Otago Alluvial Fans: High Hazard Fan Investigation

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Executive summary

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 hill slopes and valleys. They owe their origins 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 the valley floor encourages the deposition of sediment, which accumulates over time to form a fan-shaped landform. More than 2000 alluvial-fan areas, equating to 6% of the total land area, have been mapped in Otago.

The principal hazards on alluvial fans are inundation by flood water, debris-flow and debris-flood deposits, channel migration, deposition and erosion. The unpredictable and variable nature of alluvial-fan hazards means that they are potentially very hazardous. Despite that, their elevated profile, with good drainage, makes them attractive places for people to live.

In 2006, the Otago Regional Council (ORC) commissioned a review of the hazards associated with alluvial fans in Otago. This regional review mapped all alluvial-fan features larger than $0.5km^2$ in area throughout the region in a Geographic Information System (GIS) and classified each based on the fan's activity status - active or inactive - and the primary depositional process: floodwater dominant, debris dominant or a composite of both floodwater and debris.

Following completion of the regional review, ORC staff consulted closely with each territorial local authority (TLA) to identify active alluvial-fan areas that warranted further investigation. This led to supplementary work on the nature and characteristics of alluvial fans in the 27 identified study areas, set within a regional perspective of alluvial-fan active processes. Using this dataset, a subset of 'high-hazard' alluvial fans was identified that warranted further specific investigation to determine existing or potential future vulnerability and consequences of the alluvial-fan hazards.

In consultation with each TLA, ORC staff undertook a review of district-planning zones that intersect active alluvial-fan areas and have an existing or a greater potential for future development. This 'screening process' has determined a subset of eleven specific alluvial fans that intersect existing or future community areas which also have a high level of hazard exposure. This report summarises the existing catchment and fan characteristics of each of those eleven alluvial fans and describes the hazard associated with each.

The fans selected within this investigation do not necessarily represent those fans in Otago with the highest level of hazard; rather this subset has been selected based on existing and future development potential.

The report concludes that parts of Queenstown, Wanaka and Roxburgh townships are exposed to intermittent alluvial-fan hazards. Hazard areas have been defined for particular alluvial fans in these communities that may be subject to alluvial-fan processes in the future. Elsewhere, communities in the Makarora Valley have a level of residual exposure to alluvial-fan hazards, should channels migrate laterally across the fan surface in the future.

1. Alluvial fans in the Otago region

Alluvial-fan landforms develop where a steep gully emerges from its confines onto a flatter valley floor, or at locations where sediment accumulates in response to changes in stream gradient and/or width (Figure 1.1). Primarily formed by intense, heavy rainfall, the overall development of these features is episodic, often spanning time scales of decades to centuries. Flooding events can be unpredictable and hazardous on alluvial fans, potentially involving fast-moving sediment-laden floods or slurry-like flows of debris which can break out from existing streams and forge new, sometimes unexpected paths. Sediment-laden floods or flows are damaging and destructive, and pose a threat of injury or death to people. Less serious hazards include floodwater inundation, sediment erosion or build-up, which may cause damage to land and infrastructure.

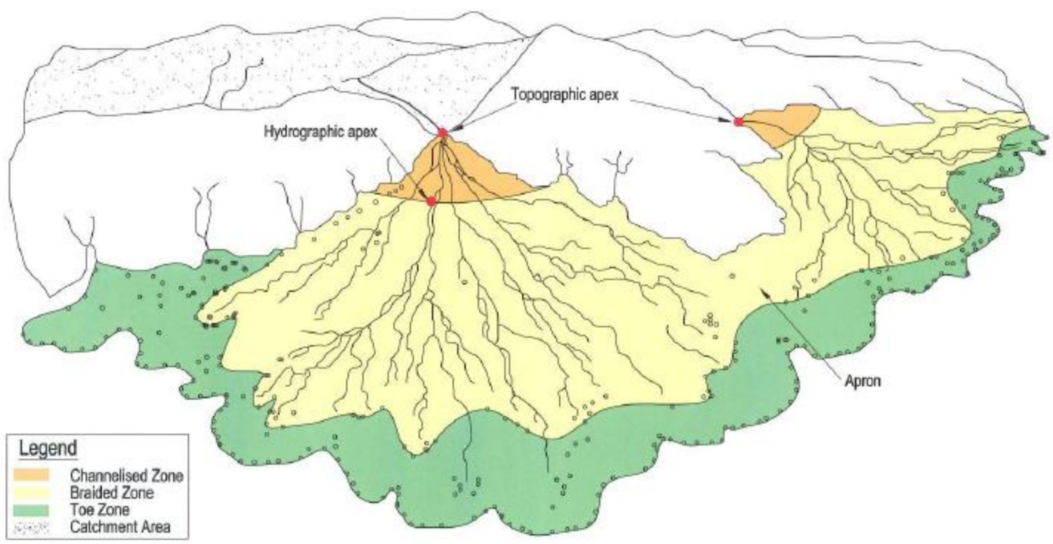


Figure 1.1 Diagrammatic representation of an alluvial fan, noting key features (Opus, 2009)

The form and setting of alluvial fans makes them an attractive location for residential development, with gentle elevated slopes and good drainage. In Otago, fan streams are often ephemeral or inconspicuous, creating an impression that little or no hazard exists. Throughout the region, residential development has continued to encroach upon fan areas, with little recognition of the hazard exposure. In response, ORC contracted a regional-scale hazard assessment of alluvial fans in 2007 (Opus, 2007). Fan areas were mapped at 1:50,000 scale, identifying and classifying 2197 separate fan areas using a GIS map database. The investigation found that significant alluvial-fan landforms occupy at least 1970km^2, which is 6% of Otago's total land area. Fan areas were classified as active or inactive and allocated a primary depositional process (i.e. floodwater dominant, debris dominant or composite, thereby providing additional information on potential hazards). Implications for existing communities and future district-planning objectives were identified through consultation with each TLA and consideration of their respective district-plan zones. Twenty-seven alluvial-fan areas, many of which were located on the lateral margins of existing communities, were considered to warrant further investigation. For each area, the entire fan system was mapped, including areas of historical fan activity, upper catchment stability and channel type, using aerial photography and field investigations. The resulting dataset provides a comprehensive record of historical fan activity and existing catchment stability to identify high-hazard areas that coincide with existing, planned or future areas of development.

1.1 Specific high-hazard alluvial fans

Eleven high-hazard alluvial fans were identified from the twenty-seven areas studied in the supplementary investigation (Barrel *et al*., 2009). Through consultation with each TLA, the development potential for each district-planning zone was ranked and matched against the active alluvial-fan areas. This 'screening' process identified areas of existing development or zones with a high potential for development that intersect active alluvial-fan areas. This process identified ten fans in the Queenstown-Lakes District, one fan in the Central Otago District and no fans in the Waitaki, Dunedin City and Clutha districts that warranted further investigation (Table 1).

Table 1 Specific high hazard alluvial-fans identified within the Otago region

District	Specific alluvial fans
Queenstown Lakes	Pipson Creek (Makarora), Flaxmill Creek (Makarora), Johns Creek (Hawea), Stoney Creek (Wanaka), Waterfall Creek (Wanaka), Walter Peak (Wakatipu), Bob's Cove (Wakatipu), Brewery Creek (Queenstown), Reavers Lane (Queenstown), Kingston Creek (Kingston)
Central Otago	Reservoir Creek (Roxburgh)

To determine the hazards associated with each alluvial fan, the following information was acquired and collated:

- the extent of existing and potential catchment instability that may contribute significant sediment and/or debris supply to the fan surface
- the potential for debris-dam formation and identification of existing landforms in the upper catchment that provide evidence for historical damming
- vegetation characteristics of the catchment and potential for log-jam dam formation
- the identification and mapping of palaeo-channels on the fan surface and the potential for these to be re-occupied through channel avulsion
- observations of previous debris-flow deposits, their location and potential for future debris flow, by inspection of existing soil profiles, to determine the general frequency and derivation of events
- observations of channel incision down the fan surface, the location of the hydrographic and topographic apices and key inflection points
- the potential for aggradation and lateral migration of active channels and the likely risk of avulsion
- the potential for significant erosion of existing channels and possible effects.

The holistic environment setting of each alluvial fan is discussed. Catchment and fan characteristics are described to gain an understanding of the current and potential geomorphic processes that define the observed and anticipated alluvial fan hazards. The extent of alluvial-fan hazard has been mapped for each specific fan. These areas have been defined by combining active alluvial-fan areas mapped by Barrel *et al.* (2009), extending potential hazard areas using stereoscopic aerial photography and ground verification, and integrating the results of previous site-specific investigations. It is important to note that these hazard areas represent the full extent of possible unmitigated future alluvial-fan activity. Alluvial-fan hazards will vary spatially within this boundary, depending on the nature and characteristics of the storm event and fan surface at that time.

The topographic and hydrographic apices of each fan have been identified on the respective alluvial-fan maps. The 'topographic apex' is the point, commonly where the fan head is located, where the creek or stream leaves the confines of the valley (Figure 1). This point is static and corresponds with the foothills of the source catchment. Comparatively, the 'hydrographic apex' is the point on the fan surface where the channel no longer becomes incised into the surface and therefore may migrate or adopt a braided form. The hydrographic apex is not static and may move within the channel, depending on the nature of the fan surface, channel and catchment-sediment supply. Often during storm events, the channel may aggrade and cause the hydrographic apex to move upstream quickly, promoting channel breakout or avulsion. An example of this phenomenon is shown in Figure 1.2.

Figure 1.2 Pipson Creek in March 2004 (left), looking upstream, and November 2008 (right), looking downstream. In the left image, the creek has aggraded, so that the channels are migrating laterally outside of the channels low-flow banks; the hydrographic apex is located upstream and out of sight. In the right image, excavation and channel contouring has confined the channel to a single-thread channel, far beyond the state highway; the hydrographic apex is located near the confluence with Makarora River in this image.

1.2 Alluvial-fan formation in Otago in the Queenstown Lakes and Central Otago districts

Many alluvial fans in the Queenstown Lakes District have formed during the recession of the last glacial period, around 18,000 years ago, as glaciers vacated basins and were replaced by the contemporary lakes present today. These glaciers buttressed the outlets to many of the tributary catchments in the adjacent mountain ranges during this period. After the glaciers receded, tributary base levels dropped considerably, eroding catchments and transporting sediments to the recently vacated basins; these sediments were deposited in the form of alluvial fans. Since this time, fans have progressively built out into these basins, and these processes still continue today.

The rate at which alluvial-fan landforms have developed in Otago is largely dependent on the climatic and seismic influences of the period. Since the last glaciation, large earthquake events, on plate boundary's and local-fault systems, are likely to have influenced the volume of sediment supplied by source catchments to the alluvial-fan surfaces. In addition, fluctuations in climate between warmer and cooler periods can affect the frequency and intensity of heavy rainfall events, and the level of sediment supply to fan surfaces can vary as a result. These conditions mean that alluvial-fan processes, such as debris-flow and flood events, often occur over timeframes of decades to centuries.

Alluvial fans located in the Lake Wakatipu, Wanaka and Hawea basins have been formed by catchments eroding into ancient-schist bedrock. These fans have built out onto moraine and river-terrace deposits, formed immediately following the recession of the glaciers. After the retreat of ice, these lakes were initially 20-50m higher than today. As their outlets incised into deposits left by the glacier, lowering lake levels, the surrounding alluvial fans followed suit. These conditions promoted stream incision into fan deposits, leaving abandoned terraces flanking some of the contemporary alluvial fans.

In the Central Otago District, alluvial fans have formed in response to tectonic uplift of localised mountain ranges and have maintained levels with the surrounding topography and rivers. As the Clutha River responded to significant sediment inputs post-glaciation, it has formed many river terraces which have subsequently been incised. As erosion of tributary catchments has continued, intermittent debris and flood flows have built alluvial fans out onto these older terraces.

2. Pipson Creek, Makarora

2.1 Environment setting

Located at the head of Lake Wanaka, the Makarora Valley (Figure 2.1) is a geologically young landscape, having been occupied by glaciers during the last glacial period, as discussed in Section 1.2. Incised into the western flank of the McKerrow Range, the Pipson Creek catchment flows east to west, from an elevation of 2002m at Mt Shrimpton, to around 400m, near the apex of the alluvial fan. The true-right flank of the alluvial fan is mostly pastoral farmland, while the true-left flank of the fan is heavily forested. The Makarora West community is situated on the true-left part of the fan; State Highway (SH) 6 bisects the fan and is the only direct route from Otago to the West Coast, via Haast Pass. Downstream of the state highway, the fan is dominated by pastoral farmland, with the lower-fan reaches subject to flooding and erosion by the Makarora River.

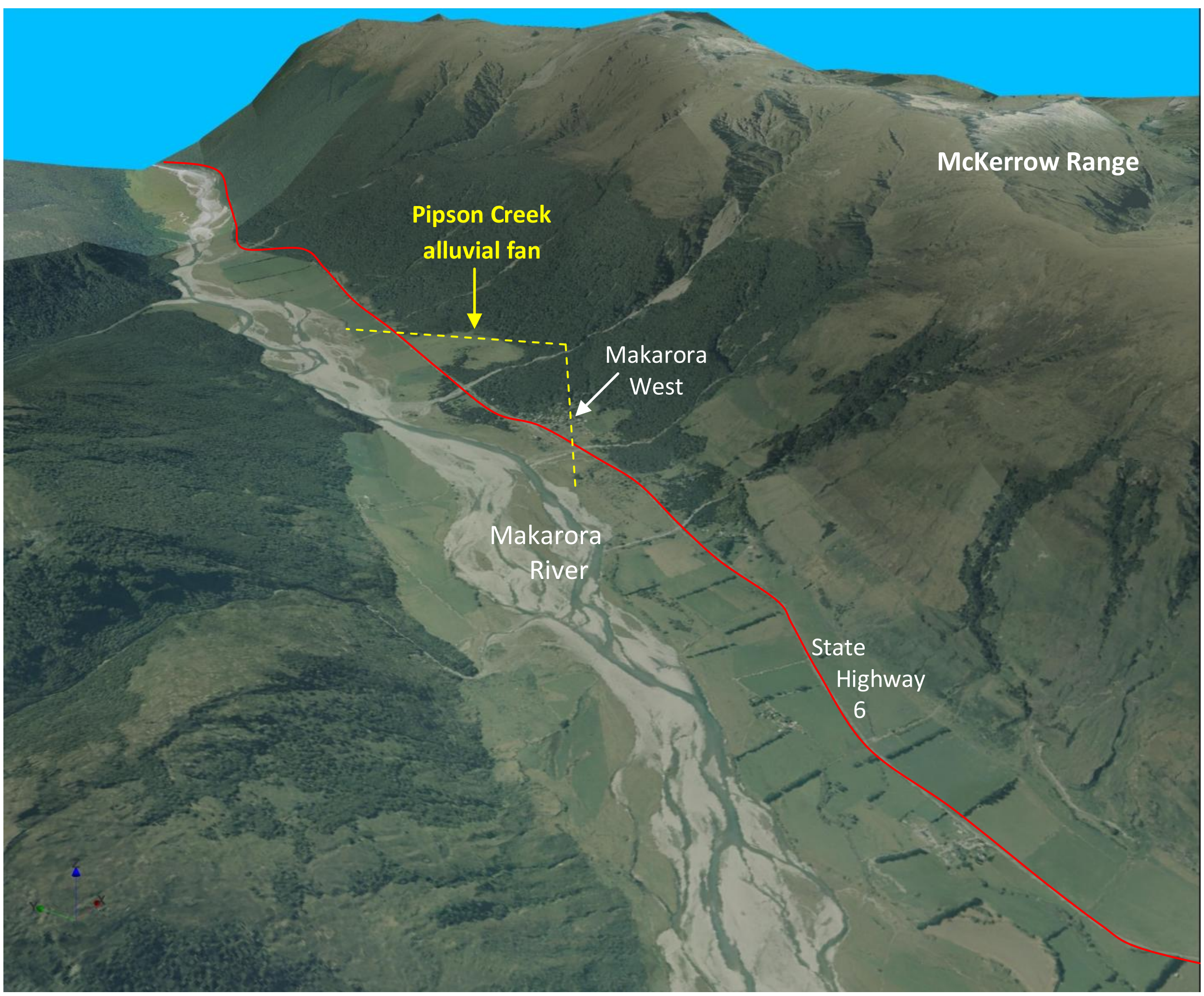


Figure 2.1 Image showing a reach of the Makarora Valley at the head of Lake Wanaka, looking upstream

2.2 Catchment characteristics

The Pipson Creek upper catchment (Figure 2.2) is defined by high-altitude, mountainous terrain, with small bushes and alpine tussocks comprising the dominant vegetation cover. The catchment is approximately 3.3km^2 in size. Slope processes in this part of the catchment are dominated by mass movement, including creep, slumping and gullying, with many fresh scarps, signifying widespread instability. Persistent mass movement is dominant on the true-right (northern) slopes of the catchment, consistent with the dip of the underlying schist bedrock. The true-left (southern) slopes of the catchment are dominated by creep processes and surficial gullying of exposed bedrock. These slope conditions, coupled with the erodible nature of the underlying schist and intense, high rainfall of the area[1], provide mechanisms for the direct supply of high-sediment loads to the Pipson Creek channel.

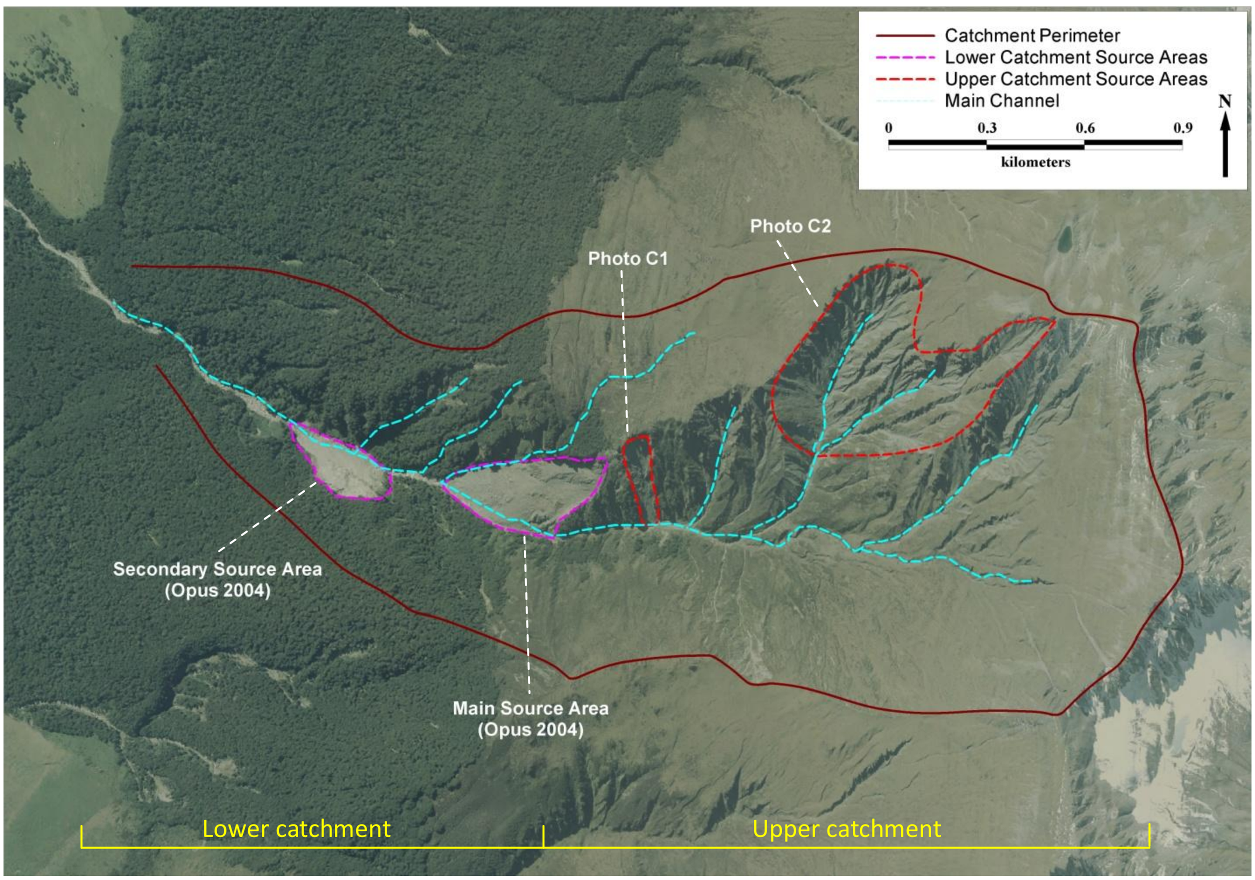


Figure 2.2 The Pipson Creek catchment, noting sediment-source areas and sites of interest; aerial photo dated March 2006

Field investigations, undertaken by ORC on 7 March 2011, indicate that the scale of upper-catchment mass-movement activity has increased in recent decades, with the pronounced reactivation of slope movements or the development of fresh scars. Figure 2.3 shows a large area of recent slope movement at the location identified as *Photo C1* in Figure 2.2. Intense-rainfall events, greater than 20mm/hour, in February 2011 and December 2010, are likely to have contributed to the reactivation of this slip, as well

[1] The mean annual rainfall at Makarora over the period 1967 to 2010 was 2400mm.

as progressive incision of the toe by Pipson Creek. Historic aerial photography (Appendix 1) indicates that this slip area has been periodically active in the past.

Figure 2.3 also shows *Photo C2* (Figure 2.2) of the upper catchment slopes on 7 March 2011. Steep fresh, gullying of bedrock in the head of the catchment shows that large clasts of material are being actively supplied to the Pipson Creek channel throughout the upper catchment.

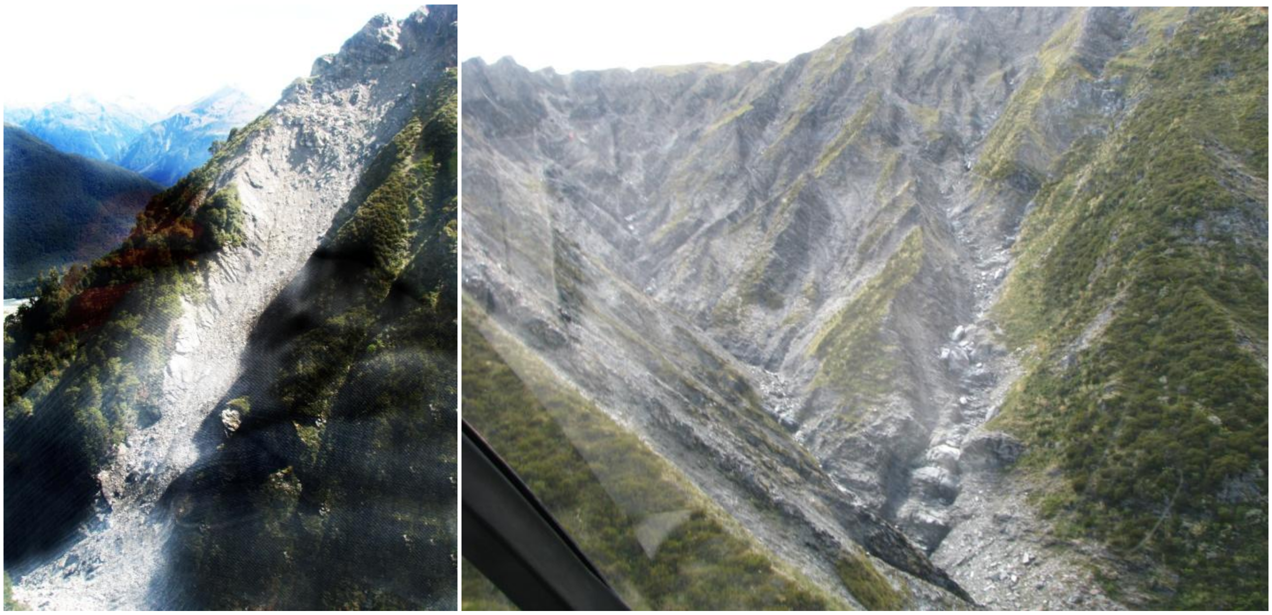


Figure 2.3 Photo C1 (left) and Photo C2 (right), showing recent mass movement in the upper catchment of Pipson Creek on 7 March 2011

The lower Pipson Creek catchment (Figure 2.2) is typified by steep rock faces, which have a predominant cover of dense bush. The channel at this location is confined and often incised to bedrock; conditions that are favourable for the efficient conveyance of debris flow. Two sediment-source areas (Figure 2.4), described in Opus (2004), contribute significant volumes of sediment and debris to the main channel during periods of high, intense rainfall. These sediment-source areas have formed as a result of channel incision by Pipson Creek over-steepening adjacent slopes. Historic aerial photography indicates that these rock-fall features have formed and developed within the last 50 years. Opus (2004) note that these locations are the primary source areas which have contributed to debris flows on the fan surface. Observations in March 2011 indicate that these rock-fall features are still being actively eroded and continue to provide large volumes of material to Pipson Creek.

Field observations indicate that the majority of the Pipson Creek catchment is dominated by mass-movement processes. An increased level of instability has been observed in the catchment over the last 50 years, a phenomenon that continues today.

Figure 2.4 Pipson Creek lower-catchment primary-source areas. The main source area, as identifed by Opus (2004), is viewed on the left, while the secondary source area is shown on the right

2.3 Fan characteristics

Pipson Creek has formed a symmetrical semicircular fan, with a stream that 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 typified by silty-sheet flood deposits. Deposits from larger debris flows extend to the Makarora River (Barrell *et al*., 2009).

Figure 2.5 shows the Pipson Creek alluvial fan and key features. Channel incision varies along the length of the alluvial fan. Near the topographic apex of the fan, where the creek leaves the confines of the valley, the channel is confined by outcrops of bedrock in places, and is incised by greater than 10m (Figure 2.6-P1). Erosion of both banks is common in this reach of the creek, as debris flows pass through efficiently due to the channel's confinement and steep gradient. The greater the distance from the source catchment, the less incised the channel becomes, mainly due to a significant reduction in channel gradient. Much of the Pipson Creek channel, as depicted by Figure 2.5, is less than 2m incised into the natural-fan surface.

As the creek continues downstream, it begins to adopt a slight meander pattern, moving from left to right. This pattern contributes to the super-elevation of bed levels next to the respective banks of the channel (Figure 2.6-P2) and can result in avulsion (break-out) of the channel across other parts of the fan surface (Figure 2.5). In addition, the concave aspect of each meander is subjected to the greatest velocities from debris and flood flow, which induces erosion of unconsolidated bank materials (Figure 2.6-P3). Observations from March 2011 identified a number of locations where Pipson Creek had avulsed from its channel onto the adjacent fan surface, as shown in Figure 2.6-P4.

ORC (2007), using dendro-chronological techniques, identified a large palaeo-channel on the southern margins of the fan surface. The oldest trees in this location were established during the 20th century, indicating that this channel has been active in recent geological times. The current channel is incised by greater than 5m below the adjacent level of the head of this palaeo-channel at present (Figure 2.6-P1).

