Natural hazards in the Cardrona Valley

Otago Regional Council
Private Bag 1954, 70 Stafford St, Dunedin 9054
Phone 03 474 0827 Fax 03 479 0015
Freephone 0800 474 082
www.orc.govt.nz

ISBN 978-0-478-37600-5

Published December 2010

Executive summary

The Cardrona Valley and its environs have a complex hazard setting. The residents and wider community are exposed to a range of hazards, including flood inundation, sedimentation and erosion, seismic hazards, mass movement, and alluvial fan hazards. The level of exposure is defined by the nature, magnitude, and frequency of these hazards. This document identifies and describes each hazard, while discussing the effects they may have on residents and community based on current knowledge.

Flood hazards, in the form of inundation, erosion and sedimentation, are dynamic in the Cardrona River. The extent and location of flood hazards can vary considerably during each flood event, as observed in November 1999, due to variations in tributary flow and sediment supply, and the changing geomorphology of the surrounding environment. The area subject to flood hazard has been identified and is presented in the form of a composite map generated using a combination of hydraulic modelling, observations of historical flood extents and extensive on-site landform interpretation.

Erosion hazard for the length of the river has been classified. These limits have been derived based on an evaluation of the river's geomorphic processes, channel features, on-site investigations, and aerial photograph interpretation from various dates. Risk classifications, for reaches below The Larches, have been attributed High, Moderate and Low classifications to represent the level of hazard expected at each locality.

Alluvial fans are common on the Cardrona Valley floor, generally sourced from tributaries in the Crown and Criffel Ranges. These landforms are subject to random debris and flood flows and as such, have an element of relative risk associated with the unpredictable nature of alluvial fan hazards. Fans within the vicinity of the Cardrona village have been mapped at greater precision to determine fan activity over recent decades and centuries.

Mass movement, in many forms, is widespread throughout the Cardrona Valley and may impact residents and the wider community either directly, through slope failure, or indirectly, by increasing volumes of sediment to tributary channels and the Cardrona River.

Seismic hazards in the form of fault rupture, ground-shaking and liquefaction pose a risk to the Cardrona Valley due to its proximity to the Alpine Fault and the location of the NW and SE Cardrona Faults, which run almost parallel down the valley floor. During a large Alpine Fault earthquake ($\sim M_w 8.0$)[1] the Cardrona Valley may experience up to two minutes of ground-shaking, such an event has an estimated return interval of 200-300 years. Comparatively, the NW and SE Cardrona Faults have an estimated recurrence interval of about 7,500 years for magnitudes of 7.0 and 7.1 respectively.

---

[1] An earthquake with an approximate magnitude of 8.0

Table of contents

Executive summary i

1. Introduction 1

2. Environment setting 5

3. Rainfall and hydrology 7

    3.1 Rainfall 7

    3.2 Hydrology 10

4. Flood hazard 12

5. Alluvial fan hazard 17

6. Mass movement 20

7. Earthquakes and seismicity 22

    7.1 Fault movements 22

    7.2 Liquefaction and settlement of soils 23

8. Conclusion 25

9. Glossary 26

10. References 27

Appendix A—Flood Hazard Maps 28

Appendix B—Selected November 1999 Flood Photos 39

Appendix C—Modified Mercalli Intensity Scale (Opus, 2004) 47

List of figures

Figure 1.1 Cardrona Valley with respect to the surrounding ranges and landforms 1

Figure 1.2 Locality map of the Cardrona Valley showing major tributaries 3

Figure 1.3 The lower Cardrona Valley and surrounding hazardscape looking upstream. The Ballantyne Road bridge is just visible in the lower right of the image. 4

Figure 2.1 The Cardrona Valley looking towards the Criffel and Pisa Ranges from the Cardrona ski-field road. Large terrace deposits, in places incised by alluvial fans, flank the valley floor in this area. 5

Figure 2.2 The Cardrona River within the vicinity of The Larches (left) showing a confined single thread channel and downstream of The Larches (right) showing a braided depositional zone. 6

Figure 3.1 Annual rainfall totals for the Cardrona gauge, 1928 to 2009. Missing record in 1964, 1986, 2002 and 2003. Source: NIWA Climate Database 7

Figure 3.2 Projected annual mean rainfall in the South Island in 2090, relative to 1990 (as a %). Source: MfE 2008. 8

Figure 3.3 Spatial variability of extreme precipitation trends in and around the Cardrona catchment between 1951 to 2003 (see text for explanation). Data sourced from Mojzisek, 2005 9

Figure 3.4 Flow record in m^3/sec for the Cardrona River at Mt Barker recorder from 2 December 1976 to 1 April 2010, with a gap in record from 21 October 1988 to 23 February 2001. 11

Figure 3.5 Flow record in m^3/sec for the Cardrona River at Albert Town recorder. The record exists from 28 September 1978 to 9 January 2002 11

Figure 4.1 Debris dam formed in the upper Cardrona River catchment in November 1999 12

Figure 4.2 True left bank erosion of the Cardrona Valley Road near The Larches, November 1999 14

Figure 4.4 True right bank erosion downstream of The Larches, November 1999 15

Figure 4.5 True right bank approach of the Ballantyne Road bridge following November 1999 flooding 16

Figure 4.6 Representative cross-section located between the State Highway and Ballantyne Road for 1988, 2000 and 2002 16

Figure 5.1 Photograph showing the Little Meg alluvial fan and source catchment in the lower Cardrona Valley 17

Figure 5.2 Map of alluvial fan deposits greater than 0.5 km^2 in the Cardrona Valley (Opus 2009) 18

Figure 5.3 Alluvial fan deposits within the vicinity of Cardrona village (Barrell et al, 2009) 19

Figure 6.1 Large schist landslides flank much of the western slopes of the Criffel Range....20

Figure 6.2 Large lobate landslide deposit, formed by periodic failure and progressive erosion of active slopes in a tributary of the Cardrona River, Crown Range....21

Figure 6.3 Mass movement in the Cardrona River upper catchment resulting from the over saturation of slopes during the November 1999 flood event 21

Figure 7.1 Map showing active faults close to the Cardrona Valley 23

Figure 7.2 Areas possibly susceptible to liquefaction near the Cardrona Valley (Opus 2004)....24

Figure A.1 Flood Hazard Map 1 29

Figure A.2 Flood Hazard Map 2 30

Figure A.3 Flood Hazard Map 3 31

Figure A.4 Flood Hazard Map 4 32

Figure A.5 Flood Hazard Map 5 33

Figure A.6 Flood Hazard Map 6 34

Figure A.7 Flood Hazard Map 7 35

Figure A.8 Flood Hazard Map 8 36

Figure A.9 Flood Hazard Map 9 37

Figure A.10 Flood Hazard Map 10 38

Figure B.1 The Cardrona Valley Road in the upper valley reaches, November 1999....39

Figure B.2 The Cardrona River upper valley reaches looking upstream, November 1999....39

Figure B.3 Debris dam formed over the Cardrona Valley Road in the upper valley reaches looking upstream, November 1999 40

Figure B.4 The Cardrona Valley central reaches looking upstream, November 1999....40

Figure B.5 The Cardrona Valley central reaches at the Snow Park looking upstream, November 1999 41

Figure B.6 The Cardrona Valley central reaches looking upstream, November 1999....41

Figure B.7 The Cardrona Valley central reaches looking upstream, November 1999....42

Figure B.8 The Cardrona Valley central reaches upstream of The Larches looking upstream, November 1999....42

Figure B.9 November 1999 flood sedimentation at The Larches, looking downstream 43

Figure B.10 The Cardrona Valley central reaches looking upstream, November 1999 43
Figure B.11 True right bank erosion downstream of The Larches and upstream of the Ballantyne Bridge looking downstream, November 1999 44
Figure B.12 True right bank erosion downstream of The Larches and upstream of the Ballantyne Bridge looking upstream, November 1999 44
Figure B.13 Flood sedimentation between State Highway 6 and Ballantyne Road looking upstream, November 1999 45
Figure B.14 Flood sedimentation at the Ballantyne Road Bridge looking upstream, November 1999 45
Figure B.15 Flood sedimentation below the State Highway 6 Bridge looking upstream, November 1999 46
Figure B.16 Flood sedimentation within the vicinity of Albert Town looking downstream, November 1999 46

1. Introduction

Located between the large glacial basins of Queenstown and Wanaka (Figure 1.1), the Cardrona Valley is a dynamic and changeable landscape. Prior to European settlement, the Cardrona Valley was typical of the arid, tussock dominated inland Otago landscape. Following the discovery of gold in 1862, two settlements were established to provide services and facilities to the thriving mining industry. These were known as the upper valley township, located at the present-day Cardrona village, and the lower township, located next to Tuohys Creek (Figure 1.2). In 1873, the mining population had grown to approximately 450. However, by 1881 this number had dropped to about 200. The region-wide flood of September 1878 devastated the lower township, ruining mines, collapsing houses, and destroying the Cardrona Valley Road[2] (Figure 1.2). This event heightened awareness of flood hazard and the implications for development situated within the wider floodplain, contributing to a decline, and ultimately the abandonment, of the lower township site.

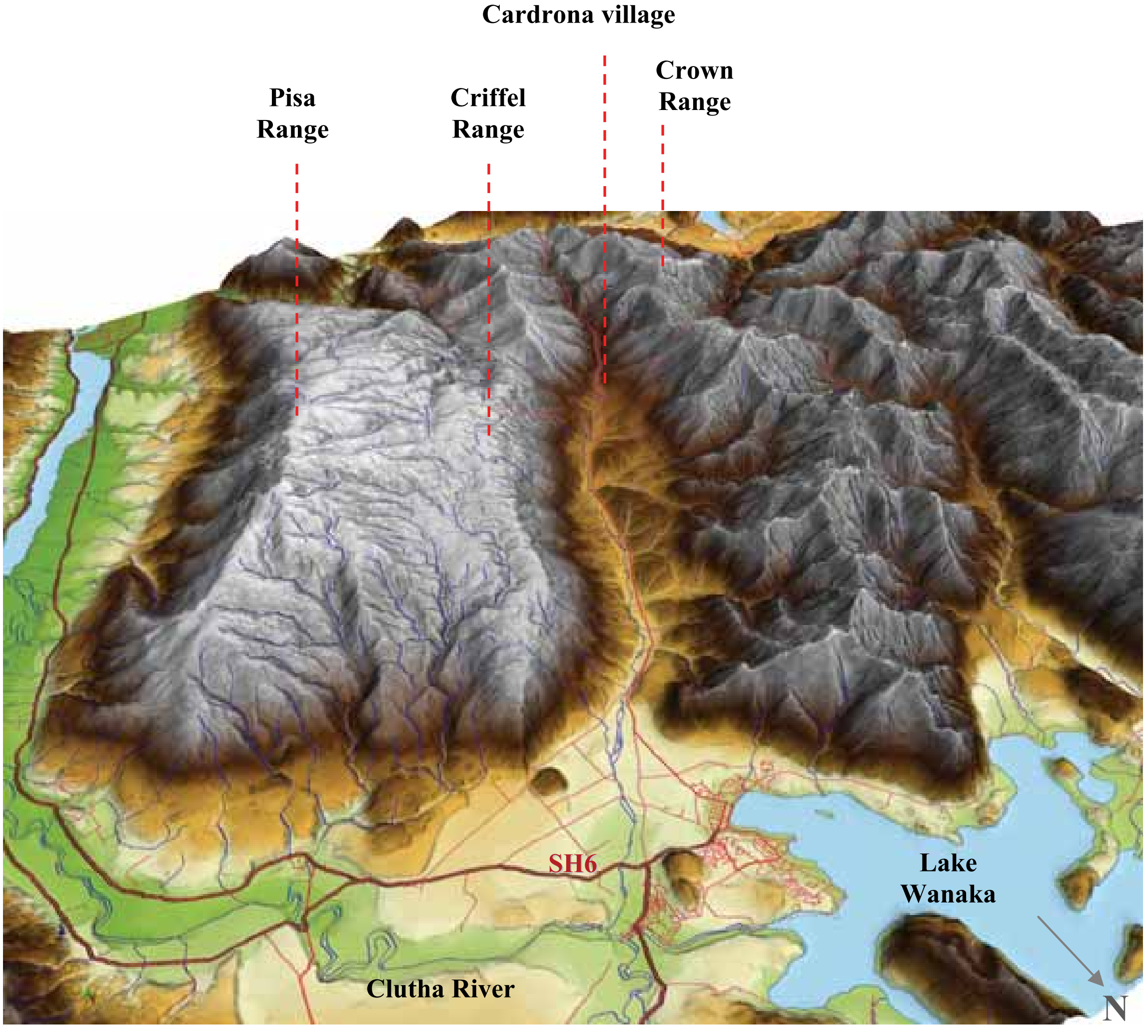


Figure 1.1 Cardrona Valley with respect to the surrounding ranges and landforms

Gold mining activities continued into the 20th century using a variety of mining techniques along the alluvial terraces flanking the valley floor and within large tributaries, such as the Branch Burn. With the decline of mining in the 1890's, many parts of the Cardrona village were re-located to Luggate and Pembroke (Wanaka).

---

[2] Historic information sourced from: http://cardrona.eprints.otago.ac.nz/

Pastoral farming dominated land use within the valley for much of the 20th century with tourism activities, such as ski fields, and activities such as commercial gravel extraction becoming more prominent in recent decades.

The Cardrona Valley's proximity to Wanaka (Figure 1.2) and a greater demand for development in the Queenstown-Lakes District has seen an increase in lifestyle block development near the Cardrona River. The Queenstown Lakes District Plan shows that zoning within the Cardrona Valley is dominated by the Rural General Zone. In the upper valley there are localised areas of Rural Visitor Zones currently present, while downstream of The Larches, Rural Lifestyle and Rural Residential zones are located on the true left bank of the river. Depending on the nature of each proposed activity, natural hazards are generally an assessment consideration for development in these zones.

The Queenstown-Lakes District Council (QLDC) projects that by 2029 the residential population of the Matukituki census area, of which the Cardrona Valley comprises 18% of land area[3], will have increased to 707, while peak day population is estimated to increase from 531 in 2006 to 1042 by 2029. Accordingly, the number of residential dwellings is also projected to increase from 207 in 2006 to 377 by 2029[4]. The growing population of this area, and related demand for development increases the level of human exposure to natural hazards.

The Cardrona Valley has a complex hazard setting (Figure 1.3), being exposed to flood hazards in the form of inundation, erosion and sedimentation. Furthermore, mass movement and seismic hazards, generated by earthquakes, have the potential to affect not only valley residents, but also infrastructure, such as access routes, that the wider community depends upon. This is particularly relevant where the Cardrona Valley Road is the shortest route between Queenstown and Wanaka, and one of the three routes out of Queenstown.

