Flood and erosion hazard in the Clutha River/Mata-Au between Queensberry and Lake Dunstan

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Overview

Figure 1 **The Clutha River/Mata-Au looking downstream to Lake Dunstan, November 1999, the exact time and date of the photograph is unknown (Appendix 2).**

This report summarises earlier technical investigations, and recent work undertaken to model flood hazard in the Upper Clutha Valley between Queensberry and Lake Dunstan. A composite flood hazard map has been created which shows valley floor areas which may be subject to river flooding during a 1:100 year flood event (based on current knowledge), and alluvial fan areas which may be subject to debris and/or flood flows. The effects of ongoing sedimentation of the delta in the Upper Clutha Arm of Lake Dunstan are also described, and the vulnerability of river banks and terrace risers[1] to erosion has been analysed and mapped.

Decisions on land use need to take into account the nature and the extent of the natural hazard setting of the Upper Clutha Valley to ensure that activities are compatible with the hazard exposure. This report is intended to raise awareness of the community's vulnerability to natural hazards and to help inform good decision making in this regard. The report shows that a small number of existing houses and other assets are either located within the mapped flood hazard area, or are potentially vulnerable to erosion hazard associated with the Clutha River/Mata-Au.

[1] steeply sloping banks which separate two terrace levels

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1. Introduction

The Clutha River/Mata-Au catchment is the largest in New Zealand, covering an area of some 21,000km^2 (Figure 2). The Clutha River/Mata-Au itself commences at the outlet of Lake Wanaka, then flows through to Lake Dunstan, where it joins with its largest tributary, the Kawarau River at Cromwell. The river then makes its way to the Pacific Ocean near Balclutha, via Clyde and Alexandra.

This report summarises flood, alluvial fan and erosion hazard in the reach of the Clutha River/Mata-Au between Queensberry and Lake Dunstan (the study area), as shown in Figure 3. The catchment area upstream of this point is approximately 6,000 km^2, much of which lies along the Southern Alps, an area which experiences regular high intensity rainfall events. Previous flood events in this catchment have resulted in wide-spread inundation in parts of the Upper Clutha Valley, along with significant changes in the shape of the river and its floodplain, due to bank erosion and sedimentation. During the Gold Rush era of the1860s, flood events resulted in multiple deaths (ORC, 1999) demonstrating the dangers associated with the Clutha River/Mata-Au. The information contained in this report will allow the natural hazards affecting the Clutha River/Mata-Au valley between Queensberry and Lake Dunstan to be better understood and will help to inform good decision making in regards to land use and future development.

This updated description of flood and erosion hazard has been made possible by:

- the collection of LiDAR[2] data in April 2009 by Contact Energy Limited (CEL)
- river cross-section data collected between 1995 and 2013 (obtained by the ORC and CEL)
- alluvial fan mapping (Opus, 2009)
- aerial photography and field observations
- the use of hydraulic modelling (Opus, 2014).

As well as mapping flood extents, an indication of inundation depth during a flood event of 2,082m^3/s is provided.[3] Where possible, the flood hazard associated with high flows in the Clutha River/Mata-Au is distinguished from that associated with alluvial fan activity on tributary streams in the study area.

[2] **L**ight **D**etection **A**nd **R**anging – essentially a mass of spot height information captured over a wide area using an aircraft mounted laser. This data has a vertical accuracy of ±0.2m with a standard deviation of 0.06m.
[3] A flow of 2,082m^3/s has an estimated return period of 100 years based on current information – see Appendix 1

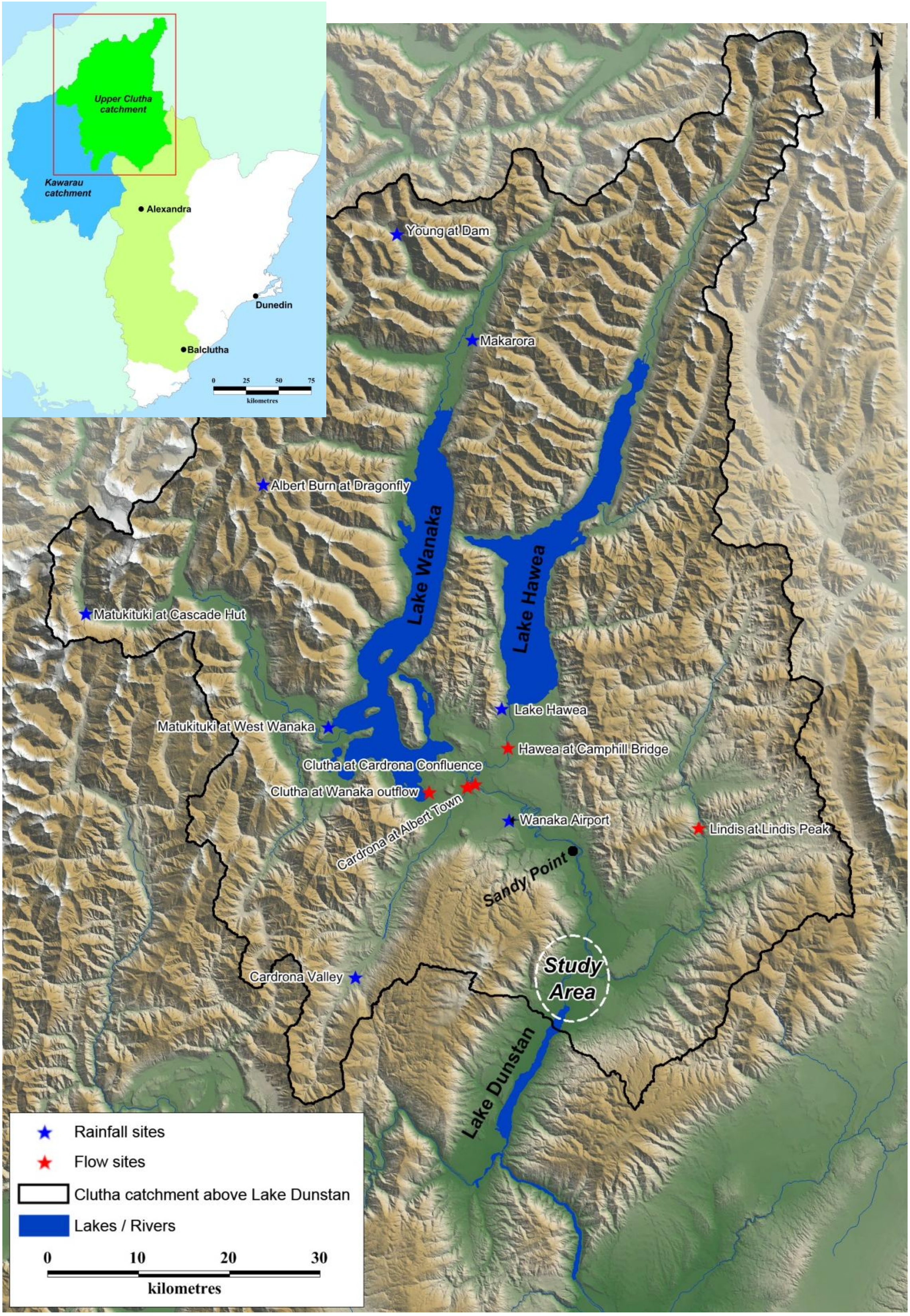


Figure 2. **The location of the study area in the Upper Clutha Valley. The location of rainfall and flow monitoring sites, and other locations mentioned in the text are also shown.**

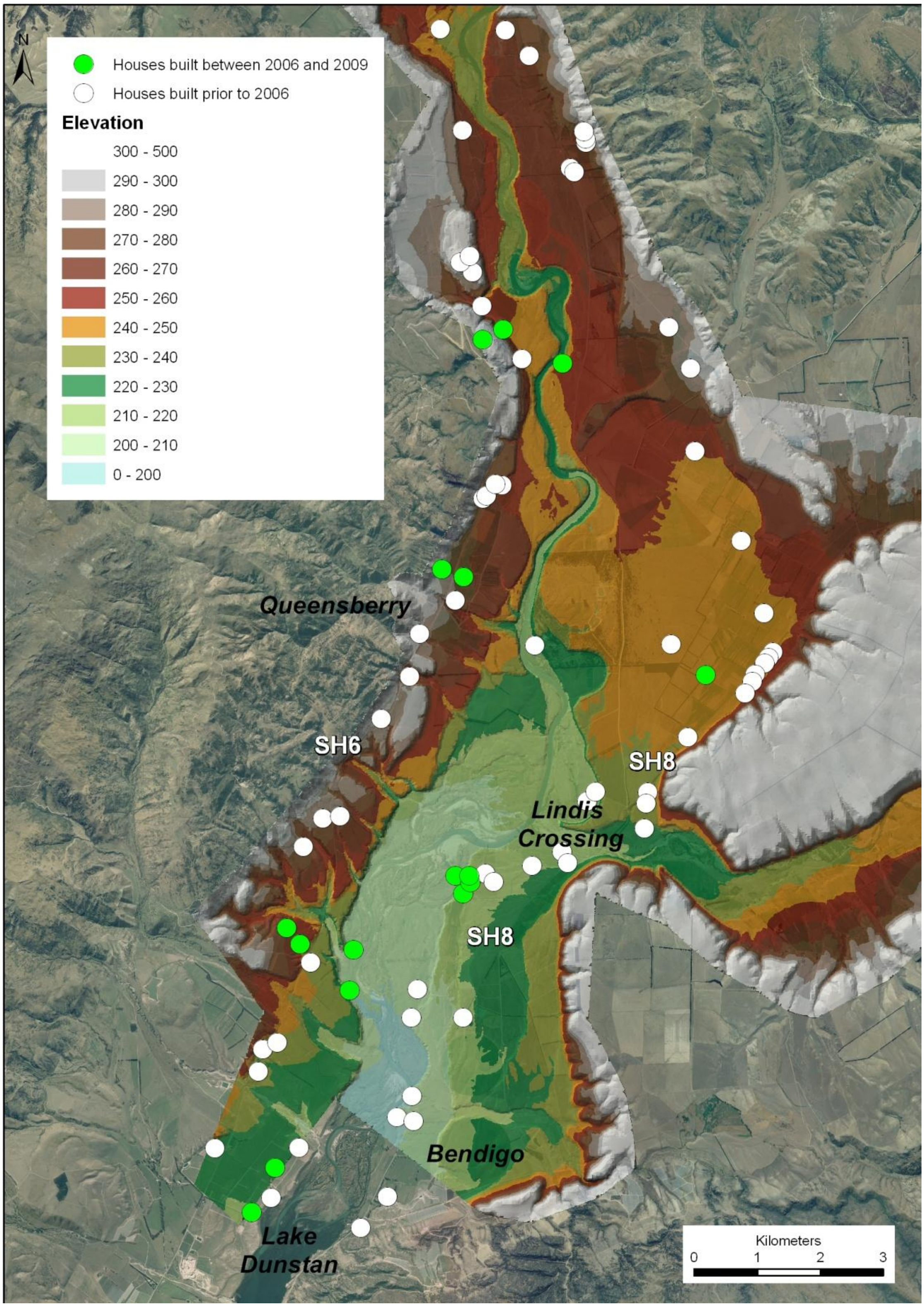


Figure 3. **Topography of the Upper Clutha Valley above Lake Dunstan, and the location of dwellings in the vicinity of the study area that were built between 2006-2009 when aerial photography was collected.**

2. Environment Setting

The Clutha River/Mata-Au catchment upstream of Lake Dunstan drains an area of 6,014km^2, which has a diverse topography (Figure 2) and a wide variation in rainfall. In the far west, the country is mainly mountainous with peaks to nearly 3,000m. Larger tributaries such as the Matukituki, Makarora and Hunter Rivers drain from the Southern Alps into Lakes Wanaka and Hawea. To the south and east, the catchment is characterised by lower mountain ranges which contribute to flows in smaller rivers, such as the Cardrona, Lindis and Motatapu.

