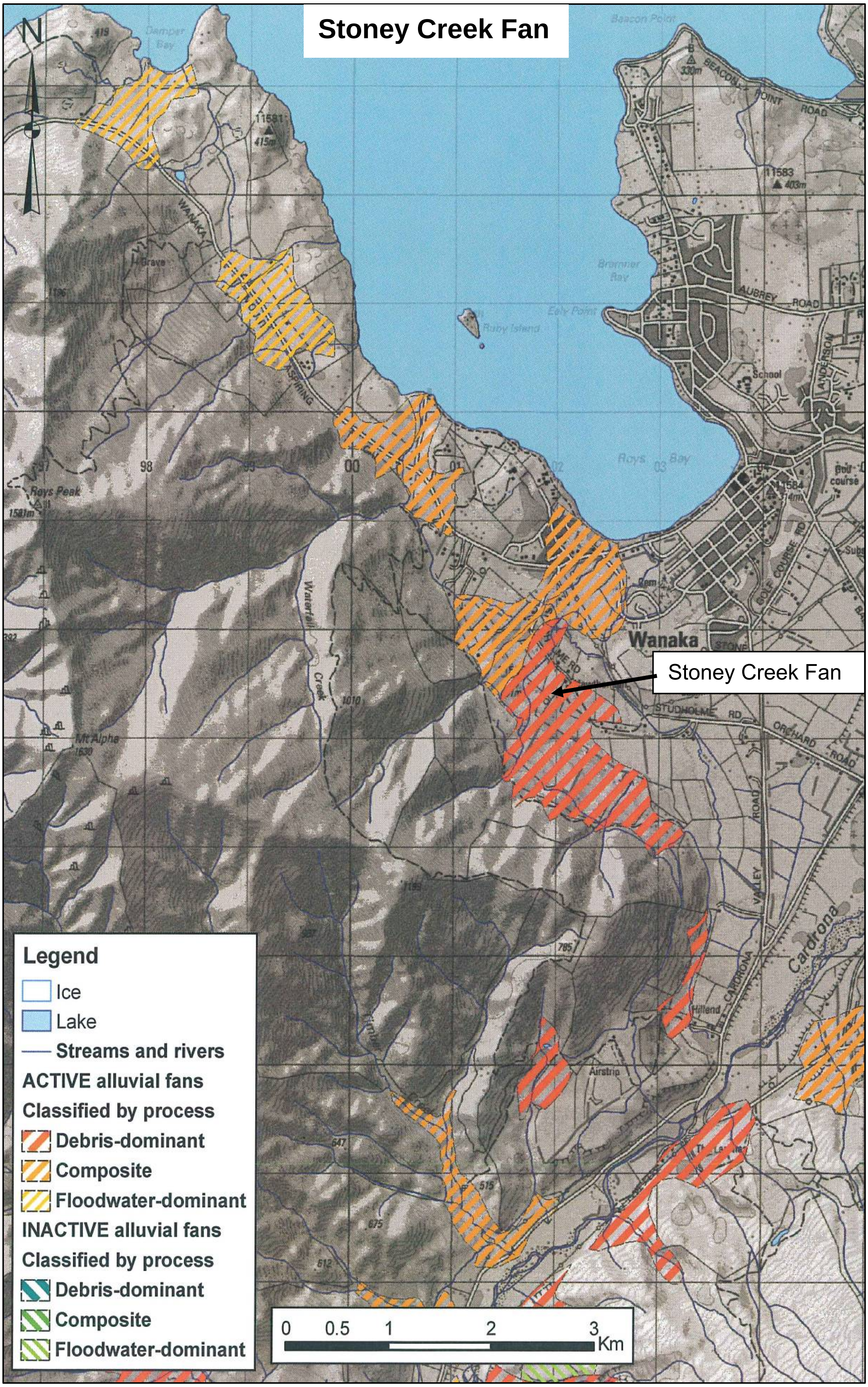
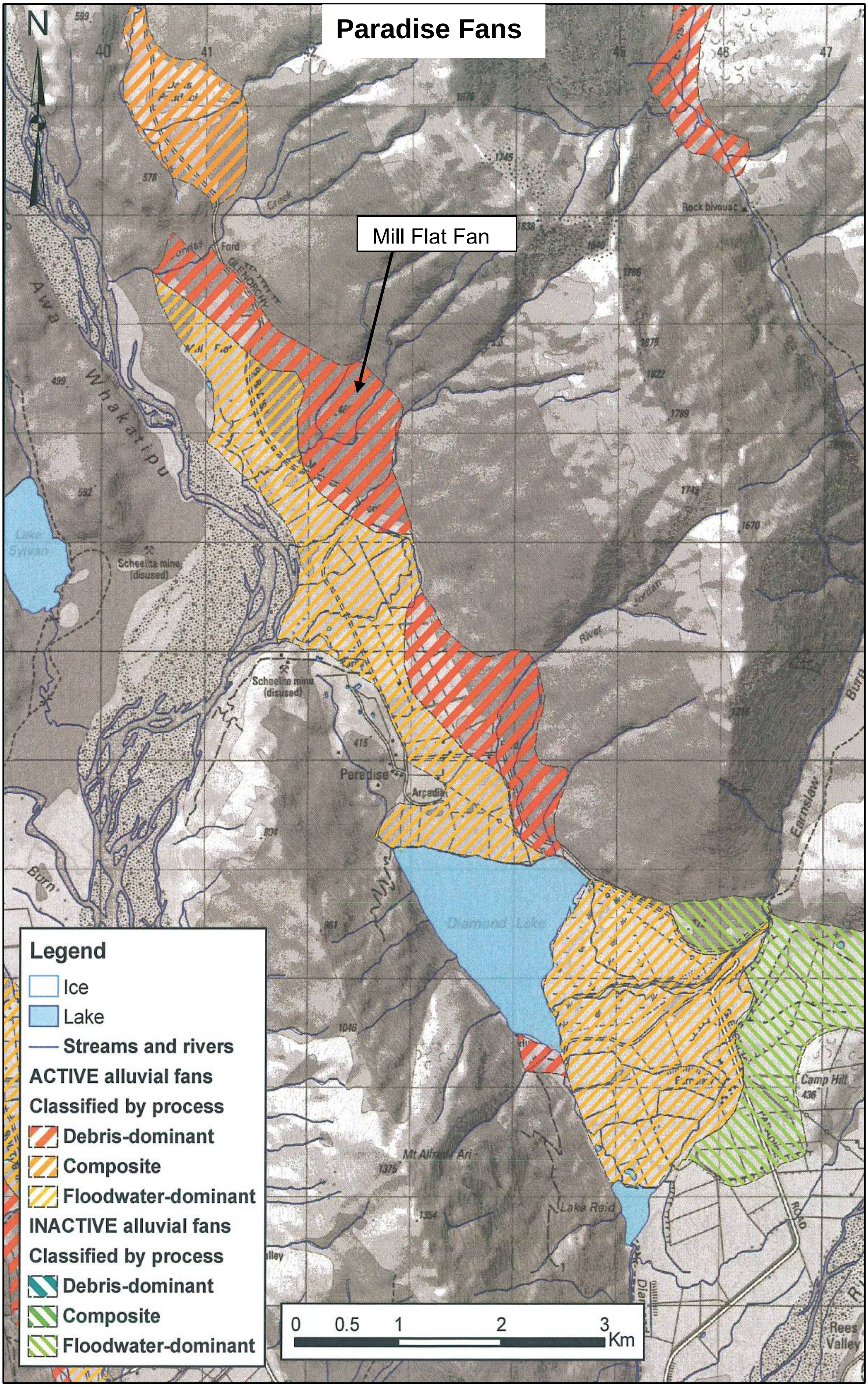