Increased demand for development in the Cardrona Valley raises the community's risk profile with respect to these hazards. Further intensification or spread of development within the valley will increase this risk, which may be compounded by changes in climate. Therefore, the Cardrona Valley's projected increase in population, coupled with the dynamic and changeable nature of its hazard setting, has prompted this study to raise awareness of the community's vulnerability and to inform decision-making in this regard. The study is supported by technical investigations and complements earlier work on morphology published in *Channel Morphology and Sedimentation in the Cardrona River (ORC, 2010).*

---

[3] The resident population of the Cardrona Valley comprised approximately 70 % of the total population of the Matukituki Census Area in 2006

[4] Population projections and census information sourced from www.qldc.govt.nz

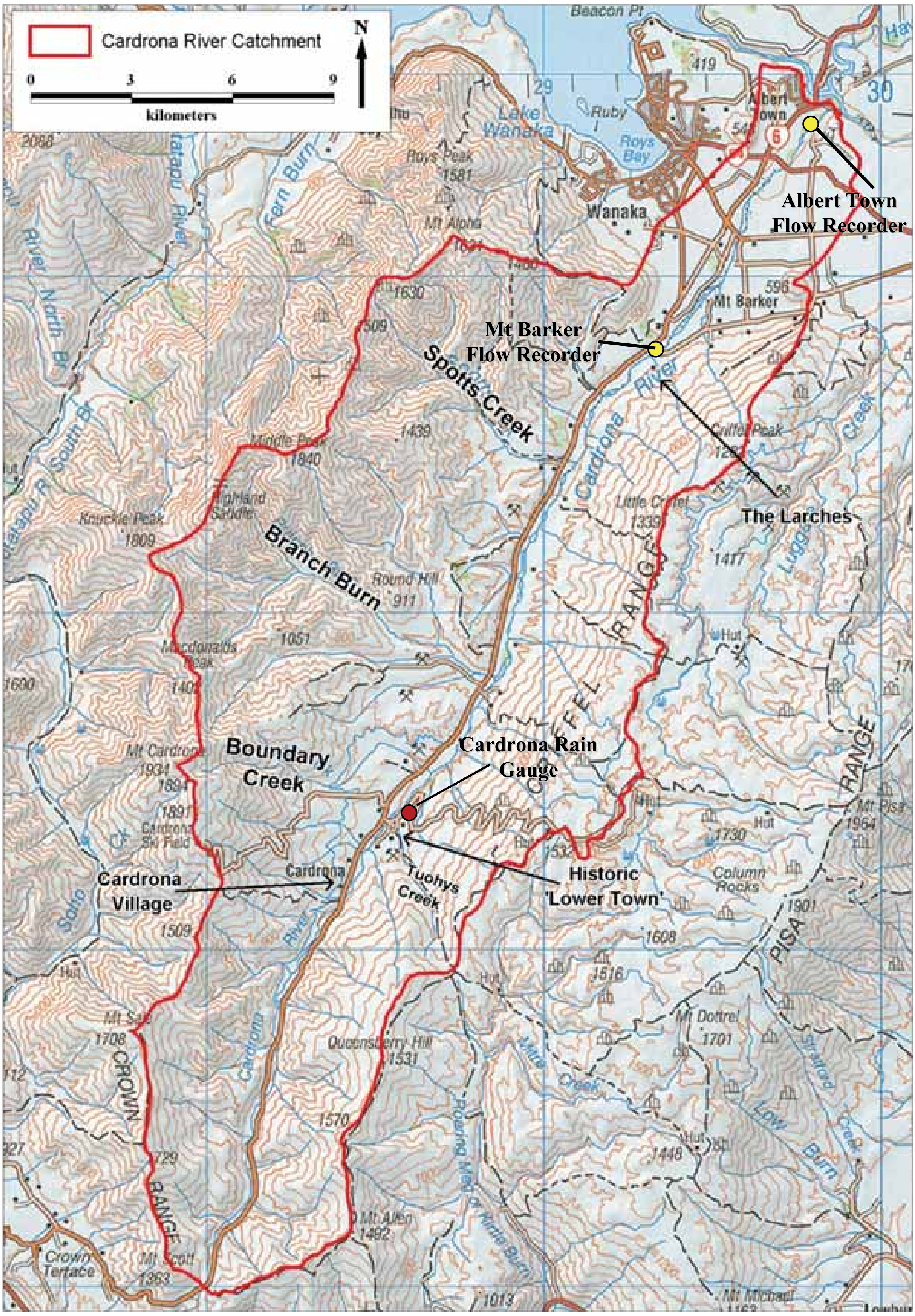


Figure 1.2 Locality map of the Cardrona Valley showing major tributaries

Figure 1.3 The lower Cardrona Valley and surrounding hazardscape looking upstream. The Ballantyne Road bridge is just visible in the lower right of the image.

2. Environment setting

The Cardrona River catchment (Figure 1.2) drains an area of approximately 337 km^2 and is bound by the Crown Range to the south and west, and the Criffel and Pisa Ranges to the east. The river flows in a north-easterly direction from its headwaters at the crest of the Crown Range, to its confluence with the Clutha River/Mata-Au adjacent to Albert Town (Figure 1.2), a distance of approximately 40 km. The catchment rises to an elevation of 1936m at Mt Cardrona, in the Crown Range, and terminates at 273m near the Clutha River confluence.

The flanking ranges, composed of highly erodible schist, have been formed and uplifted by the active NW and SE Cardrona Faults (refer to Chapter 7). The Cardrona River and its tributaries have deeply eroded into the basement schist, forming the contemporary valley that exists today. On the valley's lower slopes very old terraces (Figure 2.1), which pre-date the last glacial period about 12,000 – 15,000 years ago, are being actively eroded, and consequently contribute sediment to the river. At the base of these terraces and the confluence of many of the tributaries, alluvial fans (refer to Chapter 5) have formed and act as temporary storage areas for sediment until a flood with sufficient energy can transport the material downstream.

Figure 2.1 The Cardrona Valley looking towards the Criffel and Pisa Ranges from the Cardrona ski-field road. Large terrace deposits, in places incised by alluvial fans, flank the valley floor in this area.

Changes in the channel morphology and sedimentation characteristics of the Cardrona River over recent decades have been comprehensively described in the report *"Channel Morphology and Sedimentation in the Cardrona River'* (ORC, 2010). The geomorphology and shape of the valley floor is dictated by the interaction between the river and the adjacent valley slopes. In the river's upper reaches, the channel is steep and incised into schist bedrock, forming a confined channel. Downstream of Cardrona village to The Larches (Figure 1.2), the valley floor widens and the river form varies between confined single-thread and braided channel forms. This reach is influenced by sediment inputs derived from the adjacent tributaries, such as the Branch Burn and Spotts Creek.

At The Larches, the valley constricts and becomes narrow in turn leading to a confined river form. Downstream of The Larches to the State highway, a braided depositional zone in the river exists, as the river loses its ability to transport sediment (Figure 2.2). Naturally, these reaches are dominated by a wide, braided channel which migrates across the wider floodplain. However, over recent decades, extensive modification of these areas, including commercial gravel extraction, has removed the complexity of this braided channel form. Furthermore, this location experienced significant channel migration and aggradation during the November 1999 flood event (ORC, 2010). Downstream of the State Highway, the river is confined by willow growth along the channel margins. At the confluence with the Clutha River a small depositional delta has formed.

Figure 2.2 The Cardrona River near The Larches (left) showing a confined single thread channel, and downstream of The Larches (right) showing a braided depositional zone.

3. Rainfall and hydrology

3.1 Rainfall

The frequency and magnitude of flood events is closely related to the rainfall events from which they are derived. Annual rainfall at the Cardrona rain gauge site (Figure 1.2) has not shown any significant trend since records began in 1928. However, there have been several periods which have been wetter than normal (1978-84, 1993-2000), and also drier periods (1973-77, 2005-08) (Figure 3.1). The Ministry for the Environment (MfE, 2008) predicts that annual rainfall at Queenstown, 35 km to the southwest, will increase by approximately 12% by the end of the 21st century.[5] Figure 3.2 shows that a significant increase in annual average rainfall is predicted across western Otago (including the Cardrona catchment) by the end of this century.

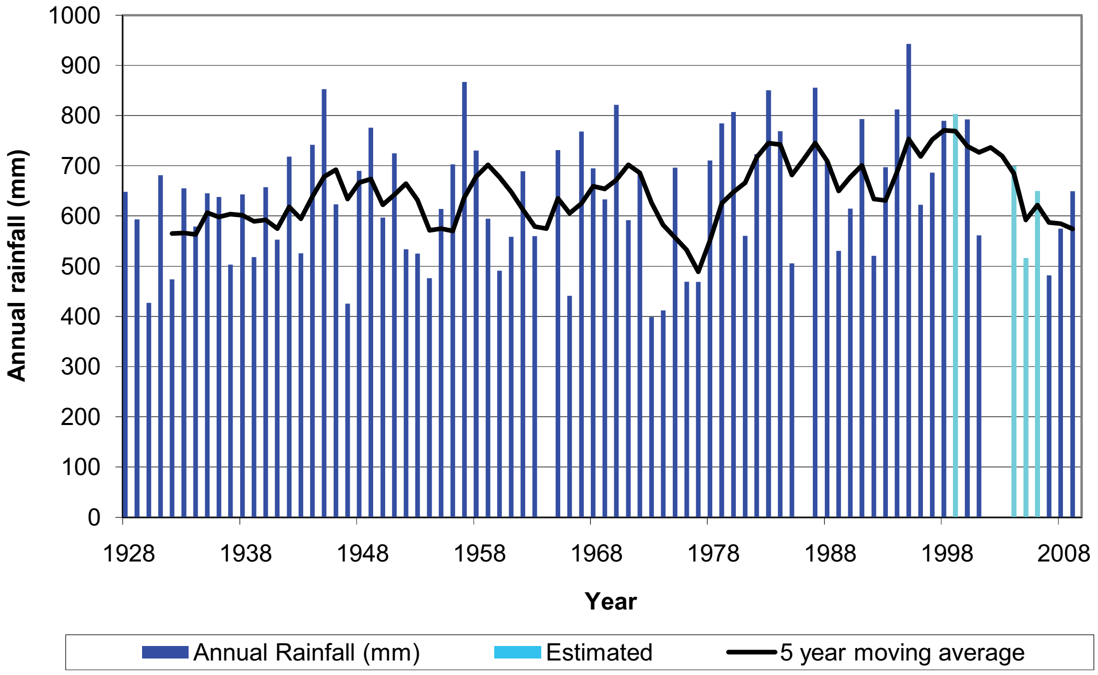


Figure 3.1 Annual rainfall totals for the Cardrona gauge, 1928 to 2009. Missing record in 1964, 1986, 2002 and 2003. Source: NIWA Climate Database

---

[5] A range of between -2% and +34%

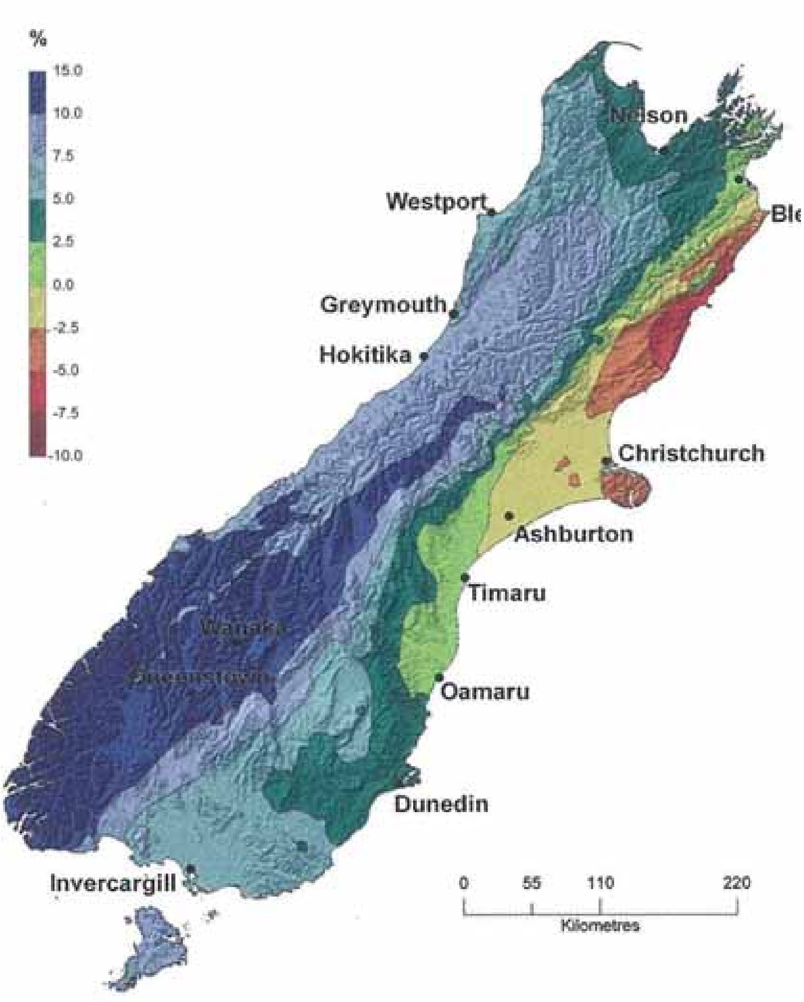


Figure 3.2 Projected annual mean rainfall in the South Island in 2090, relative to 1990 (as a %). Source: MfE 2008.