In the lower reaches of the fan, there is little elevation difference (freeboard) between the natural channel level and the level of the surrounding alluvial-fan surface. As shown in Figure 2.5, the channel has been considerably modified by in-channel excavation and works downstream of the SH 6 bridge.

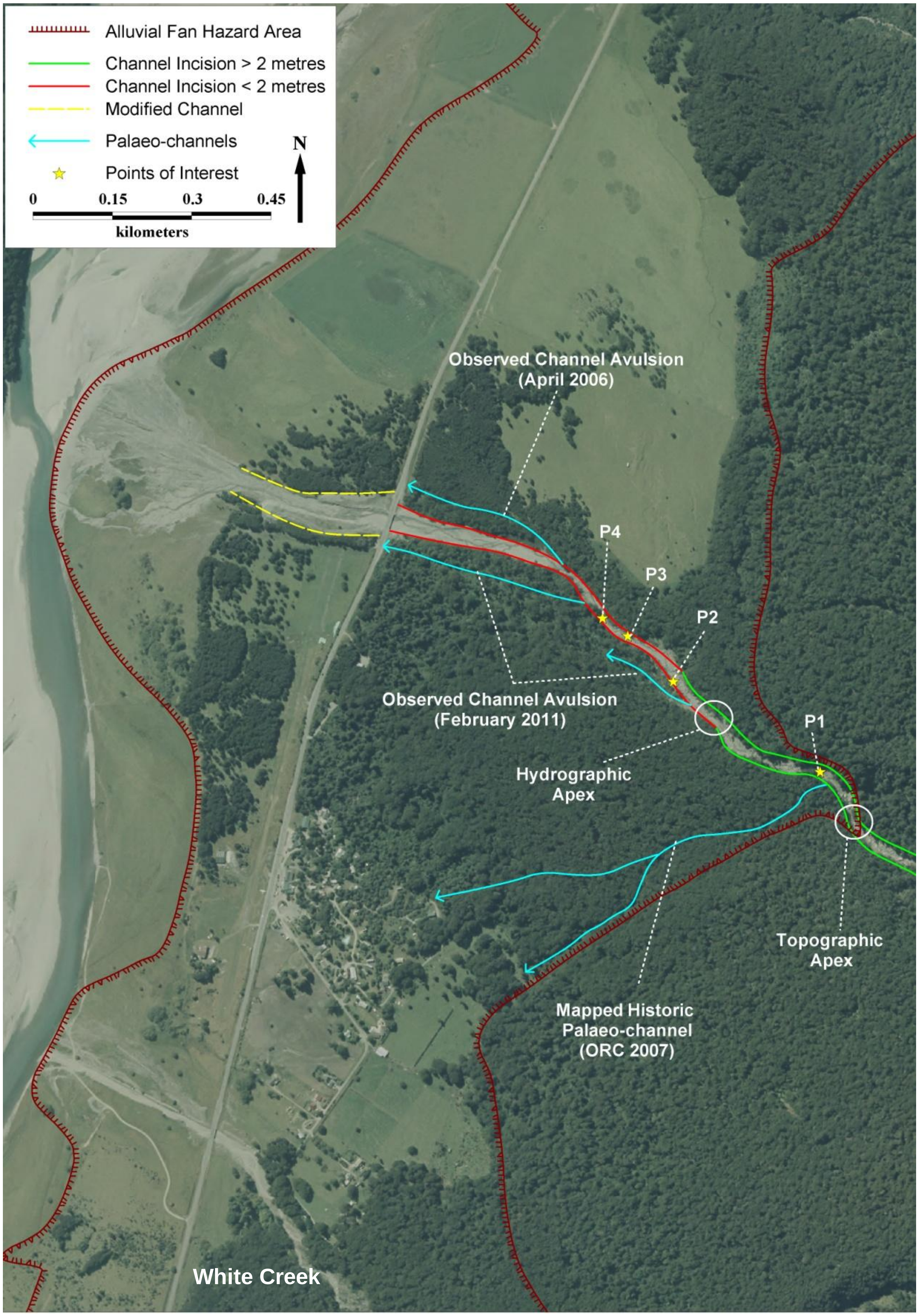


Figure 2.5 Pipson Creek alluvial fan, noting some key alluvial fan features; aerial photo dated March 2006

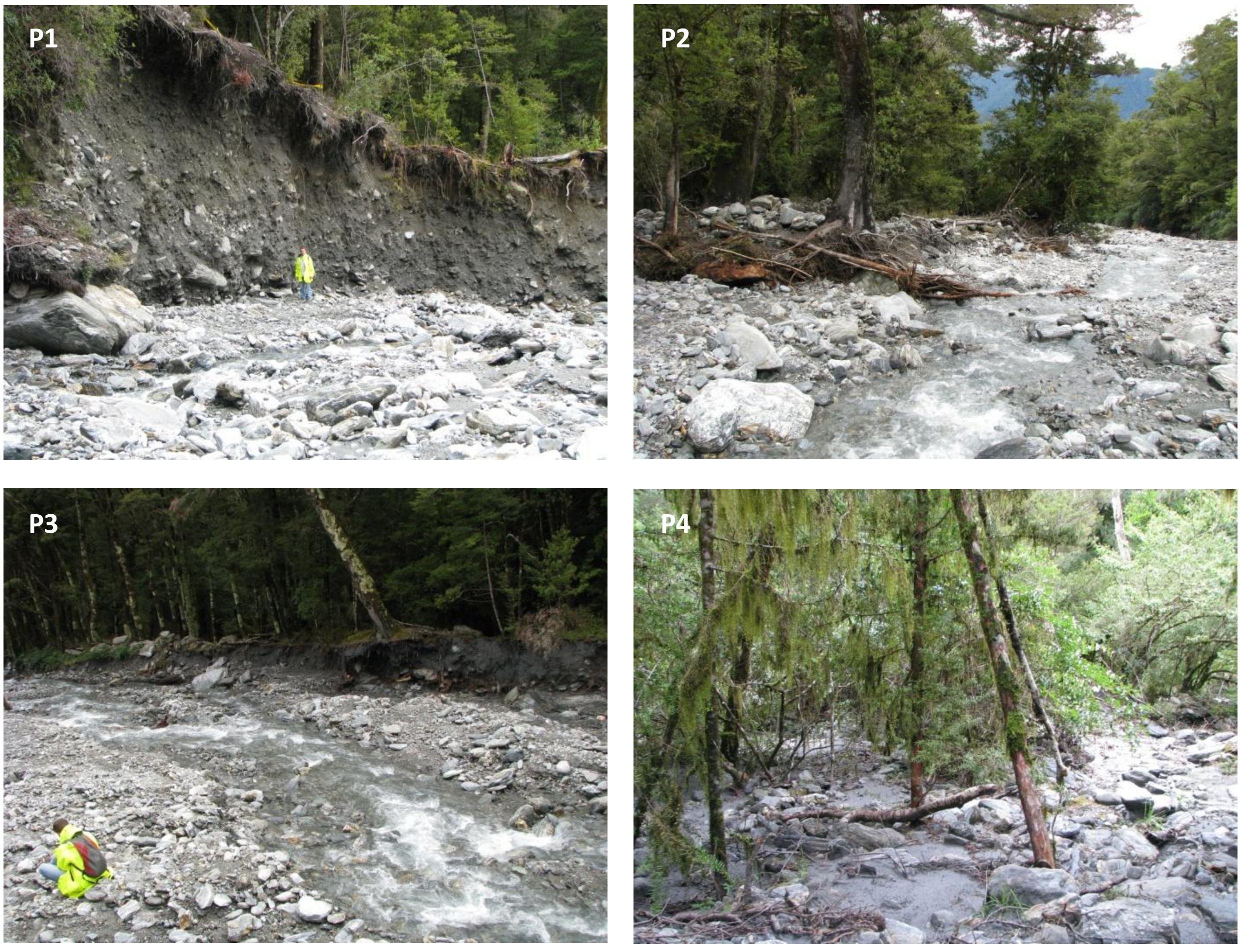


Figure 2.6 Photographs relating to the points of interest identified in Figure 2.5. P1 shows greater than 10m of channel incision into the alluvial-fan surface near the fan-topographic apex. P2 shows super-elevation of the true right of the Pipson creek bed, causing avulsion onto the true-left alluvial-fan surface. P3 shows the concave aspect of a slight channel meander, inducing erosion of the true-right bank. P4 shows deposition on the alluvial-fan surface as a result of Pipson Creek avulsing from its channel.

2.4 Pipson Creek alluvial-fan hazard

Debris and flood flows have been well documented on the Pipson Creek alluvial fan in recent decades (Table 2.1). Figure 2.7 shows in-channel aggradation and channel avulsion resulting from large debris and debris-flood flows.

The alluvial-fan hazards associated with Pipson Creek generally consist of high-velocity-debris and debris-flood flows, channel avulsion, bank erosion and floodwater 'sheet-flow' inundation. Upper parts of the fan are subject to high-velocity debris flow where the channel is currently confined and steep. As the fan and channel gradients change downstream, debris-flood deposits are more common, with considerable channel aggradation occurring during and in the immediate recession of the debris-flow event. In these reaches and downstream, bank overflow and channel avulsion is common on both the left and right banks, with less than 2m of channel incision (Figure 2.5). Downstream of the SH6 bridge floodwater inundation in the form of 'sheet-flow' is more common, depending on the size of the event.

Rates of catchment erosion have accelerated in recent decades, which has been reflected in large debris-flow events impacting the fan surface. Due to the scale of catchment instability, it is anticipated that debris-flow events will continue in this manner into the foreseeable future.

Table 2.1 Total rainfall and maximum intensity measured at the Makarora rainfall gauge and observed effects on Pipson Creek. The Makarora rainfall gauge is located approximately 2km south of Pipson Creek, at around 320m above sea level. Older observations sourced from Opus (2004). All events list in this table impacted and/or covered the SH 6 bridge.

Date	Rainfall total	Max. rainfall intensity	Event
February 2011	129.5mm (22 hours)	21.5mm/hr	True-left channel break-out upstream of bridge. Highway inundated.
December 2010	123mm (36 hours)	26.5mm/hr	
January 2008	123mm (18 hours)	18mm/hr	Highway inundated.
April 2006	59.5mm (18 hours)	13mm/hr	Break-out of channel on both banks upstream of bridge. Highway inundated.
March 2004	78.5mm (9 hours)	13.6mm/hr	Break-out of channel on both banks upstream of bridge. Highway severely inundated.
February 1998	70.5mm (9 hours)	8.5mm/hr	Break-out of channel on both banks upstream of bridge.
December 1995	Gauge relocated	Gauge relocated	
September 1995	Gauge relocated	Gauge relocated	Break-out of channel on both banks upstream of bridge.
January 1994	Gauge relocated	Gauge relocated	
December 1989/ January 1990	Gauge relocated	Gauge relocated	

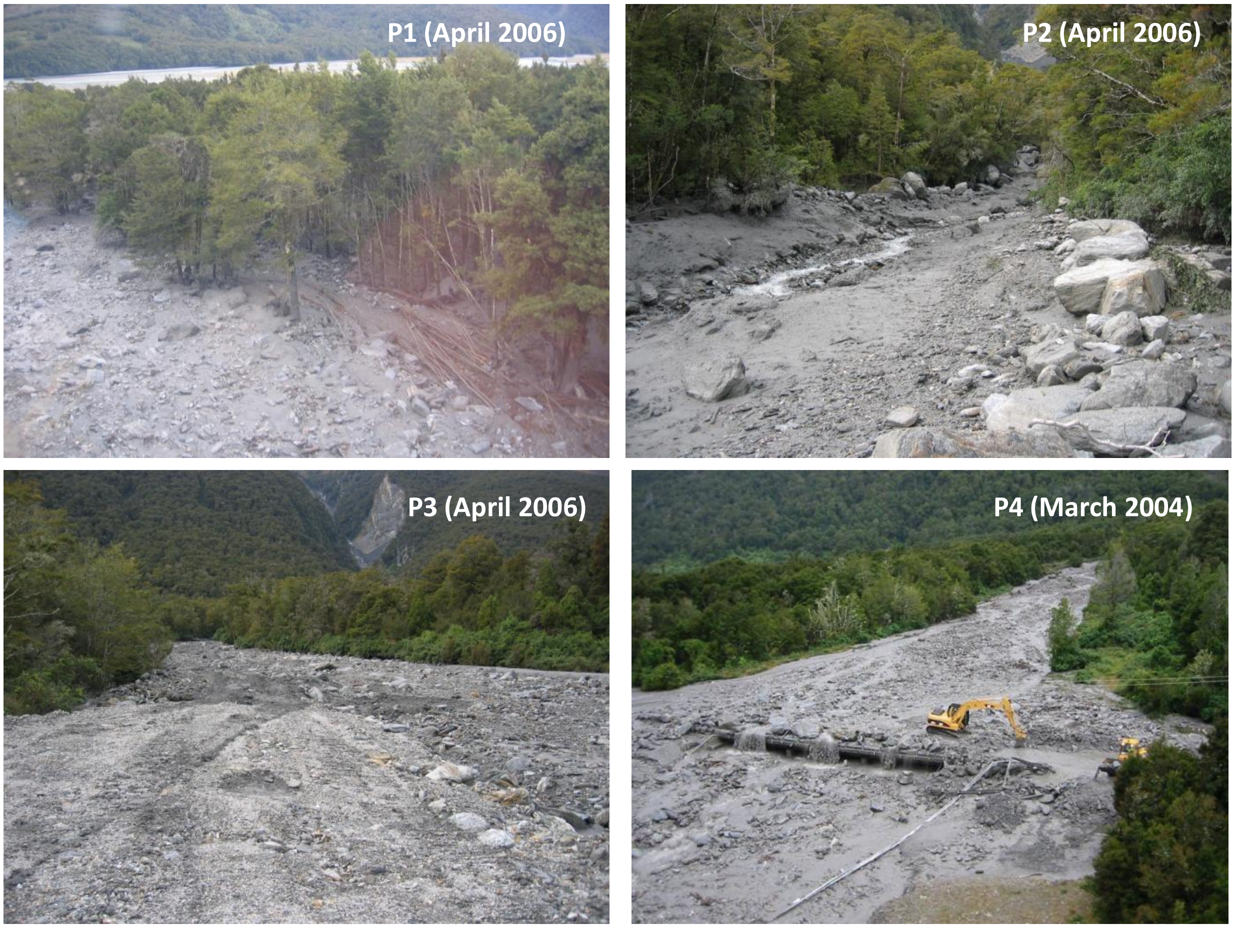
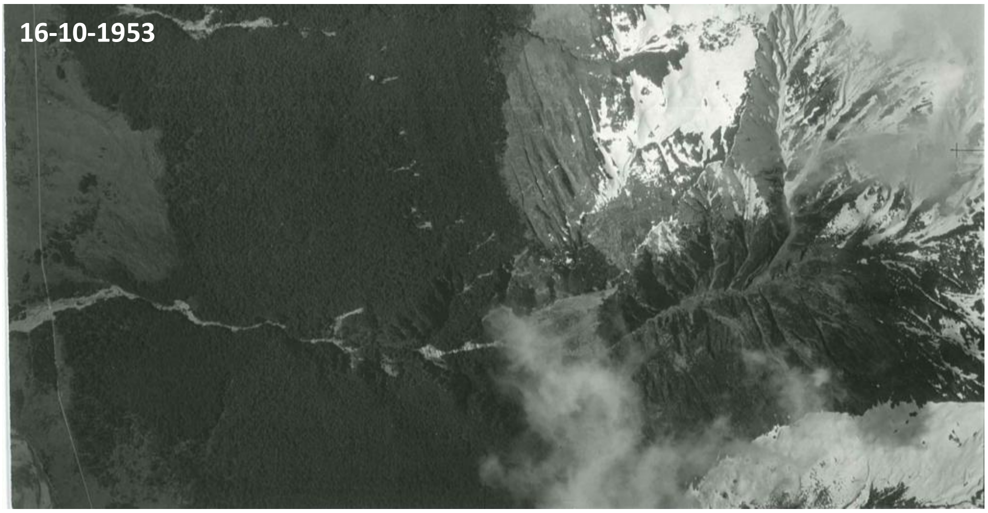


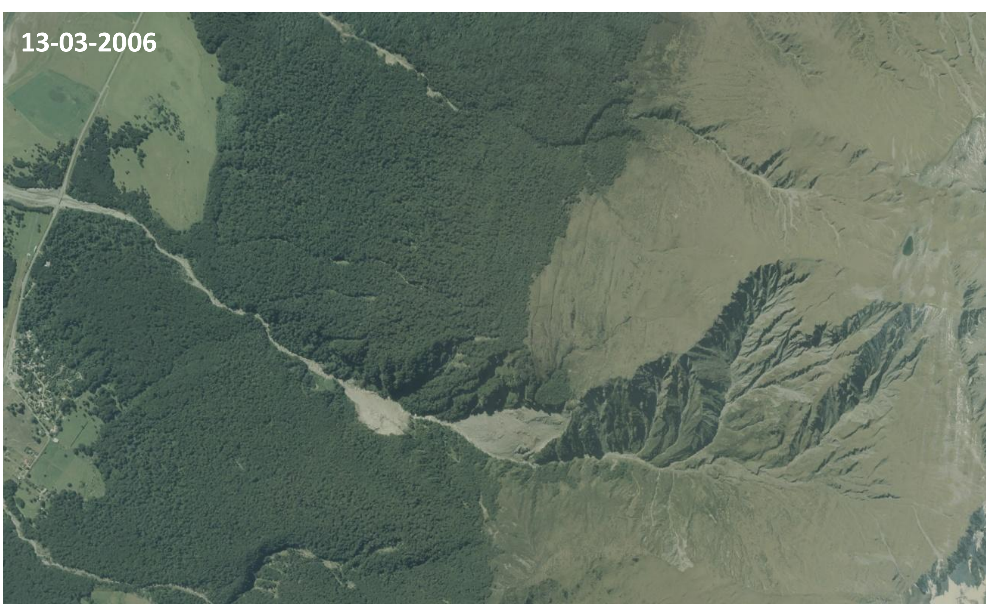
Figure 2.7 Pipson Creek, following large debris flows in 2004 and 2006. Photo P1 shows significant bank overflow on the true-right channel upstream of the SH6 bridge. Photo P2 shows large levee embankments formed on the outside of the channel, which are indicative of high-velocity-debris flows on the upper fan. Photo P3 shows bank-full conditions upstream of the SH6 bridge, after debris flow in 2006. Photo P4 shows bank-full conditions, upstream of the SH6 bridge, after debris flow in 2004.

Debris-flow events in Pipson Creek will recur, as has been observed in recent times. Channel aggradation, erosion, bank overflow and avulsion will occur in varying magnitudes, depending on the nature and characteristics of the storm event and condition of the catchment. It is likely that bank overflow and aggradation will occur in those locations where channel incision is less than 2m and further upstream in very large events. While the fan is heavily forested, woody debris and trees often exacerbate the possible effects of debris flow and cannot be relied upon as suitable mitigation.

It is noted that a level of risk exists for the Makarora West community from debris flow derived from Pipson Creek. Should a large sediment input cause the channel to aggrade considerably at the head of the alluvial fan, there is potential for Pipson Creek to avulse and re-occupy or form new channels in the direction of the Makarora West community. In addition, flows that avulse from the channel further down the fan may also re-occupy palaeo-channels towards parts of the community.

Historic Aerial Photographs
Pipson Creek, Makarora





3. Flaxmill and Oturaki creeks, Makarora

3.1 Environment setting

Located at the head of Lake Wanaka, the Makarora Valley (Figure 3.1) is a geologically young landscape, having been occupied by glaciers during the last glacial period, as discussed in Section 1.2. Incised into the western flank of the McKerrow Range, the Flaxmill and Oturaki creek catchments flow east to west from an elevation of 1944m at Mt Constitution, in the Flaxmill Creek catchment, to around 400m near the apices of the alluvial fans. The Makarora East community is located on the southern margin of both alluvial fans next to SH 6. As with Pipson Creek, the state highway bisects both fans and is the only direct route from Otago to the West Coast, via Haast Pass. The remaining parts of both alluvial fans are dominated by pastoral farmland.

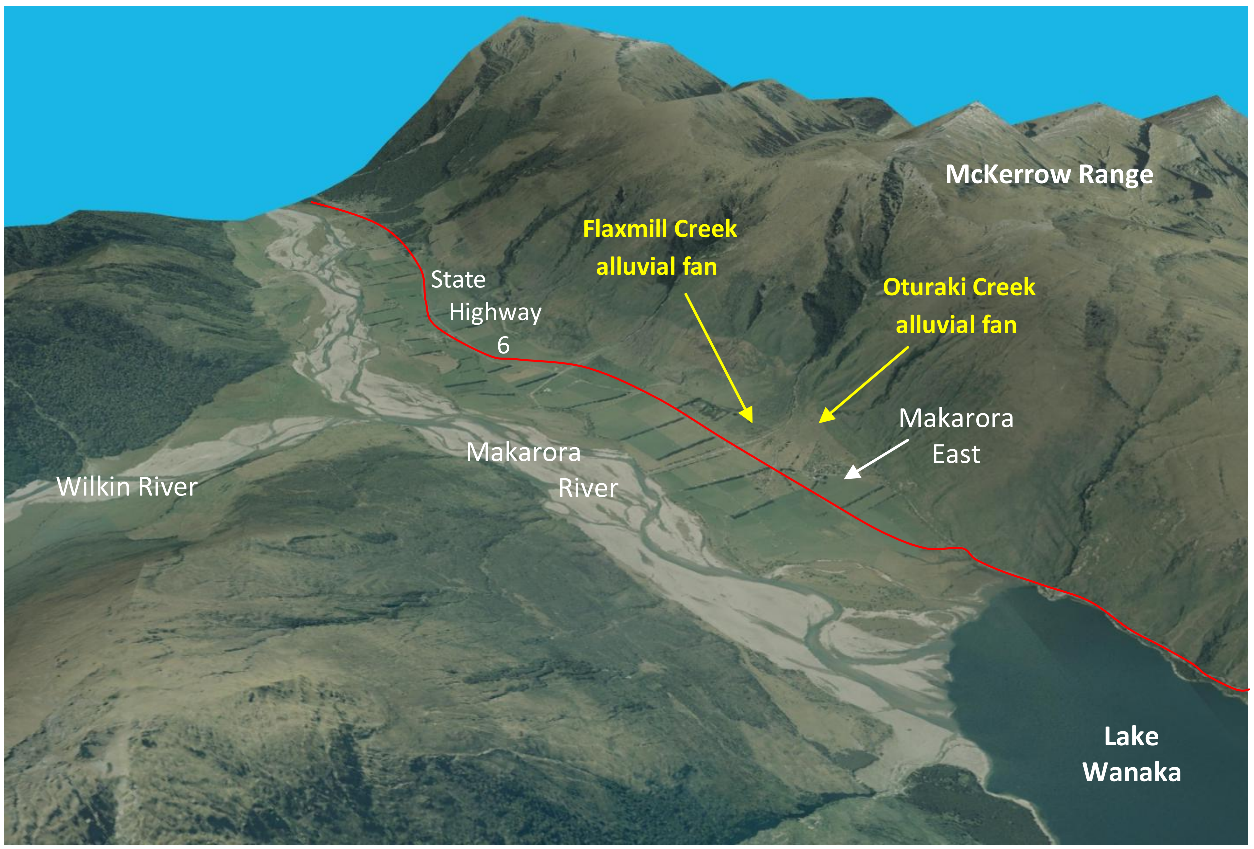


Figure 3.1 Image showing the lower Makarora Valley at the head of Lake Wanaka

3.2 Catchment characteristics

The Flaxmill and Oturaki creek catchments are shown in Figure 3.2 and have catchment sizes of 3.1 and 0.8km^2, respectively. Like Pipson Creek, the upper slopes of both catchments are defined by high-altitude, mountainous terrain, with small bushes and alpine tussocks being the dominant vegetation cover. Slope processes in this part of the catchments are dominated by mass movement, including creep, slumping and gullying, with many fresh scarps, signifying widespread instability. Persistent mass movement is dominant on the true-right (northern) slopes of the catchment, consistent with the dip of the underlying schist bedrock. The true-left (southern) slopes of each catchment are dominated by creep processes and surficial gullying of exposed bedrock. These slope conditions, coupled with the erodible nature of the underlying schist and intense, high rainfall of the area, provide mechanisms for the direct supply of high sediment loads to each creek's channel.

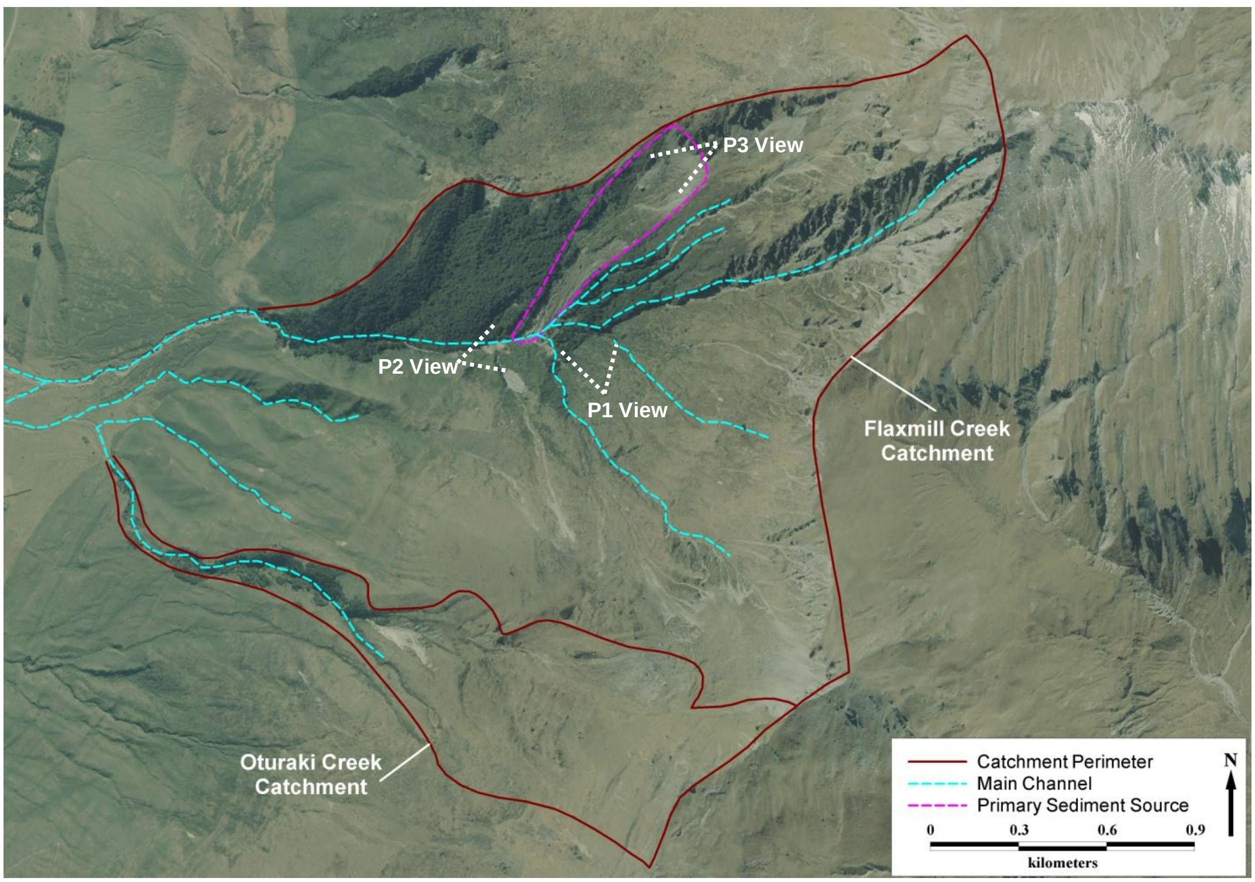


Figure 3.2 The Flaxmill and Oturaki creek catchments; aerial photo dated March 2006

Field investigations, undertaken by ORC on 7 March 2011, indicate that a primary-sediment-source area in Flaxmill Creek (Figure 3.2) is actively providing sediment to the channel (Figure 3.3). The absence of vegetation on this slip area, particularly when compared to 2006 aerial photography (Appendix 1), indicates that it has been active during the period 2006 to 2011. Intense rainfall events, greater than 20mm/hour, in February 2011 and December 2010, have likely contributed to the reactivation of this slip, as well as progressive incision of the toe by Flaxmill Creek.