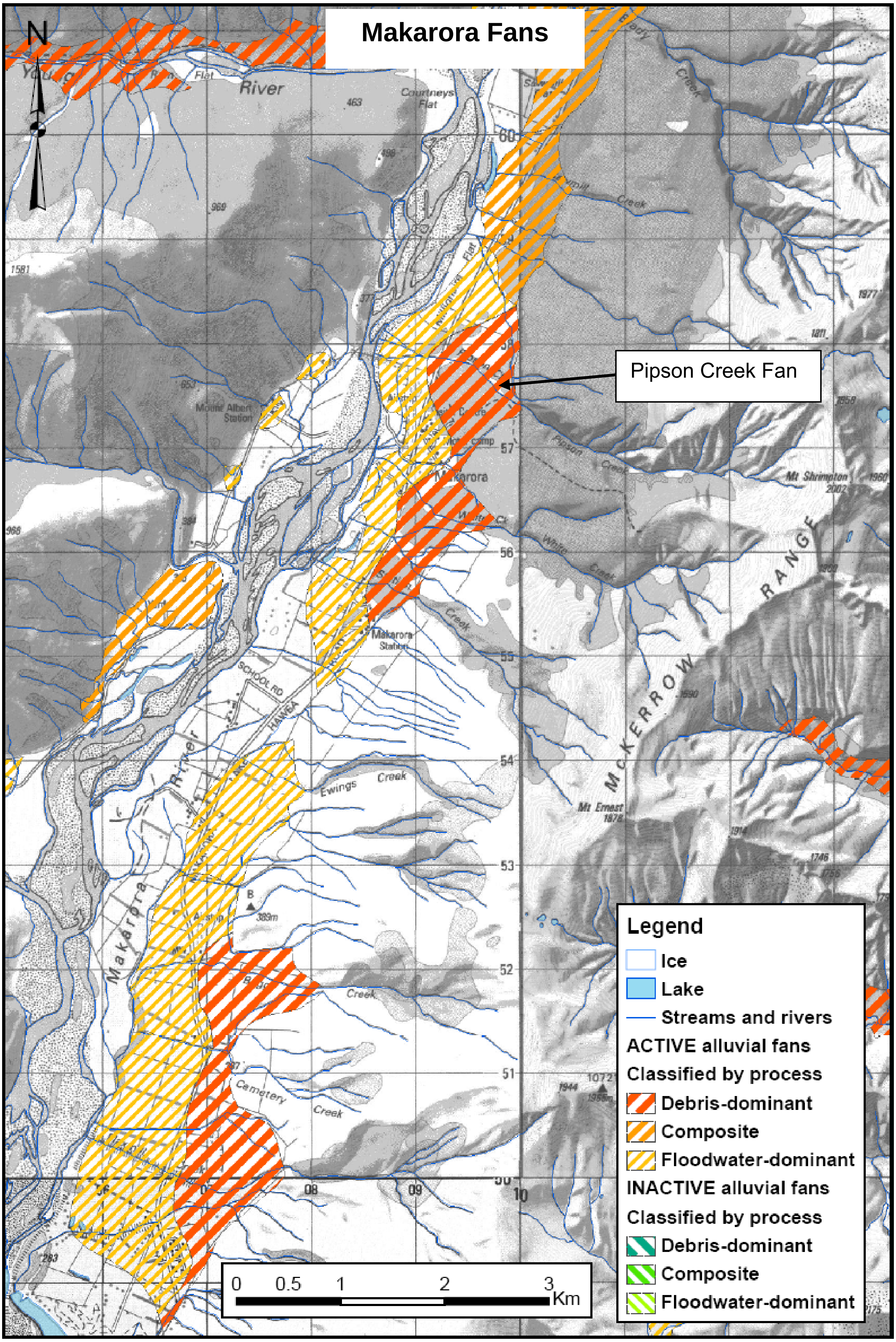