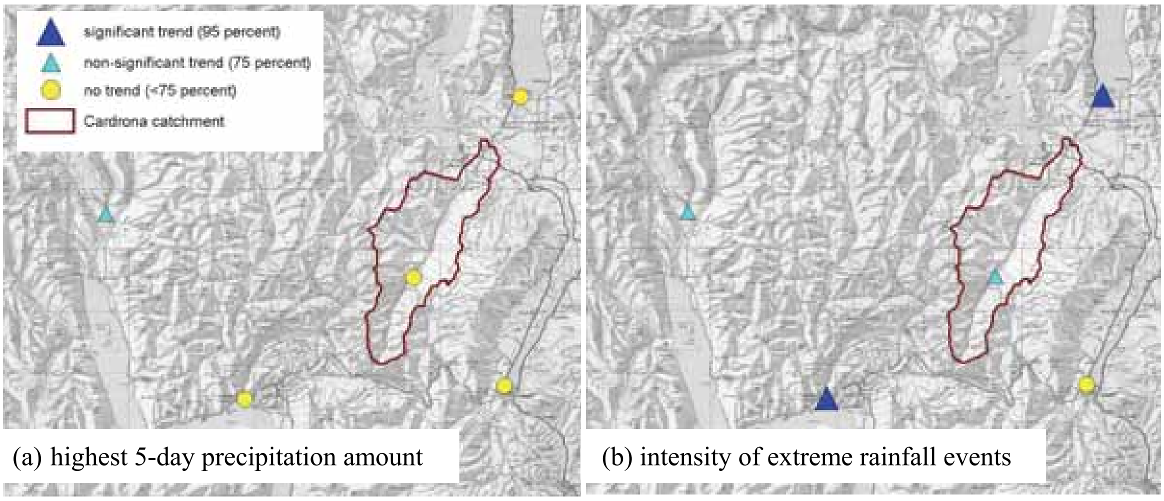
Of more importance to flood frequency and magnitude are changes in the characteristics of extreme rainfall events (i.e. storm events). In an analysis of historical rainfall patterns in the South Island, Mojzisek (2005) found that there was no statistically significant[6] change in the intensity or frequency of extreme rainfall events at the Cardrona rain gauge between 1951 and 2003 (Figure 3.3).

Figure 3.3 shows four different indices which can be used to describe changes in extreme rainfall patterns. The trend for each of these indices between 1951 and 2003 is shown for the Cardrona rain gauge, and for four other neighbouring sites (Queenstown, Lake Hawea, Cromwell and Earnslaw). Figure 3.3 (a) shows changes in the highest 5-day precipitation amount, (b) shows changes in the intensity of extreme rainfall events, (c) shows changes in the number of very wet days[7], while (d) shows changes in the percentage of annual rainfall which falls on very wet days.

---

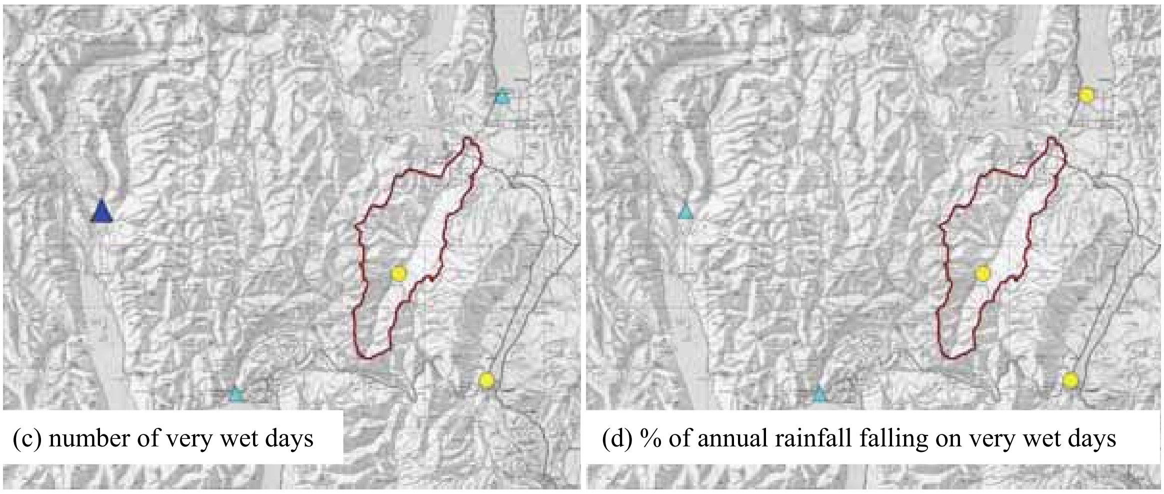
[6] Statistical significance **means that something is probably true** (i.e. not due to chance). The most common level of significance, used to mean something is good enough to be believed, is 95%. This means that the finding has a 95% chance of actually having occurred, rather than just being a random event.

[7] Mojzisek (2005) used the number of very wet days as an indicator of extreme precipitation frequency. It refers to the number of days with rainfall totals in the top 5% of those recorded at a particular site during a reference period from 1961 - 1990.



(a) highest 5-day precipitation amount

(b) intensity of extreme rainfall events



(c) number of very wet days

(d) % of annual rainfall falling on very wet days

Figure 3.3 Spatial variability of extreme precipitation trends in and around the Cardrona catchment between 1951 and 2003 (see text for explanation). Data sourced from Mojzisek, 2005

Figure 3.3 shows that the only statistically significant increasing trends to have occurred in this region since 1951 is in the intensity of extreme rainfall events at Queenstown and Lake Hawea (b), and in the number of very wet days at the Earnslaw gauge (c). A number of other non-significant trends (at the 75% level) were also observed, indicating that there was some increase in the intensity and frequency of extreme rainfall events in this region between 1951 and 2003.

Average temperature in Otago is predicted to increase by approximately 2°C by 2100. Given that a warmer atmosphere can hold more moisture,[8] there is an obvious potential for heavier extreme rainfall across Otago (MfE, 2008). In addition, the mountainous nature of the Cardrona catchment and the surrounding area (Figure 1.1) may have a local influence on any regional trends in heavy rainfall patterns. At this stage, it is difficult to assess whether the local topography will intensify or moderate the effects of a warmer climate on rainfall patterns in the Cardrona catchment.

---

[8] About 8% more for every 1°C increase in temperature

3.2 Hydrology

The Cardrona River flow record has been monitored at two long-term sites: Mt Barker and Albert Town (Figure 1.2). Figure 3.4 shows the flow record for the Mt Barker site, which operated from 2 December 1976 to 21 October 1988, then closed for several years and was re-opened on 23 February 2001. Figure 3.5 shows the flow record for the Albert Town site, which operated from 28 September 1978 to 9 January 2002.

Flow in the Cardrona River is generally greater at Mt Barker than downstream at Albert Town (Otago Regional Council, 2007). Average flow at Mt Barker is approximately 15% higher than at Albert Town, due to water being lost to groundwater recharge and abstraction for irrigation. Peak flood flows at Mt Barker are also generally higher than downstream at Albert Town. This is shown clearly for a series of flood peaks during the 1980’s, when both recorders were operating (Figures 3.4 and 3.5).

Figure 3.4 shows that high flows at Mt Barker have occurred less frequently and have been of a lower magnitude over the last decade than during the late 1970’s and 1980’s. The mean annual flood at Mt Barker between 1977 and 1988 was 75 cumecs, while this decreased to 45 cumecs between 2001 and 2009. The largest flood event in the Cardrona River since records began occurred on 17 November 1999. The Mt Barker recorder was not operating at this time, but the Albert Town gauge recorded a peak flow of 124.2m^3/s for this event (Figure 3.5). The November 1999 flood had a significant influence on channel form and morphology, and there have been no flows of similar or higher magnitude recorded over the last decade.

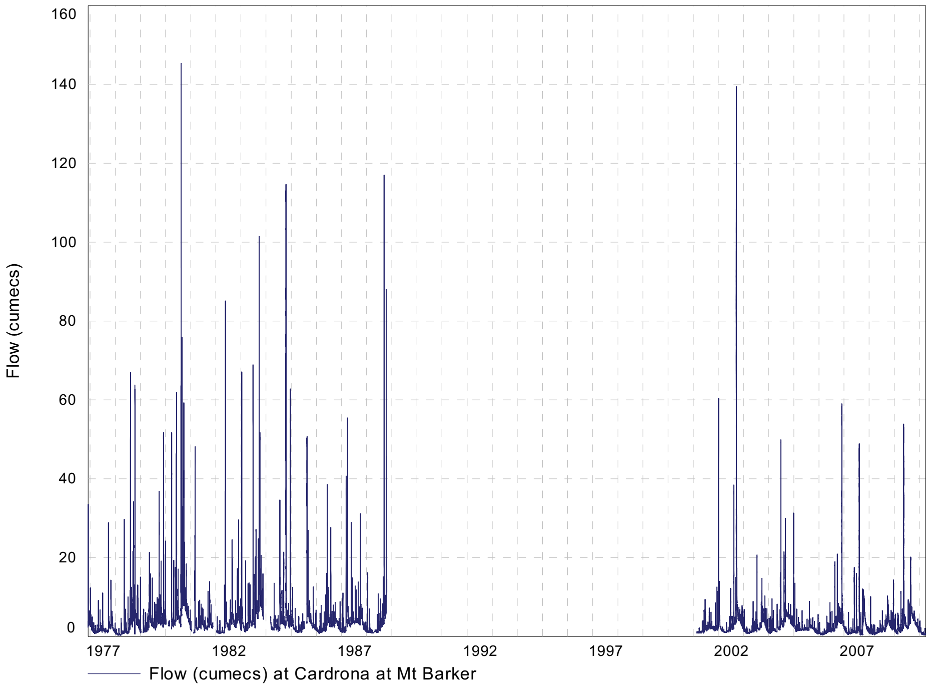


Figure 3.4 **Flow record in m^3/sec for the Cardrona River at Mt Barker recorder from 2 December 1976 to 1 April 2010, with a gap in record from 21 October 1988 to 23 February 2001.**

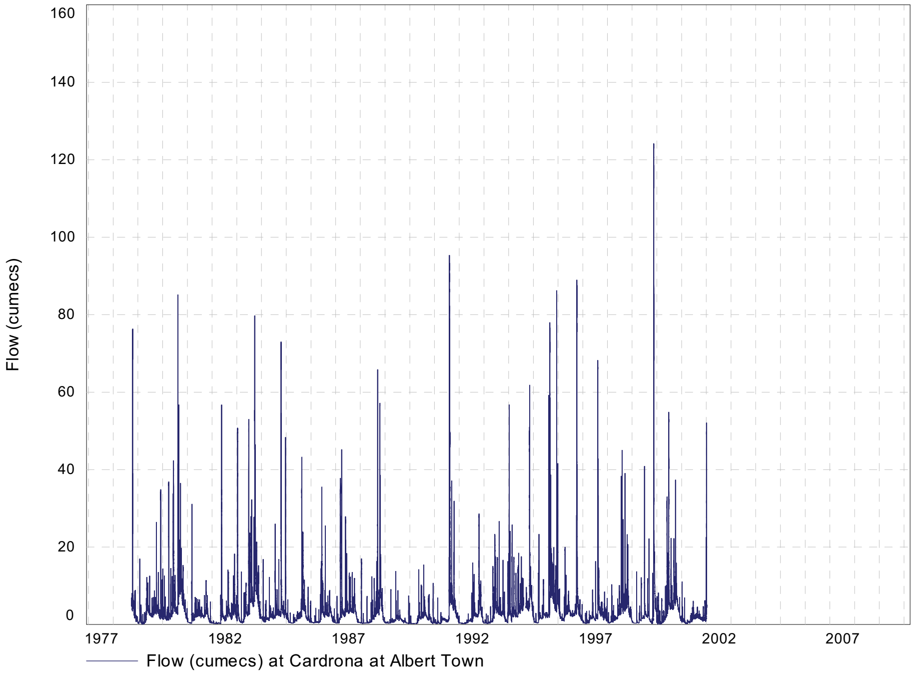


Figure 3.5 **Flow record in m^3/sec for the Cardrona River at Albert Town recorder. The record exists from 28 September 1978 to 9 January 2002**

4. Flood hazard

Flood hazards, in the form of inundation, erosion and sedimentation, are extremely variable and dynamic in the Cardrona River. The extent and location of flood hazard can vary considerably during each flood event, due to variations in tributary flow and sediment supply, and the changing geomorphology of the surrounding environment.

The area subject to flood hazard (Appendix A) has been identified along the length of the Cardrona River and represents locations that may be subject to flood inundation and sedimentation during any particular flood event. It is presented as a composite map, generated using a combination of hydraulic modelling, historical flood extents and extensive on-site landform interpretation. GHD (2010) mapped flood extents for a number of scenarios based on existing hydrological and rainfall information. These extents were adjusted based on observations of the November 1999 flood event (Appendix B) and through site investigations, which identified locations that may be exposed to flood hazard. The maps (Appendix A) identify locations that are exposed to Cardrona River flood hazard.

As noted, the characteristics of flood hazards derived from the Cardrona River are variable and unpredictable. Upstream of the Cardrona village, the channel is steep, confined, and incised into bedrock. Flood hazards within this reach of the river are generally confined to the main channel as flows run off efficiently due to the steep grade of the channel. However, due to this confinement, rapid sedimentation caused by tributary streams can block the river channel forming a dam of impounded water and debris (Figure 4.1) which may subsequently fail. Such a failure may lead to a torrent of water and debris flowing rapidly downstream, causing erosion and significant amounts of sedimentation across the floodplain.

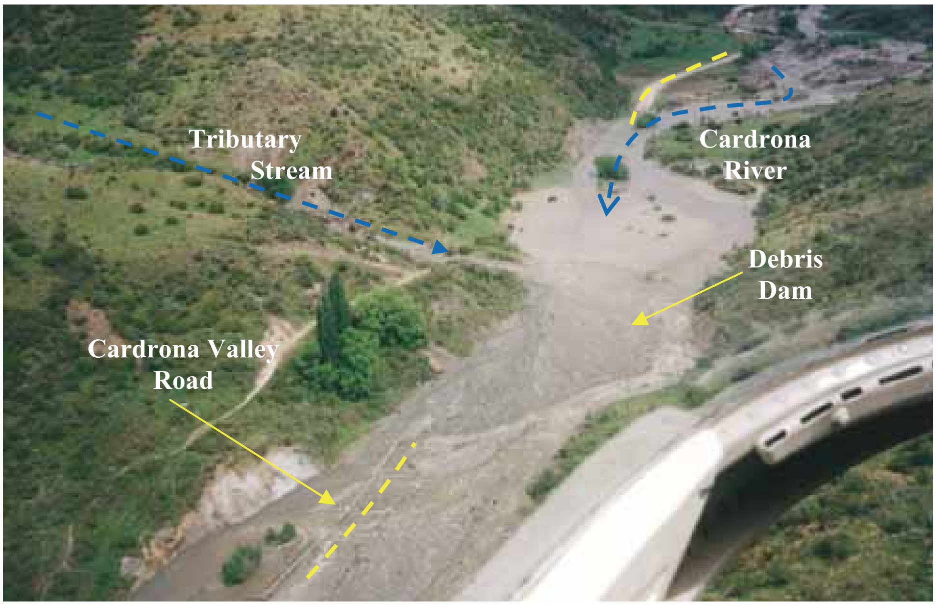


Figure 4.1 Debris dam formed in the upper Cardrona River catchment in November 1999

The geomorphology of the river's central reaches, downstream of the Cardrona village and upstream of The Larches (Appendix A: Maps 4-10), has a relatively wide valley setting with a less steep gradient (ORC, 2010). Flood hazards within these reaches vary depending on the nature of the channel form and surrounding environment. Where the river is single thread and confined by willows, flood flows are transported relatively efficiently until channel banks are overtopped. Once floodwater spills from the ‘low-flow’ channel, it can move unpredictably across the wider floodplain depositing sediment and debris. Velocities within the main channel remain swift in these reaches causing bank erosion, particularly on meanders, which may affect infrastructure such as the Cardrona Valley Road.