2.1. Land-use and population

Used for rural and rural-residential activities (zoned as a Rural Resource area by the Central Otago District Council),[4] the margins of this reach of the Clutha River/Mata-Au are currently sparsely populated, with approximately 20 residences located on the lower terraces (Figure 3). The main types of land use are pastoral farming, viticulture and horticulture. Investment in more efficient forms of irrigation has resulted in more intensive agricultural land use on some properties.

There has been an increased demand for residential and rural-residential development in the Upper Clutha Valley in recent years. Between the 2006 and 2013 census the total population increased from 453 to 789, an increase of almost 75% in just seven years. Between 2009 and mid-2014, there were 66 applications to the Central Otago District Council for new rural dwellings in the Queensbury – Crippletown area. The growing population of this area and related demand for development increases the level of exposure to natural hazards and as a result increases the associated risk.

2.2. Geology and topography

The Clutha River/Mata-Au upstream of Lake Dunstan is located in a wide, shallow valley formed during late Quaternary glacial advances and retreats from the upstream Lake Wanaka and Lake Hawea catchments. Moraines and outwash terraces formed by glacial advances and retreats extend from Lakes Wanaka and Hawea downstream to Lake Dunstan (McKellar, 1960). The Lindis and Lowburn glacial advances, which extend into the study area, are documented as having an age of approximately 140,000 and 250,000 years respectively, with an ice extent as shown in Figure 4 (Beanland & Berryman, 1989). Associated with the moraine deposits are alluvial fans and outwash material spread onto the valley floor (Turnbull, 2000). These fans consist of both active floodwater-dominant fans and inactive composite fans (GNS, 2009).

To the west of the valley lies the northern extent of the Pisa Range, while the Lindis catchment and the Dunstan Mountains lie to the east. During winter, snow accumulates along both these ranges, and this contributes to runoff during spring and summer. The steep rock slopes, and most of the base rock within the valley consist of quartzofeldspathic schist, which rapidly erodes by physical and chemical weathering in this environment (Ministry of Works and Development, 1977).

[4] The Rural Resource Area comprises the rural environment of the Central Otago District and is distinct from urban areas on the basis of its environmental character (CODC, 2008).

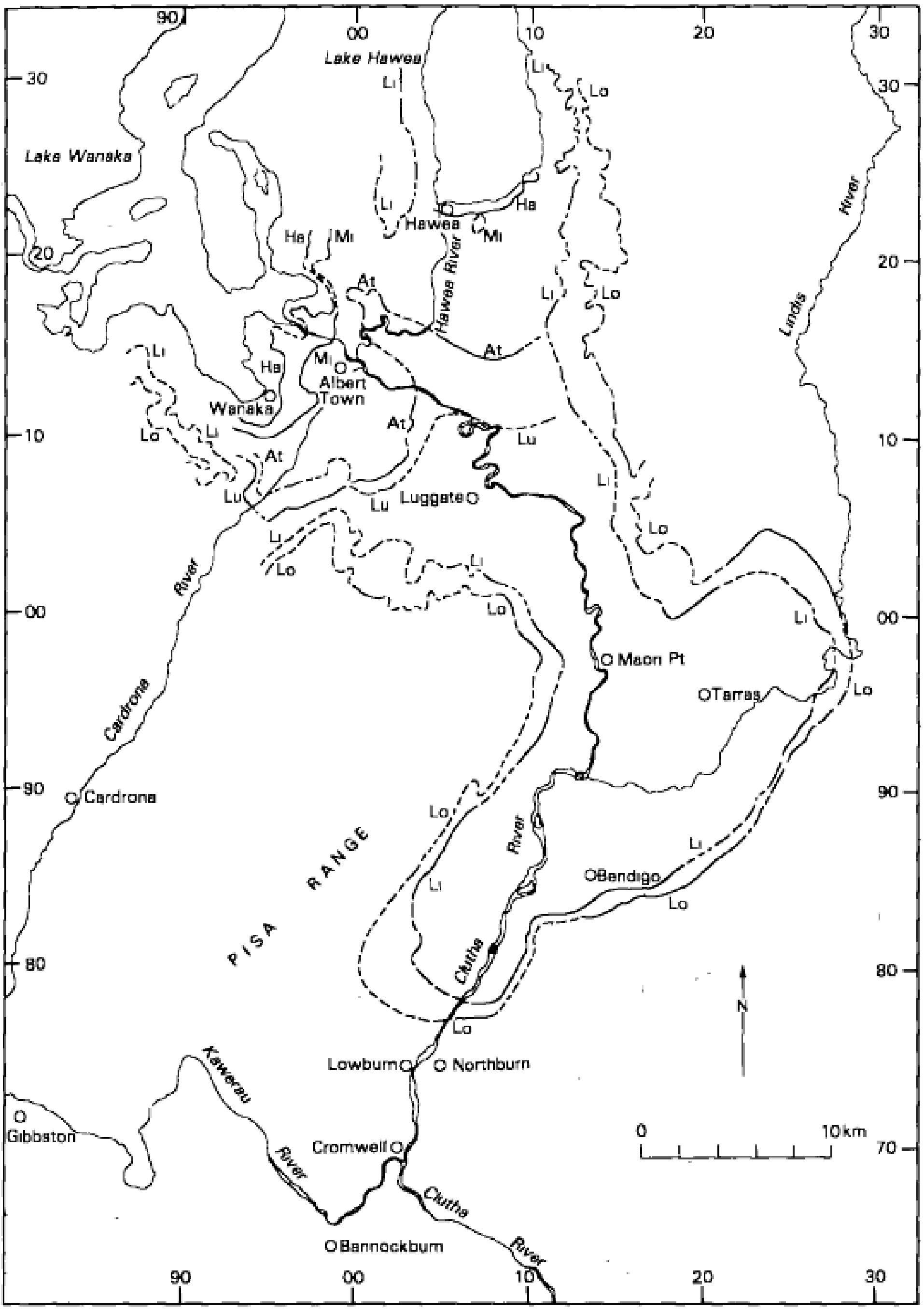


Figure 4. **Approximate location of Quaternary ice margins identified by Beanland & Berryman (1989): Ha=Hawea, MI= Mt Iron, AT= Albert Town, Lu= Luggate, Li= Lindis, Lo= Lowburn (Beanland & Berryman, 1989).**

Queensberry[5] is located on the true right bank of the river, 15km downstream of Luggate and 13.5km upstream of Lake Dunstan. The river is incised and restricted between steep banks at this point (Figure 5).

[5] Queensberry is a locality rather than a settlement.

Figure 5. **View of the Clutha River/Mata-Au looking downstream, adjacent to Queensberry, during a period of high flow (approximately 700m^3/sec) on 15 January 2013. Lake Dunstan can be seen at the top right of the image.**

Downstream of Queensberry the river changes from a single thread incised river to a more braided form, with a broad floodplain bounded by alluvial terraces which flank the valley floor (Figure 6). The wider floodplain is not significantly elevated above the braided 'low-flow' channel. As a result, the river can migrate within the bounds of the terraces, causing sedimentation and erosion, particularly at higher flows. Opus (2011) described this reach as showing inherent instability due to its hydraulic steepness.

Figure 6. **View of the Clutha River/Mata-Au looking downstream, adjacent to Locharburn, during a period of high flows (approximately 700m^3/sec) on 15 January 2013.**

The river discharges to Lake Dunstan at Crippletown, where it forms a delta, part of which makes up the Bendigo Wildlife Reserve (Figure 7). Lake Dunstan was created when the Clyde dam was constructed near the township of Clyde, and was filled from April 1992 till September 1993. The average rate of sediment deposition into Lake Dunstan from the Clutha River/Mata-Au has been estimated at 168,000m^3/yr (Cowan, 1992). This sediment supply has produced a slowly prograding delta, although the rate of delta growth is considerably lower than that experienced at the mouth of the Kawarau River, which has a sediment load of approximately 1,320,000m^3/yr (Cowan, 1992).

Figure 7. Clutha River/Mata-Au discharging into the northern end of Lake Dunstan on15 January 2013. The Bendigo Wildlife Reserve is located on the true left of the river mouth.

2.3. Rainfall

This section of the Clutha River/Mata-Au is fed by the outflows of two lakes, Wanaka and Hawea, as well as several other smaller watercourses. Lake Wanaka is fed by two major rivers, the Makarora and the Matukituki while Lake Hawea is predominantly fed by the Hunter River. These rivers have their sources in the mountains of the Southern Alps, a region of high precipitation. Nor-westerly storms tend to provide the most significant inflows to Lakes Wanaka and Hawea, particularly in spring and summer, when rapid snow melt can exacerbate flood flows. Orographic effects play an important role in determining precipitation patterns in these upper catchment areas (Mojzisek, 2005). Moisture-laden westerlies are forced upwards by the Southern Alps, producing high precipitation on the upper slopes. Moisture is removed by orographic lift, leaving drier air on the leeward, eastern side, where a rain shadow is often observed.

2.4. Hydrology

Flood hazard in the study area is associated with the Clutha River/Mata-Au and its tributaries. Figure 8 shows the confluence of the Clutha and Hawea Rivers at Albert Town, 25km north of the study site, with the smaller Cardrona River also merging just downstream.

Figure 8. **The confluence of the Hawea, Clutha and Cardrona rivers during a period of high flows on 15 January 2013. The Clutha River/Mata-Au at the Cardrona Confluence site was flowing at 700m3/s at this time.**

The Cardrona River with a catchment area of 346 km^2 and a maximum recorded flow of $124m^3/s$ at Albert Town, can, therefore, make a modest contribution to flood flows in the Clutha River/Mata-Au (Table 1 and Figure 11). The Lindis River joins the Clutha River/Mata-Au approximately 3.5km downstream of Queensberry, and 10km upstream of Lake Dunstan.[6] The contribution of the Lindis River to total flow in the Clutha River/Mata-Au during medium to low flows is normally small, with water abstracted for irrigation, and lost to groundwater. However, the catchment is relatively large (1,050 km^2) and when it does receive heavy rainfall, particularly in the more mountainous country to the north, the river can contribute significantly to flood flows in the Clutha River/Mata-Au, as shown during the November 1999 event (Figure 11).

The annual average flow, and flood flow characteristics of key monitoring sites in the Upper Clutha catchment are shown in Table 1 along with the catchment area above each site. Appendix 1 provides more detail on the characteristics of flood flows at these sites.

[6] Distances measured following the main river channel, as shown in aerial photographs collected in February 2006.

Table 1. Mean annual flow, mean annual flood and maximum flow on record at flow recording sites above Lake Dunstan. The location of these sites is shown in Figure 2.

River Location (catchment area)	Length of record	Mean annual flow (m^3/s)	Mean annual flood event (m^3/s)	Maximum recorded flow (m^3/s)
Clutha Wanaka outflow[7] (2,628km^2)	**Feb 1933 – Apr 2014**	**200**	**516**	**1,444 (18 Nov 1999)**
Hawea Camphill Bridge (1,428km^2)	**Mar 1969 – Apr 2014**	**66**	**210**	**346 (19 Jul 1968)**
Cardrona Albert Town (346km^2)	**Sep 1978 – Jan 2002**	**2.9**	**55.5**	**124 (17 Nov 1999)**
Clutha Below Cardrona confluence (4,405km^2)	**Apr 1992 – Apr 2014**	**271**	**738**	**1,617 (17 Nov 1999)**
Lindis Lindis Peak (542km^2)	**Sep 1976 – May 2014**	**6.2**	**93**	**322 (13 Dec 1995)**

The site which gives the best indication of flood flows in the Clutha River/Mata-Au that may affect the study area is the ‘Clutha River/Mata-Au at below Cardrona confluence’ station. Continuous records of river flow at this site commenced in April 1992. The ten largest flows at this site since then are shown in Figure 9. The largest flood occurred in November 1999, peaking at 1,617m^3/s. A flood event in October 1878 is likely to have resulted in flood flows at this site of a similar or larger magnitude to those in November 1999. An estimated flow for the October 1878 flood, derived from lake level records in Lake Wanaka, is also shown in Figure 9. The record from the site shows that the largest flows in this reach of the river generally occur between November and January (Figure 10).