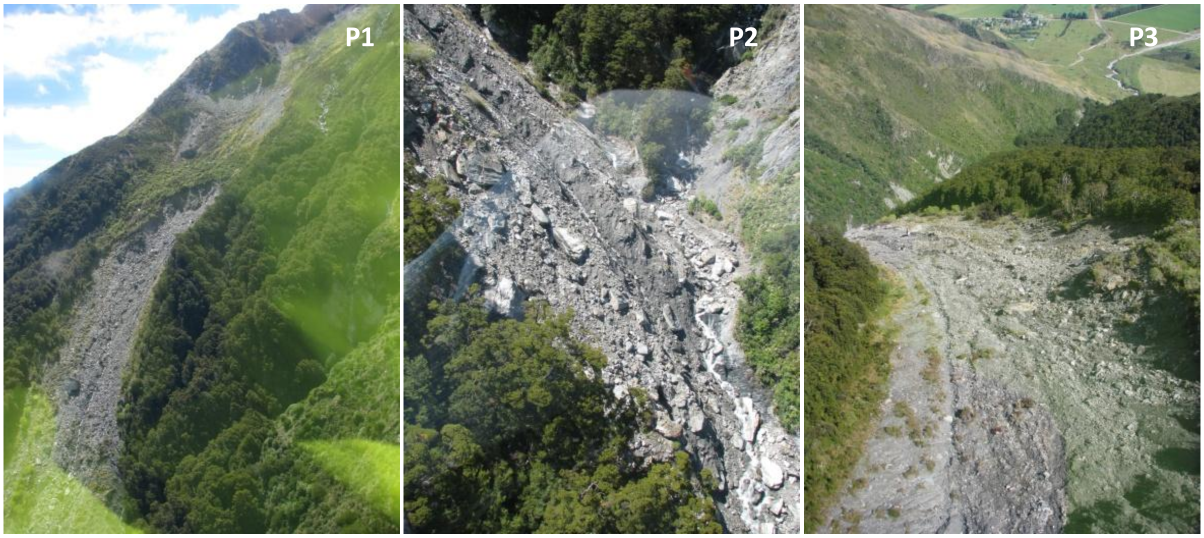


Figure 3.3 The primary-sediment-source area in the Flaxmill Creek catchment on 7 March 2011, as annotated in Figure 3.2. Photo P1 shows the fresh face of this slip area, leading up to the head of slide where instability has been initiated. P2 shows the toe of the primary-source area and shows incision by Flaxmill Creek. The fresh slip face is observed in Photo 3, indicating the recent removal of material.

Aerial photography from 1953 indicates that instability in the Flaxmill Creek catchment was not as active at that time. The primary-sediment-source area (Figure 3.2) was largely vegetated and not actively supplying significant quantities of sediment to the channel. By 1999, this area was very active.

The Oturaki Creek catchment similarly indicates a rather benign level of catchment instability in 1953, compared to the increased fresh scarps evident in 1999 (Appendix 1).

3.3 Fan characteristics

Flaxmill Creek has formed a symmetrical semicircular fan, with a stream that 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 typified by silty-sheet flood deposits. Oturaki Creek has also created an alluvial fan that coalesces with the Flaxmill Creek alluvial fan.

Figure 3.4 shows Flaxmill and Oturaki creeks' alluvial fans and key features. Channel incision varies along the length of the Flaxmill Creek alluvial fan. Near the topographic apex of the fan, where the creek leaves the confines of the valley, the channel is incised by between 3-5m (Figure 3.5). In this reach of the fan, the channel is subject to rapid aggradation during storm events, as observed in Figure 3.5. Such aggradation has historically induced avulsion of the channel, spilling debris flows across the true-left alluvial-fan surface, with large lobate-debris deposits observed in this location. In addition, large palaeo-channels exist (Figure 3.5), where flow has historically been transferred down the southern part of the fan surface. The true-right fan surface is elevated above the true left in this location, as mapped in Barrel *et al*. (2009).

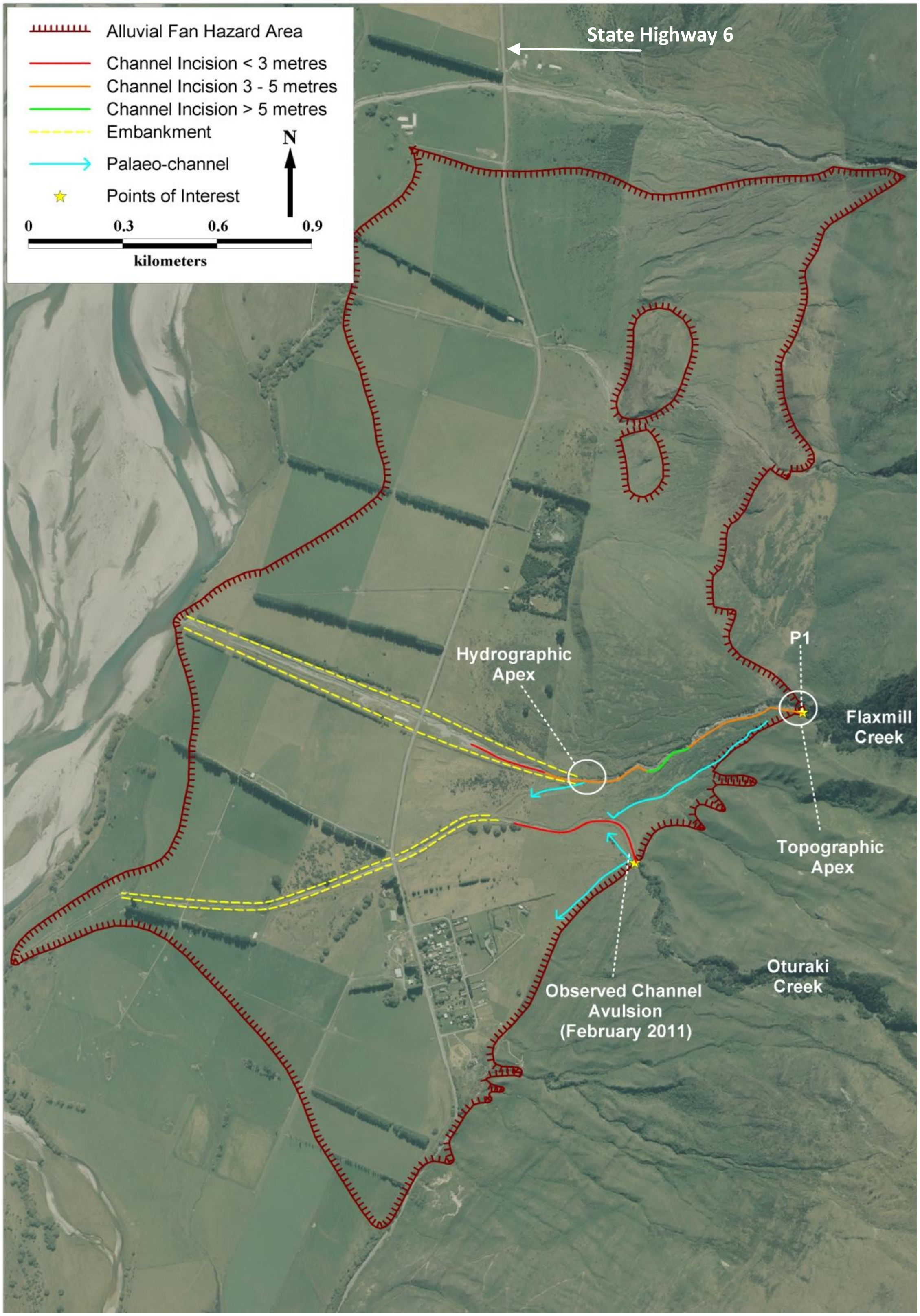


Figure 3.4 Flaxmill and Oturaki creek alluvial fans, noting some key alluvial fan features; aerial photo dated March 2006

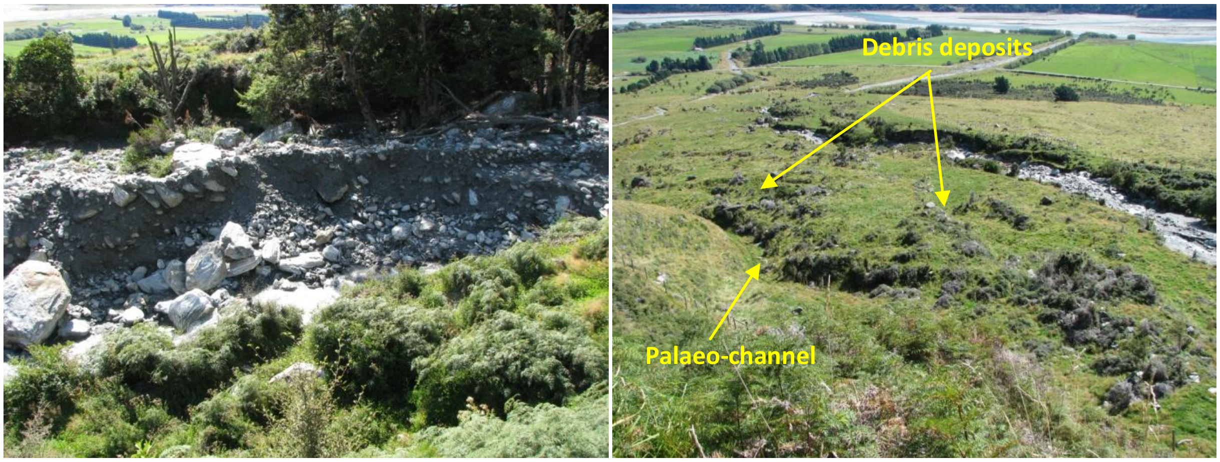


Figure 3.5 Flaxmill Creek alluvial fan just downstream of P1, as shown on Figure 3.4. At this location, metres of recent channel aggradation (left) have been incised by the active channel. Large debris deposits and palaeo-channels (right) are located on the true-left surface of the alluvial fan.

Downstream, the Flaxmill Creek alluvial fan is incised into its surface by greater than 3m, until its hydrographic apex is reached, where the fan becomes less than 3m incised. At this location, channel avulsion is common, as observed in January 1994 (Figure 3.6). Where the channel has less than 1m incision, channel aggradation commonly results in avulsion. In the lower reaches, Flaxmill Creek is confined by informal embankments that are subject to aggradation and erosion; these embankments are easily breached during large flood events, as observed in January 1994.

Oturaki Creek has a fan area much smaller than Flaxmill. However, it still has the potential to transfer debris and floodwaters beyond the state highway, as shown in Figure 3.6. Observations in March 2011 indicate that the channel of Oturaki Creek has little to no incision of the fan surface (Figure 3.7). Channel aggradation at the head of the fan is common, with avulsion of the channel onto the true-left alluvial-fan surface observed in March 2011. Avulsion along the length of the channel (Figure 3.4) is likely to continue in the future. The true-left surface of the alluvial fan is dissected by a number of historic palaeo-channels (Figure 3.4), many of which flow towards the Makarora East township.

Figure 3.6 Flaxmill and Oturaki creeks, following the storm event of January 1994

Figure 3.7 Channel aggradation at the head of the Oturaki Creek alluvial fan (left) and channel avulsion and sediment deposition down the true left of the fan, March 2011 (right)

3.4 Flaxmill Creek alluvial-fan hazard

Debris and flood flows have been well observed on the Flaxmill Creek alluvial fan in recent decades. Figure 3.6 shows considerable in-channel aggradation and channel avulsion, from debris and debris-flood flows in January 1994.

The alluvial-fan hazards associated with Flaxmill Creek generally consist of high-velocity-debris and debris-flood flows, channel avulsion, bank erosion and floodwater 'sheet-flow' inundation. Upper parts of the fan are subject to high-velocity debris flow where the channel is currently confined and steep. As channel gradients lessen downstream, debris-flood deposits are more common, with considerable channel aggradation occurring during and in the immediate recession of the debris-flow event. In these reaches, and downstream, bank overflow and channel avulsion is common on both the left and right banks, with less than 3m of channel incision (Figure 3.4). Downstream of the SH6 bridge, floodwater inundation in the form of 'sheet-flow' is more common, depending on the size of the event.

Debris-flow and flood events in the Flaxmill Creek catchment are the result of prolonged and/or high-intensity rainfall events in the upper catchment. Mass-movement processes and slope instability are widespread in the catchment, with large areas of active landslides contributing high-sediment loads to the active channel. Due to the scale of catchment instability, it is anticipated that debris-flow events will continue in this manner into the foreseeable future.

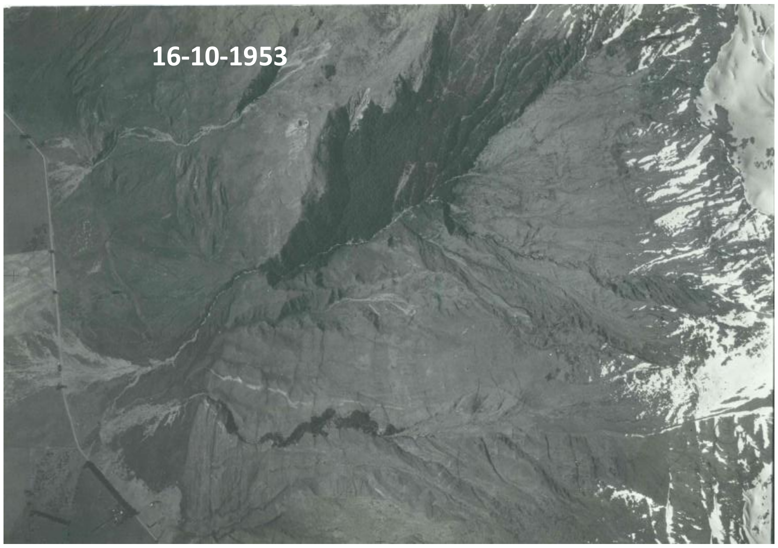
Channel aggradation, erosion, bank overflow and avulsion will occur in varying magnitudes, depending on the nature and characteristics of the storm event and the condition of the catchment. It is likely that bank overflow and aggradation will occur in those locations where channel incision is less than 3m, and further upstream in large events. It is noted that a level of risk exists for the Makarora East community from debris flow derived from Flaxmill Creek.

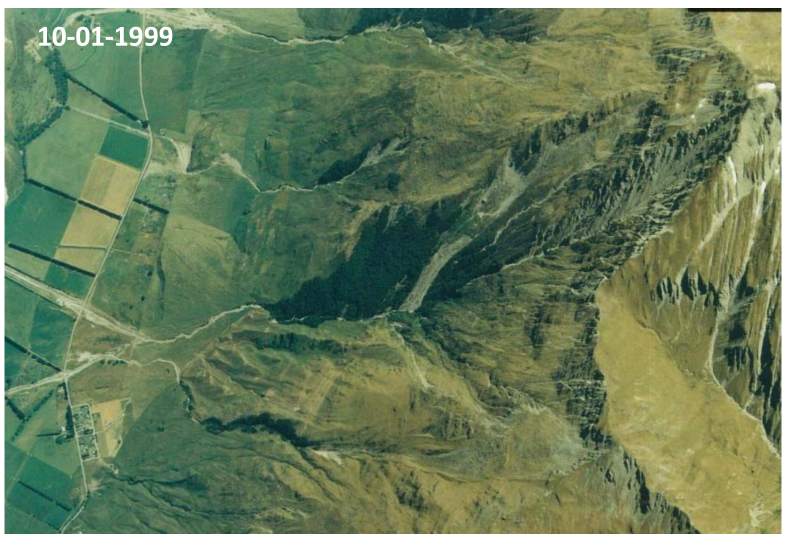
3.5 Oturaki Creek alluvial-fan hazard

The Oturaki Creek alluvial fan is superposed onto the greater Flaxmill Creek alluvial fan. The alluvial-fan hazards associated with this creek are largely aggradational, where recurring debris and debris-flood flows deposit sediment across the fan surface. Due to very little channel incision, the creek has the potential to migrate and avulse across the fan surface, as observed in Figure 3.7.

The lateral migration of channels was well observed in January 1994, with large areas of the fan surface being subjected to flows and subsequent sedimentation (Figure 3.6). In the lower reaches, the fan is more susceptible to floodwater inundation processes and is likely to reoccupy palaeo-channels on the southern margins of the fan in the future.

Historic Aerial Photographs
Flaxmill and Oturaki creeks, Makarora





4. Johns Creek, Grandview Range

4.1 Environment setting

Located at the southern end of Lake Hawea, the Hawea Basin (Figure 4.1) is a geologically young landscape, having been occupied by glaciers during the last glacial period, as discussed in Section 1.2. Incised into the western flank of the Grandview Range, the Johns creek catchment flows east to west, from an elevation of 1456m at Breast Peak, to around 420m, where the channel leaves the confines of the valley. Most of the fan surface is dominated by pastoral farmland, with some farm and ancillary buildings near the head of the fan. On the fan's lower margins, the creek is bound on both banks by a small community at Gladstone. Just upstream of the community, Gladstone Road crosses Johns Creek by way of a ford.

Figure 4.1 Image showing the location of the Johns Creek alluvial fan in the Lake Hawea Basin

4.2 Catchment characteristics

The Johns Creek catchment is approximately 11km^2 in size (Figure 4.2). The catchment is generally defined by high-altitude, mountainous terrain, with small bushes and alpine tussocks comprising the dominant vegetation cover. Slope processes in this part of the catchment are dominated by mass movement, including creep, slumping and gullying, with many fresh scarps, signifying widespread instability. Slope instability is widespread at the head of the catchment, particularly on northern-facing slopes, where slopes are mantled with landslide debris, which is being eroded and transported to the valley floor (Figure 4.3-P1). These slope conditions, coupled with the erodible nature of the underlying schist, provide conditions for the direct supply of sediment to the active channel.

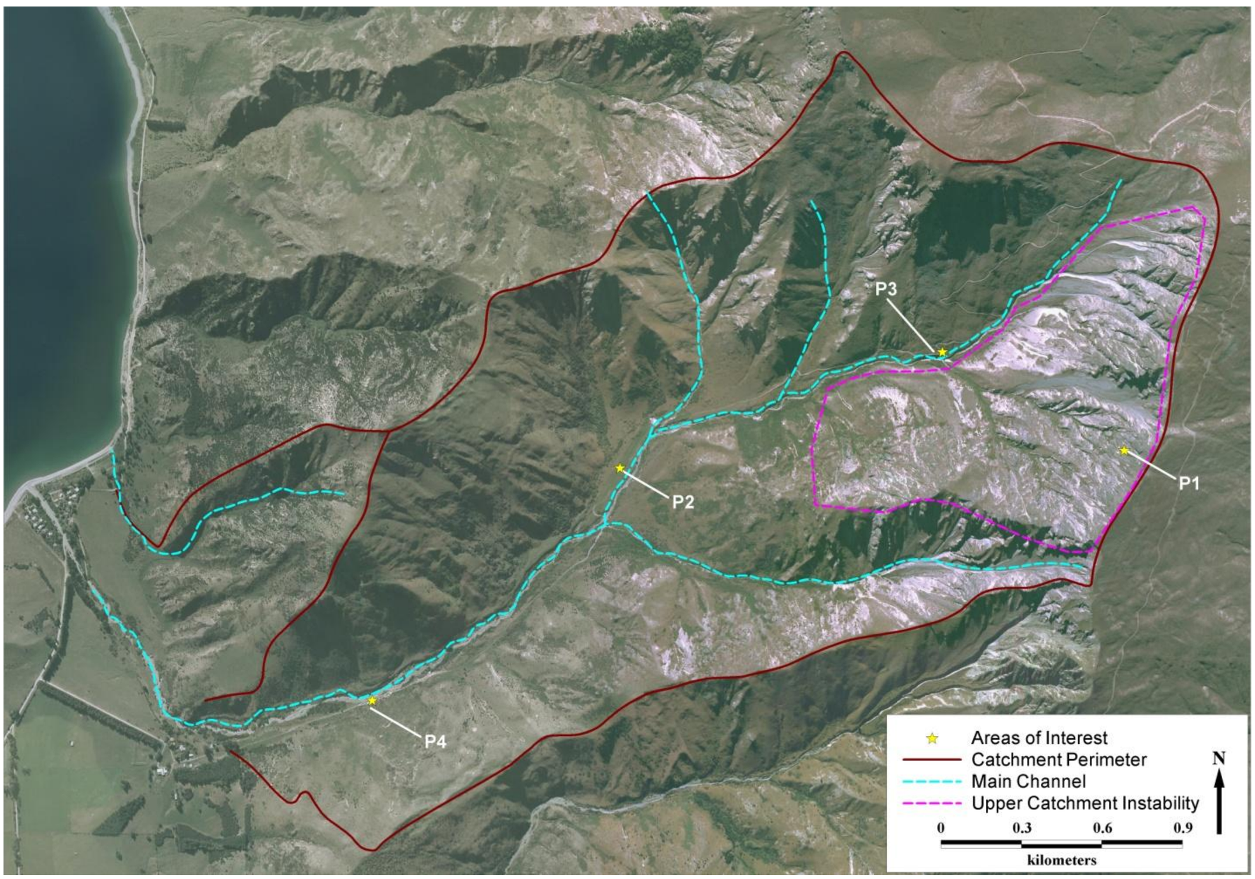


Figure 4.2 The Johns Creek catchment, noting sites of interest; aerial photo dated April 2005

The valley floor of the Johns Creek catchment is very well incised into basement schist, which is reflected in the relatively shallow 14% grade of the channel between the head of the fan and location P3 (Figure 4.2). These conditions have allowed the deposition of large amounts of sediment within the catchment's active channel, probably on the recession of debris-flow events (Figure 4.3-P4). Subsequent to their deposition, the contemporary channel has incised into these deposits, reworking the sediments downstream. The widespread erosion and instability of slopes, coupled with bed and bank erosion in the Johns Creek catchment, provide large quantities of unconsolidated sediments conducive to the initiation of debris flows.

Figure 4.3 Photographs relating to the points of interest identified in Figure 4.2. P1 shows persistent mass movement on northern-facing slopes at the head of the Johns Creek catchment. P2 shows the wide valley setting of the Johns Creek catchment and incised channel into mid-catchment fan deposits. P3 shows chaotic landslide debris on the catchment's true right, where these deposits are being actively eroded by the creek. P4 shows a close-up of incision in the channel mid-catchment.

4.3 Fan characteristics

Johns Creek has formed a semicircular fan that coalesces with the large Grandview Creek fan on its southern margin. Due to the presence of the Grandview Creek fan, much of the Johns Creek alluvial-fan activity has been confined to the northern half of the fan, where the contemporary channel is located today. Sediment-laden flood flows and intermittent-debris flows occur on the fan surface. Sediment is transported across the fan surface, but is also eroded from the bed and banks of the creek.

Figure 4.4 shows the Johns Creek alluvial fan and key features. Channel incision varies along the length of the alluvial fan. The true-right bank is incised into the higher fan surface by greater than 5m downstream of the topographic apex. Just upstream of the topographic apex, in P1, overbank deposition was observed in a number of locations, where debris flows have reached elevations above the existing bank height (Figure 4.5-P1). This phenomenon becomes less prevalent as the creek turns northwards and becomes more incised into the wider fan surface. Downstream of this location, the true-left bank of the fan becomes less incised, with less than one metre incision between the current channel level and adjacent topography, as observed in P2. The channel in this reach is wide and heavily laden with fresh sediment and debris, indicating that it is often active. In this reach, a palaeo-channel is situated on the left bank, where flow can be transferred a considerable distance behind earth embankments to lower parts of the fan.

At P4, the creek is impounded by an elevated ford, which depending on its formation, may redirect flow towards adjacent banks. Downstream of the ford, the channel is confined by informal embankments that consist of unconsolidated sediments excavated from the creek. On the true-left bank, a palaeo-channel, approximately the same level as the current channel, is present. Elevated above this palaeo-channel are residential properties some 2-3m higher than this channel (P5). Residential properties are also present on the true-right bank downstream of the ford (P6).