In these reaches, flood hazards are further influenced by the contribution of sediment and flow from large tributaries such as the Branch Burn and Spotts Creek (Appendix A: Maps 4 and 5). Downstream of the confluence of these tributaries, the Cardrona River channel widens considerably due to the input of flow and sediment from these streams (ORC, 2010). Flood flows at these locations migrate across the sediment-laden braided channel and as a result, the course of the river can change unpredictably during flood events. Significant in-channel sedimentation also causes the grade of the channel to become less steep, elevating flood levels, and causing flood waters to migrate across the wider floodplain.

At The Larches (Appendix A: Map 4), the valley floor narrows considerably promoting a high-velocity single thread, sinuous channel form which efficiently transports sediment and flow. As banks are overtopped, flood flows migrate across the wider floodplain, depositing sediment and debris. As the majority of flow is concentrated in the main channel, the high velocities can cause significant bank erosion in this reach. Further, the proximity of the Cardrona Valley Road means that it is susceptible to a significant erosion risk, a phenomenon which was observed during the November 1999 flood event (Figure 4.2).

Downstream of the Larches, the river form markedly changes to exhibit a sediment-rich braided channel margin incised into post-glacial terraces and moraine deposits (Appendix A: Maps 1-3). In these reaches, the wider floodplain is not significantly elevated above the braided ‘low-flow’ channel. As a result, the river migrates easily within the bounds of the high terraces, causing some sedimentation and bank erosion even at low flow.

Due to the generic nature of the topography in these reaches, the location of flood flows are changeable and unpredictable. In addition, as this is primarily a large depositional area (ORC, 2010), in-channel sedimentation commonly occurs during flood events, elevating flood levels and causing channels to change course over the wider floodplain frequently.

Figure 4.2 True left bank erosion of the Cardrona Valley Road near The Larches, November 1999

At the confluence with the Clutha River (Appendix A: Map 1), Cardrona River flood extents will be greater if the level in the Clutha is also elevated due to flooding. Groundwater levels in and around Albert Town are also affected by flood flows in the Clutha and Cardrona Rivers. Preliminary studies[9] indicate that groundwater levels at Albert Town are perched and have a distinct correlation with the level of the Albert Town lagoon. Therefore, high flood levels in the Clutha and Cardrona Rivers may also affect the observed groundwater levels in parts of Albert Town.

4.1 Erosion hazard

The effects of bank erosion were well observed during the November 1999 flood event (Appendix B). In the valley, upstream of The Larches, significant bank erosion removed large sections of the Cardrona Valley Road (Figure 4.2), while downstream of The Larches, significant lengths of terrace were eroded, removing property and outflanking the Ballantyne Road bridge (Figures 4.4 and 4.5).

Long-term trends in erosion of channel banks can also be observed in cross-section profiles. Figure 4.6 shows a representative cross-section located between the State Highway and Ballantyne Road bridges. Between 1988 and 2000, the right bank at this location eroded 25m with a further 52m of erosion occurring between 2000 and December 2002. Most of this erosion is most likely to have occurred in large flood events in 1994, 1995, 1999 and September 2002 (ORC, 2010).

Cardrona River erosion hazard has been mapped and is presented in Appendix A. These limits were derived based on an evaluation of the river's geomorphic processes, channel features, on-site investigations in 2007 and 2009, and aerial photograph interpretation from various dates. In the central reaches, above The Larches, the erosion

---

[9] The Cardrona River's surface and groundwater resources are the focus of a current investigation by the Otago Regional Council.

hazard has been labeled as "Indicative (Not-categorised)" which represents locations where erosion is possible, but where the level of risk has not been defined. Below The Larches, erosion hazard has been mapped and attributed a High, Moderate, or Low risk classification. The risk classifications note:

- **High -** Erosion risk is mapped where the channel was directly adjacent to the terrace margin resulting in active erosion
- **Moderate** – Erosion risk was mapped near the bounding terraces or where it is considered that channels have the potential to migrate laterally towards these terraces
- **Low** – Terrace erosion risks are low in these areas and are associated with sections of terrace that are unlikely to be exposed to lateral migration of the channel in the near future. These are typically higher level floodplains that separate the terrace from the active channel

While risk classifications have been identified; the actual extents and likelihood of bank erosion during a particular flood event is influenced by the nature and magnitude of hazard at that time. Locations that are situated between the areas subject to flooding and the defined erosion hazard lines should be regarded as a buffer (Appendix A). While these areas are not identified as being directly subject to inundation, a risk exists where the river channels may laterally migrate or avulse towards these areas, in turn establishing the erosion potential for those locations. In addition, activities within the floodplain, such as tree planting, provide conditions that are more resistant to erosion, and therefore may concentrate flow towards other locations.

Figure 4.4 True right bank erosion downstream of The Larches, November 1999

Figure 4.5 True right bank approach of the Ballantyne Road bridge following November 1999 flooding

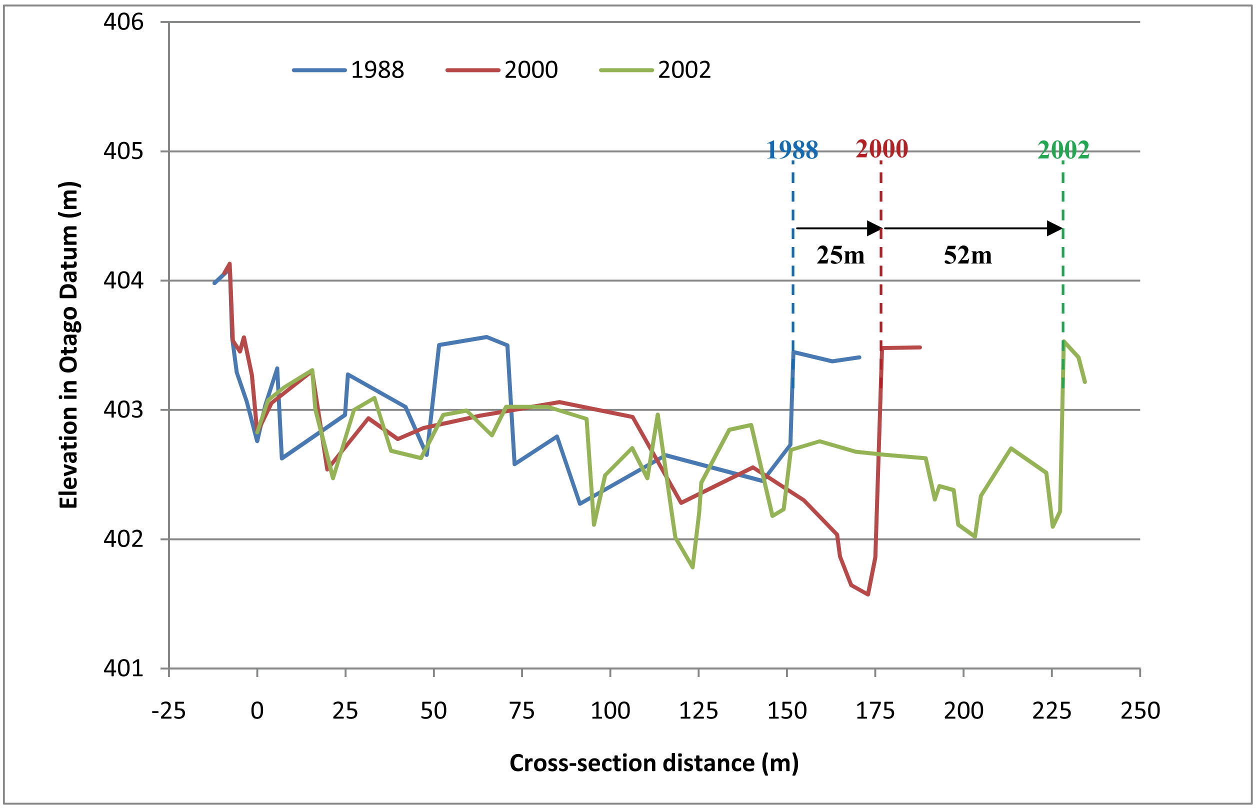


Figure 4.6 Representative cross-section located between the State Highway and Ballantyne Road for 1988, 2000 and 2002

5. Alluvial fan hazard

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. They are formed as sediment-laden flood and/or debris flows, leave the confines of a valley, and subsequently lose energy, depositing sediment. Most commonly located at the base of valley slopes, alluvial fans are often elevated surfaces with good drainage. These characteristics often make them attractive places to site development without the risk of alluvial fan hazards being fully realised.

Flood and debris flow hazards on alluvial fans can occur infrequently, sometimes over timeframes of decades to centuries, and are therefore often not well recognised. These flows generally occur suddenly without warning and are unpredictable and destructive. Channel migration across the fan surface (avulsion) is a hazard common to the alluvial fan environment. Sedimentation, floodwater inundation, and debris flows are all possible, depending on the characteristics of the source catchment and surrounding geomorphology.

In the Cardrona Valley, active alluvial fan landforms are common on lower valley slopes (Figures 5.1 and 5.2). On the valley floor, particularly in places where the valley becomes more confined, alluvial fans directly supply sediment to the Cardrona River, or act as temporary storage areas until a flood with sufficient energy can erode and transport these sediments downstream.

Opus (2009) has mapped alluvial fan landforms greater than 0.5 km^2 surface area along the length of the valley (Figure 5.2). Many active alluvial fans have formed from a range of depositional processes from the Criffel and Crown Ranges. In the vicinity of the Cardrona village, Barrell et al (2009) have mapped alluvial fan landforms in more detail, identifying fan activity over recent decades and centuries (Figure 5.3). The recognition of these landforms, and the processes from which they have been formed, contributes to the understanding of alluvial fan hazard and associated risk within the Cardrona Valley.

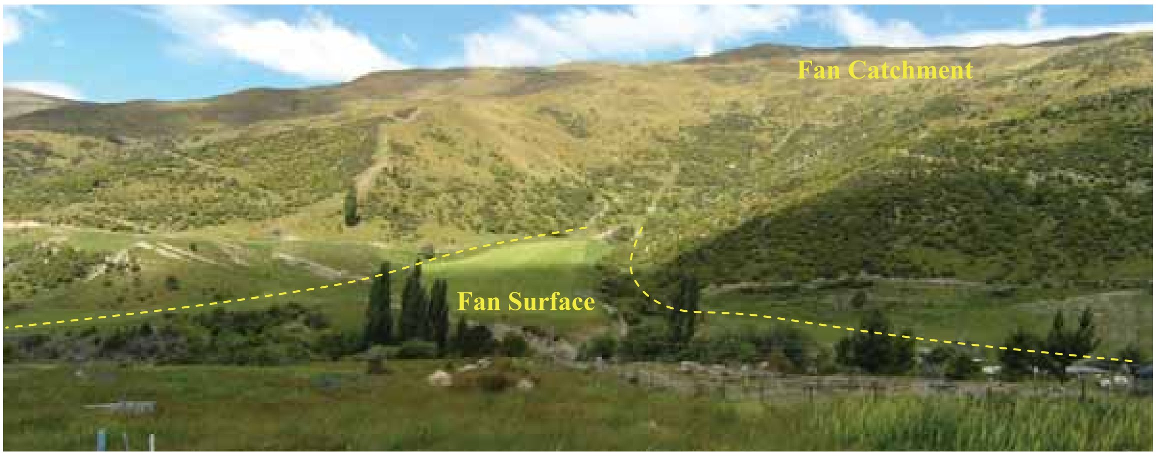


Figure 5.1 **Photograph showing the Little Meg alluvial fan and source catchment in the lower Cardrona Valley**

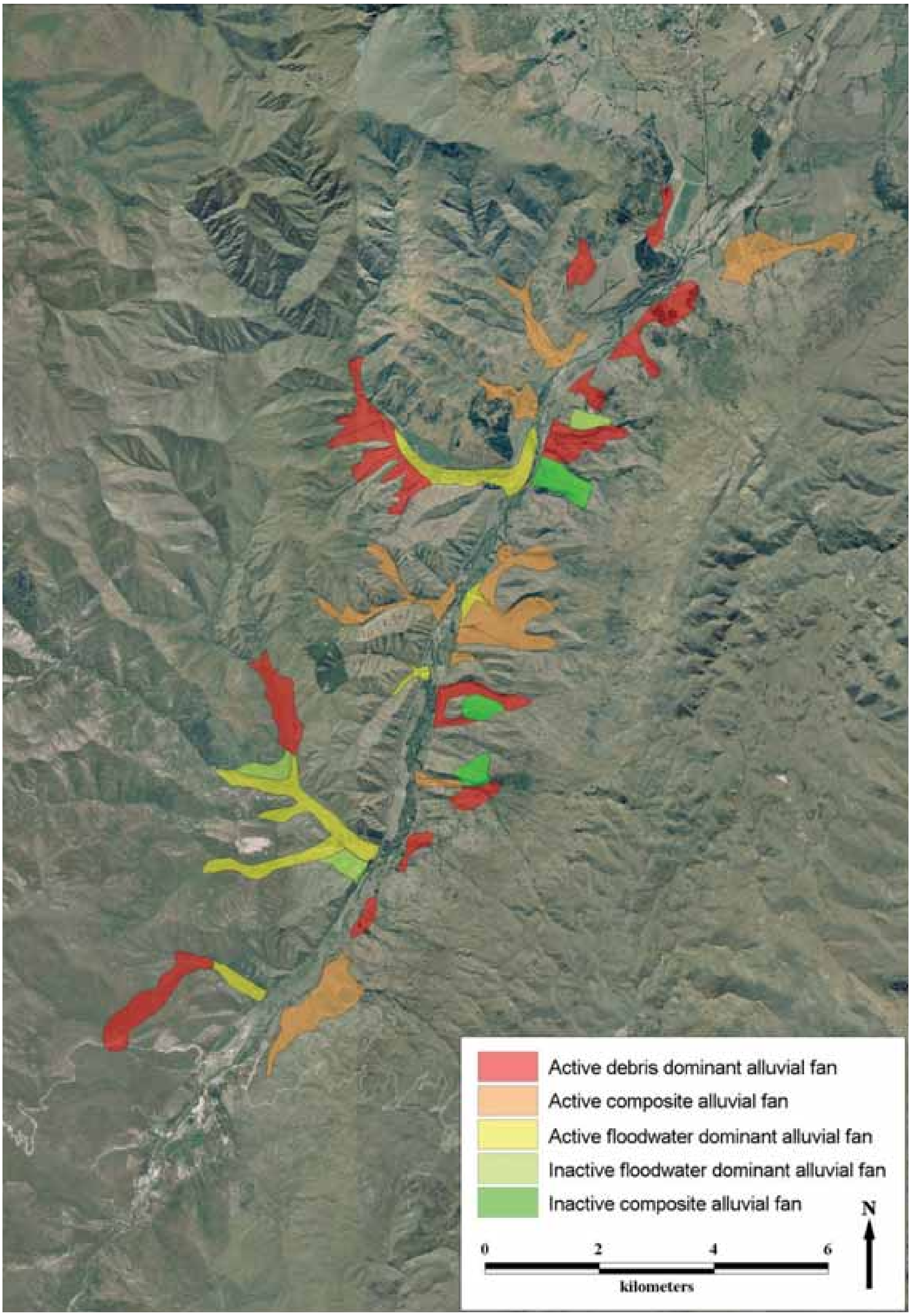


Figure 5.2 Map of alluvial fan deposits greater than 0.5 km^2 in the Cardrona Valley (Opus 2009)