[7] The outflow from Lake Wanaka is determined from lake level records and historic flow ratings at Roy’s Bay, some 6.5km from the outlet. Observations of lake level date back to 1933 (ORC, 2000).

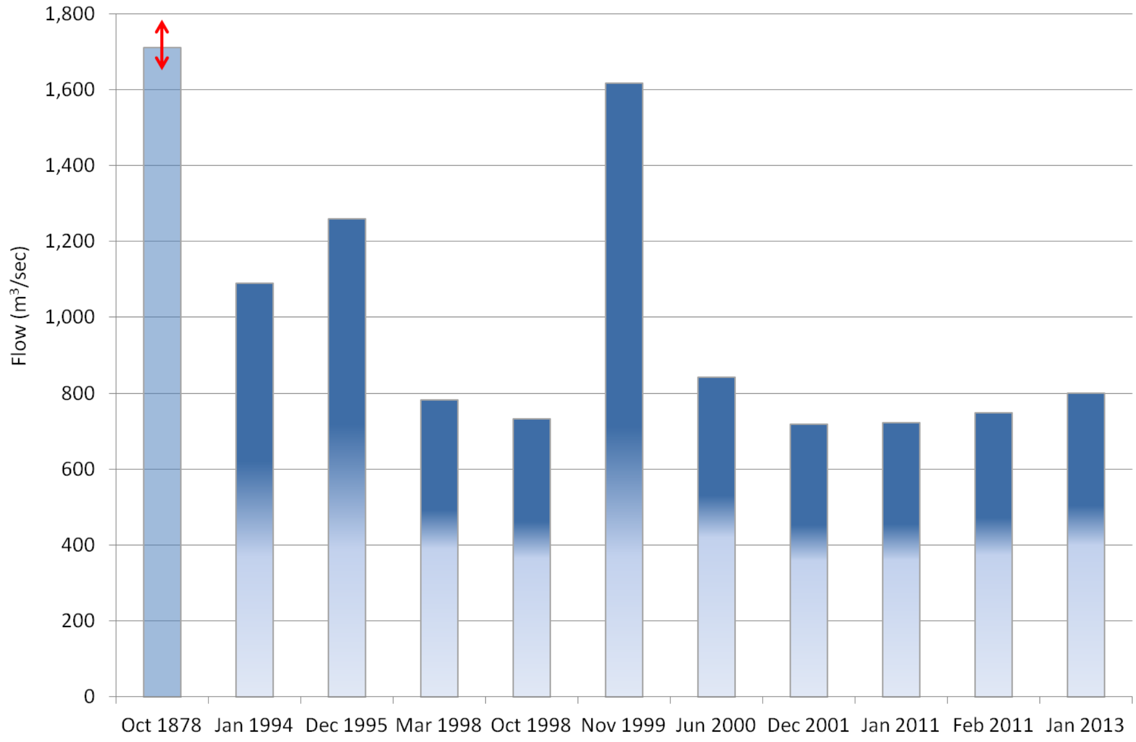


Figure 9. **The ten highest flows in the Clutha River/Mata-Au below the Cardrona confluence between April 1992 (when records commenced) and January 2013. The estimated peak flow of the October 1878 flood is also shown although the accuracy of this value is lower than for more recent flood events (see Appendix 1 for more detail).**

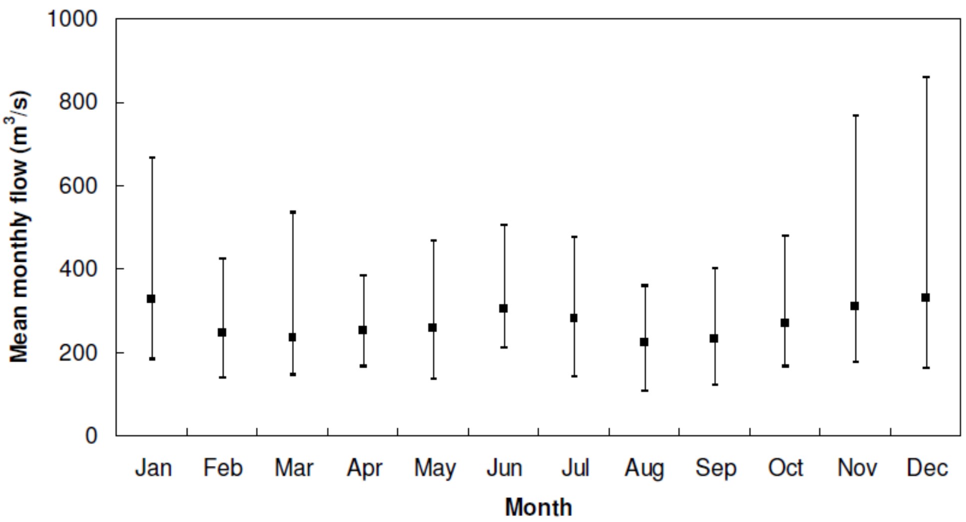


Figure 10. **Clutha River/Mata-Au below Cardrona confluence mean monthly flows (1993 to 2009). Source: Wild, 2012.**

2.5. Characteristics of flood events

The characteristics of every flood event are different, depending on the duration, extent and intensity of rainfall across the entire catchment. In addition, a moderating influence on the magnitude and duration of flood peaks in the Clutha River/Mata-Au is the 'start' level of

Lakes Wanaka and Hawea, i.e. the level of these lakes prior to the heavy rainfall event (or events). This is particularly true for Lake Hawea, as lake levels and outflows to the Hawea River are artificially controlled by the Hawea Dam and are restricted to a maximum flow of 200m^3/sec. Consent conditions require Contact Energy Limited to manage outflows in such a way that flows do not exceed 800m^3/sec in the Clutha River/Mata-Au at the Cardrona Confluence hydrological site (Consent, 2001.392). Reducing outflows from Lake Hawea to less than what is flowing into the lake will result in the lake level rising more rapidly than would otherwise occur.

Figure 11 shows that during the November 1999 flood, the contribution of the Hawea River was very small during the peak of the event, as water was able to be held back in Lake Hawea. When the lakes are already relatively high, then a heavy rainfall event in their upper catchments can raise them to very high levels, resulting in higher outflows to the Clutha River/Mata-Au.

Despite its size, the 1999 flood did not have a significant effect on people or assets in the study area, as there was little development within the active floodplain. However, many lives were lost during a flood event in 1863, when high flows swept through a miners encampment at low-lying Sandy Point, 13km upstream of Queensberry (ORC, 1999). Since 1999, a number of smaller floods have occurred, although none have exceeded 850m^3/s (Figure 9).

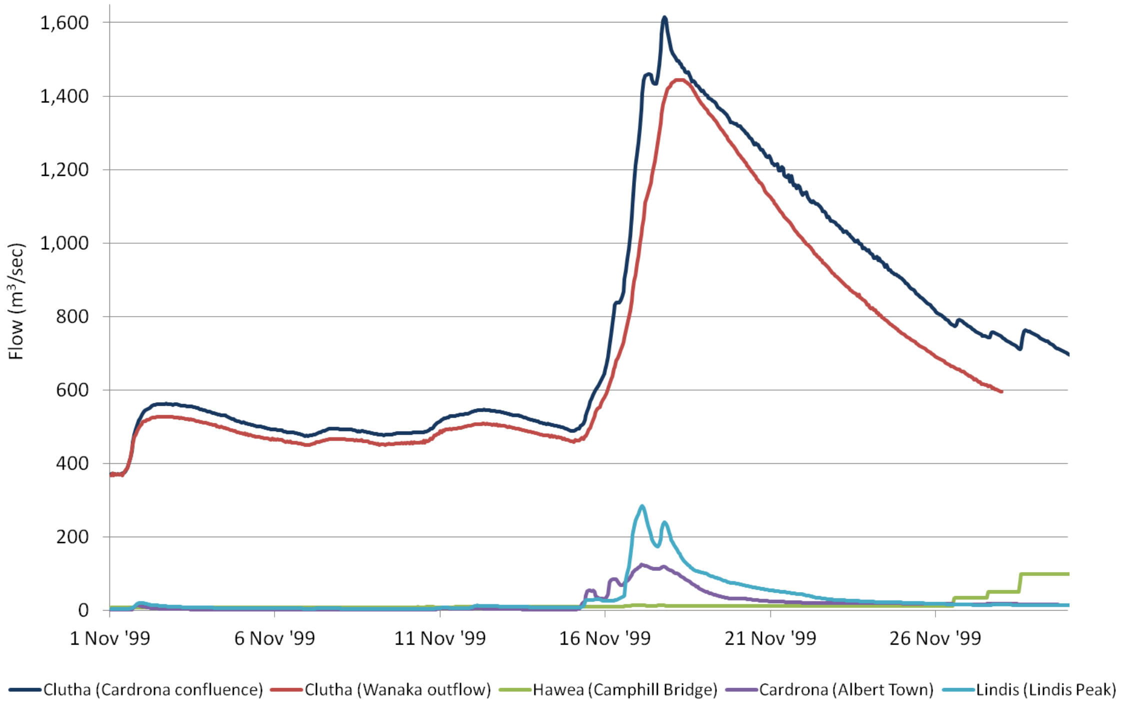


Figure 11. **River flows during November 1999 in the main stem and major tributaries of the Clutha River/Mata-Au upstream of Lake Dunstan**

3. Hazard mapping

This report takes a holistic view of the hazards associated with alluvial fan activity and high river flows and identifies:

- valley floor areas which may be subject to river flooding
- river banks and terrace risers which may be vulnerable to erosion
- alluvial fan areas which may be subject to debris and/or flood flows.

Sections 3.1 and 3.2 describe the flood hazard of the Clutha River/Mata-Au, while the following sections describe the hazard associated with erosion of the river bank and terrace risers, and areas which may be affected by alluvial fans.

3.1. Flood hazard

Flood hazard in the study area has previously been described and mapped by the Otago Regional Council (ORC, 1999; ORC, 1993). The mapping is primarily based on the observed flood extent from the January 1994, December 1995, and the November 1999 floods (Figure 9). Mapping was not completed using modelling or topographical information and the accuracy of the flood hazard margins are therefore indicative only. This flood hazard map is available online via the Otago Natural Hazards Database[8] (available at www.orc.govt.nz).

A hydraulic model of the Clutha River/Mata-Au between Queensberry and Lake Dunstan has been developed (Opus, 2014) to improve the understanding of flood hazard. The model was used to identify the area likely to be affected by a flood with an estimated return period of 100 years (Figure 12). Such a flow, not the biggest possible, has a reasonable chance (63%) of occurring in any 100-year period, and is something that could realistically be experienced by a person during their lifetime. Such a flood would result in a flow of 1,685m^3/s in the Clutha River/Mata-Au at Queensberry, and a flow of 2,082m^3/s below the confluence of the Lindis River.[9] This is larger than the flow of 1,800m^3/s experienced during the November 1999 flood (Figure 9) and other flood events that were used to map the observed flood hazard area.