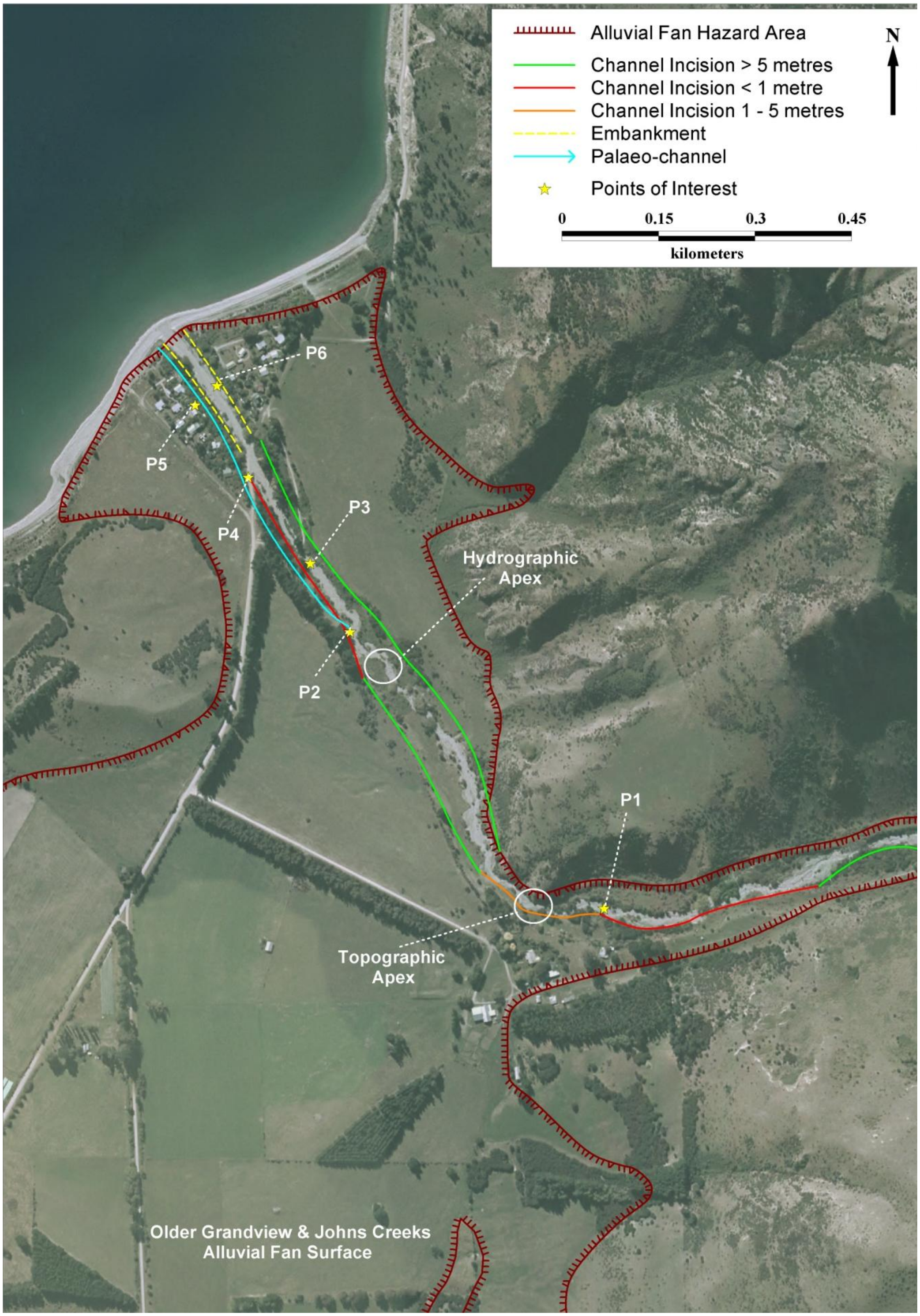


Figure 4.4 Johns Creek alluvial fan, noting some key alluvial fan features; aerial photo dated April 2005

Figure 4.5 Photographs relating to the points of interest identified in Figure 4.4

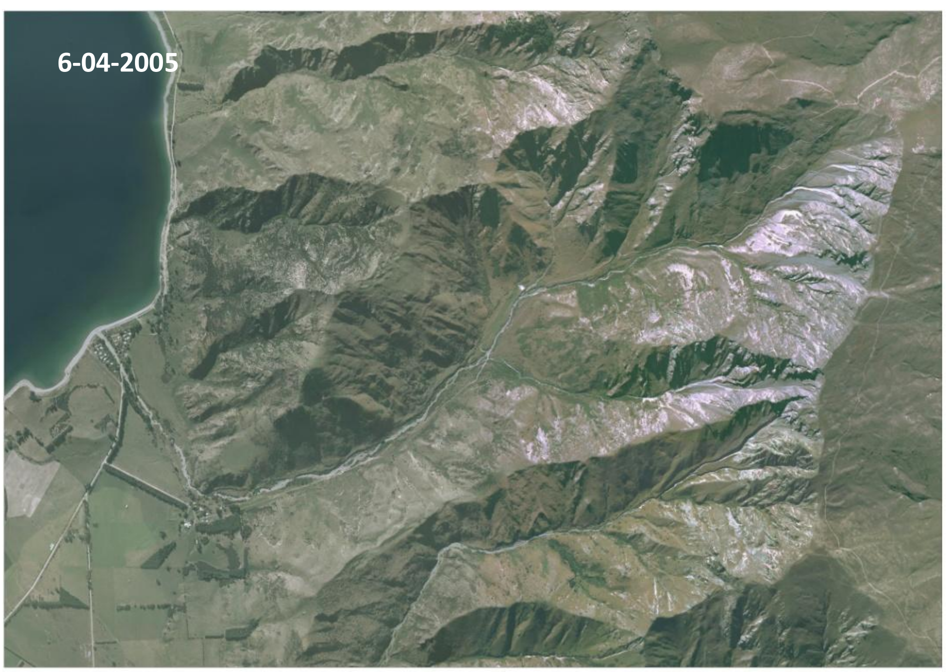
4.4 Johns Creek alluvial-fan hazard

While generally confined to the active channel, debris and flood flows are a regular occurrence on the Johns Creek alluvial fan. Sediment-laden debris-flood flows rework the bed and banks of the channel that comprise pre-existing alluvial fan deposits. These flows are efficiently transported through the upper reach of the alluvial fan where the channel is incised by greater than 5m. On lower parts of the fan, avulsion of the channel is probable on the true-right bank, with the reactivation of palaeo-channels and lateral migration of flows across the fan surface likely in large events.

Debris flows and flood events in the Johns Creek catchment are the result of prolonged and/or high-intensity rainfall events in the upper catchment. Mass-movement processes and slope instability is widespread in the catchment, with large areas of active landslides contributing high-sediment loads to the active channel. In the lower catchment and on the valley floor, the erosion of old-fan deposits and the bed and banks provide large amounts of sediment to induce debris-flood flows. Due to the large volume of sediment available to the active channel, it is anticipated that debris and debris-flood flows are likely to continue into the foreseeable future in this catchment.

Channel aggradation, erosion, bank overflow and avulsion will occur in varying magnitudes, depending on the nature and characteristics of the storm event and condition of the catchment. It is likely that bank overflow and aggradation will occur in those locations where channel incision is less than 2m and in other locations during very large events. It is noted that a level of risk exists for properties located on the lower margins of the fan. While avulsion is probable on the left bank, properties are generally located on an elevated terrace, compared to the right-bank properties, which have very little distinguishing elevation change from the contemporary channel level.

Historic Aerial Photographs
John's Creek, Grandview Range



5. Stoney Creek, Wanaka

5.1 Environment setting

Located near the southern shores of Lake Wanaka, the Wanaka Basin (Figure 5.1) is a geologically young landscape, having been occupied by glaciers during the last glacial period, as discussed in Section 1.2. The Stoney Creek catchment headwaters are incised into the eastern flank of the West Wanaka ranges, which include Roys Peak and Mount Alpha, and range in altitude from 1160-1320 metres above sea level (masl). The creek's outlet flows into Lake Wanaka at an elevation of 288m at the western end of Roys Bay.

Historically, the Stoney Creek alluvial fan has been used intensively for pastoral farming. An increasing demand for development and residential properties in the Wanaka district has subjected the fan to urban encroachment, whereby the lower fan margins have been developed. The often ephemeral state and benign appearance of the creek does not give a full appreciation of the potential alluvial-fan hazard, as observed in November 1999 and January 2004.

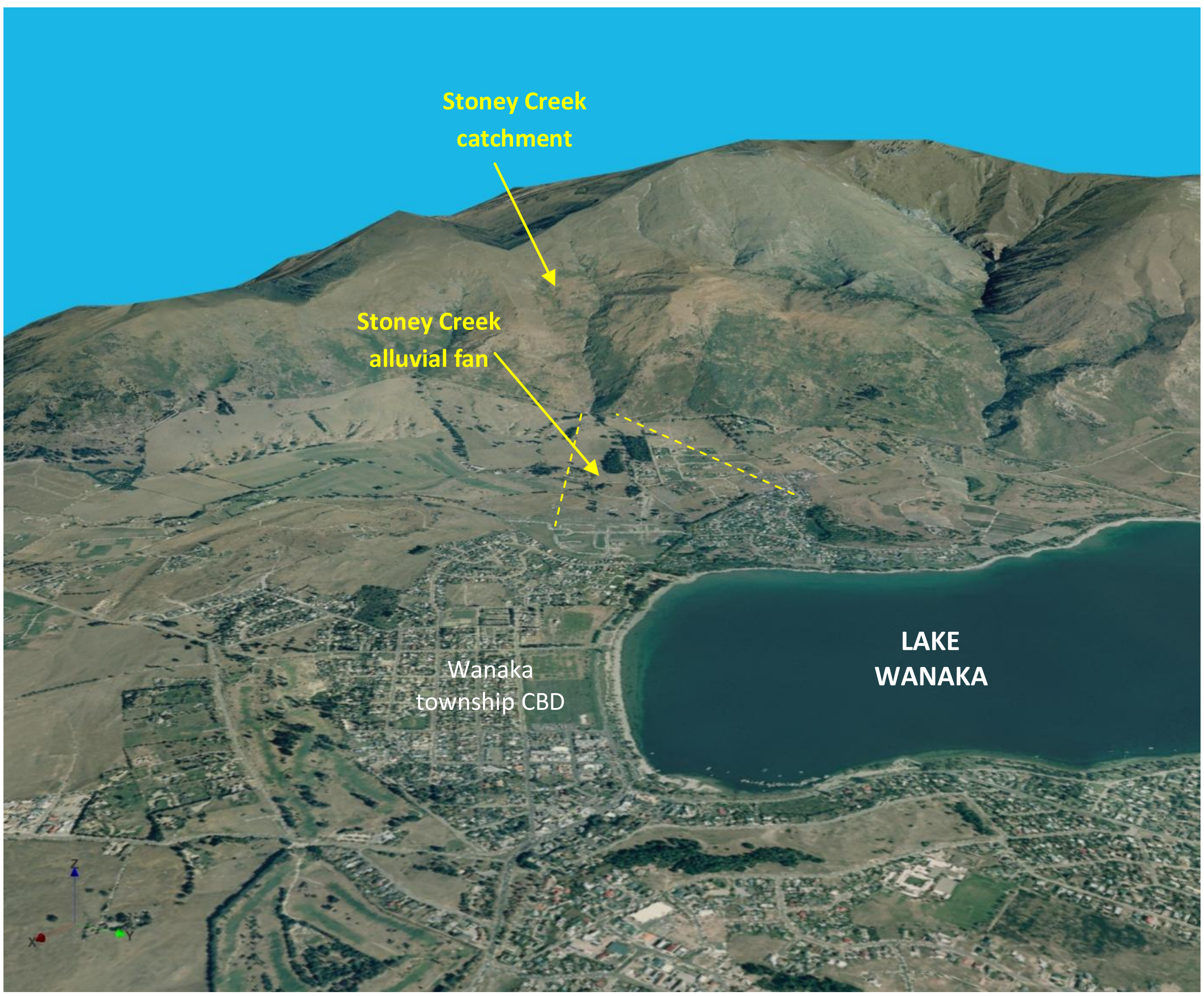


Figure 5.1 Image showing West Wanaka, including the Stoney Creek catchment and indicative fan area. The Wanaka CBD is situated in the lower-centre of the image.

5.2 Catchment characteristics

The Stoney Creek catchment is approximately 1.6km^2 in size. The upper catchment of Stoney Creek is formed in a large landslide, with a headwall that extends into the upper Waterfall Creek catchment. Large (catchment-scale) and deep (>5m) landslides are extensive on slopes at higher elevations, with shallow (up to 2m) mass-movement features superposed onto these larger features. The depth of catchment instability reflects the depth of weathering on these slopes.

The predominant geomorphological processes in the catchment are mechanical weathering, erosion and mass movement. Mechanical-weathering processes are dominated by freeze-thaw, where the basement schist and overlying sediments are broken down by congelifraction (the freezing of interstitial water particles leading to expansion, fracturing and disintegration of particles). Slope deposits - consisting of schist clasts and gravel fines, derived from the basement schist - are interpreted to be a result of this freeze-thaw weathering process. Periglacial till or loess deposits have not been formally identified in this catchment; however, some gravel fines may have been derived from these processes.

These slope deposits are primarily transported downslope by mass-movement and erosion processes, such as slides, flows, gullying and rilling. In general, mostly fine gravels and silts are provided to the streams by these processes. However, the steep gradient of the upper catchment watercourses provides sufficient energy to transport large grain sizes, up to 5m in diameter, during storm events.

The ‘large wet slide’ (Figure 5.2) on the true-left slopes of the catchment is shown in Figure 5.3. Following a magnitude 6.7 earthquake, 60km west of Milford Sound on 16 October 2007, parts of this slide were subject to surficial-debris flow, initiated by a sudden release of water in a pre-existing headscarp. Observations by ORC in November 2007 identified that this slide area is very active, with high groundwater levels and many surface channels. In addition, the toe of this slide area is being actively eroded by Stoney Creek.

On the evening of 30 January 2004, a storm event, concentrated above the Stoney Creek catchment, caused an upper channel of the Waterfall Creek catchment to aggrade and divert flow across the catchment divide into the Stoney Creek catchment (Figure 5.4). This phenomenon contributed sediment and flow to Stoney Creek exacerbating the alluvial-fan hazards downstream. Following this storm event, ORC undertook earthworks at the catchment divide to train the channel towards Waterfall Creek.

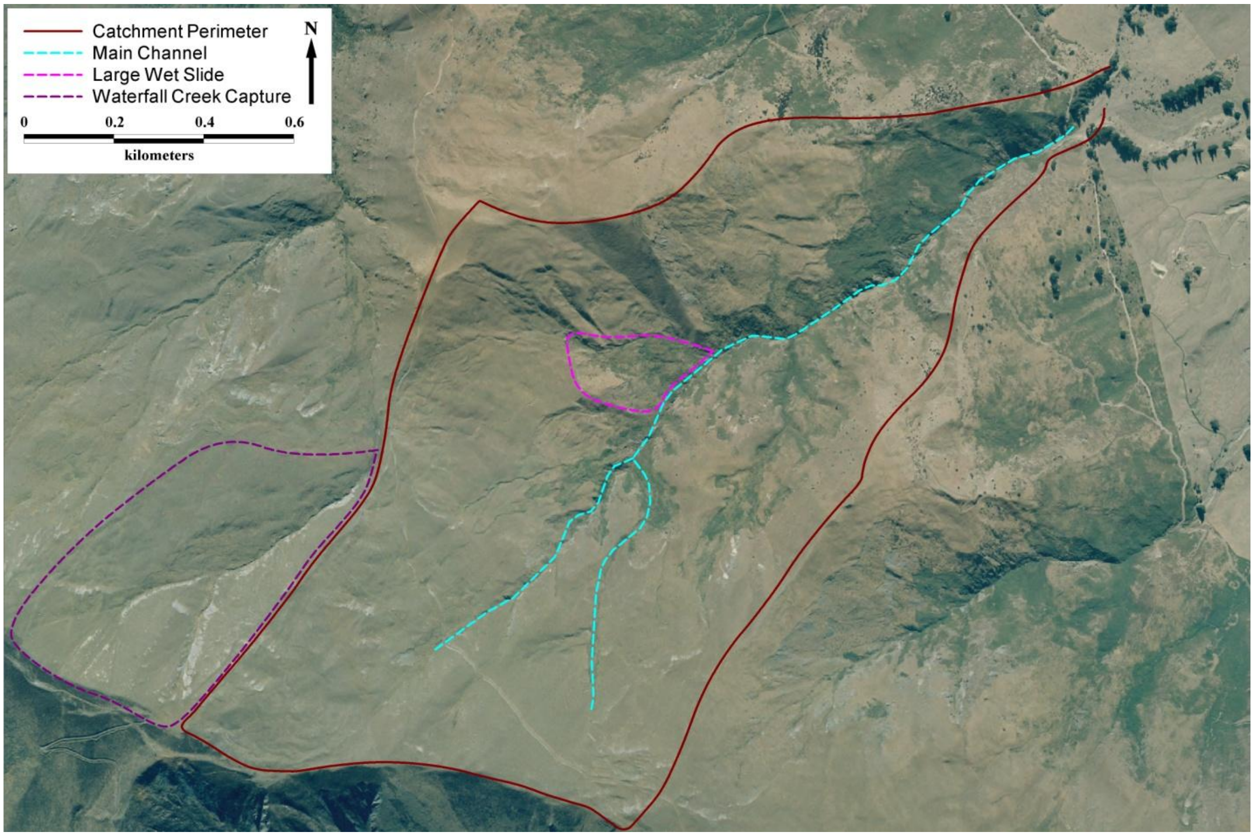


Figure 5.2 The Stoney Creek catchment, noting areas of interest; aerial photo dated March 2006

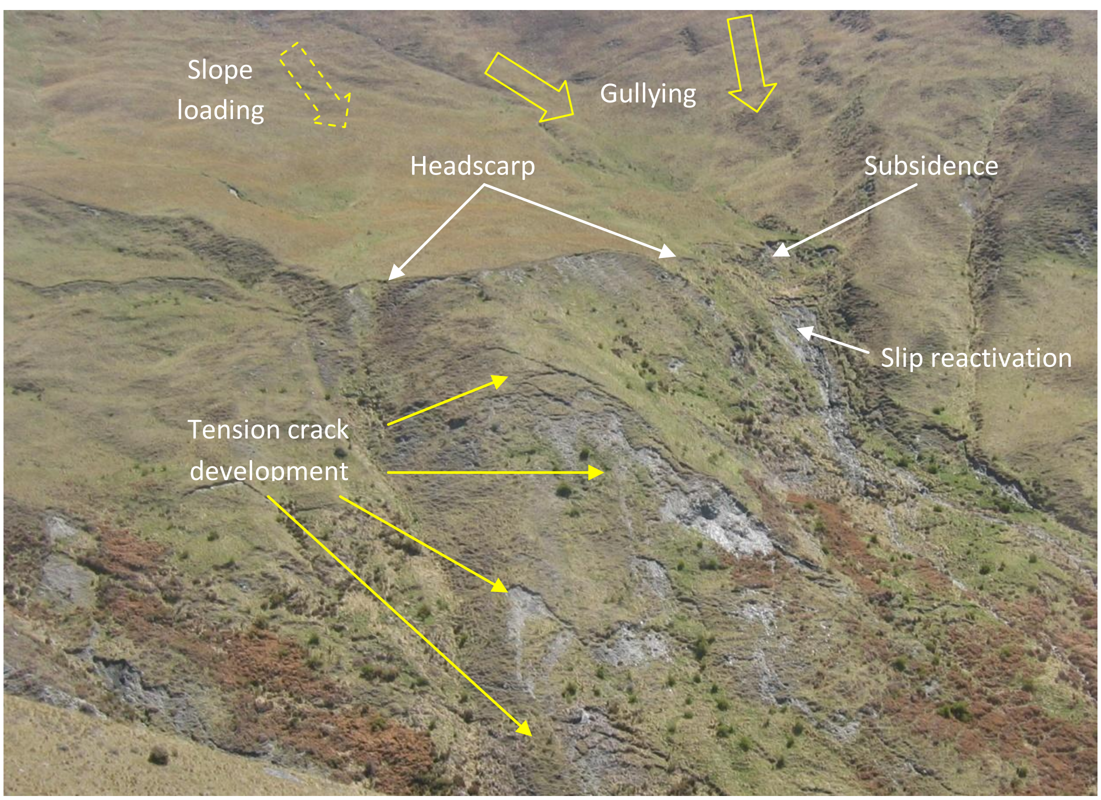


Figure 5.3 Catchment instability on true left of Stoney Creek, 6 November 2007

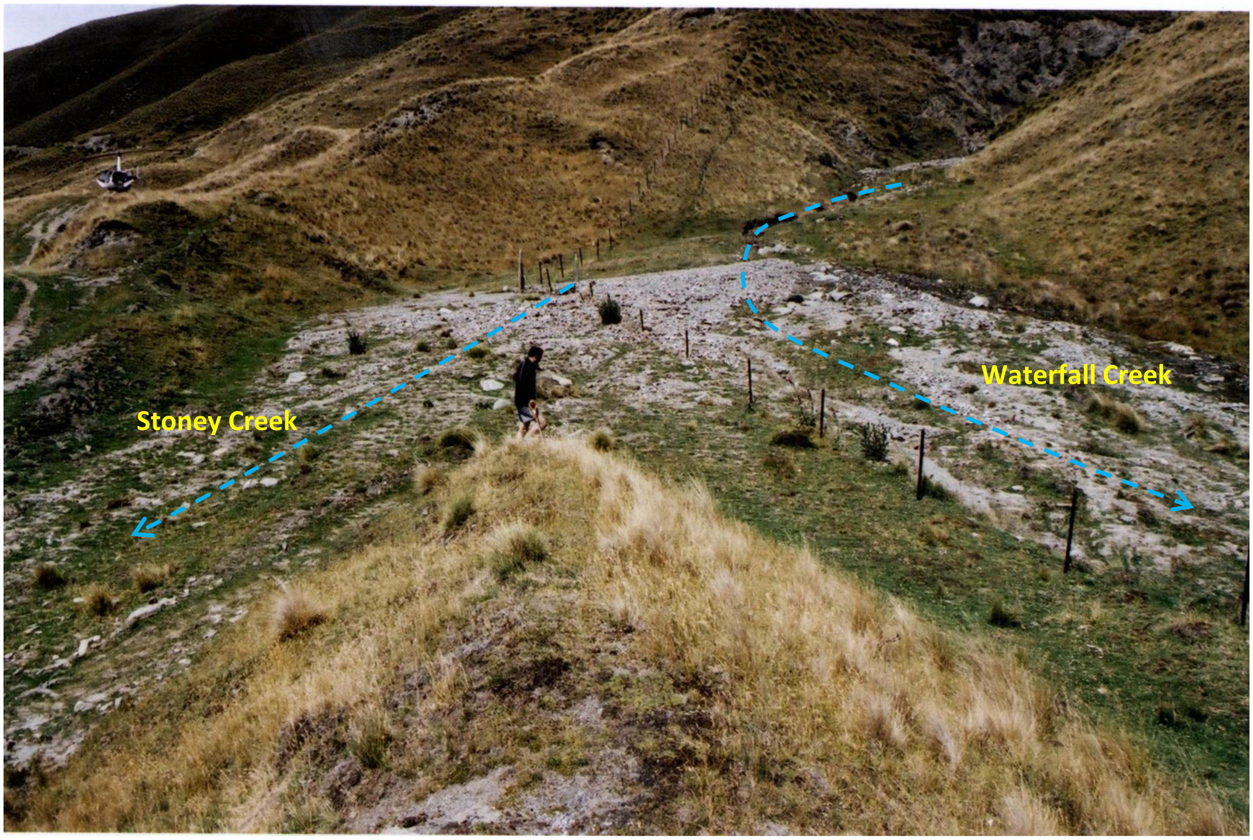


Figure 5.4 The headwaters of Waterfall Creek, where the creek switches across the catchment divide to enter the Stoney Creek catchment, taken shortly after the storm event of 30 January 2004

5.3 Fan characteristics

Stoney Creek loses energy where the catchment gradient decreases as it emerges onto the piedmont terrace at the head of the alluvial fan. The reduction in flow energy, and the loss of flow to groundwater beyond the valley confines, causes the stream to deposit most of its sediment load on the alluvial-fan surface. Due to the deposition of this sediment, the Stoney Creek alluvial fan is subject to lateral migration (avulsion) of channels as a result of channel aggradation or blockage during storm events. These conditions provide great uncertainty in regard to the location of future flow paths on the fan surface.

Stoney Creek currently occupies a central position on its alluvial fan (Figure 5.5). The topographic and hydrographic apex locations are at the head of the alluvial fan. Here, the stream is incised by up to 2m, but has migrated laterally from its current position in the past, as indicated by the presence of prominent palaeo-channels to the north and south. Downstream, the channel becomes less incised and has less than one metre incision for much of its length. Historic palaeo-channels, as a result of channel avulsion, are common across the fan surface where flood and/or debris flows have eroded new channels during storm events; a selection of large palaeo-channels is depicted in Figure 5.5.

The ORC has undertaken some hazard-mitigation works as part of the Stoney Creek Flood Protection Scheme, which has reduced the potential for avulsion and channel aggradation on parts of the Stoney

Creek alluvial fan. These works have included construction of a debris trap to promote debris detention to reduce the likelihood of channel aggradation on the lower fan, and channel-shaping works to provide sufficient capacity for the efficient transfer of design flows. These works and works by others have been undertaken in the area marked as 'modified channel' in Figure 5.5. The works by ORC are to a rural standard and to the minimum standard expected for an urban area.

5.4 Stoney Creek alluvial-fan hazard

As discussed, the often ephemeral state and benign appearance of Stoney Creek does not give a full appreciation of its potential alluvial-fan hazard. In November 1999 and January 2004, storm events in the catchment resulted in debris and flood flows across many parts of the fan surface, with the main channel being subject to avulsion, aggradation and erosion along its length (Figure 5.6).

The Stoney Creek alluvial-fan hazard area (Figure 5.5) has been derived from the active alluvial-fan areas mapped by Barrell *et al*. (2009) and those areas subject to alluvial-fan hazard identified by ORC in 2006. Barrell *et al*. (2009) identified areas that have been subject to sedimentation and debris deposition from past storm events and are still subject to these alluvial-fan processes. The ORC (2006) investigation identifies those locations that have a level of risk from Stoney Creek alluvial-fan hazards and includes areas that may not have been subject to easily identifiable sedimentation or debris deposition in the past. It is noted that the alluvial-fan hazard area depicted to the north merges with the hazard derived from the adjacent Waterfall Creek catchment.

Depending on the nature and characteristics of each storm event, any part of the hazard area may be subject to debris or debris-flood flows, channel avulsion, erosion or floodwater inundation. Upper parts of the fan are slightly more incised than downstream and will convey debris and flood flows more efficiently. As the fan and channel gradients lessen downstream, debris-flood deposits are more common with channel aggradation and avulsion more prevalent. These processes occur upstream of the existing works undertaken by the ORC.

The existing ORC channel works will have no effect on the extent and magnitude of alluvial hazards observed upstream of their current location (i.e. upstream of Studholme Road). This is also true for those parts of the fan that are impacted by debris and/or flood flows occurring as a result of channel avulsion on the upper fan. Future works in this reach of Stoney Creek may reduce the potential for channel avulsion and the extent of observed channel aggradation downstream.