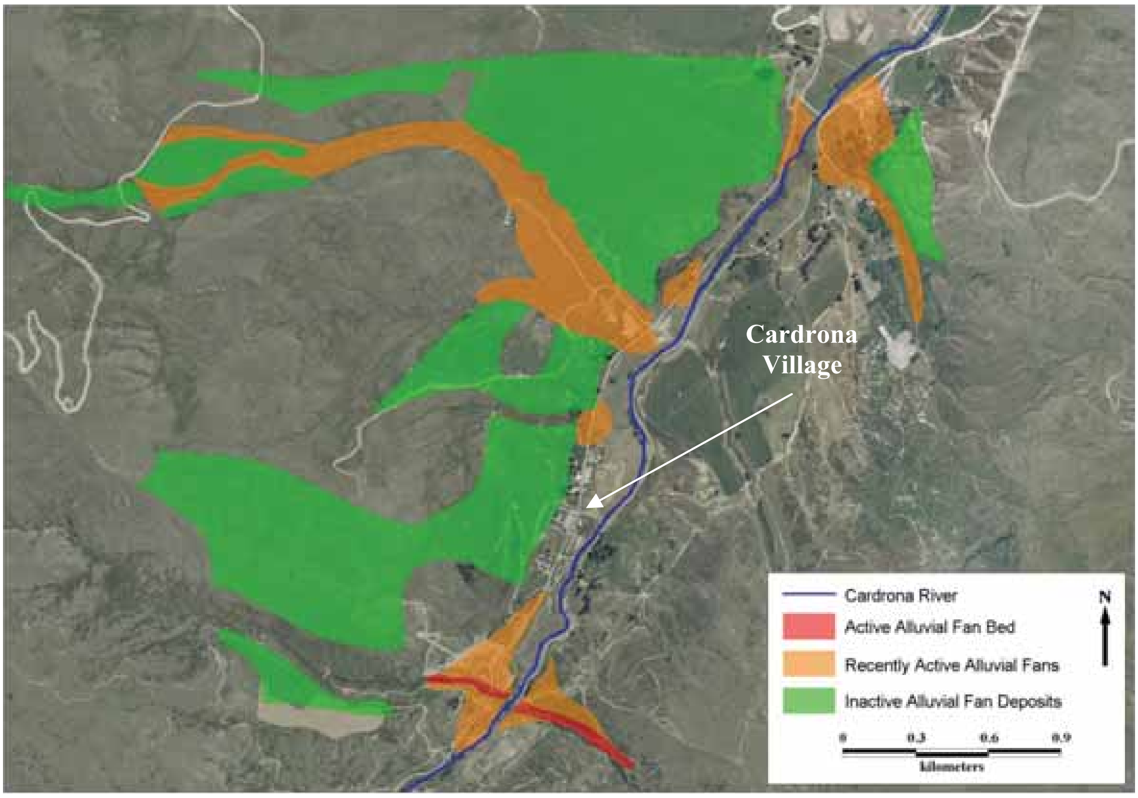


Figure 5.3 Alluvial fan deposits within the vicinity of Cardrona village (Barrell et al, 2009)

6. Mass movement

Mass movement takes many forms and is widespread throughout the Cardrona Valley. During the last glacial period, 12,000 – 15,000 years ago, many of the surrounding landscapes and basins, such as Queenstown and Wanaka, were occupied by large glaciers. This did not occur in the Cardrona Valley however (McDonnell and Craw 2003). Rather, large schist landslides (Figure 6.1) flanking the valley slopes formed during this time from geological activity such as valley uplift, and from incision of the Cardrona River and other streams. Many of these landslides continue to form today, and/or are re-activated during periods of over saturation from large storm events.

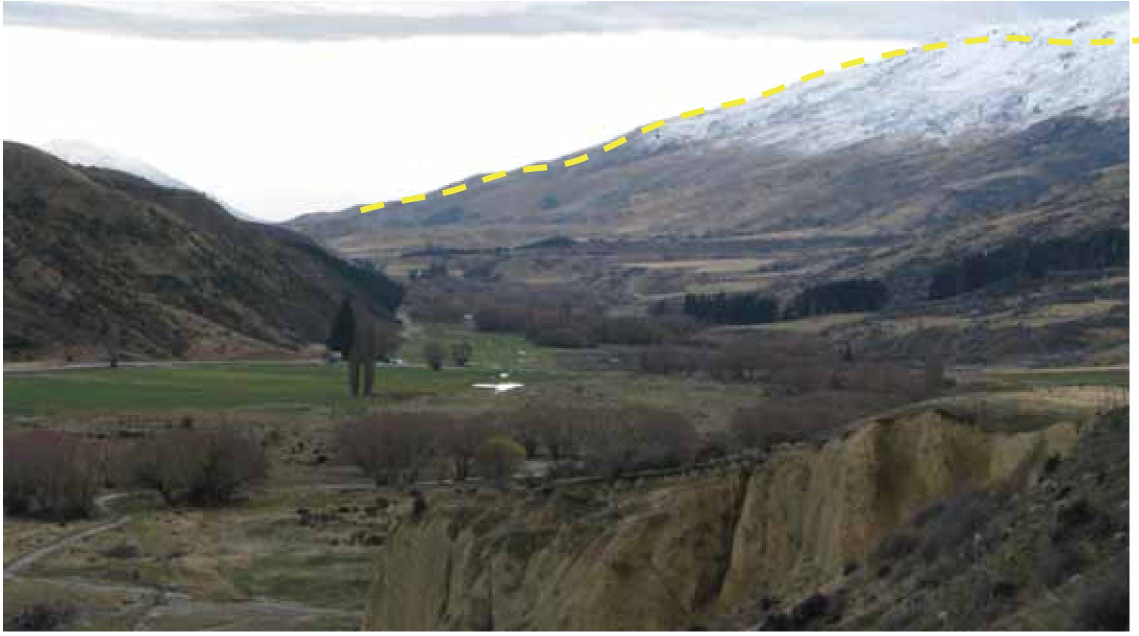


Figure 6.1 Large schist landslides flank much of the western slopes of the Criffel Range

Mass movements, largely in the form of slope failures, have the potential to contribute significant volumes of sediment to the river, which can in turn alter the flood hazard of the river. Slope failure in any part of the valley can contribute sediment directly to the channel through large-scale sliding or smaller amounts over longer time periods through the progressive erosion of active slopes (Figure 6.2). Newly-activated slope failures, such as those observed in November 1999 (Figure 6.3) often expose fresh slopes or bare rock faces that may also erode and contribute fresh sediment to tributaries and the Cardrona River.

The actual risk posed to people, property and infrastructure from mass movement failure in the Cardrona Valley has not been determined as part of this investigation. This risk is best determined on a site specific basis, where all variables that may contribute to mass movement processes can be identified adequately.

Figure 6.2 Large lobate landslide deposit, formed by periodic failure and progressive erosion of active slopes in a tributary of the Cardrona River, Crown Range

Figure 6.3 Mass movement in the Cardrona River upper catchment resulting from the over-saturation of slopes during the November 1999 flood event

7. Earthquakes and seismicity

Earthquakes occurring locally and regionally present a hazard within the Cardrona Valley. Seismic risk, or the risk due to earthquakes, depends on the magnitude, frequency, and nature of the earthquake; its distance from the subject area; and the susceptibility of the underlying ground to seismic shaking. Seismic activity affecting the Cardrona Valley is most likely to originate from the Alpine or NW and SE Cardrona Faults (Figure 7.1). Seismic activity can generate both direct and indirect hazards, including fault movements, liquefaction, settlement and mass movement.

7.1 Fault movements

The Alpine Fault (Figure 7.1) is located along the western edge of the Southern Alps and has the capability to generate very large earthquakes (~M_w8.0) relatively frequently (estimated every 200-300 years). It passes within 78 km of the Cardrona Valley and has the potential to create approximately two minutes of immediate ground shaking in the valley during a M_w8.0 event. Opus (2004) note that an event of this size will have a Modified Mercalli intensity of MVII (Appendix C) which indicates:

- People are alarmed and experience difficulty standing
- Substantial damage to fragile contents of buildings
- Some windows cracked and buildings damaged
- Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings

Located within the Cardrona Valley, the NW and SE Cardrona Faults (Figure 7.1) have an estimated recurrence interval of about 7,500 years for magnitudes 7.0 and 7.1 events respectively. An event of this magnitude is estimated to create fault rupture displacement of up to 2 metres at some locations on the fault.

Opus (2004) describes many other local faults, including the Nevis Fault, Pisa Fault and Grandview Fault, near the Cardrona Valley, which may have considerable seismic risk. While the recurrence intervals of some faults have been estimated, seismic risk also exists from unidentified active faults that have not been studied in great depth.

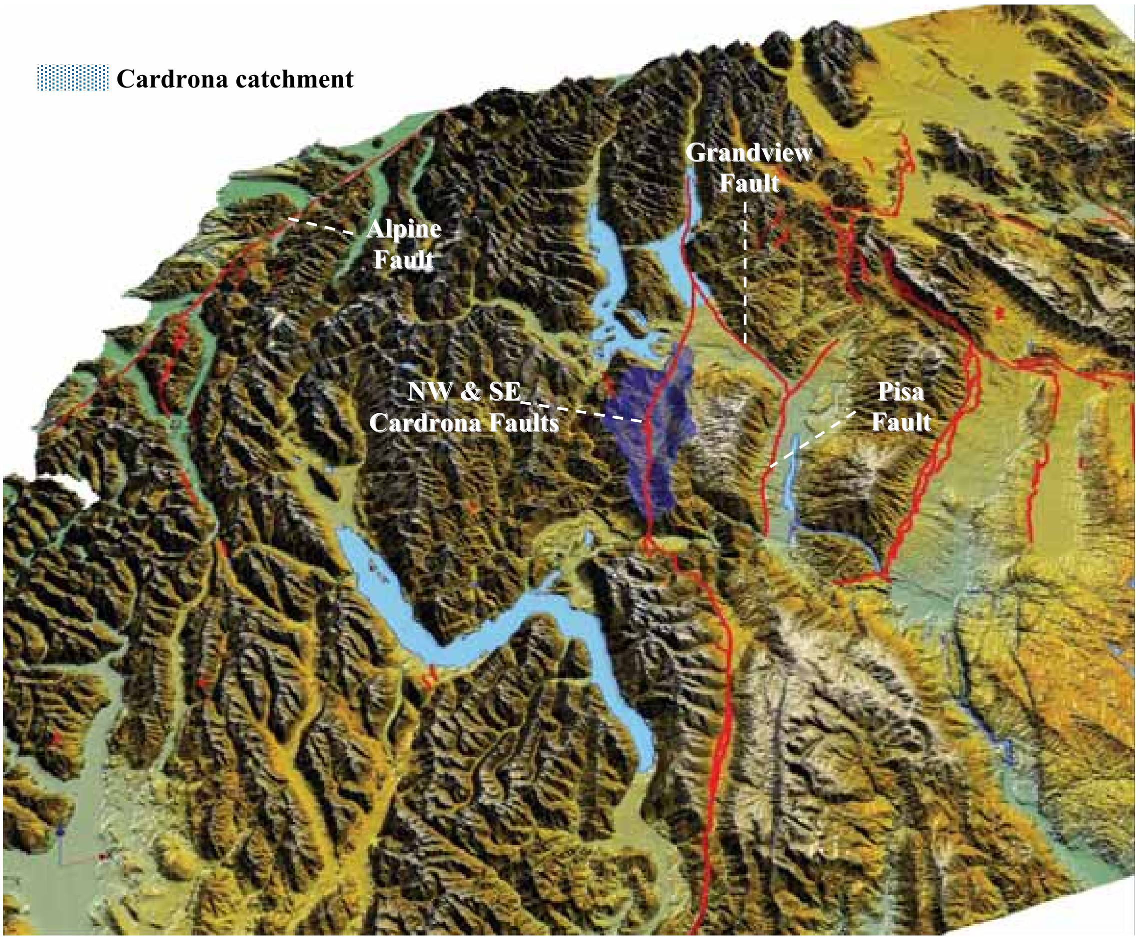


Figure 7.1 Map showing active faults close to the Cardrona Valley

7.2 Liquefaction and settlement of soils

Another seismic risk within the Cardrona Valley is the liquefaction of soils due to seismic shaking (Figure 7.2)[10]. Liquefaction occurs when sediments and soils are shaken, often by earthquakes, and lose their ability to stay cohesive. As the sediments are shaken, they act like a fluid or shaken jelly, causing deformation, settlement, and sometimes lateral spread toward water bodies. Historical records and studies of liquefaction in New Zealand suggest that the magnitude of shaking felt in the Cardrona Valley, from a M_w8.0 Alpine Fault event would cause localised areas of liquefaction and settlement of soils (Opus, 2004). This could cause damage to older building structures, infrastructure (including roads and underground pipes), and moderate ground damage.

---

[10] Areas that have been defined as possibly susceptible to liquefaction (Figure 7.2) are based on general geological information and therefore represent indicative extents only.