The model utilised river bathymetry and flood plain topography data sourced from LiDAR and surveyed river cross-sections between 1995 and 2013 to determine the extent of the flood hazard area. This data was provided by both CEL and ORC. The margins of the mapped flood hazard area shown in Figure 12 do not take account of any super-elevation of the water level on the outside bend of the river, or localised backwater effects due to impedances such as debris or sedimentation in the channel. These, and other effects, may lift water level above that modelled for this investigation in certain locations.

A sensitivity check was completed on the modelling by increasing and decreasing the Clutha River/Mata-Au input flow by 20 percent and graphing the changes at 9 of the 12 cross-section locations (Appendix 4). The difference in the extent and depth of the modelled flood hazard area when the flow is increased or decreased is minimal (<5m) at most cross-sections. Only one site shows a change in the extent of flooding greater than 15m (UC7).

[8] This database also contains a series of photographs taken during an aerial fly-over of the Upper Clutha Valley during the November 1999 flood event.
[9] An explanation of how this flow was determined is provided in Appendix 1.

The characteristics of flood hazard associated with the modelled 1:100 year flow are described below. Four cross-section locations (as shown in Figure 13 and Figure 14) are used to help describe the extent and depth of flooding through the study area.

The main differences between the extent of the modelled flood area and the observed flood hazard map is on the true right bank opposite the Lindis river confluence and on the true left bank near the junction of SH8 and Bendigo Loop Road (Figure 12). At these locations the modelled flood area extends beyond that of the observed flood hazard map. The observed flood hazard map, which is not restricted to river flooding and includes the mouths of alluvial fans and smaller tributary catchments (Figure 12), extends beyond the modelled extent in several locations where alluvial fans are present.

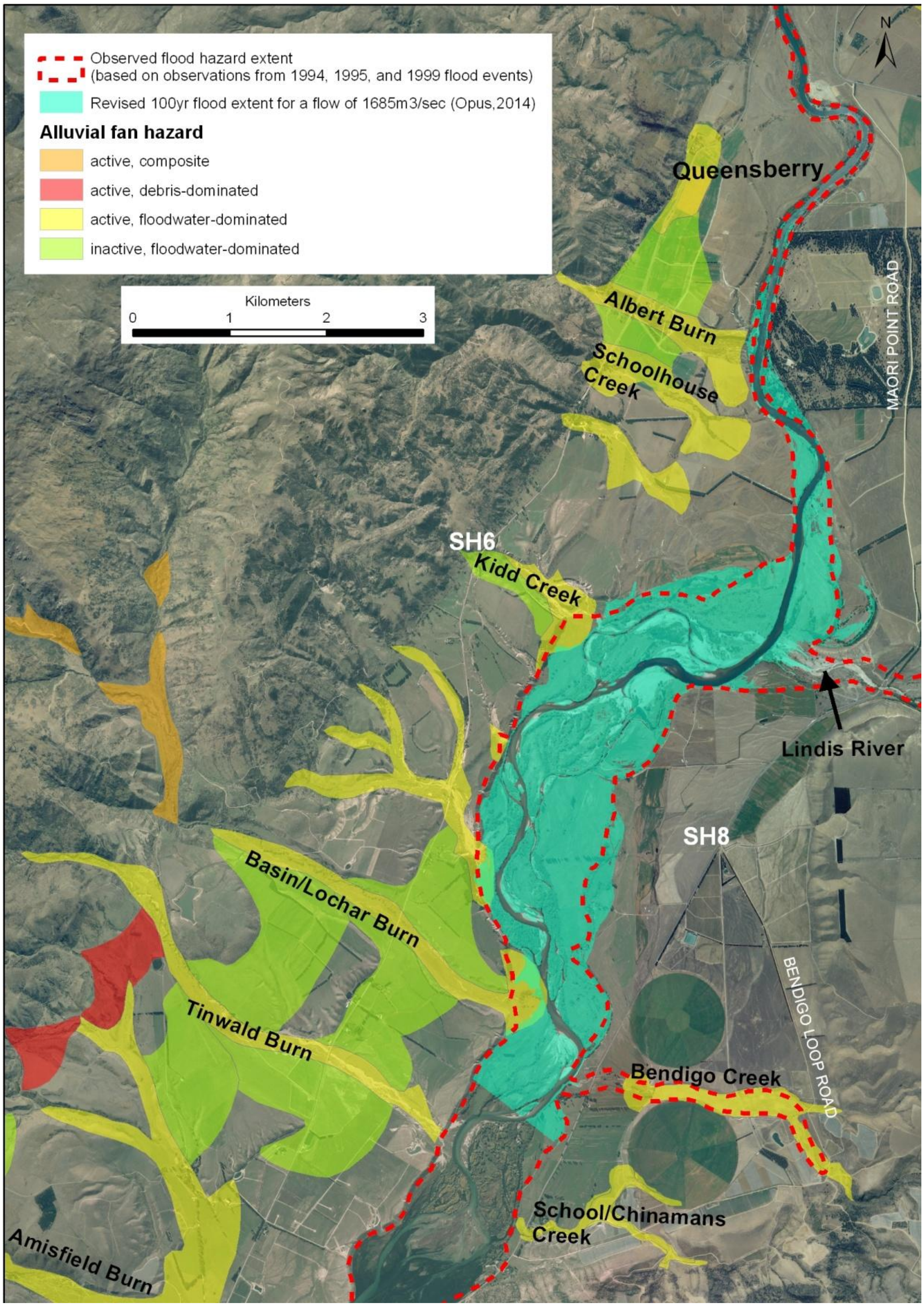


Figure 12. **The margins of the Clutha River/Mata-Au in the study area which will be inundated during a 1:100 year flood (as modelled by Opus, 2014).[10] The dashed red line shows the observed flood hazard area, which is based on observations of 3 flood events in the 1990s. Alluvial-fan deposits on the margins of the river are also shown (as mapped by Opus, 2009).**

[10] The flood hazard area modelled by Opus (2014) could not be extended below Bendigo, as no LiDAR is available for this area. The floodplain is constrained by terraces through this reach (Figure 18) and the observed flood hazard extent is likely to provide a good estimation of a 1:100 year flood event.

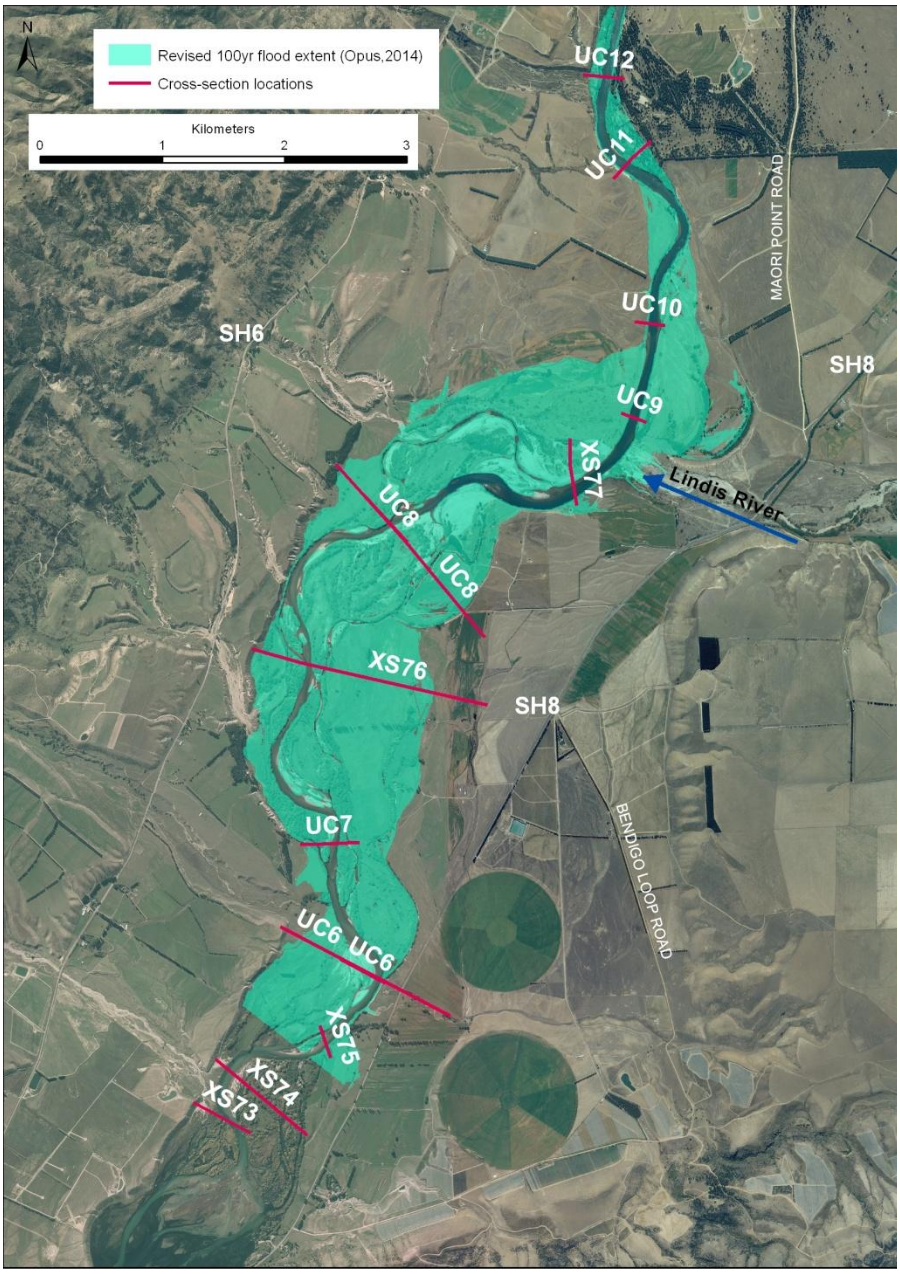


Figure 13. Location of four representative cross-sections (as shown in Figure 14) used to describe the extent and depth of flooding through the study area

The margins of the Clutha River/Mata-Au floodplain vary considerably in their form through the study area. The upper section (adjacent to Queensberry) is steep, confined and incised into alluvial terraces. Flood hazards within this reach are confined to the main channel. Below the confluence of the Albert Burn, the floodplain begins to widen, and at section UC11, extends for approximately 350m. The modelling shows that during a 1:100 year flood event, the depth of water in the main channel at UC11 would exceed 7m, and the depth of inundation on the adjacent floodplain would be between 2 and 4m (Figure 14).