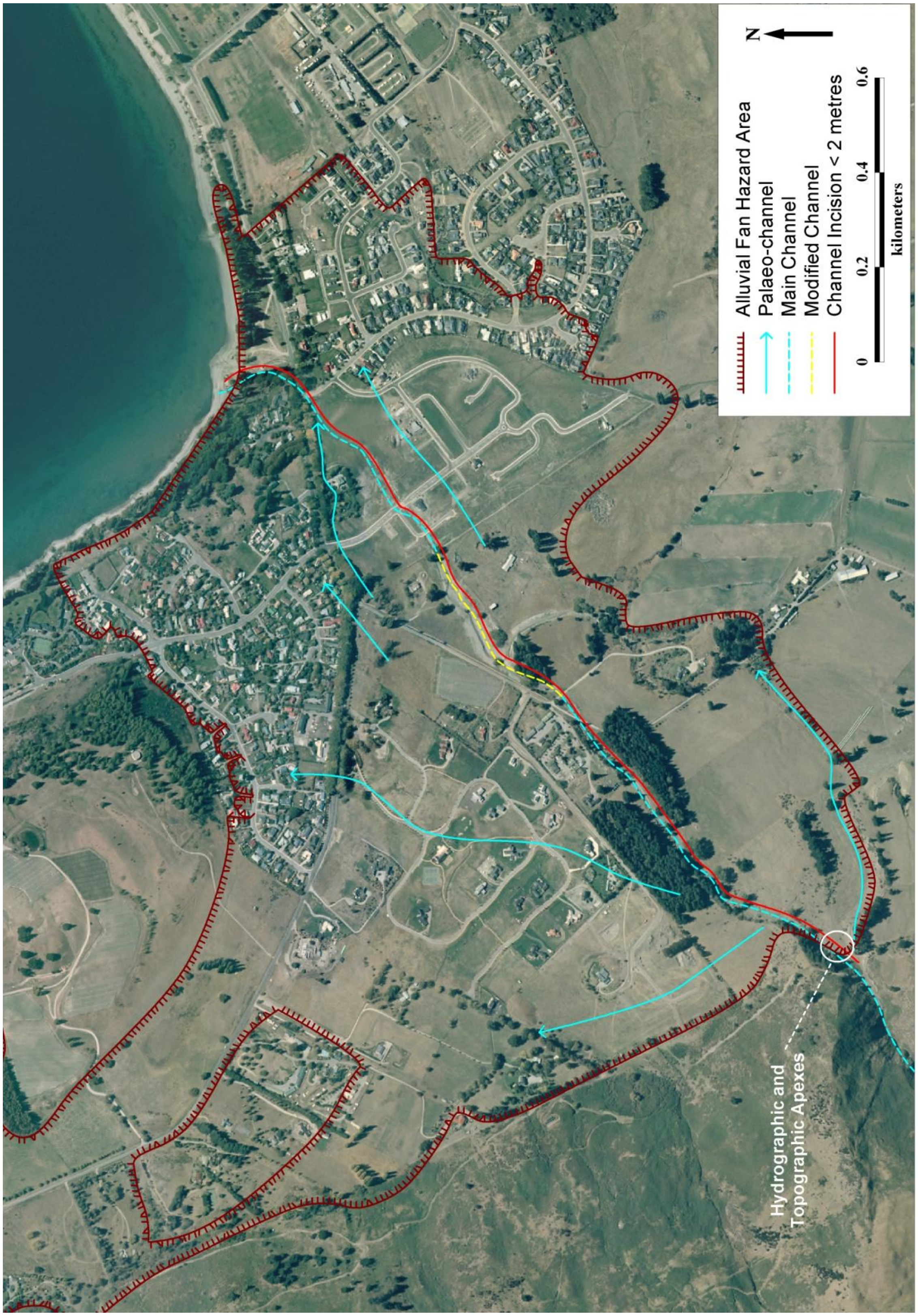


Figure 5.5 The Stoney Creek alluvial fan, noting the identified hazard area and other key features; aerial photo taken in March 2006

Figure 5.6 The effects of debris and flood floods derived from Stoney Creek in January 2004. Top left: Channel and bank erosion and overbank-debris deposition near the head of the alluvial fan. Top right: Channel aggradation and debris deposition in the Stoney Creek channel. Bottom left: Channel aggradation near Studholme Road resulting in channel avulsion and a build-up of sediment against adjacent fencing. Bottom right: Channel and bank erosion near the Stoney creek outlet at Lake Wanaka

Historic Aerial Photographs
Stoney Creek, Wanaka

6. Waterfall Creek, Wanaka

6.1 Environment setting

The Waterfall Creek catchment is located on the eastern flank of the mountain group that includes Roys Peak and Mount Alpha, to the west of Wanaka. The creek flows east to west, from an elevation of 1630m at Mt Alpha, to around 360m at the topographic apex of the alluvial fan. The catchment is typical of a 'hanging valley' created by a buttressing glacier during the last glacial period. Here, channel incision in the catchment of Waterfall Creek has not occurred at a rate efficient enough to erode the base level of the catchment to the equivalent level of the surrounding glacial basin. Therefore, as the creek exits its catchment, it steepens in gradient considerably, creating a waterfall down to the contemporary alluvial-fan surface. Like Stoney Creek, the alluvial fan has been used historically for intensive pastoral farming, although has it not been subject to the same demand for urban or semi-urban encroachment.

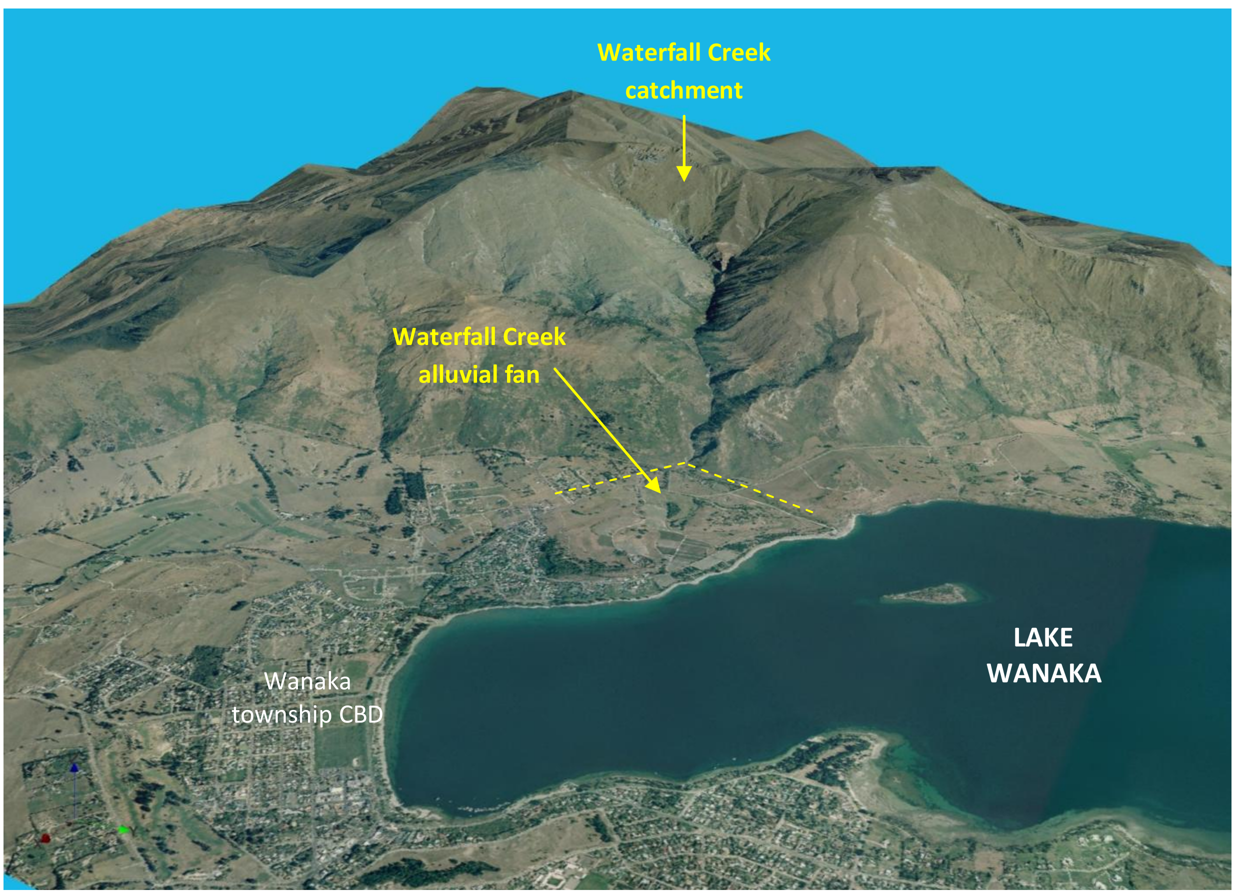


Figure 6.1 Image showing West Wanaka, including the Waterfall Creek catchment and indicative fan area. The Wanaka CBD is situated in the lower-left of the image.

6.2 Catchment characteristics

The upper Waterfall Creek catchment is defined by high mountainous terrain, with small bushes and alpine tussock being the dominant vegetation cover (Figure 6.2). Slope processes in this area are dominated by mass movement, with creep, slumping, gullying and fresh scarps, signifying instability (Figure 6.3). Large-scale mass movement is dominant on east to south-east facing slopes, consistent with the dip of the underlying schist foliation; while north to north-east facing slopes exhibit undulating hummocky terrain. These conditions provide mechanisms for the direct transportation of high-sediment loads to the channel. In-channel slumping on steep gradients and an abundance of freshly formed scarps are common in this part of the catchment.

The mid-catchment consists of steep slopes, with a more incised single channel, which is joined by tributaries from both flanks of the valley. Widespread slope instability is present on both sides of the channel and where slides meet the base of the valley; toe incision by Waterfall Creek is common (Figure 6.3). Slope creep and hummocky terrain is also evident throughout this part of the catchment.

Recent large-scale slope instability and failure is common throughout lower parts of the catchment, particularly on true-left slopes. The channel in this reach is deeply incised into the valley-floor sediments and basement schist further downstream. Toe incision of slide features by Waterfall Creek is a common factor in exacerbating slope instability within these reaches by over-steepening slope material (Figure 6.4).

Two large slides, located just upstream of the alluvial-fan apex, have formed on the dip of the schist foliation and are actively contributing large amounts of material to the Waterfall Creek channel (Figure 6.4). The size of the slide headwalls have increased in recent decades. Sudden failure of these features has the potential to block the confined channel, in turn creating a debris dam, which may be prone to subsequent failure. Should significant lubrication of these failure planes occur during high-intensity rainfall events, catastrophic failure may occur.

Observations of the catchment channel conditions by the ORC in November 2007 identified old-bed levels and depositional-bench deposits, indicating that the transportation and deposition of debris flows have occurred in the past (Figure 6.4). Many of these deposits and features lie well above (1-2m) the contemporary channel level, indicating that a quiescent phase of debris-flow activity and in-channel aggradation has occurred in recent times.

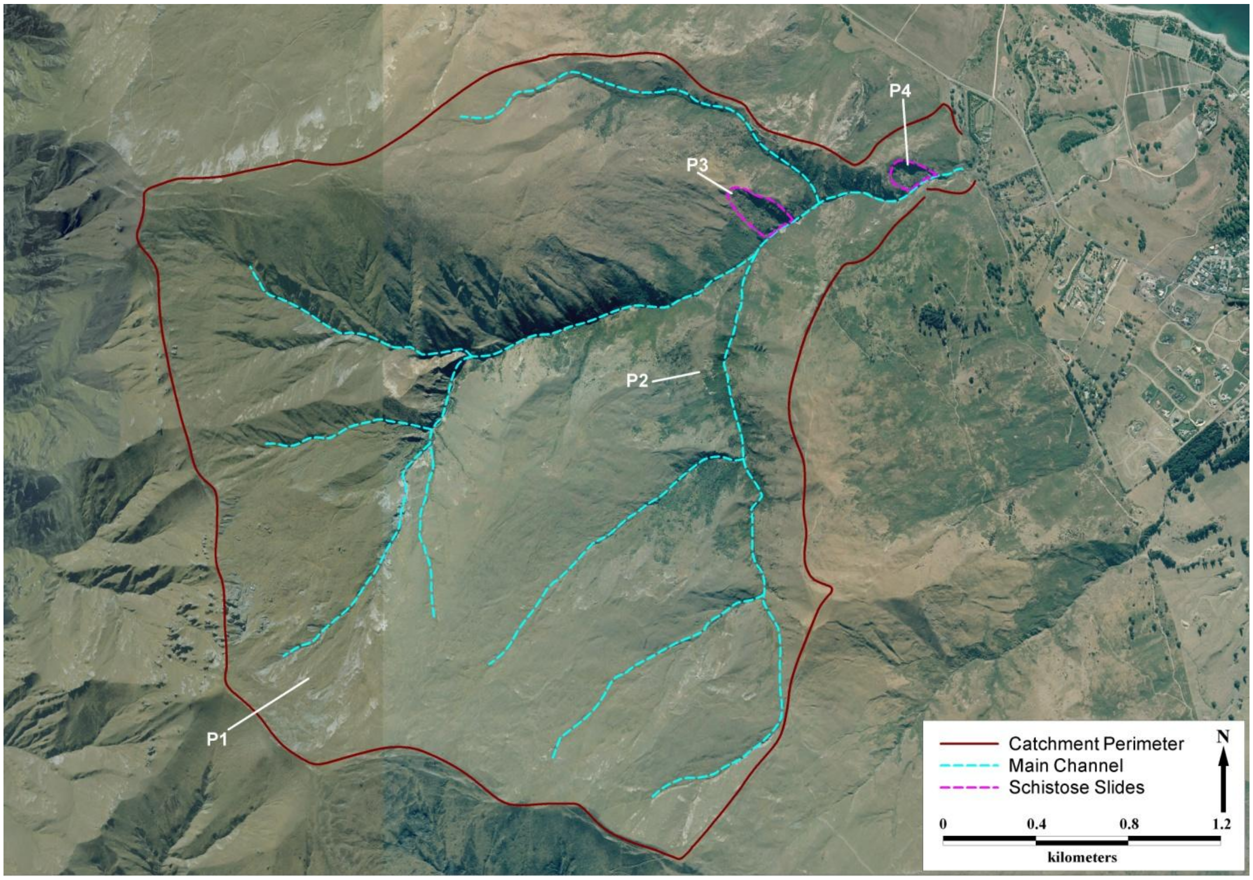


Figure 6.2 The Waterfall Creek catchment, noting areas of interest; aerial photo dated March 2006

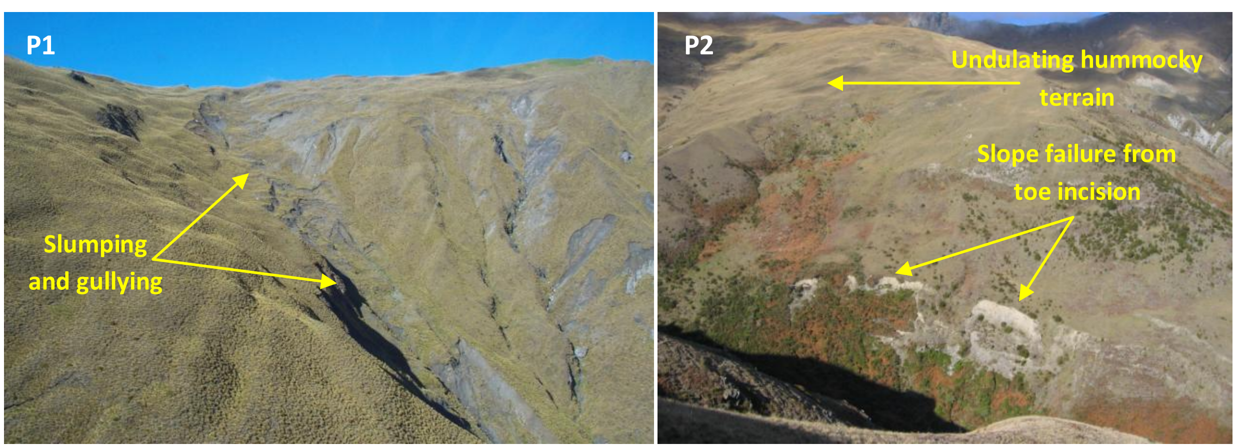


Figure 6.3 Mass-movement processes in the form of slumping and gullying in the upper Waterfall Creek catchment (left); photograph taken 09 February 2004. Slope failure, induced by toe incision by Waterfall Creek, can be seen on the right.

Figure 6.4 Top left: Large schistose slide induced by toe incision, as shown in Figure 6.2. Top right: Two large slides are evident near the Waterfall Creek alluvial-fan topographic apex. Bottom left: Toe incision of the slide, shown in P3, is contributing large volumes of sediment to the active Waterfall Creek channel. Bottom right: Old-bed levels are observed mid-catchment, indicating that debris-flow events have occurred in the catchment in the past.

6.3 Fan characteristics

Waterfall Creek has formed a semicircular fan that extends from the base of the ranges down to Lake Wanaka (Figure 6.5), and bisects large outcrops of schist bedrock and moraine deposits. Channel incision varies along the length of the fan. As the channel exits the confines of the valley, it is incised down to bedrock and is less than one metre below the surrounding fan surface (Figure 6.6-F1). Downstream, the creek becomes rapidly incised into the alluvial fan, where the erosive power of the creek has removed unconsolidated sediments and incised into the fan surface by more than 10m (Figure 6.6-F2). Just upstream of Wanaka-Mount Aspiring Road, the creek is less incised and prone to lateral migration across a wider channel width (Figure 6.6-F1). Below the road, the creek meanders between a wider channel width, incised into old moraine and post-glacial deposits.

ORC (2004) undertook an investigation that used site-specific survey information to map historic palaeo-channels onto the Waterfall Creek fan surface (Figure 6.5). Three large palaeo-channels were identified extending south-east towards West Wanaka and north-east towards Lake Wanaka.

Figure 6.5 Waterfall Creek alluvial fan, noting some key alluvial-fan features; aerial photo taken in March 2006

A large debris lobe that extends from the head of the fan to Wanaka-Mount Aspiring Road has been mapped by Tonkin and Taylor (2007) (Figure 6.6-F4). This study identified large boulders > 8 m^3 in size on the fan surface, with clasts of 5-8 m^3 extending beyond the road.

Figure 6.6 Photographs that relate to the points of interest in Figure 6.5. Top: Head of Waterfall Creek fan, showing less than 1m incision (F1) and becoming much more incised further downstream (F2). Bottom left: Waterfall Creek, looking upstream from Wanaka-Mount Aspiring Road (F3). Bottom right: Debris lobe on the Waterfall Creek fan, showing large boulders on the fan surface (F4)

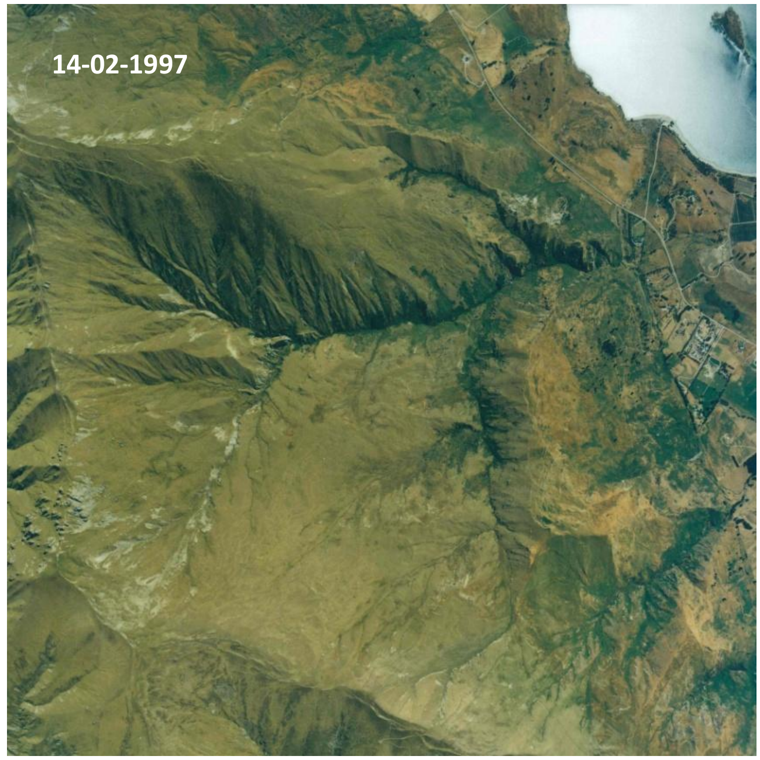
6.4 Waterfall Creek alluvial-fan hazard

Contemporary geomorphic evidence suggests that a quiescent period of debris and debris-flood flows has been observed on the Waterfall Creek alluvial fan in recent decades. This is reflected in the level of incision into the fan surface at the current channel location.

On the upper fan, less than one metre incision at the fan apices provides conditions conducive to causing channel avulsion during periods of high flow. The large sediment quantities available in the catchment and the size of the catchment indicate that channel aggradation is likely and avulsion probable at this location. Such events are likely to reoccupy historic palaeo-channels and redirect flow onto other parts of, and possibly beyond, the existing alluvial-fan limits.

Evaluation of slope stability, vegetation dynamics and geomorphic evidence in the Waterfall Creek catchment suggests that there is potential for a landslide-debris dam to form. This scenario is most likely to be triggered by a large seismic and/or high-intensity storm event, which may result in complete or partial slope failures impounding the channel. The effects of a sudden landslide-dam failure in the catchment would include rapid aggradation on the alluvial fan, particularly in the vicinity of the fan head, debris and/or debris-flood deposits spreading across the wider fan surface, erosion of the fan surface and reoccupation of historic palaeo-channels. The slides identified in Figure 6.4-P4 are active, and if sudden failure and channel impoundment were to occur, their location in the catchment means that approximately 7.2km^2 of catchment may be impounded and subject to subsequent failure.

Historic Aerial Photographs
Waterfall Creek, Wanaka



7. Bob's Cove, Lake Wakatipu

7.1 Environment setting

Located on the shores of Lake Wakatipu, the Bob's Cove area is a geologically young landscape, having been scoured by glaciers during the last glacial period, as discussed in Section 1.2. Bob's Cove is located approximately 12km west of Queenstown on the only access road to the Glenorchy township. The complex of alluvial fans in this area is known as Cove Flat and has historically been dominated by pastoral farming. Increasing urban development of these flats has occurred in recent decades, with much of the higher aspects of the alluvial fans being developed into subdivided allotments.

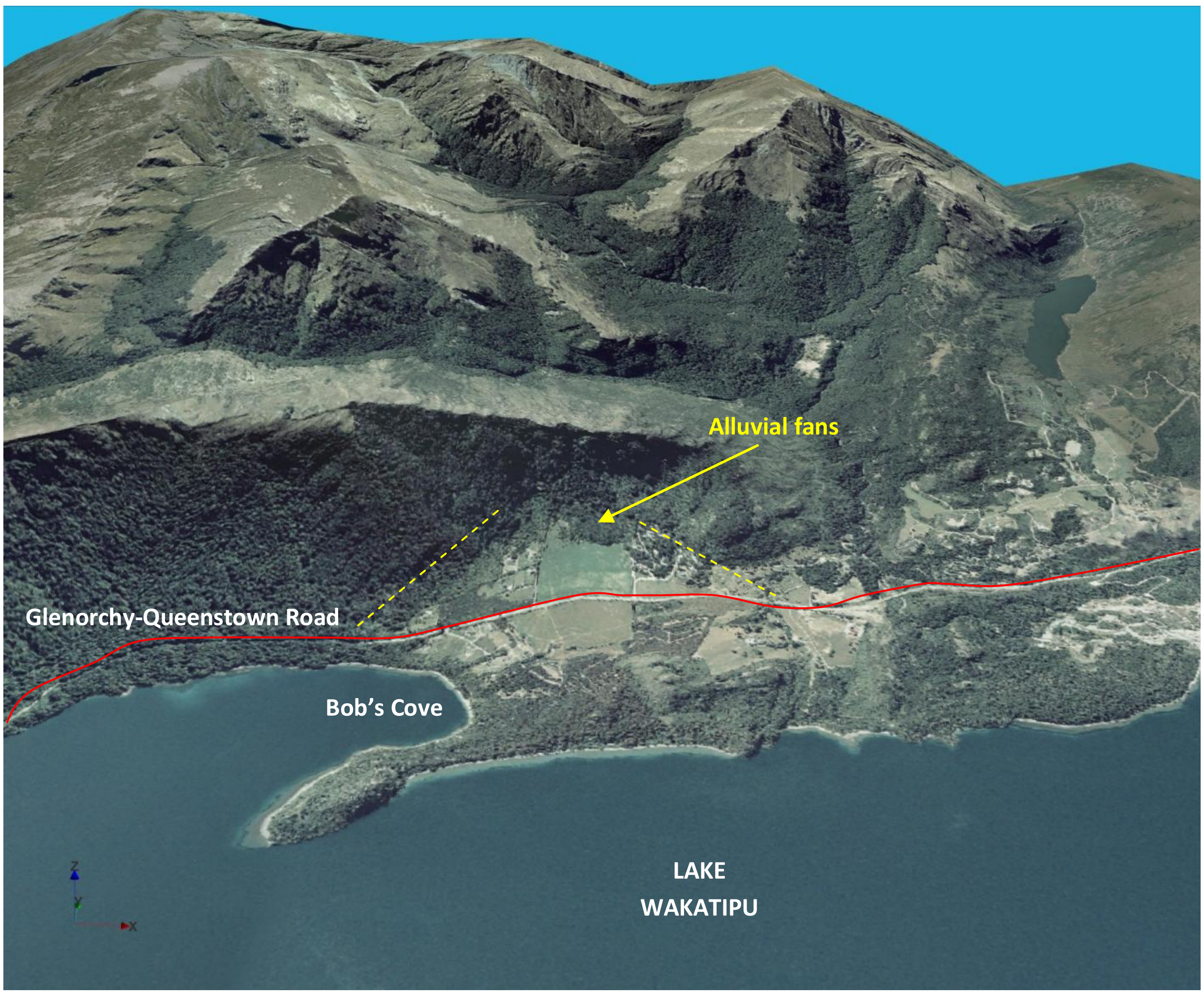


Figure 7.1 Image showing the Bob's Cove alluvial-fan complex, with respect to the surrounding environment

7.2 Catchment characteristics

The catchments that feed alluvial fans in the Bob's Cove area are very steep, ranging in grade from 81 to 57%, and have catchment areas of less than 2 km^2 (Figure 7.3). They generally peak at elevations around 800 masl and terminate at the fan apices, between 500 to 400 masl.

Slope processes generally consist of mass movements in the form of rock falls from over-steepened bluffs and gullying within some of the larger catchments. The stability of slopes in these catchments is facilitated by the dense vegetation cover, where root systems increase the coherency of shallow surface slopes and reduce ground saturation through interception (Figure 7.2).

During high-intensity or prolonged storm events, it is likely that these slopes may be subject to rapid mass movement in the form of slides or rock falls. The removal of vegetation in the catchments may exacerbate the potential for mass movement.

Figure 7.2 Steep, heavily vegetated catchments at Bob's Cove

7.3 Fan characteristics

Alluvial fans at Bob's Cove reflect the steep and rugged nature of the source catchments from which they have been derived. On the upper parts of the fans, thick vegetation cover is present in the form of bushes, scrub and trees, often obscuring evidence of past debris flows or rock falls. Areas close to and downslope of channels in these areas have been subject to alluvial-fan activity (Figure 7.4). Field observations undertaken by ORC in March 2011 confirmed the presence of ephemeral channels within these areas. Many of these channels were free from vegetation and lined with clasts less than one metre in diameter, and deposited by historic debris flows. Beyond the vegetated margin of these fans, much of the fan surface is dominated by formed subdivisions that have extensively modified the channels (Figure 7.4-F1). Larger clasts and boulders from rock-fall events were identified upslope of these formed subdivision areas (Figure 7.4-F2).