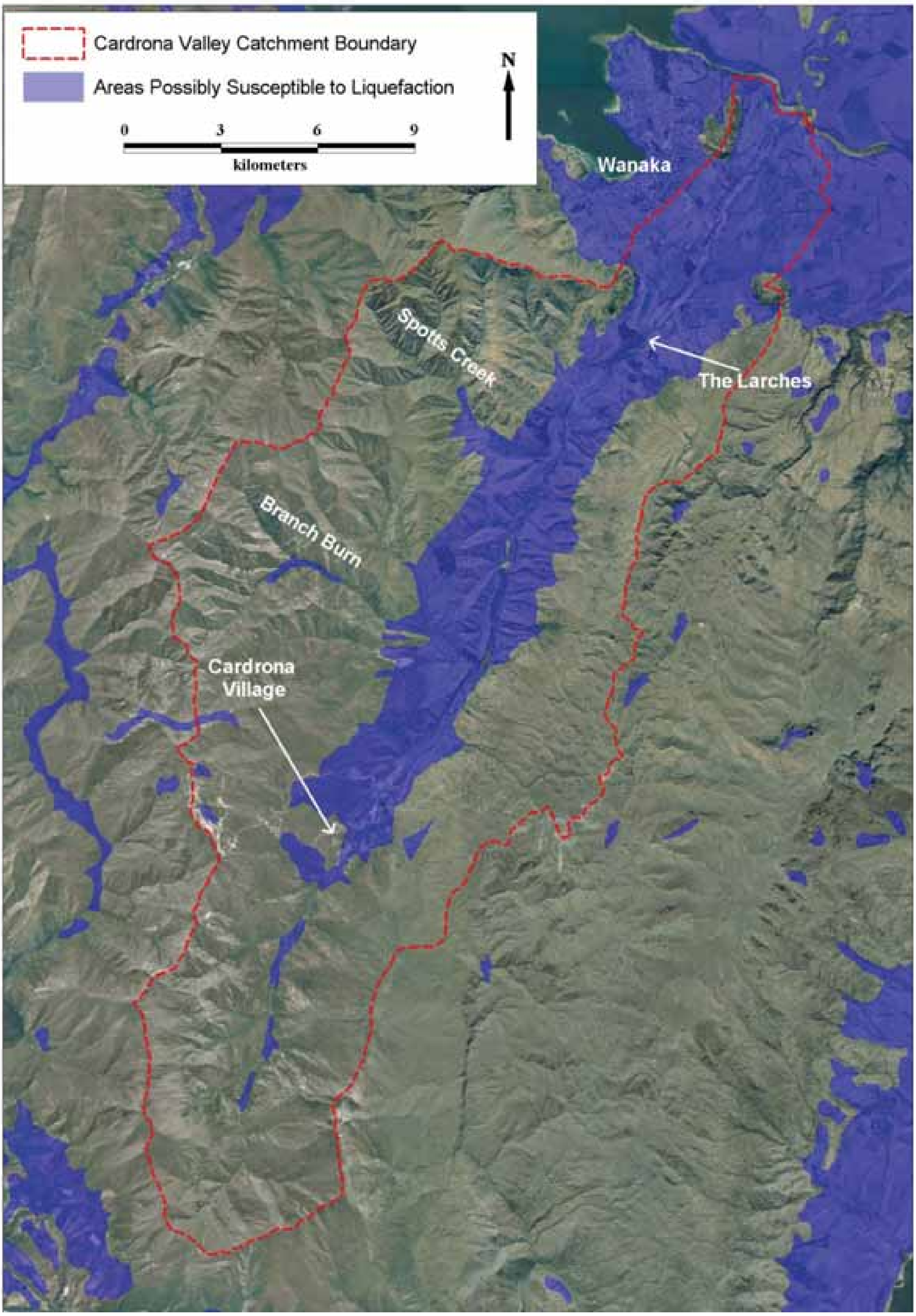


Figure 7.2 Areas possibly susceptible to liquefaction near the Cardrona Valley (Opus 2004)

8. Conclusion

The Cardrona Valley is subject to a range of natural hazards which include flood inundation, sedimentation and erosion, alluvial fan hazards, mass movement and seismic hazards. It has been demonstrated that flood hazards can vary in magnitude and location along the length of the river. The recognition of alluvial fan landforms within the valley raises awareness of debris and/or floodwater hazards, many of which are still active today. Widespread mass movement and the effects of seismic activity can affect communities either directly, through slope failure or ground movement associated with fault rupture, or indirectly by increasing sediment volumes to river channels. This in turn affects the nature and extent of flood hazards.

It is noted that based on existing climatological information, the frequency and magnitude of flood hazards may increase due to changes in climate. Further intensification or new development in hazard prone locations increases the level of community exposure to these hazards and, as a result, amplifies the associated risk.

9. Glossary

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

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

Braided river: A river characterised by a network of interconnected converging and diverging channels resembling the strands of a braid.

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

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

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.

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

Seismic hazard: Hazards derived from the effects of an earthquake.

10. References

Barrell, D.J.A., Cox, S.C., Greene, S., Townsend, D.B., (2009) *Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago.* GNS Science Consultancy Report 2009/052. Prepared for Otago Regional Council

GHD Ltd (2010) Otago Regional Council – Report for Cardrona River Floodplain Flood Hazard Study, client report prepared for Otago Regional Council

McDonnell, M., Craw, D., (2003) Stratigraphy and provenance of Pliocene greywacke-bearing conglomerate, Cardrona valley, Otago New Zealand, New Zealand Journal of Geology and Geophysics, 46 pp. 425-436

Ministry for the Environment (MfE) (2008) Preparing for climate change. A guide for local government.

Mojzisek, J., (2005) *Precipitation variability in the South Island of New Zealand.* A thesis submitted for the degree of Doctor of Philosophy at the University of Otago, Dunedin, New Zealand

Opus International Consultants Ltd (2009) *Otago Alluvial Fans Project,* Report # 1205 – Version 2, prepared for Otago Regional Council

Opus International Consultants (2004) *Seismic Risk in the Otago Region – Study Report,* Client Report SPT: 2004/23, Ref: 5C0656.00, prepared for Otago Regional Council

Otago Regional Council (2010) *Channel Morphology and Sedimentation in the Cardrona River,* Environmental engineering and natural hazards, Otago Regional Council, Dunedin, New Zealand

Otago Regional Council (2007) *The Water Resources of the Cardrona River,* Resource Science, Otago Regional Council, Dunedin, New Zealand