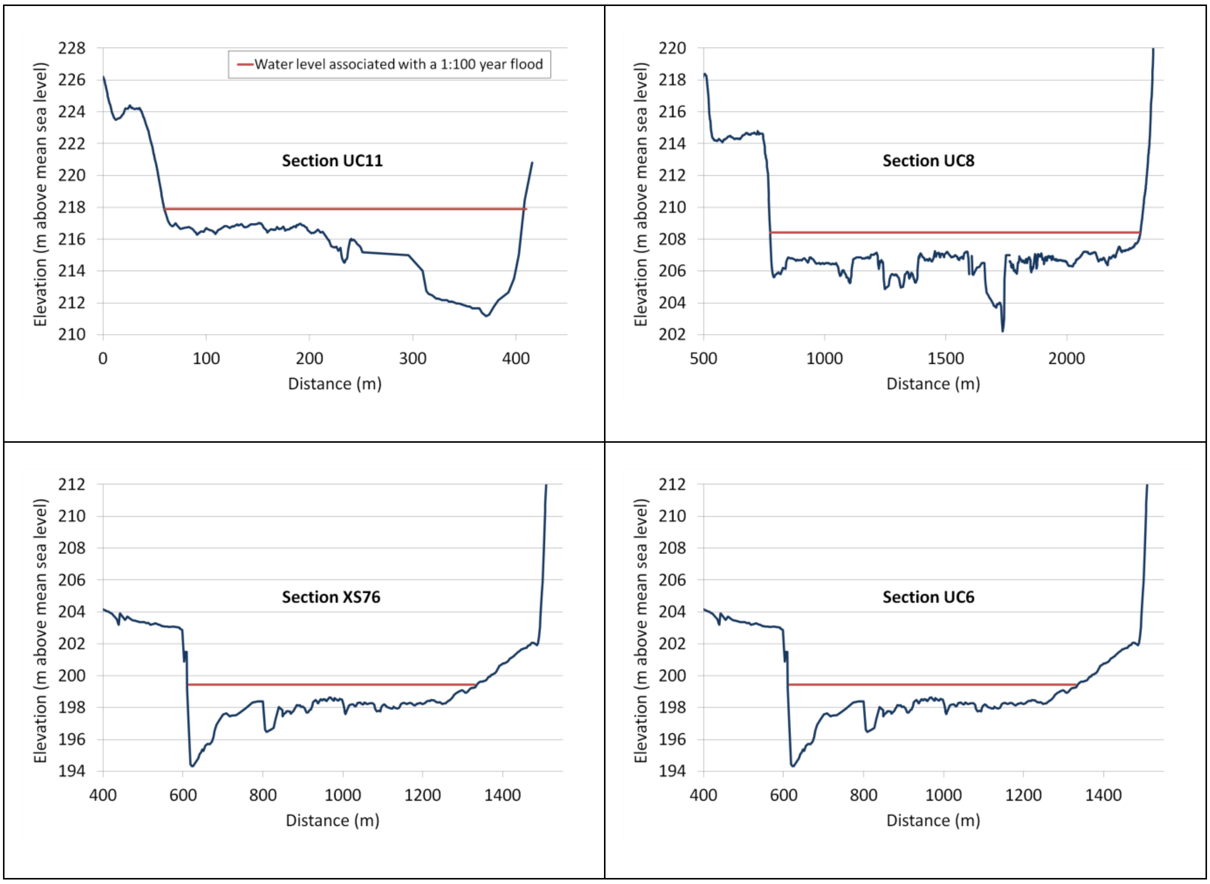


Figure 14. **Representative cross sections (looking downstream) and the water level at each location for a 1:100 year flood event (as modelled by Opus, 2014).**

As the river changes from a single-thread incised channel to a semi-braided form, the floodplain becomes broader and is less elevated above the main 'low-flow' channel (or channels). Figure 14 shows three representative cross-sections across the main channel and floodplain, downstream of the Lindis River (UC8, XS76 and UC6). Although the floodplain is considerably wider than further upstream (up to 1.4km across), inundation across the plain during a 1:100 year flood is at least 1 to 2m deep. Figure 15 shows that the effects of flooding at such a depth can be significant for vehicles, people and buildings, even if the velocity of the floodwater is very low.

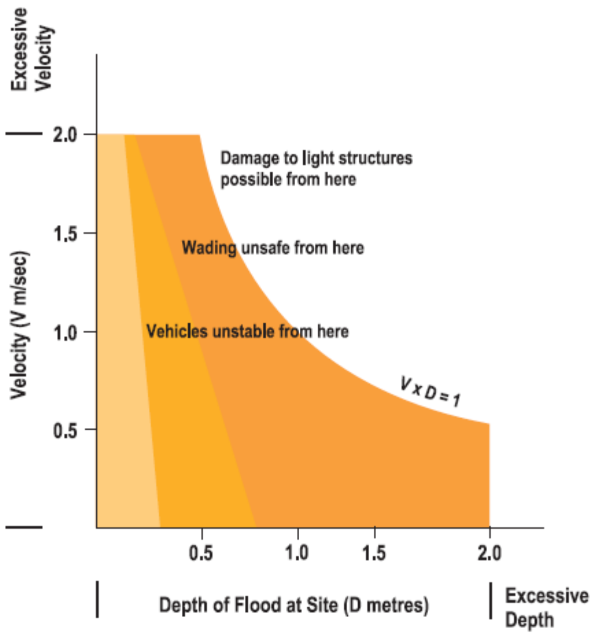


Figure 15. **Example of flood hazard classification based on the product of the velocity and depth (NSW Government, 2005)**

Once floodwater overtops the low-flow channel and flows onto the wider floodplain, it can move unpredictably across the flatter terrain, although the depth of the water will tend to be greater in the network of slightly deeper overflow channels which cross the plain (several of which can be seen in Figure 13 and Figure 14). Where floodwater is relatively deep and fast-moving, it can result in erosion of terrace risers and the banks of the overflow channels. The duration of flooding will also have an effect on the magnitude of erosion damage, i.e. the greater the length of time an area is under water, the greater the chance of damage. Sedimentation can also occur across the floodplain (as well as within the main channel), elevating flood levels and causing channels to change course across the floodplain.[11]

Areas where recent channel erosion has been observed as a result of these processes, and where there is a potential erosion hazard, are described in section 3.3. A series of photos (Appendix 2), which were taken during the November 1999 flood, help to show the general characteristics of flood flows during a large event.

There are two residential properties that sit within the 1:100 year flood hazard area modelled by Opus, as well as several other buildings and assets (sheds, roads etc). These properties are generally located on the margins of the modelled flood hazard layer, and would likely be inundated to a depth of between 0.1 and 0.4m during such an event.

The modelled flood hazard area also extends to areas identified as having a high or moderate risk from bank erosion (Section 3.3, Figure 18). If erosion continues at these locations then several more properties may be affected, either by bank erosion or by an increased exposure to flood hazard.

[11] The effect of sedimentation or erosion in the study area during flood events was not modelled by Opus. However, the long-term effects of ongoing sediment deposition at the head of Lake Dunstan were considered, as described in section 3.2

3.2. The effect of sediment deposition in the head of Lake Dunstan

Sediment deposition and the gradual formation of a river delta at the lower end of the study area have occurred since April 1992, when Lake Dunstan was formed, following completion of the Clyde Dam. Future sediment accumulation in the channel and berm areas and the additional growth of this delta is expected to influence the water level profile during large flood events (Opus, 2014). The modelling undertaken by Opus includes an estimate of how the water level associated with a 1:100 year flood event would change by the year 2030, if sedimentation continues at the same rate observed since 1992.

Figure 16. Sedimentation at the transition from the Clutha River/Mata-Au to Lake Dunstan (January 2013)

The method used to determine historical and future rates of sediment deposition is described in Appendix 3. Although the projected aggradation in the lowest part of the channel is predicted to be up to 1.8m by 2030, this aggradation produces only a small increase in flood levels. Figure 17 shows that the 1:100 year flood level is predicted to increase by up to 0.15m between 300 and 1,700m upstream of the Lake Dunstan mouth. The minimal increase in water level is due to the width of the floodplain in this area – the effect of channel infilling will be dampened by the ability of flood flows to spread out across the entire floodplain. The effect of the sedimentation will be less for smaller flows that stay contained within the channel but it may still have an effect on channel erosion and morphology change. The water level at the downstream boundary (Lake Dunstan) also helps to control the water level profile.

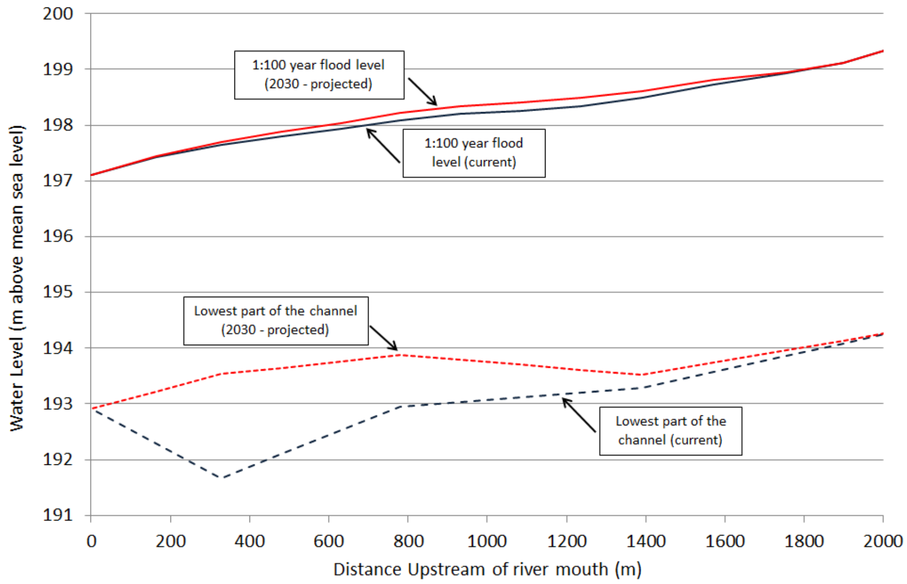


Figure 17. The current (2012) and projected (2030) level of the lowest part of the channel, and the 1:100 year flood level at the Lake Dunstan mouth of the Clutha River/Mata-Au

3.3. Erosion hazard

The erosion hazard map shown in Figure 18 was created using the following sources of information:

- LiDAR data collected in 2009
- orthometric aerial photography collected in February 2006
- site visits in December 2012 and January 2013
- detailed contour maps created by the Ministry of Works and Development in 1979
- photos and observations of flood events which occurred between January 1994 and January 2013.

An initial exercise was undertaken to map all river banks and terrace risers in the study area which were greater than 1m in height,[12] on the margins of the Clutha River/Mata-Au and its tributary streams. Terrace risers were mapped as far as SH6 on the true right of the river, and Maori Point Road/SH8/Bendigo Loop Road on the true left.[13] The likelihood of erosion occurring along each length of terrace was then categorised, based on its proximity to the active channel, recent activity and local topography. The four categories of erosion hazard are listed in the following Table.

[12] In some cases, terrace risers less than 1m in height were also mapped where these features were easily recognisable, or in close vicinity to residential dwellings.
[13] It is noted that the erosion hazard of terrace risers on the lateral margins of tributary streams is more likely to be linked to the characteristics of flood events in the tributaries themselves, rather than high flows in the Clutha River/Mata-Au. Flood events in these tributaries, which are of sufficient magnitude to cause such erosion, may occur only rarely (see Alluvial Fan section).