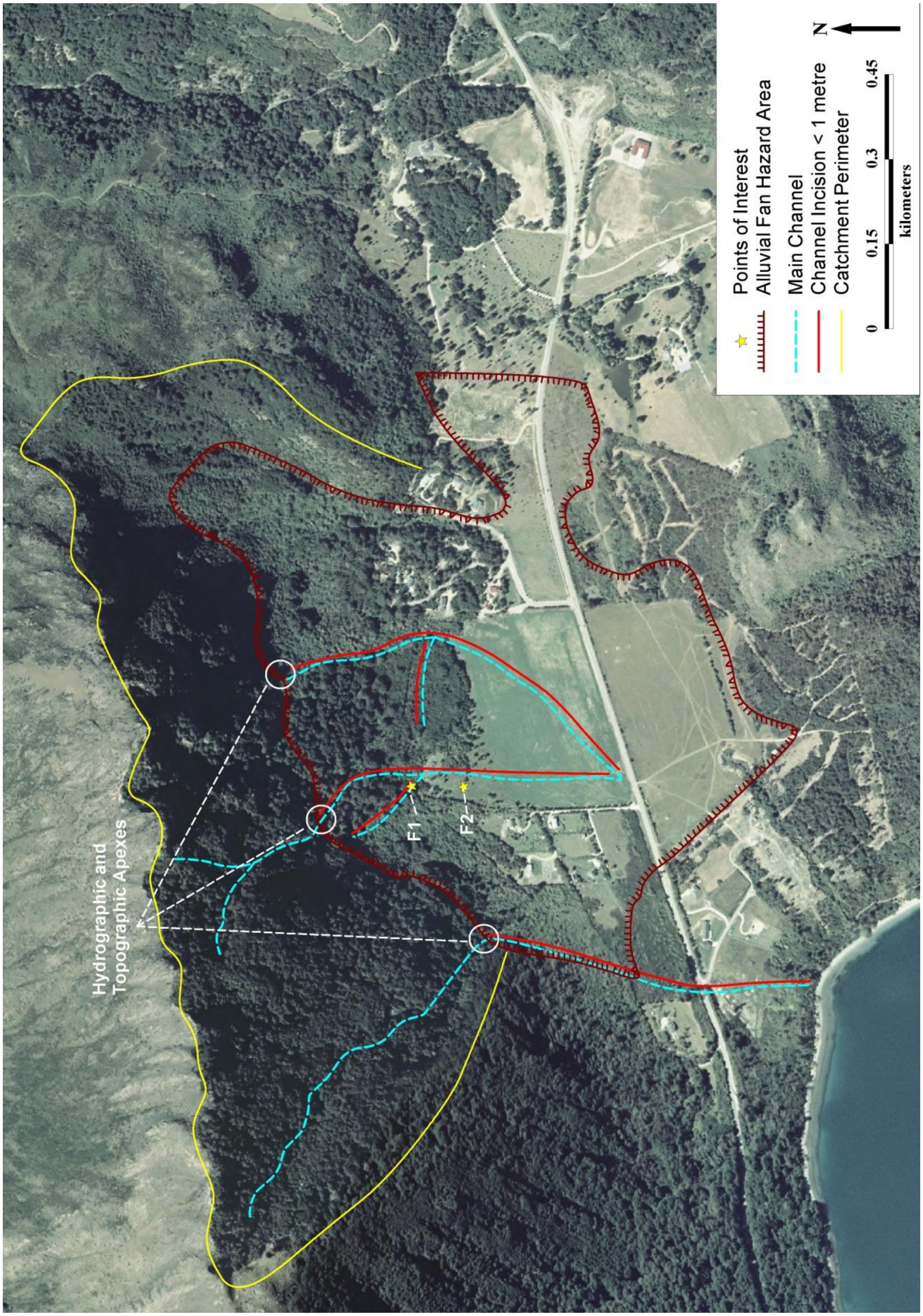


Figure 7.3 Bob's Cove alluvial fans and catchments, noting some key alluvial fan features; aerial photo taken in February 2006

Figure 7.4 Left: Ephemeral channel located within the upper forested area of an alluvial fan at Bob’s Cove; lateral-debris deposits are evident from historic-debris flow. Centre: Formed subdivision has changed the flow-path characteristics of the alluvial fans at Bob’s Cove (Figure 7.3-F1). Right: Large clasts are evident on the upslope parts of alluvial fans at Bob’s Cove (Figure 7.3-F2).

7.4 Bob’s Cove alluvial-fan hazard

As discussed, the channels that flow onto alluvial-fan surfaces at Bob’s Cove are ephemeral and therefore do not provide a full appreciation of the potential alluvial-fan hazard. Heavily forested catchments have contributed to the coherency of slopes in these catchments and decreased slope saturation, resulting in a reduced frequency of mass-movement processes. Debris-flow and rock-fall events have been infrequent in recent decades.

Depending on the nature and characteristics of each storm event, any part of the hazard area may be impacted by debris or debris-flood flows or floodwater inundation in the future. It is likely that the fan’s upper slopes will be impacted by debris-flow and rock-fall events, as these processes have occurred here in the past, forming the underlying landforms. On the fan’s lower margins, it is more likely that debris-flood or floodwater sheet-flows will occur. Due to the steep topography, it is likely that mass-movement processes may become more active should catchment conditions change.

Historic Aerial Photographs - Bob's Cove, Lake Wakatipu

8. Walter Peak, Lake Wakatipu

8.1 Environment setting

Sited opposite Bob's Cove, the Walter Peak area is similarly a geologically young landscape, having been scoured by glaciers during the last glacial period, as discussed in Section 1.2. Apart from driving around the southern end of Lake Wakatipu, the only access to Walter Peak station is by air or on the Earnslaw charter steamboat. The area is mainly pastoral farmland, with land in the vicinity of Beach Bay and the wider area having a Rural Visitor Zone within the Queenstown-Lakes District Council Plan. This zoning means that this location has been targeted by the district council for future development, which has the potential to include relatively large-scale developments.

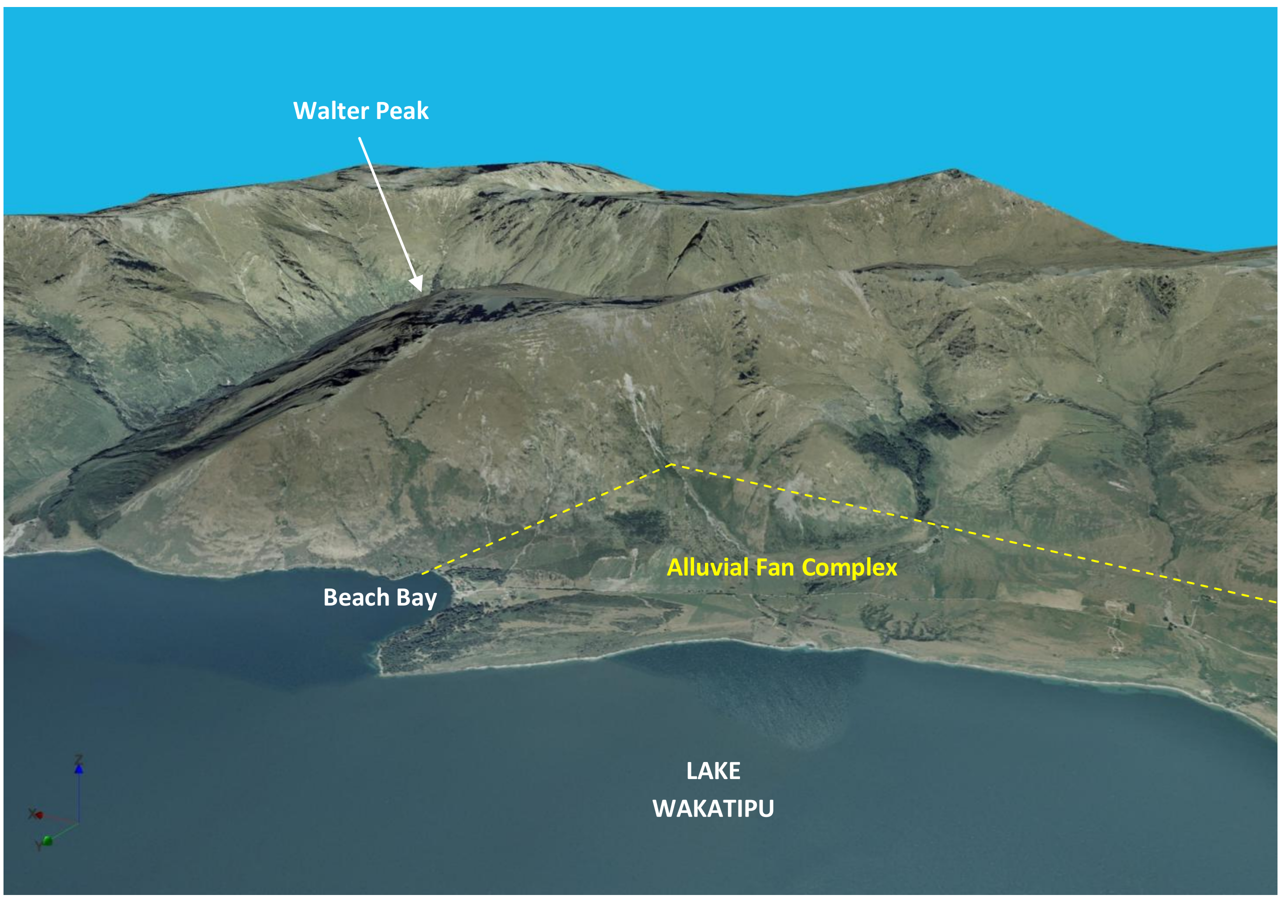


Figure 8.1 Image showing the Walter Peak alluvial-fan complex with respect to the surrounding environment

8.2 Catchment characteristics

The catchments that feed alluvial fans in the Walter Peak area are very steep and have catchment areas of less than 1.5km^2 (Figure 8.2). The most eastern catchment peaks at an elevation of 1800 masl at Walter Peak, with fan apices ranging from around 800 to 500 masl.

Slopes are generally vegetated by small bushes and alpine tussocks and are subject to widespread slope instability in the form of gullying, slumping and creep, with fresh scarps, signifying instability. Gullying and the over-steepening of slopes have led to further incision of the surficial-slope deposits, which are prone to failure and subsequent debris-flow initiation during high-intensity storm events. The active scarps evident in Figure 8.2 are examples of these processes.

8.3 Fan characteristics

During storm events, debris and debris-flood flows are common on the upper-fan areas. In the fan's lower reaches, floodwater inundation and the sedimentation of fine silts and sands is more common as larger clasts are deposited further up the fan. Channel incision is less than one metre for most of these fans, and channel aggradation and avulsion is a common occurrence.

Barrell *et al*. (2009) noted that historic flood and debris flows occurred close to the Walter Peak homestead buildings at Beach Bay in 1999 and 2002.

8.4 Walter Peak alluvial-fan hazard

The alluvial-fan hazard area has been defined by combining all the active alluvial-fan areas identified by Barrell *et al*. (2009). This area is subject to recurrent debris, debris-flood flow and floodwater-inundation alluvial-fan processes. Persistent avulsion, channel aggradation and erosion are common across all fans at this location. These very active processes need to be investigated when consideration is given to using the Rural Visitor Zone in this area in the future.

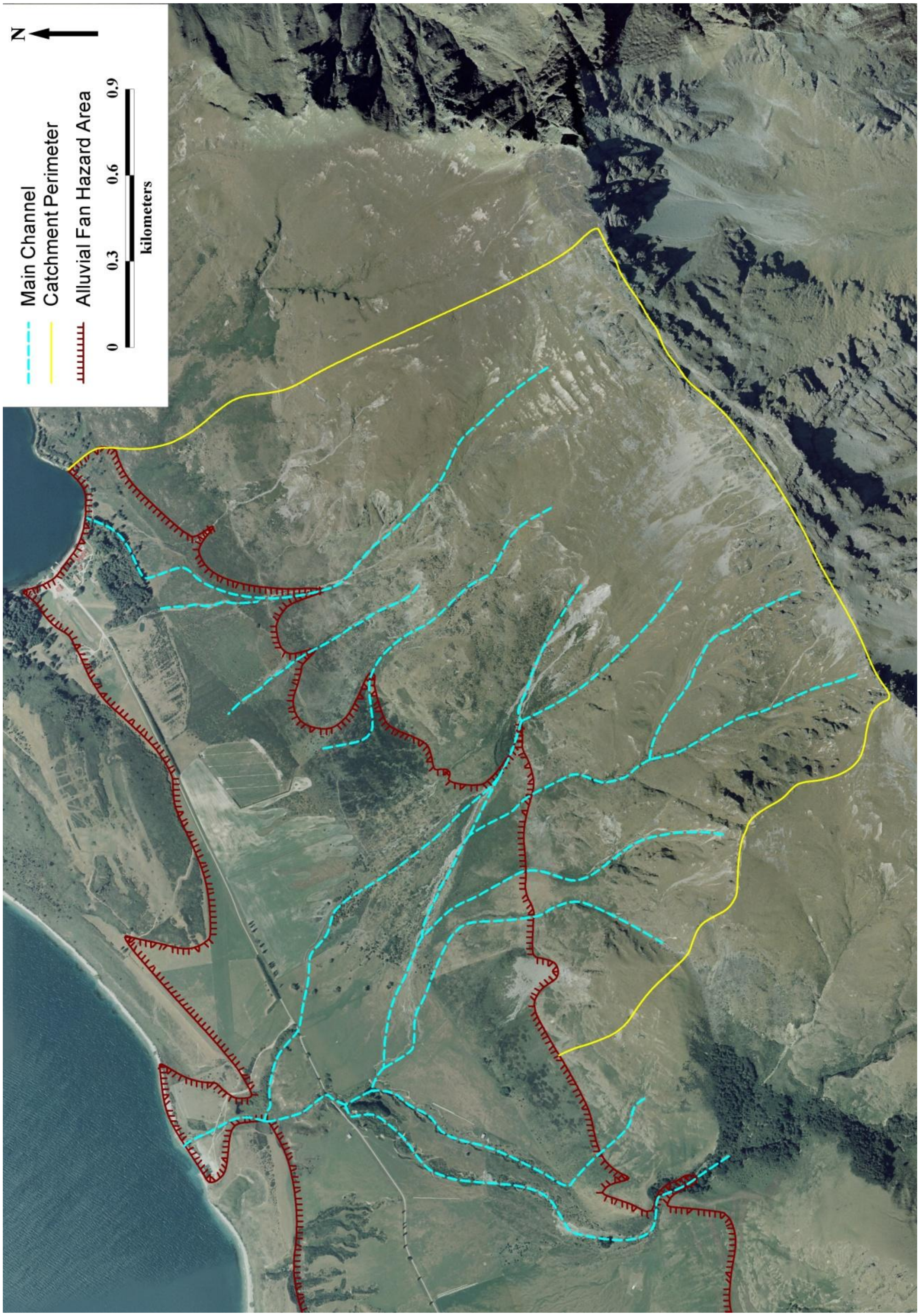
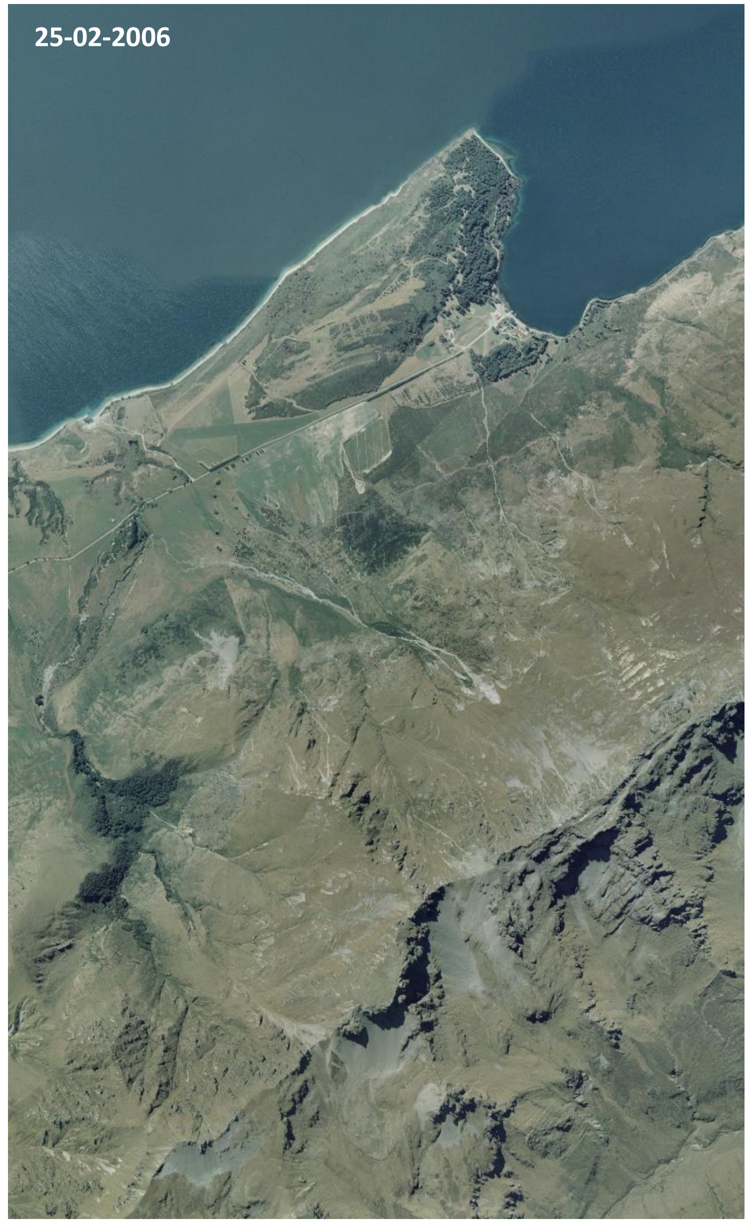


Figure 8.2 Walter Peak alluvial fans and catchments, noting some key alluvial fan features; aerial photo taken in February 2006

Historic Aerial Photographs
Walter Peak, Lake Wakatipu



9. Kingston Creek, Kingston

9.1 Environment setting

Located on the southern shores of Lake Wakatipu, the Kingston area is a geologically young landscape, having been scoured by glaciers during the last glacial period, as discussed in Section 1.2. The Kingston Creek catchment is located on the western flank of the Hector Mountains at the southern edge of Lake Wakatipu. The creek flows from an elevation of 1464m at Flat Rock to around 520m at the topographic apex of the alluvial fan. The alluvial fan is dominated by pastoral-farming activities and is bisected by SH 6 along its lower margins. Downstream of the state highway, the creek flows through the Kingston township to its confluence with Lake Wakatipu.

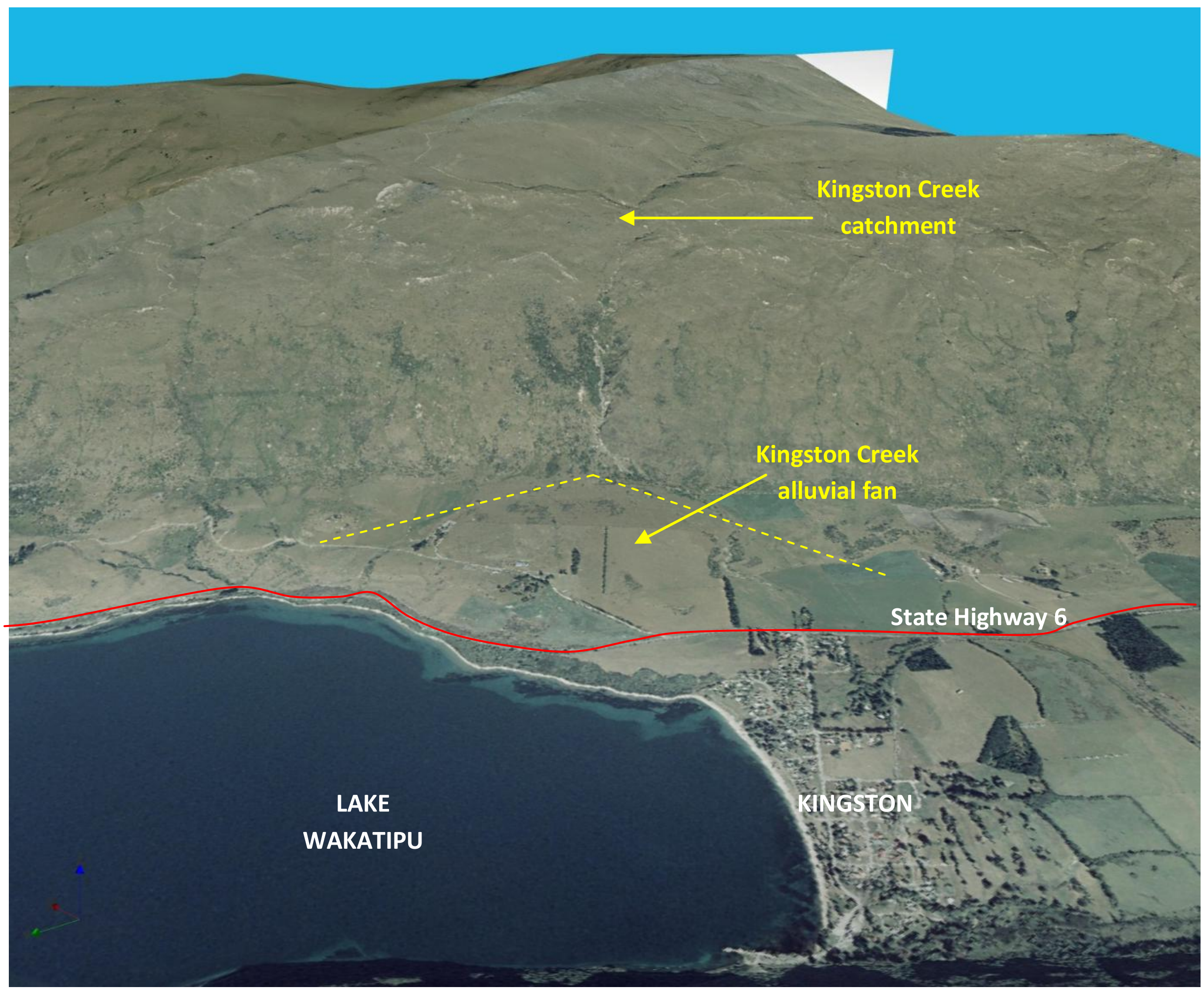


Figure 9.1 Image showing the Kingston Creek alluvial fan with respect to the surrounding environment

9.2 Catchment characteristics

The Kingston Creek catchment is approximately 3.4km^2 in size (Figure 9.2). The upper catchment, from its peak at Flat Rock to around 1100 masl, has a relatively gentle grade of 15% and is dominated by alpine tussocks. Downstream of this elevation, the creek steepens considerably to a grade of 45% down to the topographic apex.

Where the catchment steepens, the creek is eroding into post-glacial landslide deposits that flank the slopes of the Hector Mountains. These deposits were formed following the recession of the buttressing glaciers during the last glacial period. Subsequent to slope relaxation, mechanical-weathering and mass-movement processes have contributed to the widespread development of unconsolidated landslide deposits on these slopes (Figure 9.3-P1). Slope instability is common in this reach of the catchment, with the greatest volume of sediment being derived from the sediment-source area on the true right of the creek (Figure 9.3-P2).

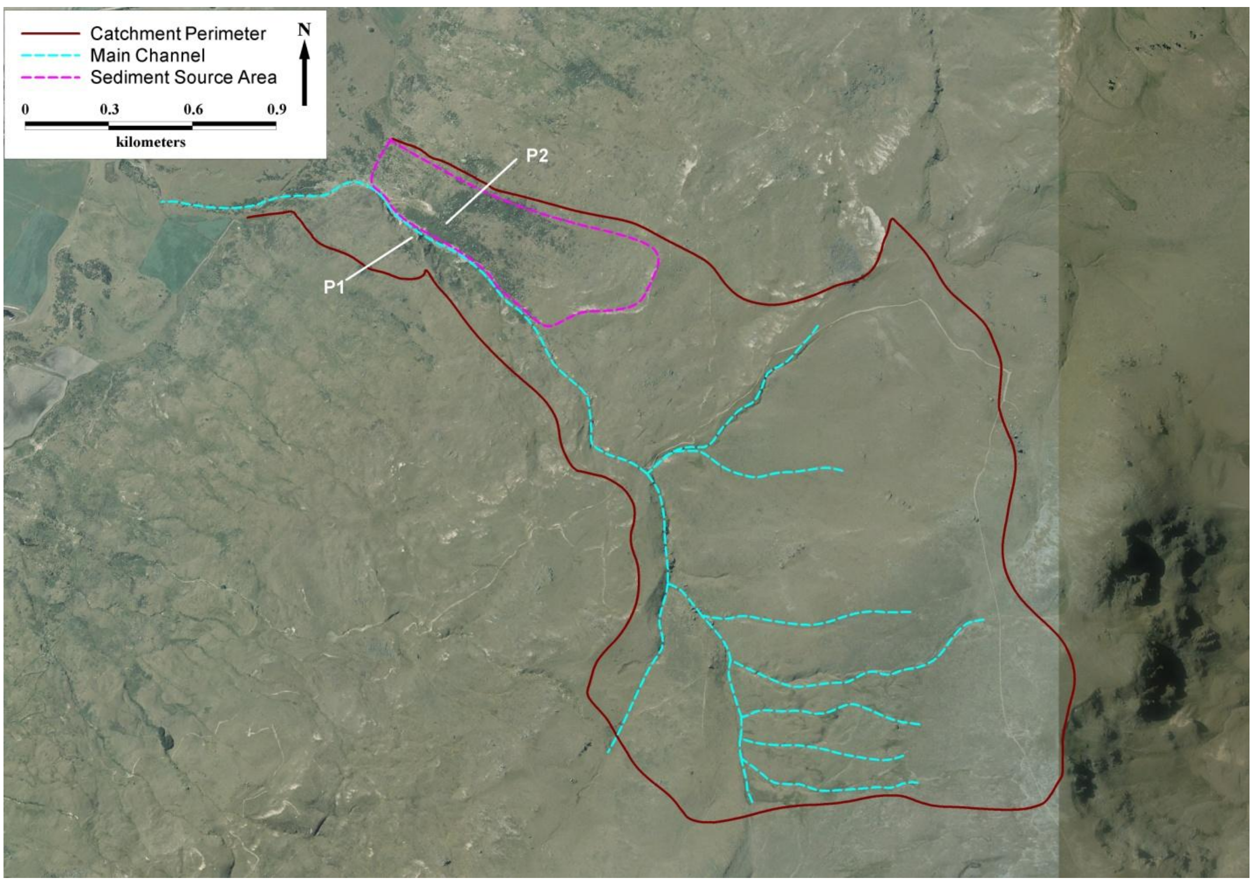


Figure 9.2 The Kingston Creek catchment, noting areas of interest; aerial photo dated February 2006

Figure 9.3 Left: Large landslide deposits flank the slopes of the Kingston Creek catchment on the channel's true left. Right: Kingston Creek, as it descends from the flatter-grade upper catchment; the creek is actively eroding landslide material in this reach of the catchment.

9.3 Fan characteristics

Kingston Creek has formed a symmetrical semicircular fan that extends from the base of the Hector Mountains to Lake Wakatipu (Figure 9.4). The dominant debris-flow processes observed at the head of the alluvial fan are a direct result of the widespread slope instability in the lower catchment (Figure 9.2). These conditions promote debris-flow processes on the upper fan and debris-flood flows further downstream. The large boulder field (Figure 9.5-F1), located just downstream of the topographic apex, has been formed by these debris flows during past events.

Large palaeo-channels are evident across much of the fan surface (Figure 9.5-F2), where Kingston Creek used to flow. These channels have incised into an older alluvial-fan surface, probably formed in the years following glaciation when Lake Wakatipu was at higher levels than those observed today. As the creek flows downstream, it becomes more incised into this deposit, eroding sediment from the bed and banks during storm events. Sediment from this fan surface contributes to the sedimentation and channel aggradation observed downstream.