Online Resources

Population and census information sourced from: http://www.qldc.govt.nz

http://cardrona.eprints.otago.ac.nz/

Appendix A—Flood Hazard Maps

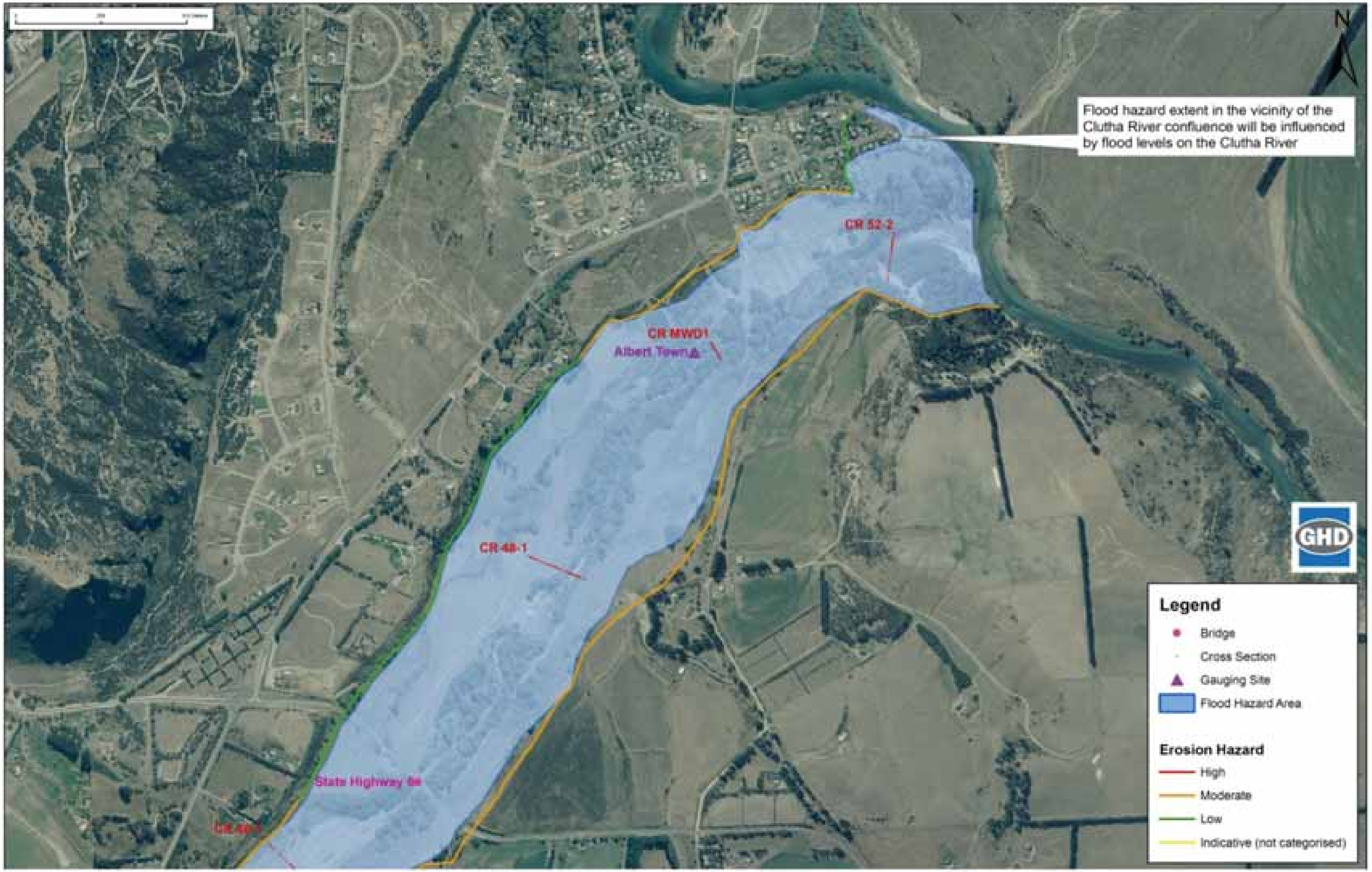


Figure A.1 Flood Hazard Map 1

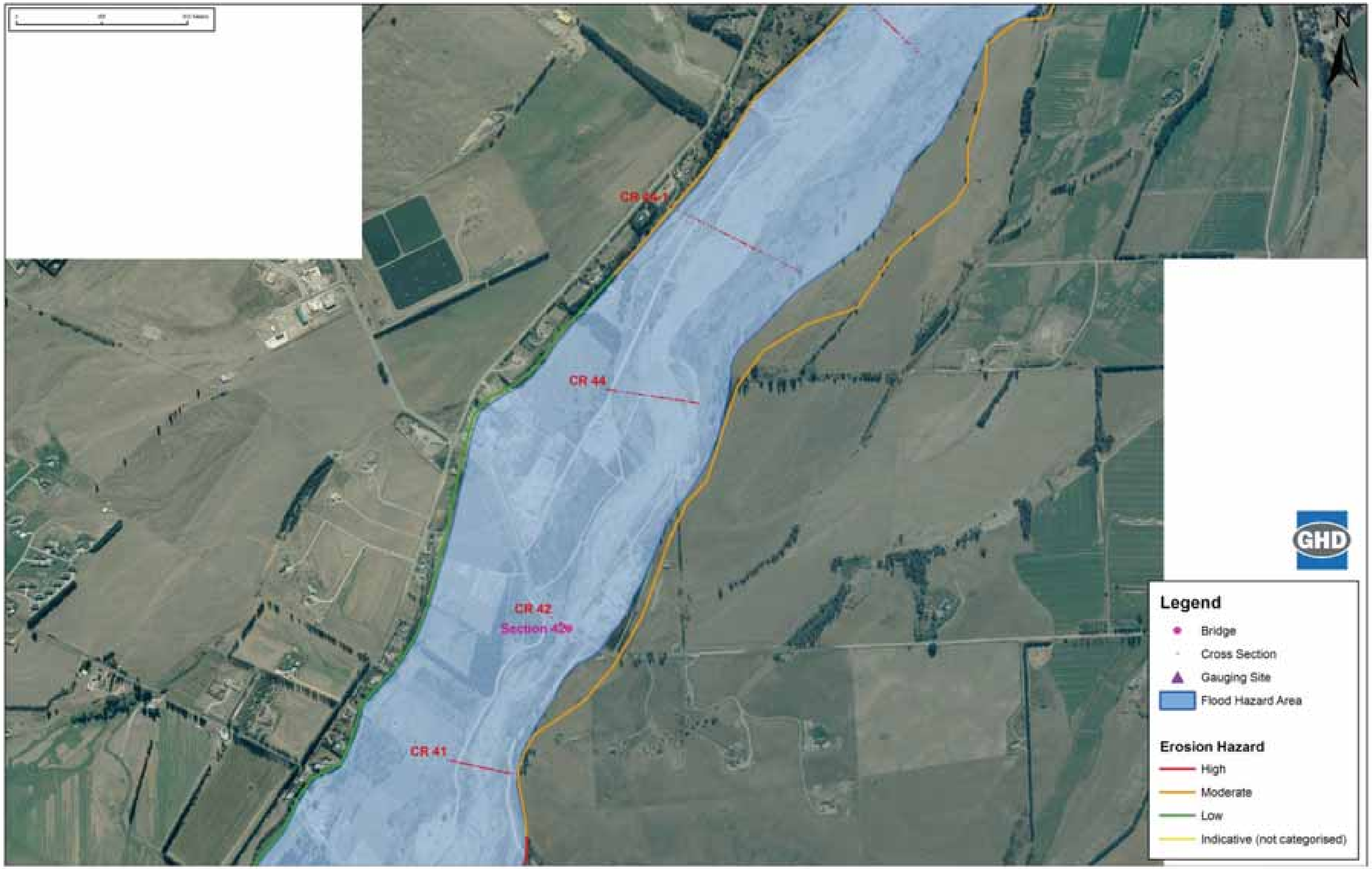


Figure A.2 Flood Hazard Map 2

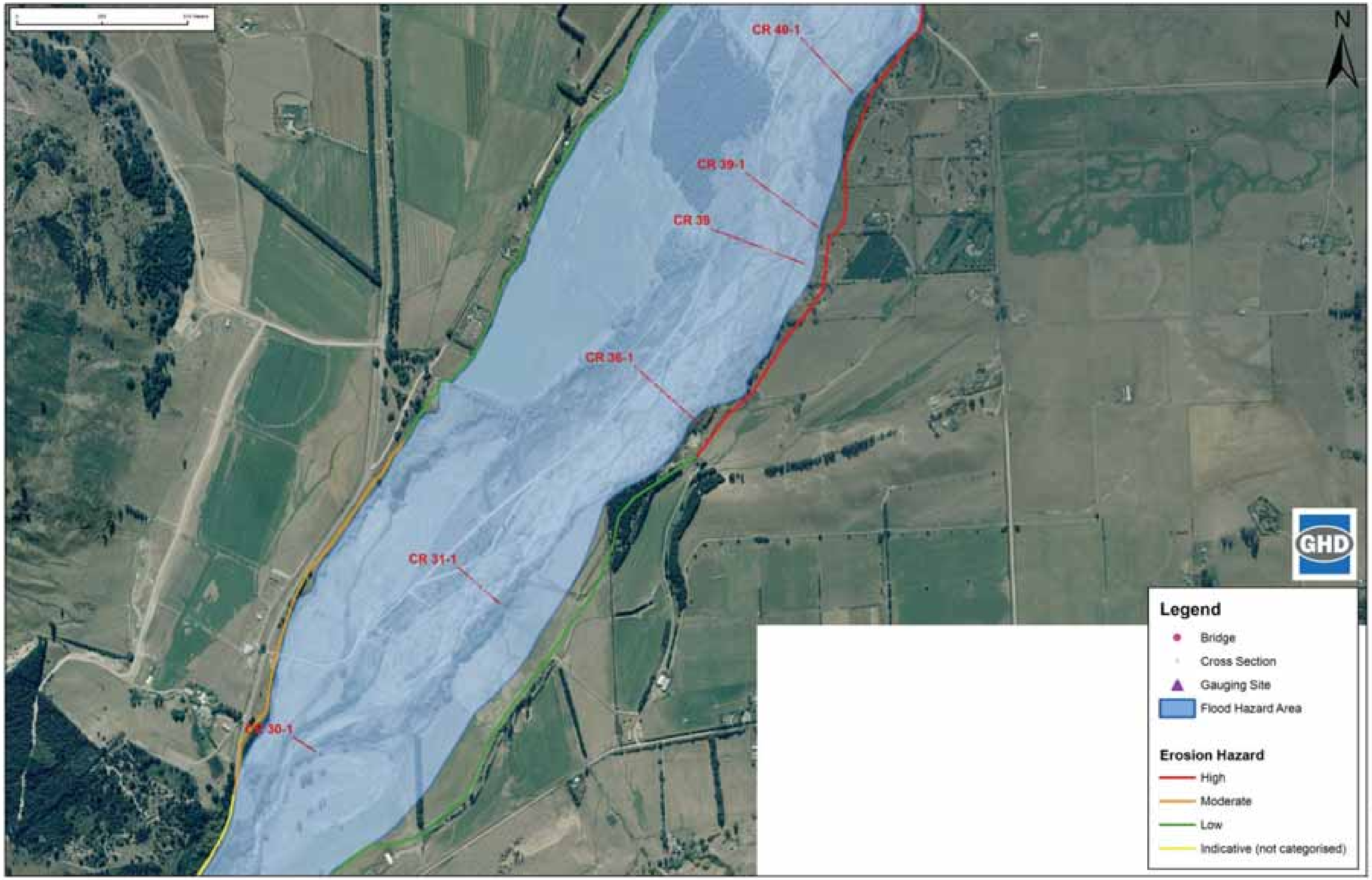


Figure A.3 Flood Hazard Map 3

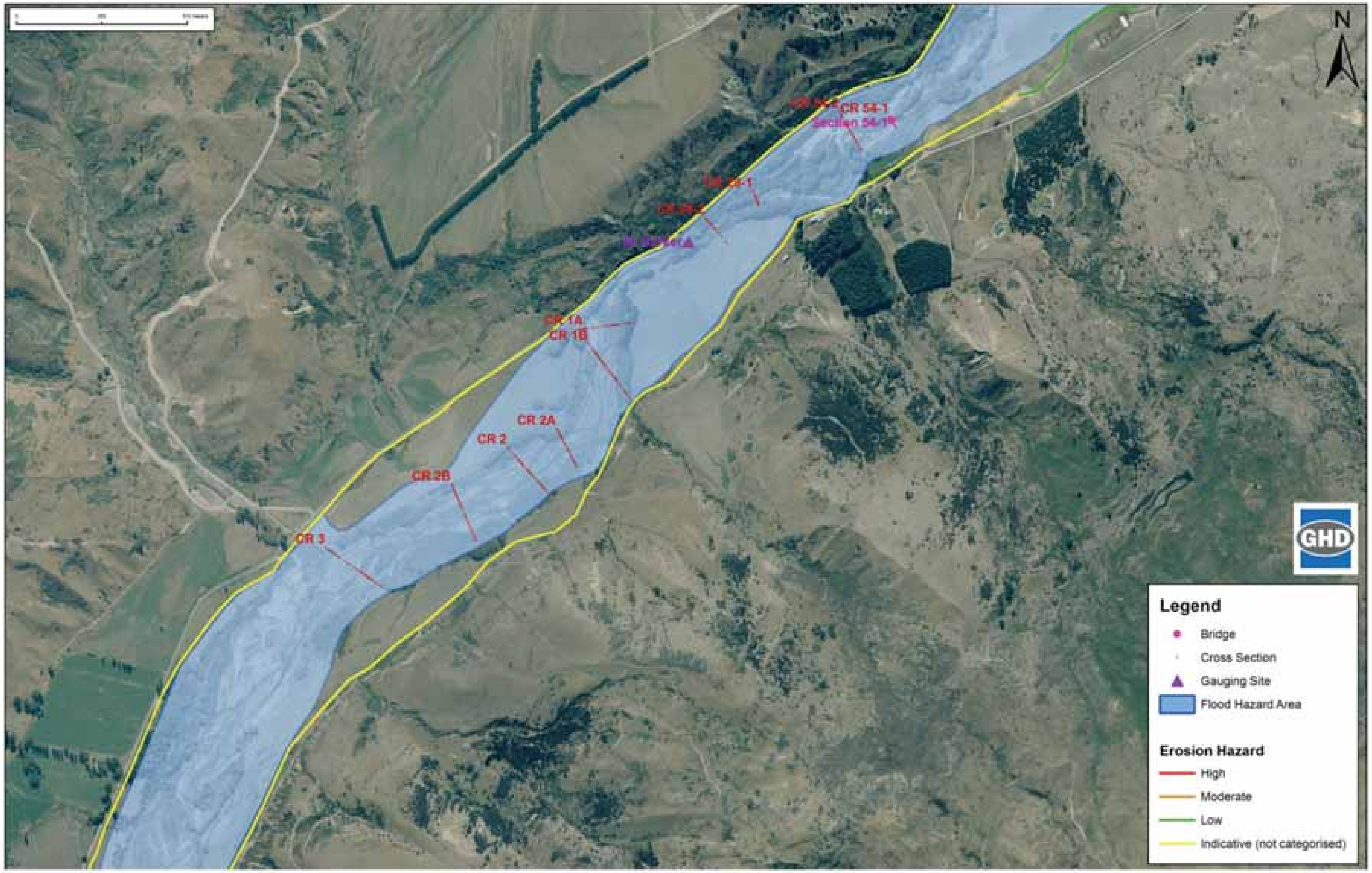


Figure A.4 Flood Hazard Map 4

Figure A.5 Flood Hazard Map 5

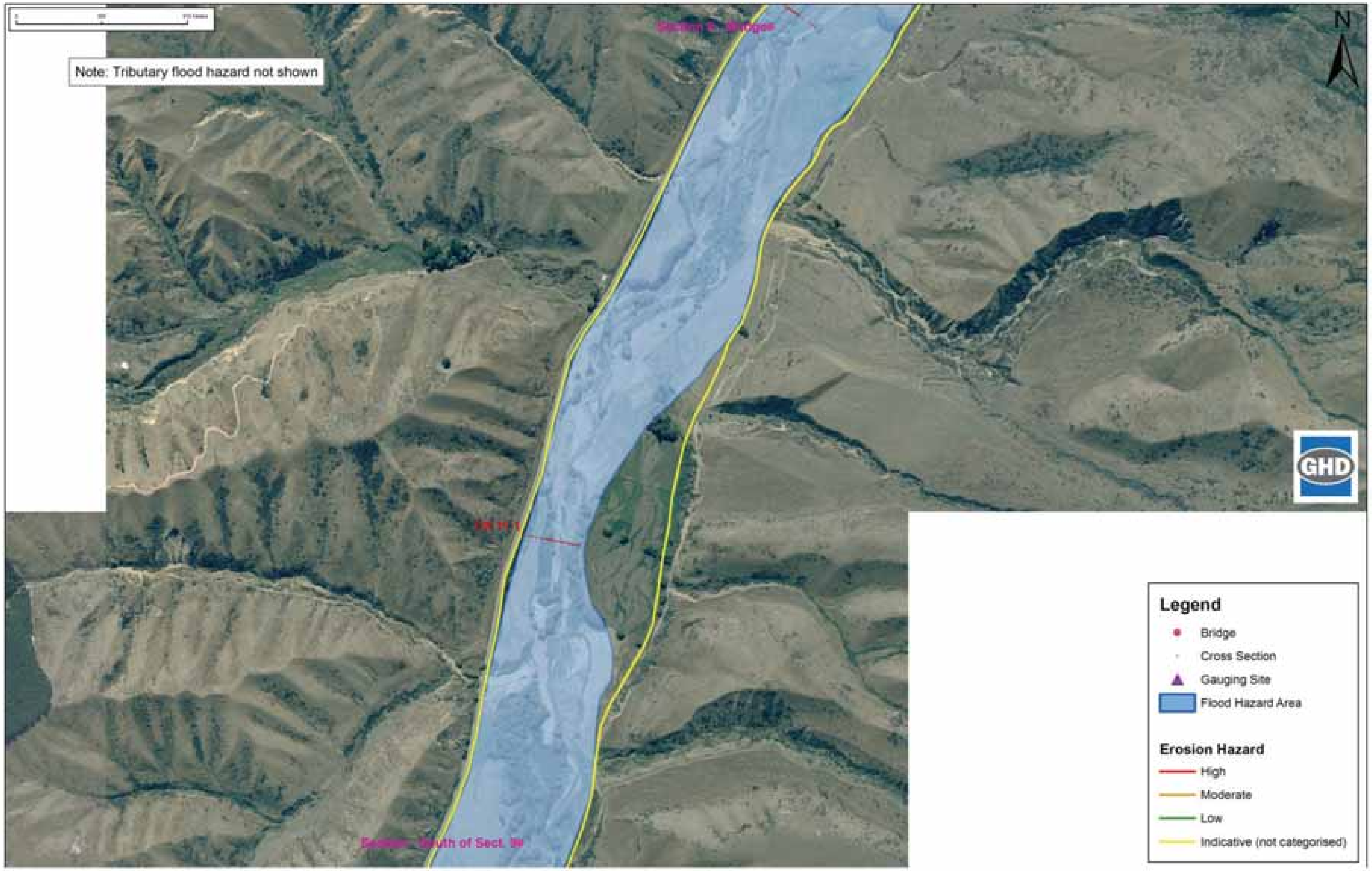


Figure A.6 Flood Hazard Map 6

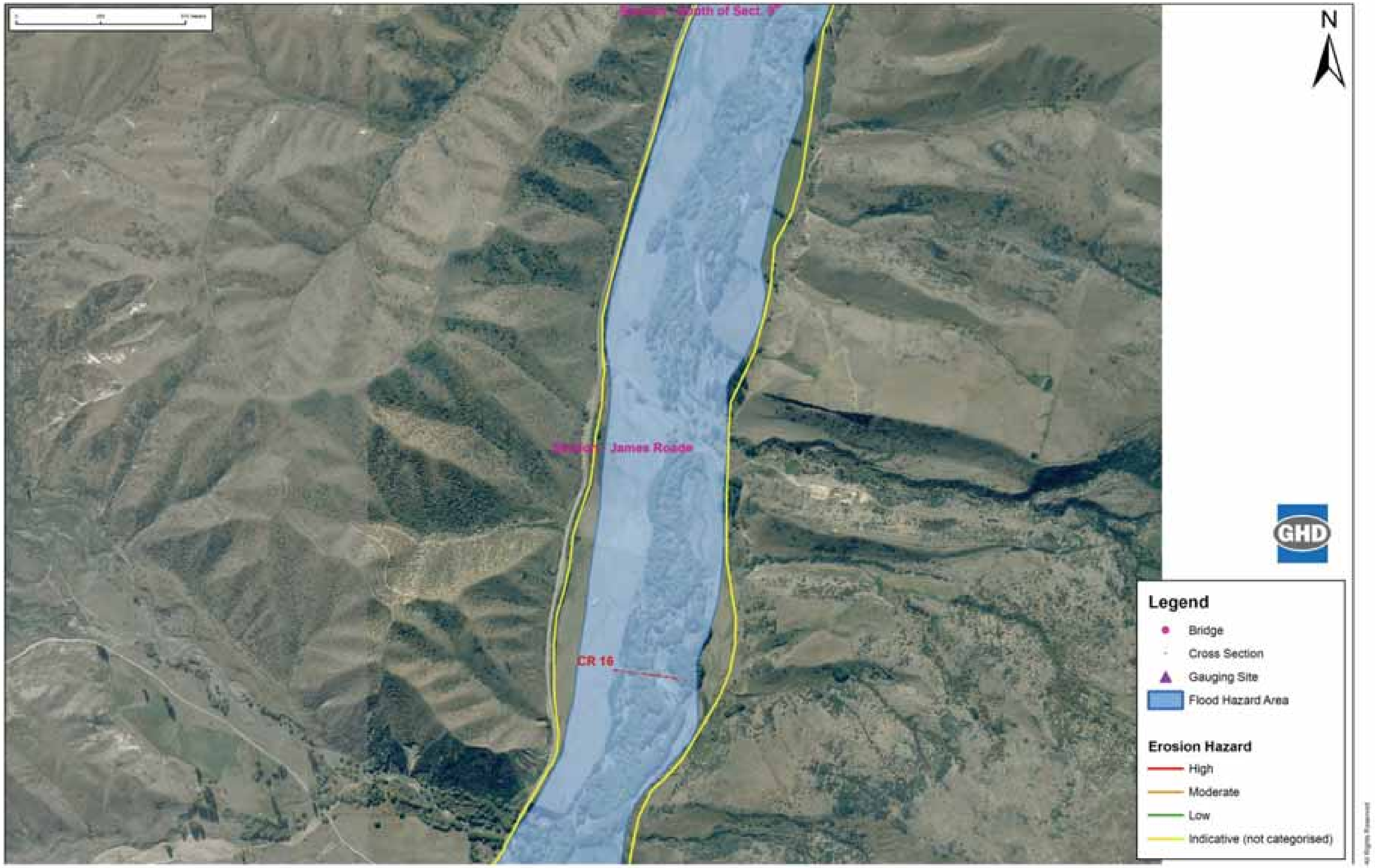


Figure A.7 Flood Hazard Map 7

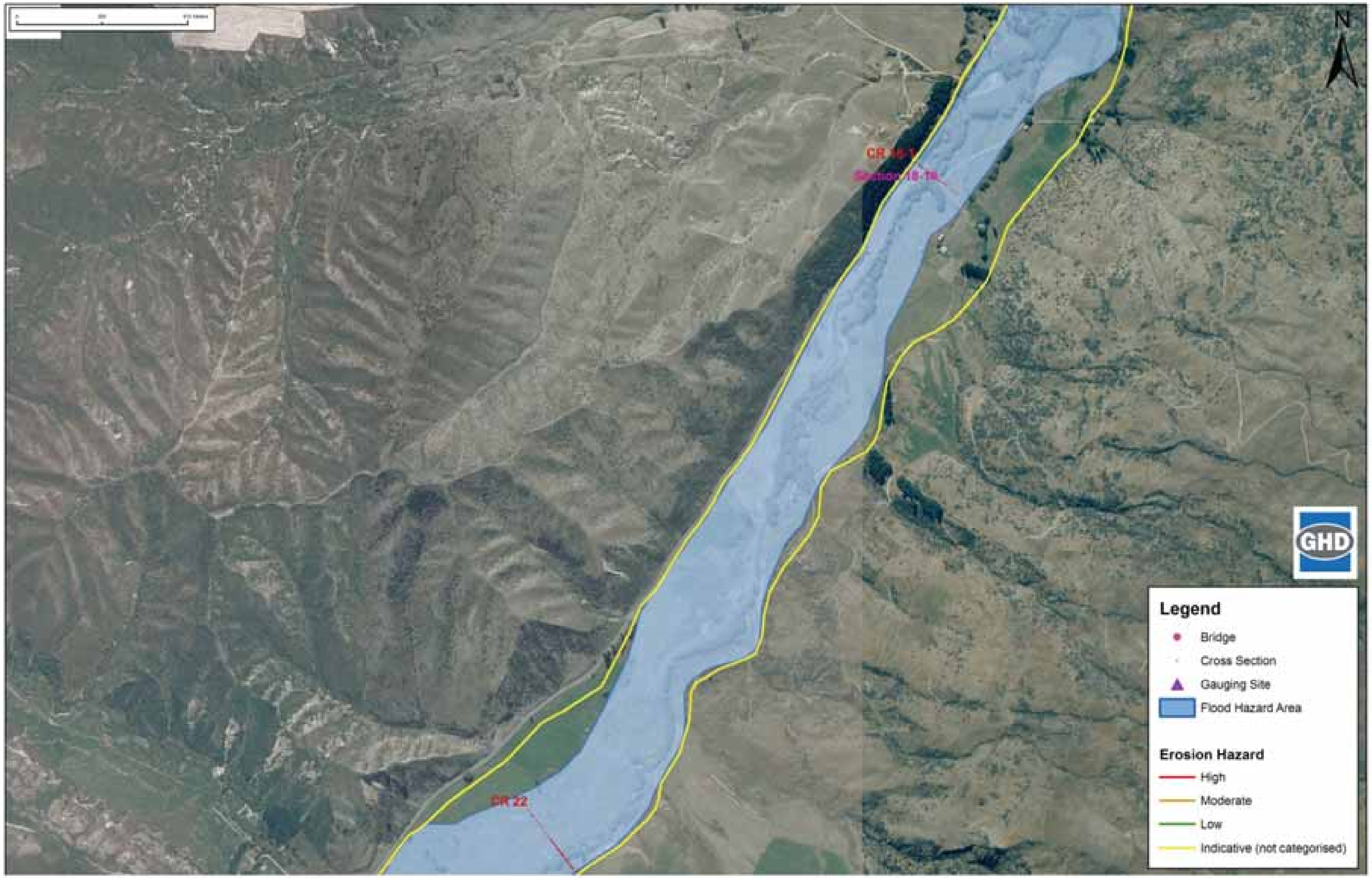


Figure A.8 Flood Hazard Map 8

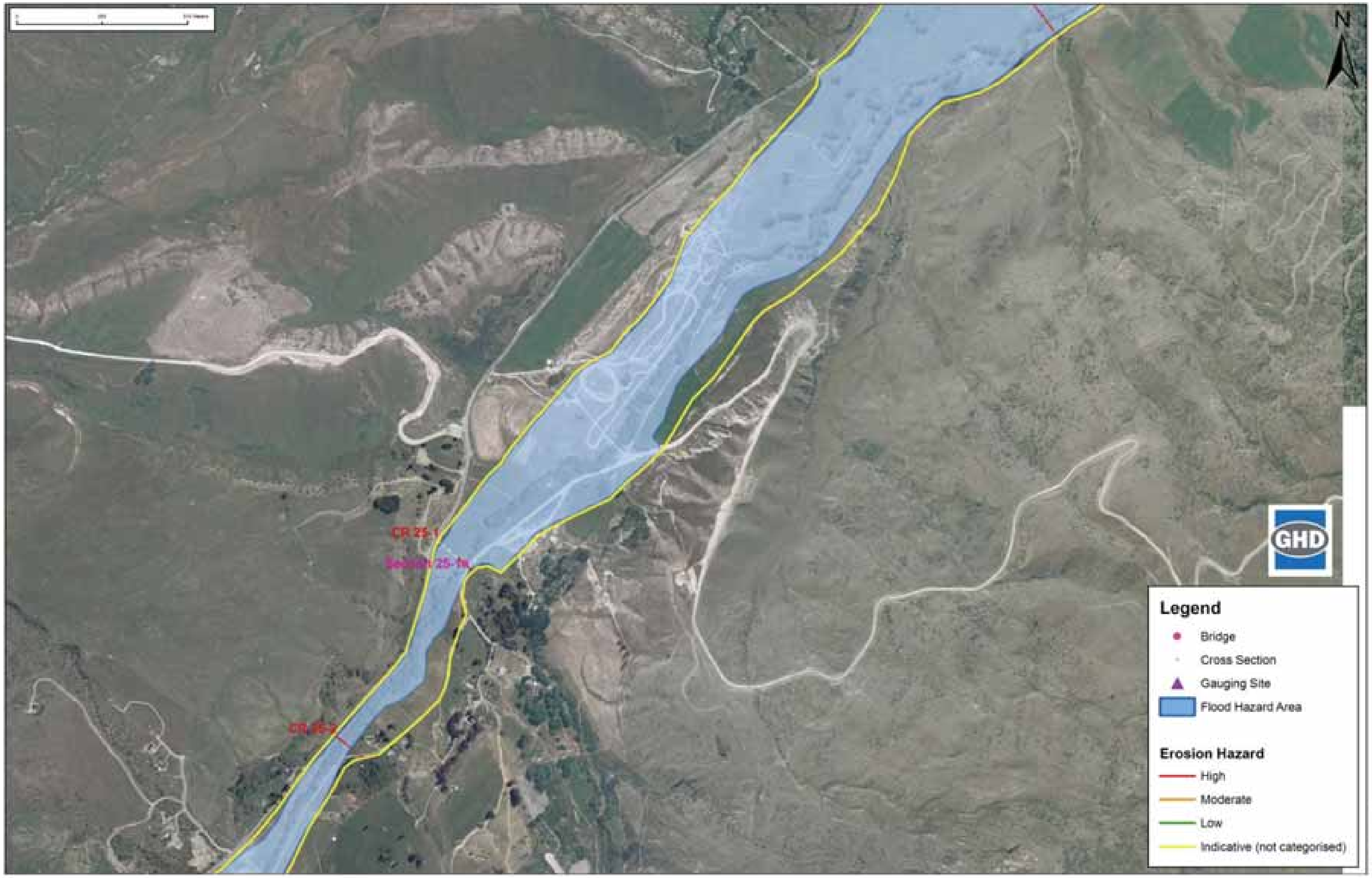


Figure A.9 Flood Hazard Map 9

Figure A.10 Flood Hazard Map 10

Appendix B—Selected November 1999 Flood Photos

Figure B.1 The Cardrona Valley Road in the upper valley reaches, November 1999

Figure B.2 The Cardrona River upper valley reaches looking upstream, November 1999

Figure B.3 Debris dam formed over the Cardrona Valley Road in the upper valley reaches looking upstream, November 1999

Figure B.4 The Cardrona Valley central reaches looking upstream, November 1999

Figure B.5 The Cardrona Valley central reaches at the Snow Park looking upstream, November 1999

Figure B.6 The Cardrona Valley central reaches looking upstream, November 1999

Figure B.7 The Cardrona Valley central reaches looking upstream, November 1999

Figure B.8 The Cardrona Valley central reaches upstream of The Larches looking upstream, November 1999

Figure B.9 November 1999 flood sedimentation at The Larches, looking downstream

Figure B.10 The Cardrona Valley central reaches looking upstream, November 1999

Figure B.11 True right bank erosion downstream of The Larches and upstream of the Ballantyne Bridge looking downstream, November 1999

Figure B.12 True right bank erosion downstream of The Larches and upstream of the Ballantyne Bridge looking upstream, November 1999

Figure B.13 Flood sedimentation between State Highway 6 and Ballantyne Road looking upstream, November 1999

Figure B.14 Flood sedimentation at the Ballantyne Road Bridge looking upstream, November 1999

Figure B.15 Flood sedimentation below the State Highway 6 Bridge looking upstream, November 1999

Figure B.16 Flood sedimentation near Albert Town looking downstream, November 1999

Appendix C—Modified Mercalli Intensity Scale (Opus, 2004)

MM1	
People	*Not felt except by a very few people under exceptionally favourable circumstances.*
MM2	
People	*Felt by persons at rest, on upper floors or favourably placed.*
MM3	
People	*Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake*
MM4	
People	*Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.*
Fittings	*Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.*
Structures	*Walls and frame of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.*
MM5	
People	*Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed.*
Fittings	*Small unstable objects are displaced or upset. Some glassware and crockery may be broken.* *Hanging pictures knock against the wall.* *Open doors may swing.* *Cupboard doors secured by magnetic catches may open.* *Pendulum clocks stop, start, or change rate.*
Structures	*Some windows Type I cracked.* *A few earthenware toilet fixtures cracked.*
MM6	
People	*Felt by all.* *People and animals alarmed.* *Many run outside.* *Difficulty experienced in walking steadily.*
Fittings	*Objects fall from shelves.* *Pictures fall from walls.* *Some furniture moved on smooth floors, some free-standing unsecured fireplaces moved.* *Glassware and crockery broken.* *Very unstable furniture overturned.* *Small church and school bells ring.* *Appliances move on bench and table tops.*

	Filing cabinets or 'easy glide' drawers may open (or shut).