Waikerikeri Fan
N
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3 Km
Lake Dunstan
Clyde
Dairy Creek
Lookout
Gun club
Golf course
Cemetery
Reservoir
Airport
McArthur Gully
Clutha
Craig-Lea
Champagne Gully
CROMWELL CLYDE ROAD
ALEXANDRA CLYDE ROAD
Central Otago Rail Trail


Roxburgh Fans
N
North Roxburgh Fan Complex
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3
Km
Roxburgh
Clutha
Teviot
Roxburgh East
Butchers


Stoney Creek Fan
N
Stoney Creek Fan
Wanaka
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3
Km


Paradise Fans
Mill Flat Fan
N
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3 Km
Whakatipu
Scheelite mine (disused)
Paradise
Arcadia
Diamond Lake
Lake Reid
Mt Alfred
Camp Hill
Rees Valley
Earnslaw
Rock bivouac
Creek


Makarora Fans
N
Pipson Creek Fan
Legend
Ice
Lake
Streams and rivers
ACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
INACTIVE alluvial fans
Classified by process
Debris-dominant
Composite
Floodwater-dominant
0 0.5 1 2 3
Km
River
Courtneys Flat
Mount Albert Station
Makarora Station
SCHOOL RD
Ewings Creek
Cemetery Creek
Pipson Creek
White Ck
McKERROW RANGE
Mt Shrimpton 2002
Mt Ernest 1878
Makarora

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