As the creek flows beyond the contemporary extent of this old alluvial-fan deposit, channel incision is less than one metre (Figure 9.5-F3). From this reach to the state highway, the channel aggrades and migrates laterally, as it is less confined than it is upstream. Sediment and debris is transported or eroded from upstream and deposited into this reach during storm events.

Downstream of the state highway, the channel is generally incised less than one metre in the vicinity of the camping ground (Figure 9.5-F4). Further downstream, as it flows between residential areas and intermittent pastoral land, the creek has varying depths of incision as it has eroded into the surrounding post-glacial deposits, which consist of moraine, beach ridge and lacustrine.

9.4 Kingston Creek alluvial-fan hazard

The Kingston Creek alluvial fan has historically been subject to recurrent debris-flow events on the upper fan. Large-scale slope instability and progressive erosion of landslide deposits in the lower catchment indicate that it is probable debris-flow events will continue into the future. Channel avulsion is likely to occur in the upper fan reaches, where debris and debris-flood flows will spread laterally. Very large storm events are likely to convey debris and debris-flood flows as far as, if not beyond, the state highway.

Continual erosion of old alluvial-fan deposits through bed and bank reworking is likely to continue into the foreseeable future on the Kingston Creek alluvial fan. These processes will contribute to sedimentation and channel aggradation further downstream, probably resulting in channel avulsion. In locations where existing channel incision is less than one metre, it is likely that channel avulsion or inundation from floodwaters that exceed channel capacity will occur.

Downstream of the state highway, floodwater and sheet-flow inundation may occur where locations with less than one metre incision (such as the Kingston camping ground) are inundated. In large events, the channel may change position upstream and no longer follow its current course, causing sedimentation and/or debris-flood flows on lower parts of the fan.

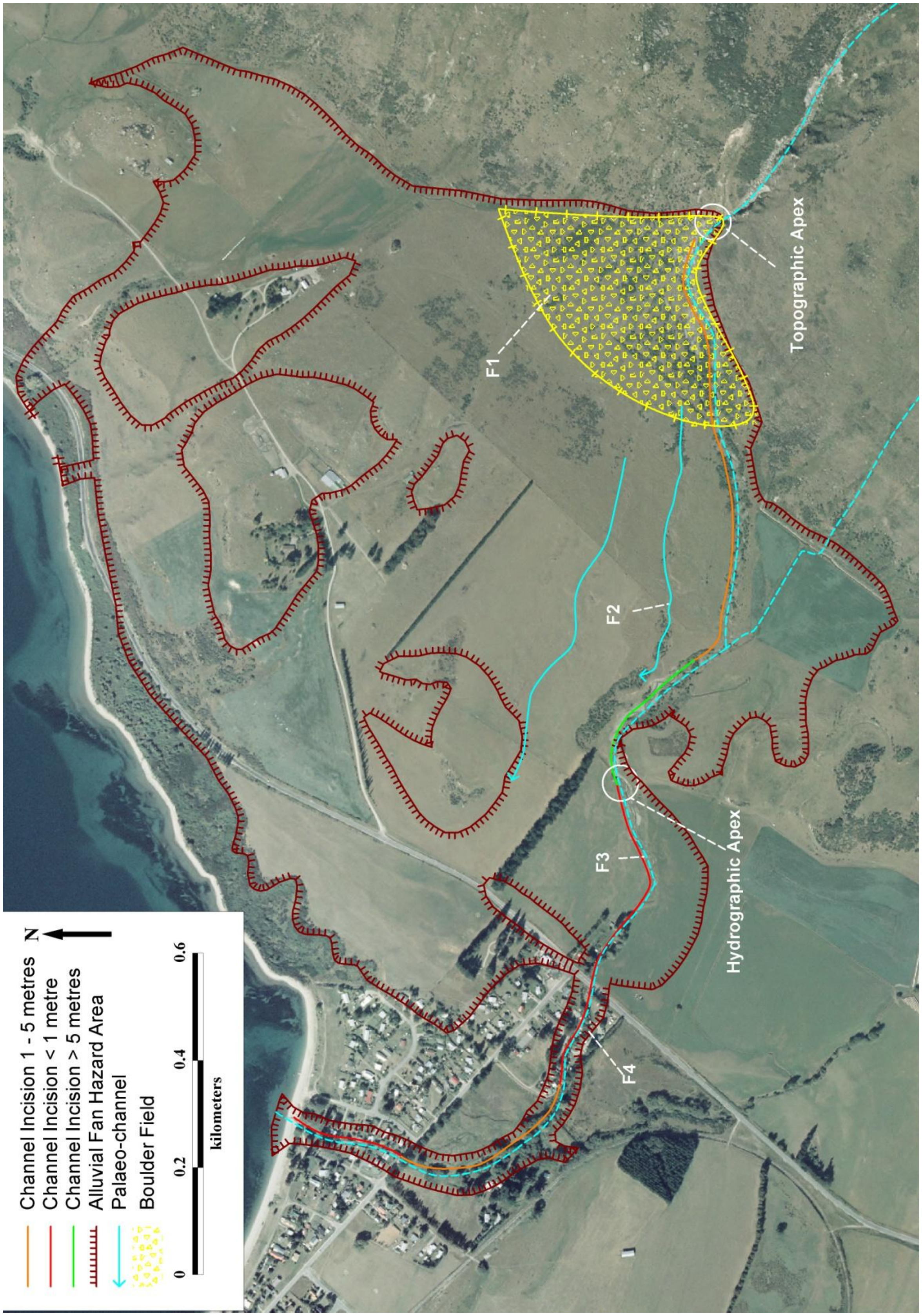
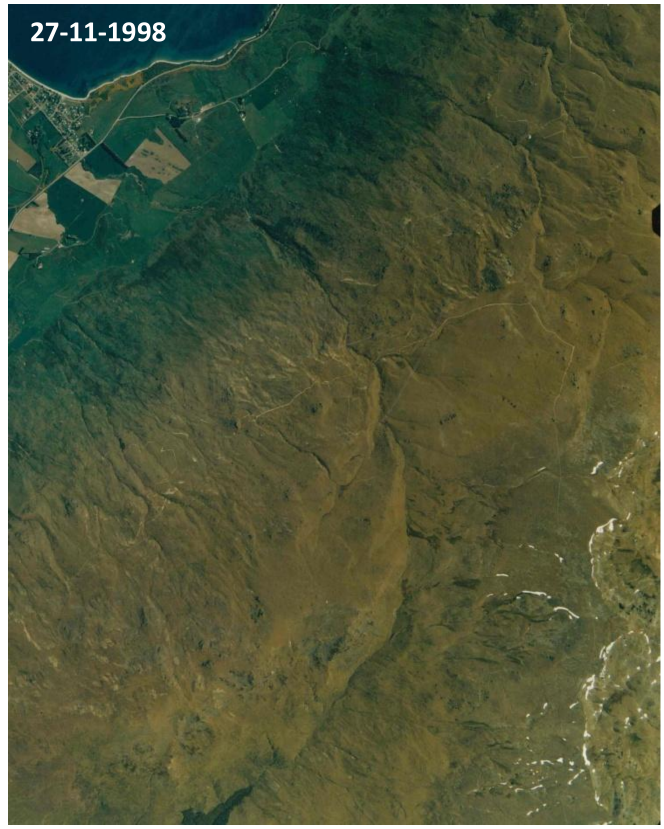


Figure 9.5 Kingston Creek alluvial fan, noting key alluvial fan features; aerial photo dated February 2006

Figure 9.5 Photographs that relate to points of interest depicted on Figure 9.4. Top left: The upper Kingston Creek alluvial fan showing a large clast boulder field at the fan head and recently overturned debris deposits in the foreground. Top right: Large palaeo-channels traverse the Kingston creek alluvial-fan surface. Bottom left: The Kingston Creek channel above SH 6 is incised less than one metre for much of its length. Bottom right: Downstream of the state highway, the creek has almost no incision through the Kingston camping ground.

Historic Aerial Photographs - Kingston Creek, Kingston



10. Brewery/Bush Creek, Queenstown

Located in the Gorge between Queenstown and the Shotover River valley, the Brewery Creek catchment (Figure 10.1) is a geologically young landscape, having been occupied by glaciers during the last glacial period, as discussed in Section 1.2. Incised into the eastern flank of the Bowen Peak mountain group, the catchment flows west to east from an elevation of 1627m at Bowen Peak to around 380m at the head of the alluvial fan. The alluvial fan has been modified extensively by urban development, consisting of residential, industrial and visitor accommodation facilities that form part of Queenstown. The fan is bisected by Gorge Road on its lower margins, where the channel flows into the Horne Creek flood-protection detention area.

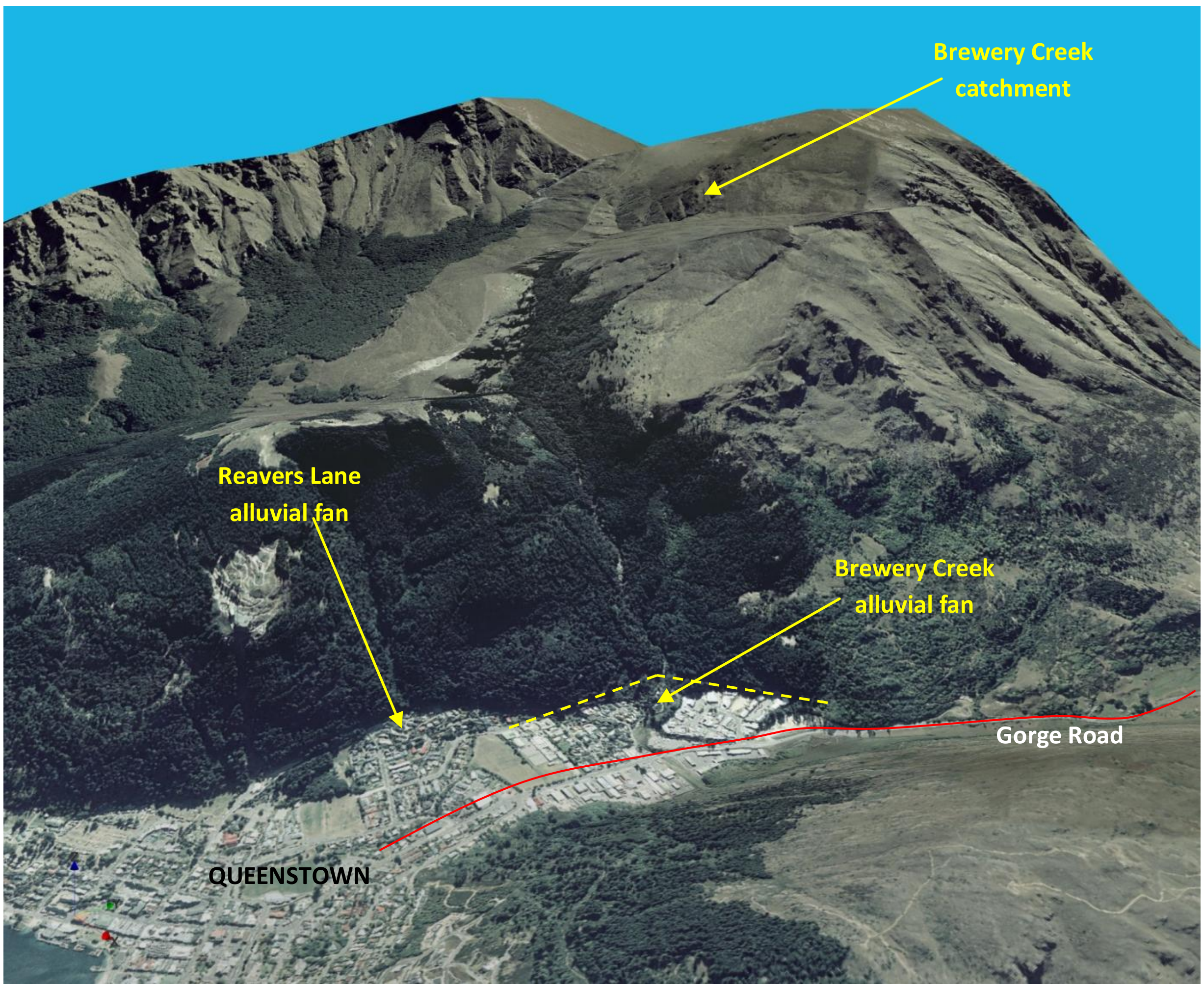


Figure 10.1 Image showing the Brewery Creek alluvial fan and catchment with respect to the surrounding environment

10.1 Catchment characteristics

The Brewery Creek catchment is approximately 8.4km^2 in size (Figure 10.2) and is very steep. The upper catchment is dominated by small bushes and alpine tussocks down to around 1000 masl, where both sides of the catchment are covered in dense forest. Large rock falls have occurred in the true-left-bank forested area in the past (Figure 10.3-P1), which is represented by the presence of much younger trees in the 2006 aerial photography (Appendix 1).

Catchment observations, undertaken by ORC in March 2011, found that Brewery Creek has incised into basement schist, which reflects the level of the current-channel invert. The true-right bank is bound by bedrock and is very steep, contributing debris, in the form of large trees, as tributaries erode and transport material efficiently on very steep grades. The true-left valley-side, next to the creek, is orientated on the foliation of the basement schist. These slopes are mantled by layers of colluvial landslide deposits, which are being eroded by the creek, thereby providing large volumes of sediment and debris to the creek (Figure 10.3-P2).

As slopes are eroded, many of the mature trees next to the creek are being undercut and fall into the creek due to over-steepening (Figure 10.3-P3). This process contributes large volumes of woody debris and tree trunks to the active channel, greatly increasing the potential for log-jam dams to form in the narrow channel (Figure 10.3-P4).

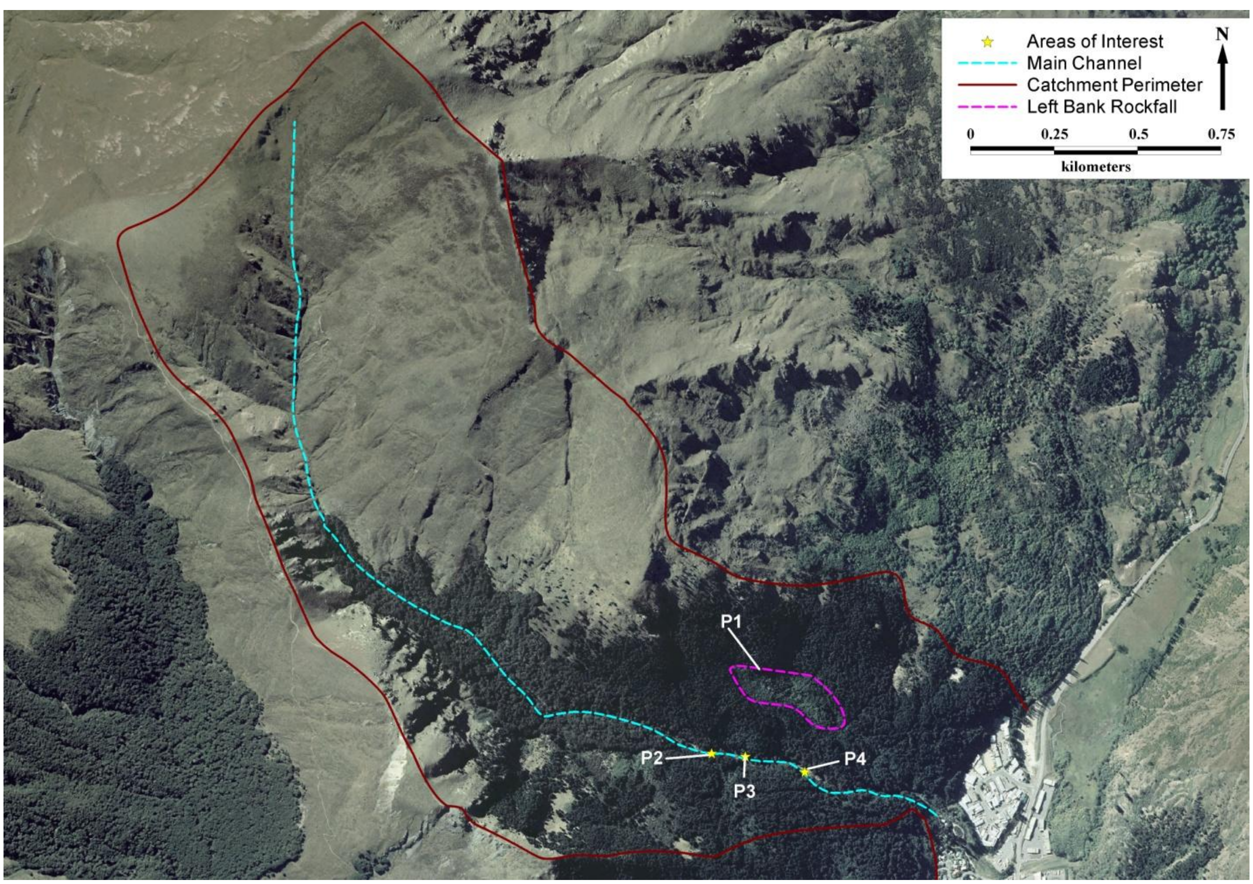


Figure 10.2 The Brewery Creek catchment, noting areas of interest; aerial photo dated February 2006

Figure 10.3 Photographs that relate to points of interest depicted in Figure 10.2. Top left: Large rock-fall boulders strewn across the Brewery Creek's left bank; this location has been succeeded by younger trees. Top right: Brewery Creek, looking upstream, colluvial landslide deposits are being eroded on the true left (image right), and the creek is bound by bedrock on the true right (image left). Bottom left: Large toppled trees lie on slopes next to the incised Brewery Creek channel. Bottom right: Log-jam dam formed in the Brewery Creek channel

10.2 Fan characteristics

Brewery Creek has formed a semicircular fan that coalesces with the wider Horne Creek flood plain in the lower valley of the Gorge (Figure 10.4). Near the topographic apex of the fan, the channel flows in a U-shaped scoured valley, indicative of historic-debris flow (Figure 10.5-004). As the channel leaves the confines of the valley, it has been extensively modified by excavation into the fan surface, suggesting that the material used to line the channel has been sourced from the alluvial-fan surface (Figure 10.5-005/006). Below Gorge Road, the channel flows unconfined across pastoral farmland down to the Horne Creek detention area (Figure 10.5).

During a debris-flow event, trees on the lateral margins of the flow often have bark and superficial layers removed from the trunk due to the flow's erosive power. Figure 10.4 shows a number of locations where historic-debris-flow heights have been measured from scars on mature trees with respect to the existing modified-channel invert and respective ground level; examples of these marks are depicted in figures 10.6 and 10.7.

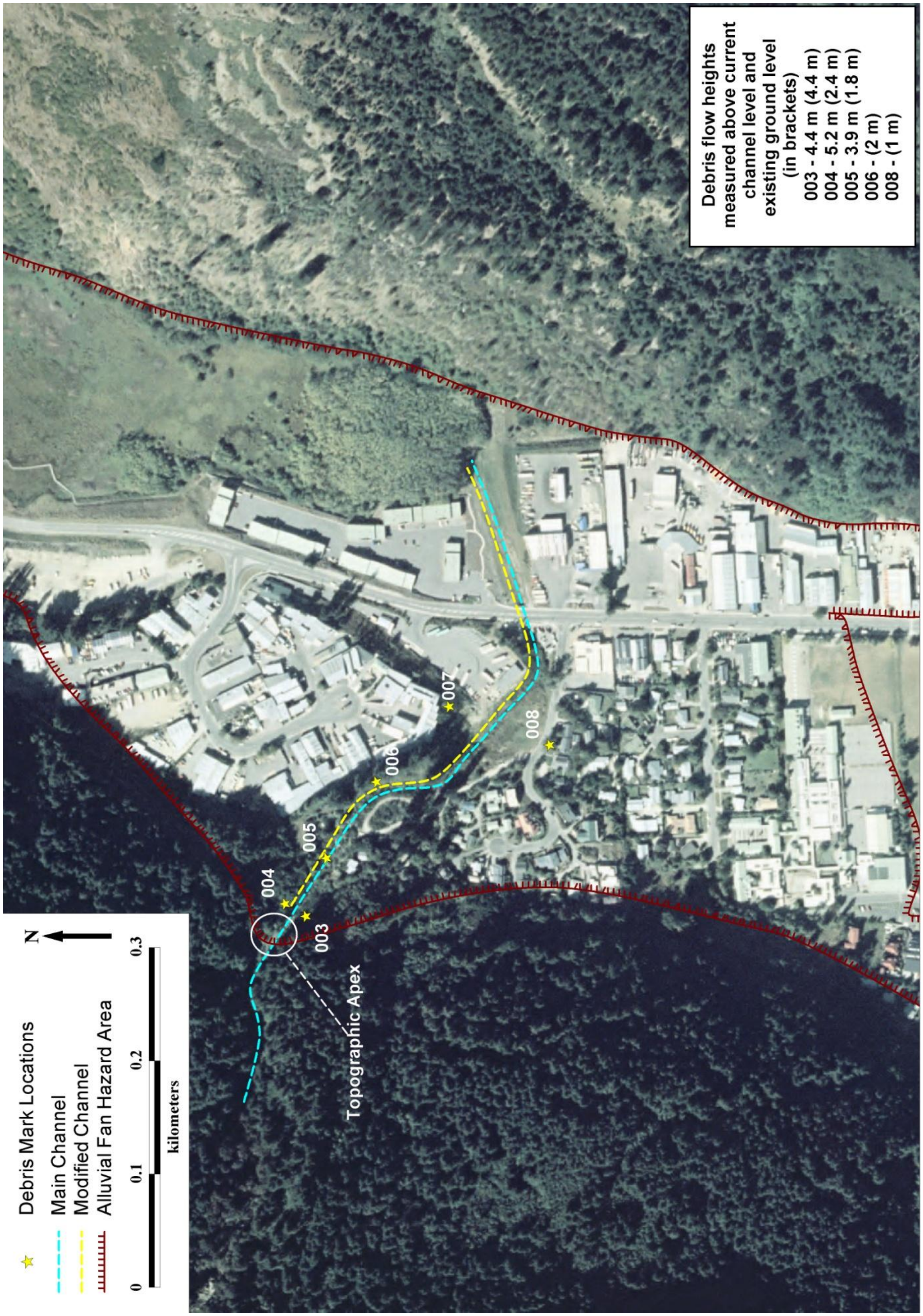


Figure 10.4 Brewery Creek alluvial fan, noting key features; aerial photo dated February 2006

Figure 10.5 Top left: The U-shaped valley near the topographic apex of Brewery Creek. Top right: Modified Brewery Creek channel downstream of the topographic apex. Bottom left: Brewery Creek's modified channel in the mid-fan area, with visitor accommodation complex in the background. Bottom right: Brewery Creek's unconfined channel below Gorge Road

Figure 10.6 Debris-impact scars on mature trees near Brewery Creek's topographic apex. Left: Debris mark at 003 (Figure 10.4), showing height with respect to ground level. Centre: Same tree as left image, with figure for scale. Right: Similar tree just downstream of mark 003

Figure 10.7 Debris-impact scars on mature trees on the Brewery Creek alluvial fan. Top left: Debris scars on left-bank trees just upstream of point 005 (Figure 10.4). Top right: Debris scar on true-left treat point 005. Mid-left: Debris scars on trees at point 006 with figure for scale. Mid-right: Looking across Bowen Street towards trees at point 008. Lower image: Trees on far side of Bowen Street at 008

10.3 Brewery Creek alluvial-fan hazard

The Brewery Creek alluvial fan has been subject to recurrent debris-flow events in the past (figures 10.8, 10.9 and 10.10). The effects of debris and flood flows on the alluvial-fan surface were exacerbated by the failure of a man-made dam in the catchment in May 1986. In November 1999, large volumes of debris and sediment inundated a large portion of the fan surface. Debris flows cut access on Gorge Road and impacted many buildings and residential properties.

The alluvial-fan hazards associated with Brewery Creek generally consist of high-velocity-debris and debris-flood flows, channel avulsion, bank erosion and floodwater 'sheet-flow' inundation. Upper parts of the fan are subject to high-velocity debris flow where the channel is currently confined and steep. As the fan and channel gradients change downstream, debris-flood deposits are more common with considerable channel aggradation, during and in the immediate recession of the debris-flow event.

Large-scale slope instability and continued erosion of landslide material adjacent to the channel in the catchment is envisaged to continue, based on catchment observations in March 2011 by ORC. It is likely that future debris-flow events will be exacerbated by the formation of debris dams and log-jam dams impounding the channel within the catchment. The sudden release of sediment and debris from failure of these features will result in rapid aggradation of the alluvial-fan surface and avulsion of channels potentially to any location identified in the hazard area (Figure 10.4).

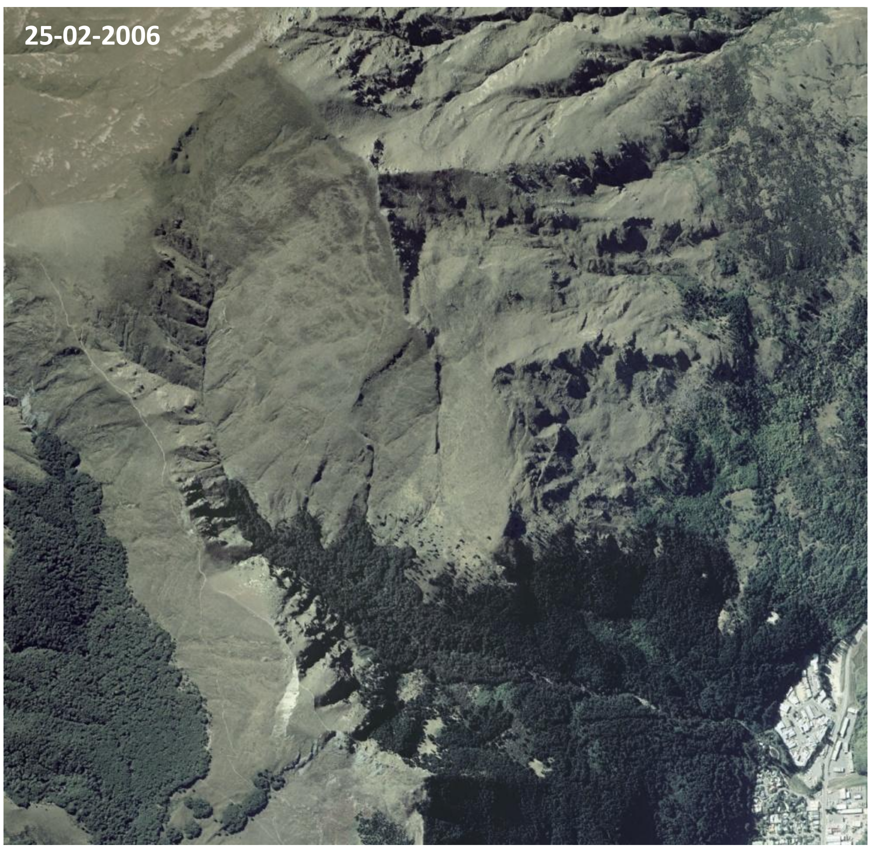
Depending on the nature and characteristics of each storm event, any part of the hazard area may be impacted by debris or debris-flood flows or floodwater inundation in the future. It is likely that the fan's upper slopes will be impacted by debris flow, as these processes have occurred here in the past, forming the underlying landforms. The removal of vegetation in the catchment may exacerbate the potential for mass movement. On the fan's lower margins, it is more likely that debris-flood or floodwater sheet-flows will occur. Due to the steep topography, it is likely that mass-movement processes may become more active should catchment conditions change in the future.