Structures	*Slight damage to Buildings Type I.* *Some stucco or cement plaster falls.* *Windows Type I broken.* *Damage to a few weak domestic chimneys, some may fall.*
Environment	*Trees and bushes shake, or are heard to rustle.* *Loose material may be dislodged from sloping ground, e.g. existing slides, talus slopes, shingle slides.*
MM7	
People	*General alarm.* *Difficulty experienced in standing.* *Noticed by motorcar drivers who may stop.*
Fittings	*Large bells ring.* *Furniture moves on smooth floors, may move on carpeted floors.* *Substantial damage to fragile contents of buildings.*
Structures	*Unreinforced stone and brick walls cracked.* *Buildings Type I cracked with some minor masonry falls.* *A few instances of damage to Buildings Type II.* *Unbraced parapets, unraced brick gables, and architectural ornaments fall.* *Roofing tiles, especially ridge tiles may be dislodged.* *Many unreinforced domestic chimneys damaged, often falling from the roof-line.* *Water tanks Type I burst.* *A few instances of damage to brick veneers and plaster or cement-based linings.* *Unrestrained water cylinders (water Tanks Type II) may move and leak.* *Some windows Type II cracked.* *Suspended ceilings damaged.*
Environment	*Water made turbid by stirred up mud.* *Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings.* *Instances of settlement of unconsolidated or wet, or weak soils.* *Some fine cracks appear in sloping ground. A few instances of liquefaction (i.e. small water and sand ejections).*
MM8	
People	*Alarm may approach panic.* *Steering of motor cars greatly affected.*
Structures	*Building Type 1, heavily damaged, some collapse.* *Buildings Type II damaged, some with partial collapse.* *Buildings Type III damaged in some cases.* *A few instances of damage to Structures Type IV.* *Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down.* *Some pre-1965 infill masonry panels damaged.* *A few post-1980 brick veneers damaged.*

	Decayed timber piles of houses damaged. *Houses not secured to foundations may move.* *Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.*
Environment	*Cracks appear on steep slopes and in wet ground.* *Small to moderate slides in roadside cuttings and unsupported excavations.* *Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes etc.*
MM9	
Structures	*Many buildings Type I destroyed.* *Buildings Type II heavily damaged, some collapse.* *Buildings Type III damaged, some with partial collapse.* *Structures Type IV damaged in some cases. Some with flexible frames seriously damaged.* *Damage or permanent distortion to some Structures Type V.* *Houses not secured to foundations shifted off.* *Brick veneers fall and expose frames.*
Environment	*Cracking of ground conspicuous.* *Landsliding general on steep slopes.* *Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, lakes etc.*
MM10	
Structures	*Most buildings Type I destroyed.* *Many buildings Type II destroyed.* *Buildings Type III heavily damaged, some collapse.* *Structures Type IV damaged, some with partial collapse.* *Structures Type V moderately damaged, but with few partial collapses.* *A few instances of damage to structures Type VI.* *Some well-built timber buildings moderately damaged (excluding damage from falling chimneys).*
Environment	*Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes.* *Landslide dams may be formed.* *Liquefaction effects widespread and severe.*
MM11	
Structures	*Most buildings Type II destroyed.* *Many buildings Type III destroyed.* *Structures Type IV heavily damaged, some collapse.* *Structures Type V damaged, some with partial collapse.* *Structures Type VI suffer minor damage, a few moderately damaged.*
MM12	
Structures	*Most buildings Type III destroyed.*

	Many structures Type IV destroyed. *Structure Type V heavily damaged, some with partial collapse.* *Structures Type VI moderately damaged.*