Table 2. Erosion hazard categories

Erosion hazard	Colour	Description
Active	**Red**	**Erosion is currently occurring (based on aerial observations during a high flow event in January 2013, and other recent investigations by the ORC).**
High	**Orange**	**Erosion of the river bank or terrace riser is likely to occur in the near future, if lateral migration of the river channel continues as at present in 'Active' erosion hazard areas.**
Moderate	**Yellow**	**Significant lateral movement of the river channel would be required before flood flows in the main channel would result in erosion of the terrace riser (i.e. terrace risers which are on the margins of the floodplain, but currently well back from the main channel).**
Low	**Green**	**The margins of the higher terrace features flank the valley floor, but are beyond the current extent of the floodplain.**

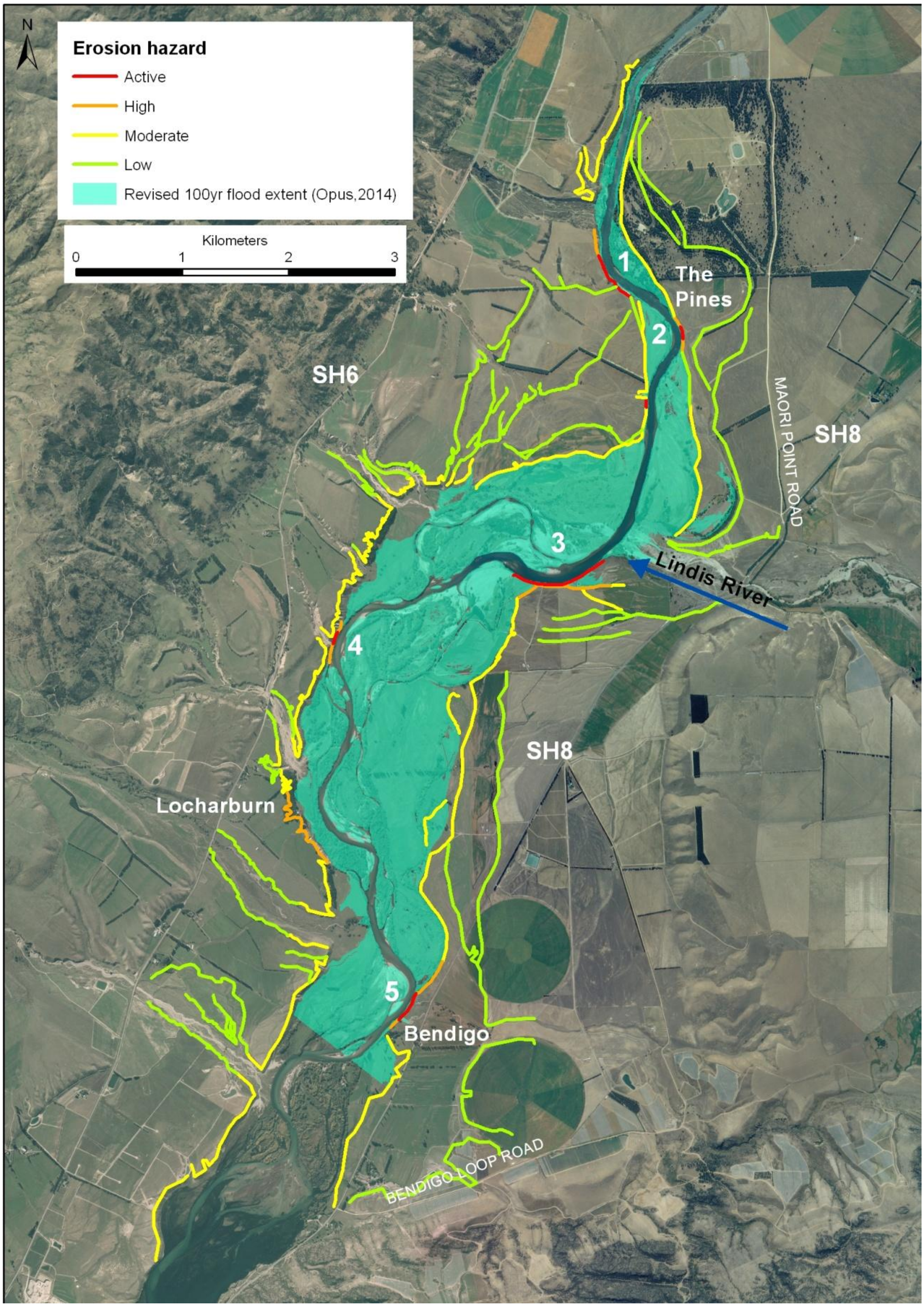


Figure 18. **Erosion hazard map. Five areas where active riverbank erosion has been recently observed are labelled.**

The main areas of active erosion occur where the river is flowing relatively fast on the outside bank of a sharp bend, and the main channel is flowing directly against the outer bank. This includes the following five locations (as labelled on Figure 18):

1. **On the true right bank, downstream of Queensberry and the Albert Burn confluence.** Continued erosion at this location would affect farmland on the true right bank (Figure 19).

Figure 19. View of the Clutha River/Mata-Au, looking downstream and showing erosion of the true right bank, downstream of Queensberry (point 1 on Figure 18). Photo taken during a period of high flow on 15 January 2013 (approximately 700m^3/sec).

2. **On the true left bank, downstream of 'The Pines'.** Continued erosion at this location would affect farmland on the true left bank (Figure 20).

Figure 20. View of the Clutha River/Mata-Au, looking downstream and showing erosion of the true left bank, downstream of Queensberry (point 2 on Figure 15). Photo taken 15 January 2013.

3. **On the true left bank, downstream of the Lindis River confluence.** Between 1995 and 2013 the rate of erosion at this location was 5.6m/year. If this rate of erosion were to continue, the houses nearest to the eroding bank (about 400m away) would be affected in about 70 years (Figure 21).

Figure 21. View of the Clutha River/Mata-Au, looking downstream and showing erosion of the true left bank, downstream of the Lindis confluence (point 3 on Figure 15). Photo taken 15 January 2013.

4. **On the true right bank, at the confluence of a small, un-named tributary, approximately 1.3km upstream of Locharburn.** If erosion continues at this location, scrub and farmland on the true right bank will be affected. SH6 is located 450m away from this location (Figure 22).

Figure 22. View of the Clutha River/Mata-Au, looking downstream and showing erosion of the true right bank (point 4 on Figure 15). Photo taken 15 January 2013.

5. **On the true left bank, near Bendigo.** A house and SH8 are located 40m and 80m, respectively, from an actively eroding bank. If the bank continues to erode, the buffer of land between the channel and the property will reduce, therefore increasing the exposure to erosion hazard into the future (Figure 23).

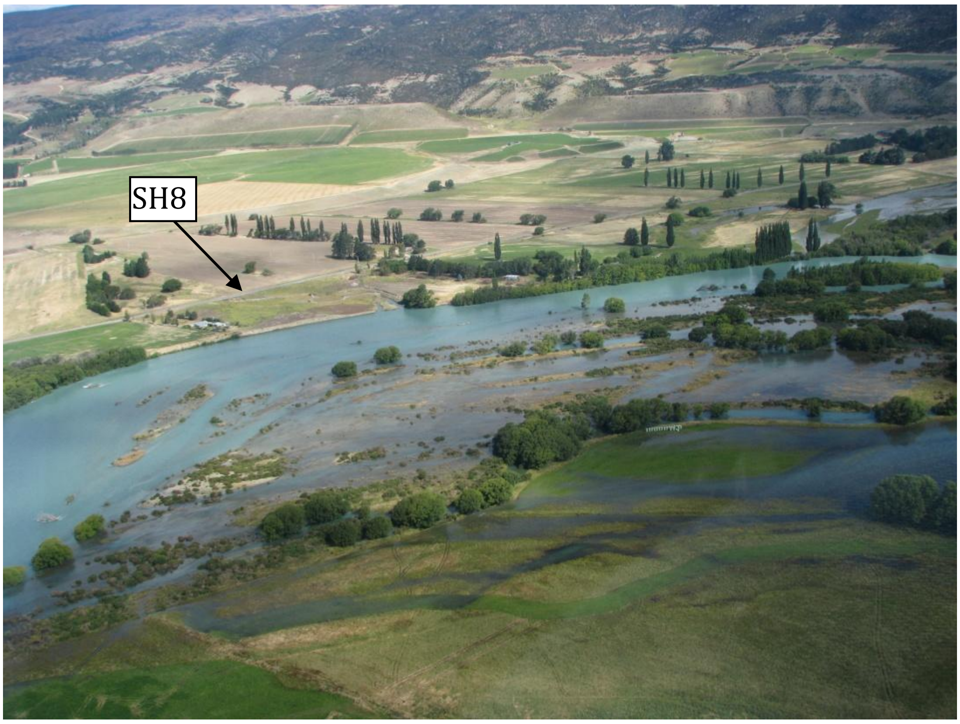


Figure 23. View of the Clutha River/Mata-Au, looking downstream and showing erosion of the true left bank, near Bendigo (point 5 on Figure 15). Photo taken 15 January 2013.

It is noted that the level of erosion hazard assigned to each river bank or terrace riser has been assessed for the current configuration of the river and its tributaries. Lateral migration of the channel in the future will alter this assessment of erosion hazard, i.e. if the river moves closer to a terrace it may change from being a moderate erosion hazard to a high erosion hazard.

3.3.1. Historical changes in the shape of the main channel

Some of the areas of active erosion identified above are also locations where major changes in the main channel have occurred over the last 65 years. Figure 24 shows the results of a comparison of the earliest (1948) and most recent (2006) aerial photos held by the ORC. This analysis shows that the main channel of the Clutha River/Mata-Au has not always occupied its current position in the floodplain.

One of the most significant changes to occur during this period was downstream of the Lindis confluence, where the main channel moved from the true right (northern) side of the floodplain to the true left (southern) side. The main channel is now located against a 5m high terrace (see the location labelled ‘3’ on Figure 18). The previous channel is now a secondary overflow path, which is occupied during flood events. The construction of Lake Dunstan has also led to the drowning of the Clutha Valley downstream from Crippletown and the morphology of the river where it now enters Lake Dunstan has also changed significantly at this location.

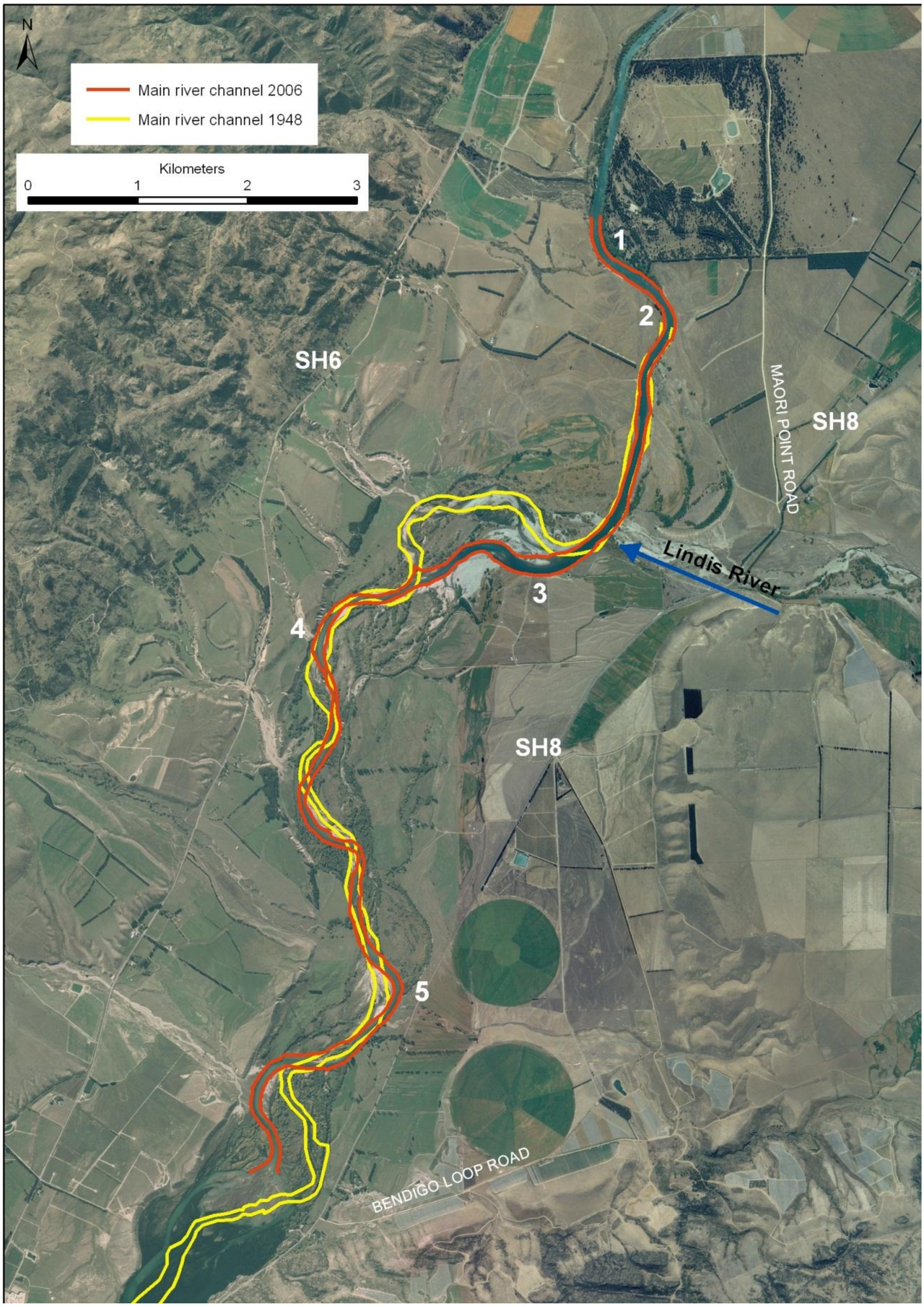


Figure 24. **The location of the main channel of the Clutha River/Mata-Au in 1948 and 2006. The location of the five areas of 'active' erosion (as identified in Figure 18) is also shown. The background layer is an aerial photo collected in 2006.**

The nature of the Clutha River/Mata-Au between Queensberry and Lake Dunstan is such that no area alongside the river can be considered completely safe from erosion and channel migration. The channel has switched locations in the past (as shown by Figure 24) and areas that are now free of bank erosion could become affected in the future. Therefore any future development of land in close proximity to the river terraces which bound the floodplain of the Clutha River/Mata-Au should give careful consideration to the ongoing effects of bank erosion and any potential risk associated with this.