Figure 10.8 Photographs of a swimming pool on the Brewery Creek alluvial fan. Top left: Pool before May 1986, showing depth with respect to figures. Top Right: Pool filled with debris, following the storm event of May 1986. Bottom: Excavated pool after the May 1986 flood event; Brewery Creek flows to the immediate left of the pool.

Figure 10.9 The intersection of Bowen Street and Gorge Road, following the November 1999 flood event (left), compared to the same view March 2011 (right). Brewery Creek flows down the centre of the road in the left image.

Figure 10.10 Brewery Creek, following the November 1999 storm event. Left: Looking north up Gorge Road on the corner with Bowen Street. Right: Sediment and tree debris carried by Brewery Creek on the downstream side of Gorge Road, 17 November 1999

Historic Aerial Photographs - Brewery/Bush Creek, Queenstown



11. Reavers Lane, Queenstown

Like the neighbouring Brewery Creek catchment, the Reavers Lane catchment (Figure 11.1) is a geologically young landscape, having been occupied by glaciers during the last glacial period, as discussed in Section 1.2. Incised into the eastern flank of the Bowen Peak mountain group, the catchment flows west to east from an elevation of around 900 masl to about 380 m at the head of the alluvial fan. The alluvial fan has been modified extensively by residential urban development, including visitor accommodation facilities. The creek outflow has been directed into the reticulated stormwater system at the head of the fan, so no longer has an obvious surface channel.

Figure 11.1 Image showing the Reavers Lane alluvial fan and catchment with respect to the surrounding environment

11.1 Catchment characteristics

The Reavers Lane catchment is very steep, rugged terrain, with a catchment area of approximately 0.5km^2 (Figure 11.2). The catchment is heavily vegetated by dense forest, which facilitates slope stability where root systems increase the coherency of shallow surface slopes and trees reduce ground saturation through interception.

Slope processes generally consist of mass movements in the form of rock falls from over-steepened bluffs and gullying near channel margins, although they are not readily identifiable due to forest cover. Aerial photography from 1966 shows a largely unvegetated catchment exhibiting some of these mass-movement processes (Appendix 1). During high-intensity or prolonged storm events, it is likely that these slopes may be subject to rapid mass movement in the form of slides or rock fall. The removal of vegetation in the catchment may exacerbate the potential for mass movement.

Site observations, undertaken by ORC in March 2011, identified a wide U-shaped lower catchment just upstream of the fan's topographic apex. This channel is indicative of having allowed debris and/or debris- flood flows onto the alluvial-fan surface in the past.

11.2 Fan characteristics

The Reavers Lane alluvial fan reflects the steep and rugged nature of the source catchment from which it is derived (Figure 11.3). The steep slope of the fan surface from the topographic apex indicates that the fan has mainly been formed by debris-flow processes in the past. Much of the past evidence of debris flow has been removed by urban development on the fan surface. Site observations in March 2011 noted large boulders near the head of the alluvial fan, which were believed to have been derived from the fan surface (Figure 11.4).

The fan has been subject to a quiescent phase of debris-flow activity in recent decades, largely in part to the succession of dense forestry in the catchment facilitating slope coherency and stability. Alluvial-fan flood flows are intended to be accommodated for by the existing stormwater drainage system (Figure 11.5).

11.3 Reavers Lane alluvial-fan hazard

As there is no surface channel across the Reavers Lane alluvial-fan surface, the full appreciation of potential alluvial-fan hazard is not well recognised. At present, a small debris screen and culvert connected to the reticulated stormwater system is relied upon to accommodate water flows derived from this catchment (Figure 11.5). Heavily forested catchments have contributed to the coherency of slopes in these catchments, and decreased slope saturation has resulted in a reduced frequency of mass-movement processes. Debris-flow and rock-fall events have been infrequent in recent decades.

Depending on the nature and characteristics of each storm event, any part of the hazard area may be impacted by debris or debris-flood flows or floodwater inundation in the future. It is likely that the fan's upper slopes will be impacted by debris-flow and rock-fall events, as these processes have occurred here in the past, forming the underlying landforms. On the fan's lower margins, it is more likely that debris-flood or floodwater sheet-flows will occur. Due to the steep topography, it is likely that mass-movement processes may become more active should catchment conditions change in the future.

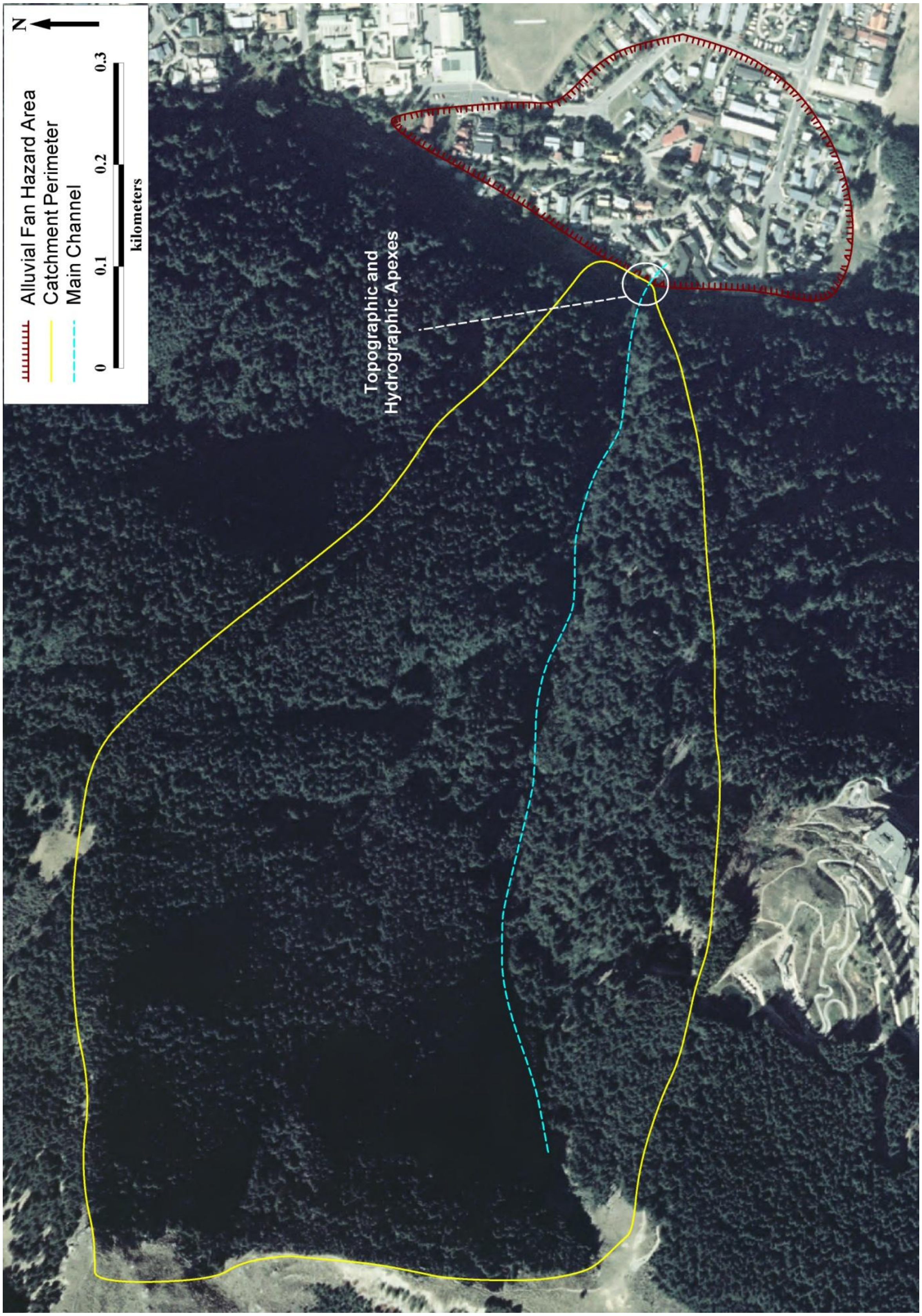


Figure 11.2 Reavers Lane alluvial fan and catchment; aerial photo taken February 2006

Figure 11.3 Reavers Lane catchment and alluvial fan

Figure 11.4 Large boulders and clasts of schist just down slope of the topographic apex of the Reavers Lane alluvial fan. While not *in situ*, it can be inferred that these boulders were derived from the alluvial-fan surface.

Figure 11.5 Reavers Lane alluvial-fan stormwater screen and culvert entrance (left). Residential properties at the head of the alluvial fan with respect to location of this structure (right)

Historic Aerial Photographs - Reavers Lane, Queenstown

12. Reservoir Creek, Roxburgh

Located on the eastern flanks of the Old Man Range, the Reservoir Creek catchment (Figure 12.1) is a geologically old landscape, as discussed in Section 1.2. The catchment ranges in elevation from 1023m at its crest to around 140m at the head of the alluvial fan. Reservoir Creek has built an alluvial fan onto old river terraces previously deposited by the Clutha River. The fan has been modified extensively by urban development and is bisected by SH 8 across the mid-fan.

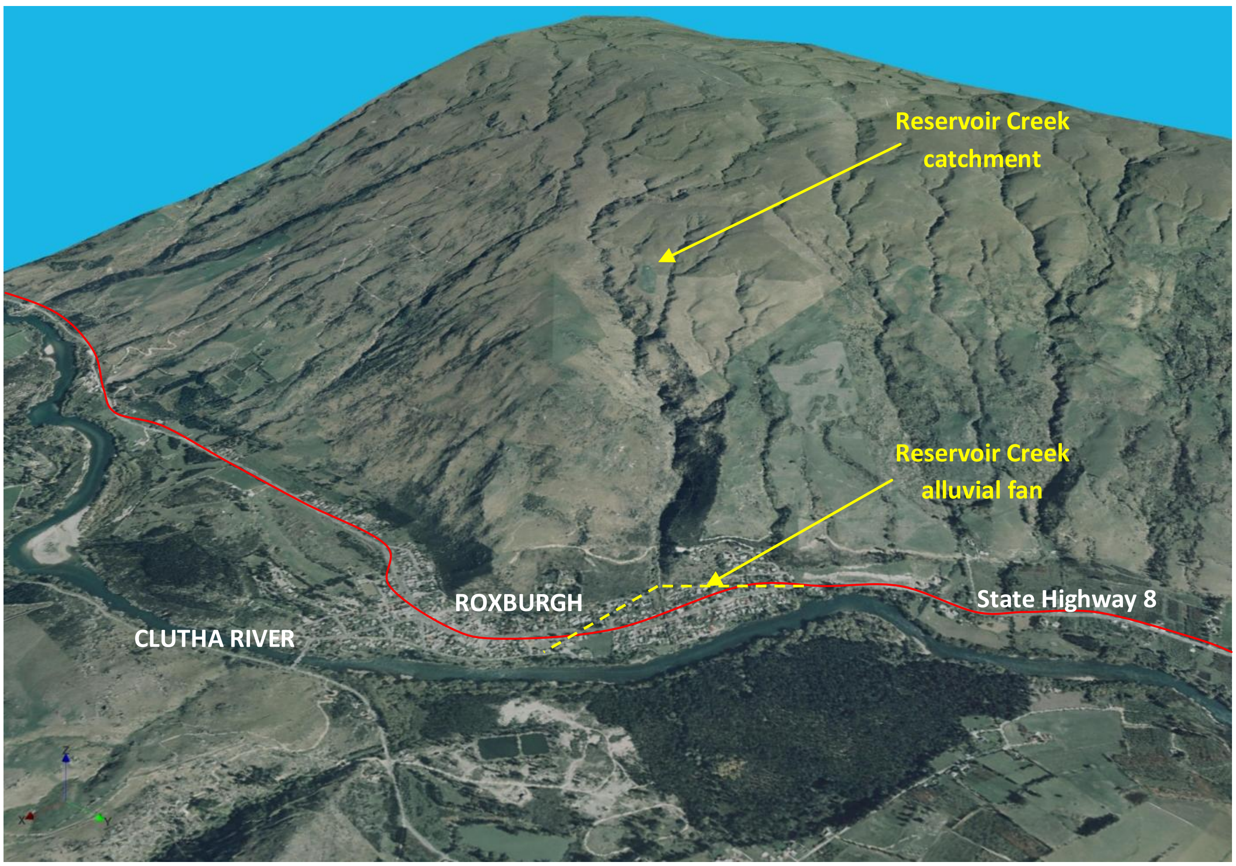


Figure 12.1 Image showing the Reservoir Creek alluvial fan with respect to the surrounding environment

12.1 Catchment characteristics

The Reservoir Creek catchment is approximately 10.4km ^{2} in size (Figure 12.2) and is steep. The upper catchment is dominated by small bushes and alpine tussocks, with no large areas of forest present.

Catchment observations, undertaken by ORC in March 2011, found that Reservoir Creek is well incised into basement schist, having been subject to progressive erosion and valley uplift in the past. Catchment slopes are mantled by large-scale mass-movement features overlain by highly weathered colluvial deposits that are being actively eroded by the creek (Figure 12.3-P1). The bed of the creek is comprised of unconsolidated debris deposits sourced from the adjacent slopes, and deposited during debris-flow events (Figure 12.3). Following the recession of debris-flow events, the channel has incised into these deposits. For much of its length, the catchment channel is well defined and confined between the adjacent slopes. These conditions are favourable for the efficient transfer of debris and flood flows down to the alluvial-fan surface.

Active slope instability in the catchment is generally the direct result of over-saturation during storm events. Slides and rock falls are common occurrences during high-intensity events, as observed in October 1978 (Figure 12.4).

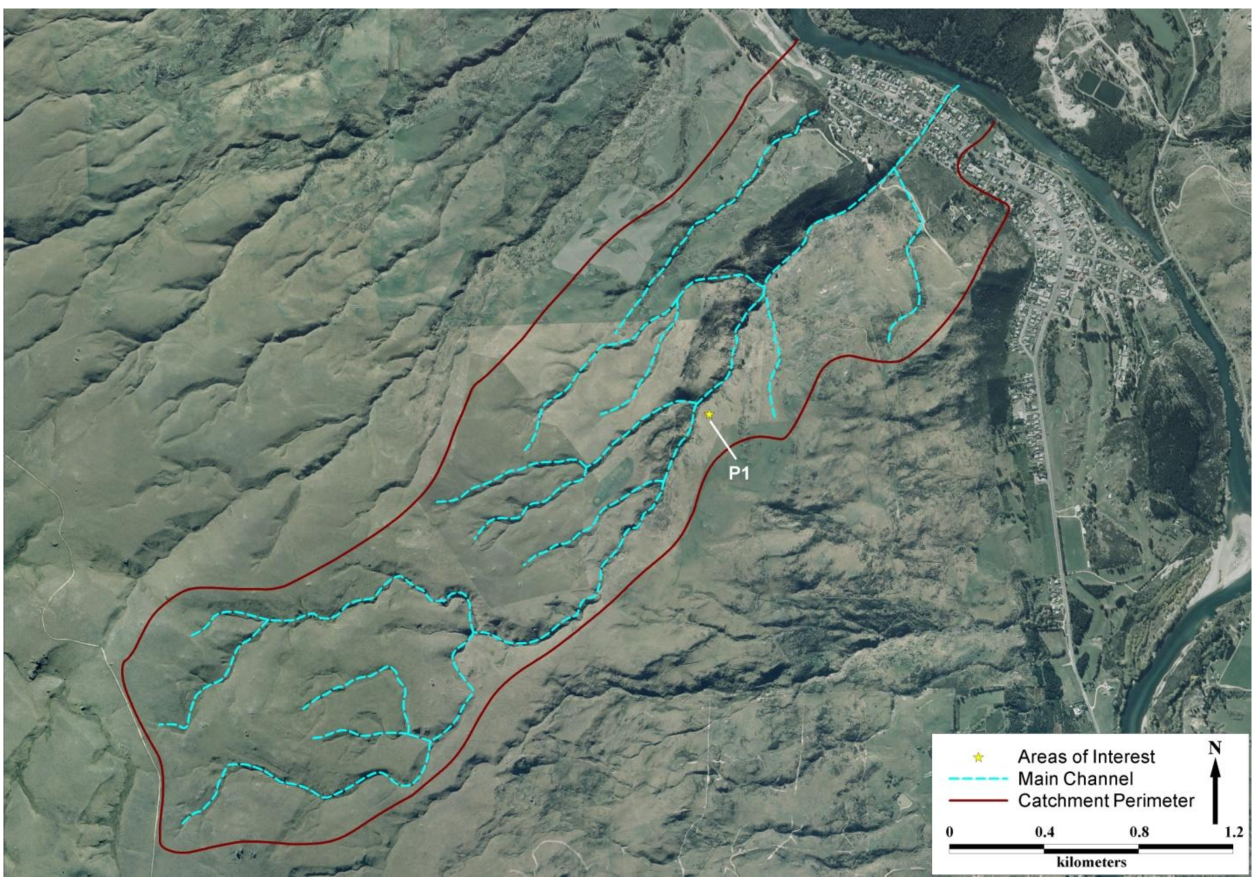


Figure 12.2 The Reservoir Creek catchment and surrounding environment; aerial photo dated March 2006

Figure 12.3 The Reservoir Creek catchment. Left: Incision into the base of the adjacent slopes contributes sediment and debris to the channel. Centre: Lower catchment on 17 October 1978, looking downstream; fresh debris deposits are evident along the length of the channel. Right: The same stretch of lower catchment as centre image, taken in March 2011, looking upstream. Debris deposits are now vegetated in this reach and have been subsequently incised by the active channel.

Figure 12.4 Left: Upper catchment debris slide almost impounding the Reservoir Creek channel, 17 October 1978. Right: Channel incision and erosion directly supply debris to the channel, 17 October 1978.

12.2 Fan characteristics

Reservoir Creek has formed a semicircular alluvial fan onto old river terraces, previously deposited by the Clutha River (Figure 12.5). At the toe of the alluvial fan, the Clutha River actively removes sediment and debris. Near the topographic apex of the fan, the channel flows in a U-shaped scoured valley, indicating historic-debris flows have passed through this location. As the channel leaves the confines of the valley, it has been extensively modified by excavation and the construction of concrete-lined channels on the fan surface (Figure 12.6). The intention of this structure is to enable the efficient transfer of debris flows down the fan surface to the Clutha River to prevent flows from spreading into residential areas.

Channel contouring and the construction of the concrete-lined channel were undertaken by the Otago Catchment Board (OCB) in 1980 and 1981 (Figure 12.6). In 1983, a storm event in the Reservoir Creek catchment caused damage to the lined channel, and further improvements were undertaken by the OCB in 1984. Upstream of the concrete-lined channel, large willows and dense vegetation has grown in the channel, following the 1984 works (Figure 12.6).

12.3 Reservoir Creek alluvial-fan hazard

The Reservoir Creek alluvial fan has been subject to recurrent debris-flow events in the past (Figure 12.7). In October 1978, debris flows overwhelmed the channel and impacted residential properties on the fan surface above and below the state highway. In response, authorities excavated the channel and constructed a concrete-lined channel to convey debris flows efficiently to the lower fan. This structure was in place by the early 1980s (Figure 12.6).

The alluvial-fan hazards associated with Reservoir Creek generally consist of high-velocity-debris and debris-flood flows, channel avulsion, bank erosion and floodwater 'sheet-flow' inundation. Upper parts of the fan are subject to high-velocity debris flow where the channel is currently confined and steep. As the fan and channel gradients change downstream, debris-flood deposits are more common (Figure 12.7), with considerable channel aggradation occurring during and in the immediate recession of the debris-flow event.

Depending on the nature and characteristics of each storm event, any part of the hazard area may be impacted by debris or debris-flood flows or floodwater inundation in the future. It is likely that the fans upper slopes will be impacted by debris flow, as these processes have occurred here in the past, forming the underlying landforms. On the fan's lower margins, it is more likely that debris-flood or floodwater sheet-flows will occur; however, debris flows may impact these areas during high-magnitude events. Catchment conditions indicate that a large volume of unconsolidated debris is stored in the active channel margin that may be transported to the fan surface in future events.

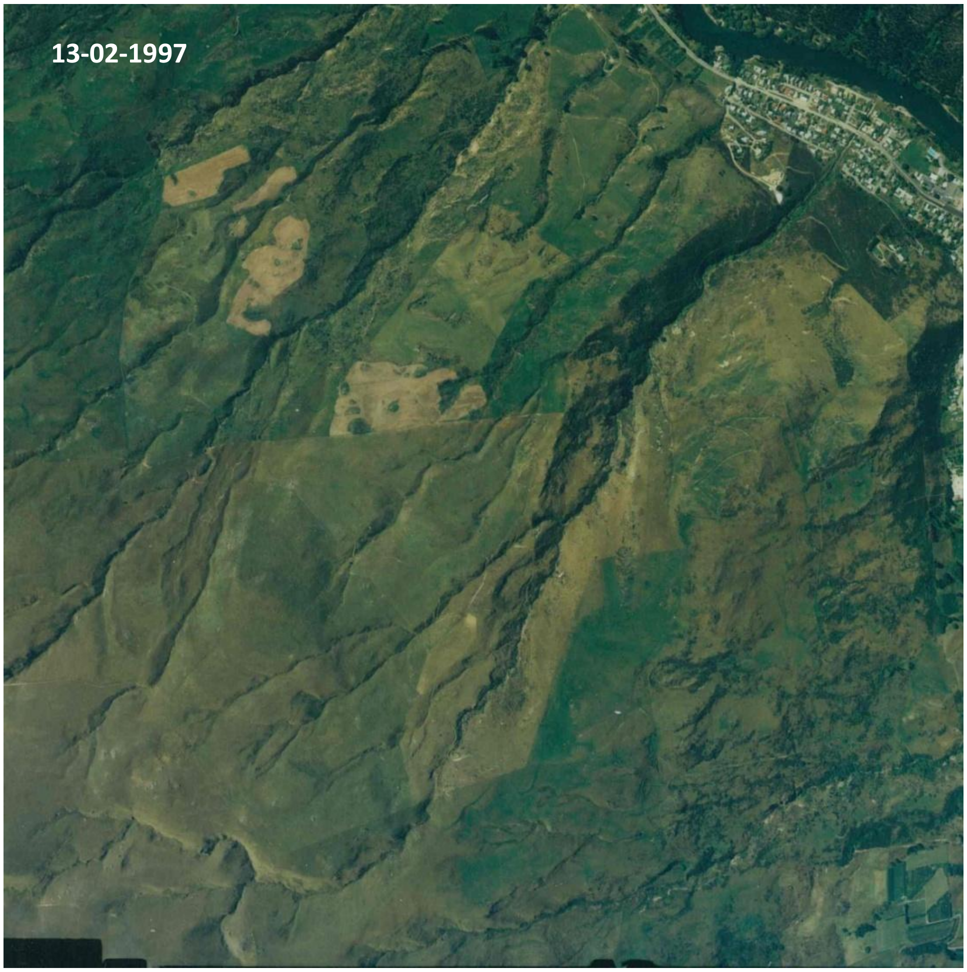
It is noted that alluvial fans to the north of the Reservoir Creek catchment, located on the northern fringe of the Roxburgh urban area, including the Quail Haven subdivision, have not been assessed as part of this investigation. These catchments are smaller than Reservoir Creek, but still have the potential to create debris and debris-flood flows and floodwater inundation on the alluvial-fan surfaces. The hazard area defined in Figure 12.5 resembles the active alluvial fan areas mapped by Barrell *et al*. (2009).

Figure 12.5 Reservoir Creek alluvial fan noting key features; aerial photo dated March 2006

Figure 12.6 Reservoir Creek concrete-lined channel, upstream of SH 8 in March 1983 (top left), and in March 2011 (top right), looking upstream. Bottom left: Reservoir Creek channel upstream of concrete-lined channel. Bottom right: Reservoir Creek concrete-lined channel below SH 8

Figure 12.7 Top: Reservoir Creek at SH 8 after the October 1978 storm event, compared to March 2011. Large volumes of debris blocked the state highway in 1978 and impacted residential property. Bottom: Reservoir Creek, looking upstream (left) and downstream (right) of SH 8 in October 1978. Large volumes of debris are evident in both images.

Historic Aerial Photographs - Reservoir Creek, Roxburgh



13. Conclusion

Eleven specific alluvial fans within the Queenstown Lakes and Central Otago districts have been assessed. Key features on each alluvial fan and their respective catchments have been identified through desktop and site-specific investigations. From these datasets, an alluvial-fan hazard area has been identified for each fan and the probable future hazards discussed.

The report concludes that parts of Queenstown, Wanaka and Roxburgh townships are exposed to intermittent alluvial-fan hazards. Hazard areas have been defined for particular alluvial fans in these communities that may be subject to alluvial-fan processes in the future. Elsewhere, communities in the Makarora Valley have a level of residual exposure to alluvial-fan hazards should channels migrate laterally across the fan surface in the future.

14. Glossary

Aggradation: To raise the grade or level of the river bed, primarily by depositing sediment accumulations

Alluvial fan: Landforms that develop where a steep gully emerges from its confines onto a flatter valley floor, or at other sites where sediment accumulates in response to changes in stream gradient and/or width

Avulsion: The abandonment of a river channel and the establishment of a new channel at a lower elevation on its floodplain as a result of floodplain/channel aggradation

Braided area: An area where sediments are deposited by numerous streams that may, over time, meander across the surface. This is generally a wide gently sloping area.

Catchment: The area from which a surface water system derives its water

Debris: Mass of loose unconsolidated material, including silt, sand, gravel, boulders and vegetation

Debris flow: A mass movement (often classified as a type of landslide) involving rapid (5-10m/s, 15-30km/hr) flow of debris containing coarse-grained, saturated material confined in a steep channel and running out onto 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 very rapid (up to ~5m/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.

Delta: A fan-shaped alluvial deposit at a river or stream mouth formed by the deposition of successive layers of sediment

Hydrographic apex: Highest point on a fan at which the stream flow is confined to a single channel

Incised/incision: A stream or channel that has been down-cut or entrenched into a surface

Interstitial: Located or forming in small narrow spaces

Lateral migration: The process whereby channels move sideways across the wider floodplain of the river

Log-jam: A pileup, dam or tangle of logs in a waterway, causing a blockage that impounds flow and debris

Mass movement: The downhill movement of surface materials under the influence of gravity, often induced or assisted by increased saturation of the slope

Morphology: The form or structure of the river

Piedmont terrace: A terrace formed or situated at the foot of a valley or mountain range

Post-glacial terrace: A landform created by the deposit of debris and/or floodwater sediments in an area previously occupied by a valley glacier

Schist: Medium- to coarse-grained metamorphic rock, composed of laminated, often flaky parallel layers

Sheet flow: An overland flow of water taking the form of a thin, continuous film over a relatively smooth surface and not concentrated in channels

Surficial: Of or relating the surface of an object or landform

Topographic apex: The head or highest point on an alluvial fan

15. References

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