3.4. Alluvial fan hazard

Parts of the Upper Clutha Valley are subject to hazards associated with alluvial fan activity, in addition to flooding and erosion associated with high flows in the Clutha River/Mata-Au. An alluvial fan is an accumulation of river or stream (alluvial) sediments that form a sloping landform, shaped like an open fan or segment of a cone (Figure 25). They form where rivers or streams exit a valley, allowing sediment-laden flows to spread over a broad area. As these flows exit the confines of the valley, they lose energy, and their ability to carry sediment decreases. This results in the deposition of layer upon layer of sediment along the boundary of the hill slopes and valley floors.

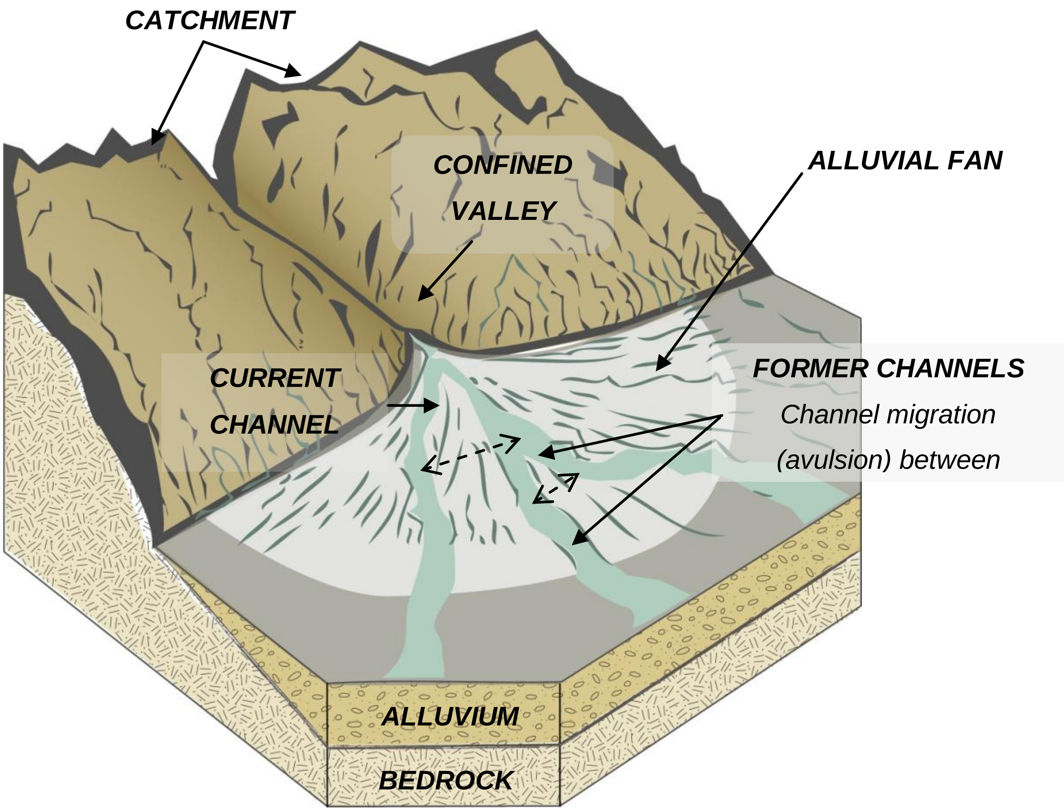


Figure 25. Stylised image of an alluvial fan

Alluvial fans are composed of sediments derived from the rock and soils within the wider alluvial-fan catchment. While not part of the alluvial fan itself, the catchment plays an important role in initiating and sustaining alluvial-fan activity as it is the source of material for development of the fan. Water from the catchment flows downslope across the fan surface.

Depending on the characteristics of the source catchment and the available sediment supply, these flows may also transport and deposit sediment down and across the alluvial fan.

Alluvial fans can experience long periods of inactivity, often from decades to centuries, only to re-activate due to extreme or unprecedented events, or due to environmental change (such as tectonic uplift or changes in the catchment sediment supply, climatic conditions and/or river/stream incision). Their often benign appearance between events does not give a full appreciation of their potential hazardous nature. In Central Otago, fan streams are often ephemeral or inconspicuous; creating the impression that little or no hazard exists. These areas can often be considered attractive places for development, with their elevated profile providing striking views and good on-site drainage. A limited understanding of alluvial-fan hazard may, therefore, lead to problems if these areas are preferred locations for development rather than areas with more obvious hazards (such as flooding across the surface of the river terraces).

The main hazards associated with alluvial fans can include debris flow, debris flood, inundation by floodwater flow, sedimentation, erosion and/or channel migration across the fan (Opus, 2009). These processes can impact on the long-term shape, elevation and characteristics of a fan surface and hence on how the surface of the fan is used. Furthermore, flood and debris flows generally occur suddenly without warning and can be unpredictable and destructive.

Alluvial-fan landforms throughout Otago with a surface area greater than $0.5km^2$ were mapped by Opus (2009), and Figure 12 shows the location of these features in the study area. Alluvial fans have developed along the margins of the valley where sediments have been deposited by streams draining the Pisa Range to the west, and the Dunstan Range to the east. Eroding bedrock in the catchments has fed sediment onto alluvial fans which have, as a consequence, built out onto the Clutha River/Mata-Au terraces. The valley-floor landscape is dominated by sequences of terraces and fans in this area (GNS, 2009). The most recent change in this landscape is the creation of Lake Dunstan. This now acts as a trap for sediment supplied by alluvial fan activity (as well as from upstream), which was previously carried away by the Clutha River/Mata-Au. Figure 26 shows an example of an alluvial-fan feature, where Kidd Creek exits from its steep upper catchment onto the floodplain of the Clutha River/Mata-Au, approximately 8km upstream from Lake Dunstan.

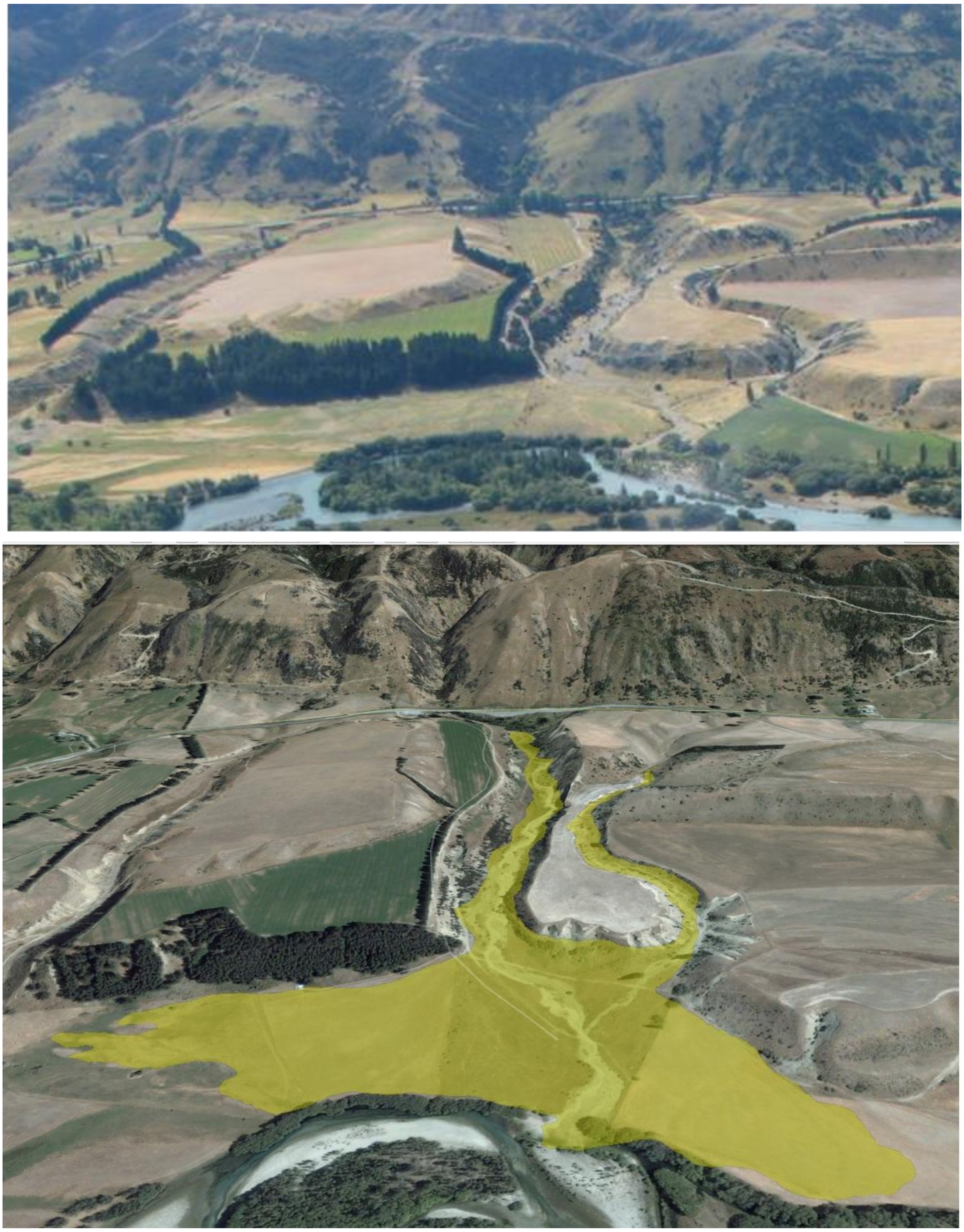


Figure 26. **Looking west across the lower reaches of an active floodwater-dominant alluvial fan that drains from Kidd Creek in the Pisa Range. The upper image was taken on 15 January 2013, during a period of high flow in the Clutha River/Mata-Au (approximately 700m^3/sec). The lower image was generated using Google Earth, and shows the approximate extent of the active floodwater-dominant alluvial fan, as mapped by Opus (2009).**

Fans have been classified based on the activity and type of depositional processes that have formed the fan surface, as these criteria reflect the scale and significance of the hazard. Alluvial fans on the margins of the Clutha River/Mata-Au between Queensberry and Lake

Dunstan are mainly floodwater-dominant alluvial fans, experiencing sheet and channel floods. No debris-dominant alluvial fans have been identified on the margins of the Clutha River/Mata-Au.[14]

Floodwater-dominated alluvial fans are characterised by water-dominated processes. During heavy rainfall, sediment-laden water from the alluvial-fan catchment is concentrated into channels flowing downslope, eventually crossing the alluvial-fan surface. As the fan's gradient reduces and the flows begin to lose velocity, fine sediment suspended in the flows is deposited across its surface.

The active floodwater-dominated alluvial fans on the west of the valley are those of Tinwald Burn, Basin/Lochar Burn, Kidd Creek, Schoolhouse Creek and Albert/Alfern Burn (Figure 12). Alluvial fan activity has also been mapped in the lower reaches of Long Gully and Tarras Creek on the eastern side of the valley, although this is not shown to extend as far as the Clutha River/Mata-Au.

Alluvial fans always present an element of hazard due to their unpredictability. They may continue to evolve in response to modifications to their upstream catchment (e.g., where changes in land use, landslide activity or earthquakes affect the availability of sediment) and changes in climate. Should long-term climate change bring about a change in rainfall intensity or storm frequency, this may affect alluvial-fan activity in the Upper Clutha Valley.

Reference to the alluvial fan areas mapped by Opus (2009) has been included in this report as alluvial fan activity can affect and be affected by flood and erosion activity along the margins of the river.[15] An example is where aggradation and sedimentation occur along the distal fringe of a fan which borders or extends into the active channel of the river. This may restrict the conveyance of flood flows, or result in the re-direction of flood flows onto adjacent areas. An understanding of the processes occurring both on alluvial fans and within the river channel/floodplain is therefore necessary to have a complete understanding of fluvial hazards in a particular area.

[14] Opus did map a debris-dominant fan in the upper reaches of the Amisfield Burn, which flows directly into Lake Dunstan (Figure 12).
[15] Events of sufficient magnitude to activate an alluvial fan in this area can be rare, however.

4. Conclusion

This report describes the characteristics and extent of the flood-related natural hazards that are experienced in the Clutha River/Mata-Au catchment between Queensberry and Lake Dunstan. It is intended to help inform good decision-making in relation to future and existing development within this study area.

The report has shown that much of the study area (including a number of existing residential properties and other assets) is vulnerable to some level of risk associated with one or more hazards, including flooding, bank erosion and alluvial fans. Due to the unpredictable nature of flood events and bank erosion, no area alongside the margins of the Clutha River/Mata-Au can be considered to be completely free of flood/erosion hazards. Additional intensification or development in hazard-prone areas would increase the risk associated with these hazards. Therefore, any decisions on land use should give careful consideration to the potential risk, and ensure that any activities are compatible with the area's hazard exposure.

5. Glossary

Fluvial: The deposits and landforms created by the action of rivers or streams and the processes associated with them.

Quaternary: The Quaternary Period is the most recent of the three periods of the Cenozoic Era in the geological timescale. The 2.6 million years of the Quaternary represents the time during which humans have existed.

Super-elevation: The difference in elevation of water surface between the inside and outside wall of a bend in a river. The centrifugal force acting on the water creates centripetal lift.

Terrace riser: Riser between two terrace levels (whether alluvial fan or river).

6. References

Beanland, S., & Berryman, K. R. (1989). Style and episodicity of late Quaternary activity on the Pisa-Grandview Fault Zone, Central Otago, *New Zealand, New Zealand. Journal of Geology and Geophysics*, 32, p. 451-461.

Central Otago District Council. 2008: Central Otago District Plan.

Cowan. G.F. (1992). Bendigo Wildlife Area Management Strategy, Department of Conservation

Hadley Consultants Ltd (2010). Riverbank Protection Works, Bendigo Reach, Tarras.

Hamilton, D. (2002). Bendigo Reaches Limited Review of Proposed Rock Bank Protection Clutha River.

GHD (2010). Cardrona River Floodplain Flood Hazard Study. Client report prepared for Otago Regional Council.

Geological Nuclear Sciences (2009). Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago. Prepared for the Otago Regional Council.

Ministry of Works and Development (1977). Clutha Valley Development: environmental impact report on design and construction proposals. Wellington: Ministry of Works and Development.

McKellar, I. C. (1960). Pleistocene deposits of the Upper Clutha Valley, Otago, New Zealand, *New Zealand Journal of Geology and Geophysics*, 3, 3, p. 432-460.

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.

New South Wales Government. 2005: Floodplain Development Manual: the management of flood liable land.

Otago Regional Council (2013). Annual Plan, 2013-14.

Otago Regional Council (2010). Decision of Commissioners Appointed by Otago Regional Council in the matter of Land Use Consent 2006.261 and Water Permit Application 2006.263 by Scope Resources Limited to construct, operate and maintain a defence against water other than in the bed of a river, and to construct a diversion of water, for a 1 in 100-year flood event for the purpose of flood protection and flood mitigation.

Otago Regional Council. 2001: Discharge Permit, 2001.392. V5.

Otago Regional Council (2000). Clutha River Catchment November 1999 Flood Report.

Otago Regional Council (1999). Draft Floodplain Management Report – Central Otago District.

Otago Regional Council (1993). Floodplain Management Report – Central Otago District.

Opus International Consultants (2014). Upper Clutha River Flood Hazard Assessment. Prepared for Otago Regional Council.

Opus International Consultants (2011). Scope Resources Ltd Appeal Review of Information. Prepared for the Otago Regional Council

Opus International Consultants and GNS Science (2009). Otago Alluvial Fans Project. Prepared for the Otago Regional Council, Dunedin.

Turnbull, I. M. (2000): Geology of the Wakatipu Area, *Institute of Geological and Nuclear Sciences*, 1:250,000 Geological Map 18, Lower Hutt, New Zealand.

Wild, M.A. (2012). Growth dynamics of braided gravel-bed river deltas in New Zealand. A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Civil and Natural Resources Engineering at University of Canterbury, New Zealand.

Appendix 1. Estimation of 1:100 year flood flow

Introduction:

To help inform an investigation into flood and erosion hazard in the Clutha River/Mata-Au between Queensberry and Lake Dunstan, Opus International Consultants Ltd were engaged to develop a hydraulic model for this reach. The model provides a water level profile for a credible, high-magnitude flood event. This Appendix explains how the input peak flow values for the Clutha, Lindis and Kawarau rivers have been derived for the model.

The main contributions to the flow in the Clutha River/Mata-Au in the study area are shown in Figure A1, and include:

- outflow from Lake Wanaka
- outflow from Lake Hawea (controlled by Contact Energy Limited)
- Cardrona River
- Luggate Creek
- Lindis River.

Flow inputs from the large number of small tributaries between Albert Town and Lake Dunstan were not considered, as they are likely to contribute only a very small percentage of the total flow. Also, the peak flow from these small catchments is likely to occur well before the peak flow on the Clutha River/Mata-Au.

The peak inflows from the catchments listed above have been added together to create a sum of river discharge into the Clutha River/Mata-Au at the Lake Dunstan Delta. The flow input for the Lindis River was inserted into the hydraulic model as a point inflow approximately mid-way through the study reach (Figure 1).

A decision was made to calculate peak flows with an estimated return period of 100 years (100-year ARI[16]) where sufficient data exists. Such a flow is not the biggest possible but has a reasonable chance (63%) of occurring in any 100 year period, and is something that could realistically be experienced by a person during their lifetime.[17]

[16] Annual Return Interval

[17] It is noted that 1 or 2 large flood events in a river can significantly change the estimated return period associated with a specific flow, and that the 100 year ARI flows used for this calculation are based on currently available information. It is also noted that any estimate for a 100 year ARI flow applies to the location of the flow monitoring site. The return period of a particular event may vary across the wider catchment, depending on the contribution of each tributary. For these reasons, the 100 year. ARI flood peaks derived for this analysis are estimates only.

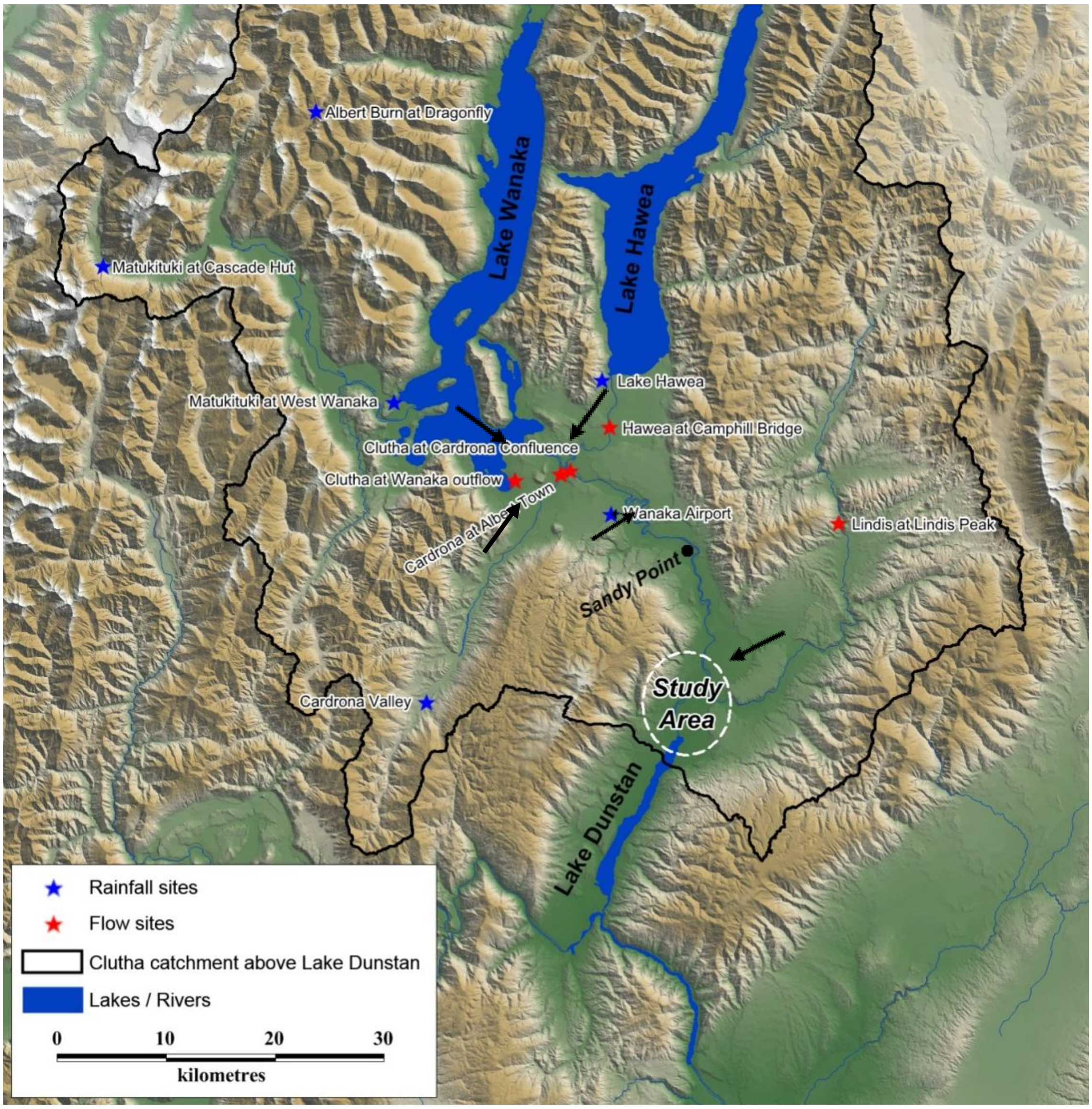


Figure A1. **The major contributing catchments to flow in the Clutha River/Mata-Au (black arrows), for which input flows have been calculated.**

Both observed and modelled flood flows have been used to derive the input peak flow values for the hydraulic model, along with an understanding of the characteristics of flood events in each of the Clutha, Lindis and Kawarau catchments. The methodology used to create these flows is discussed below. This methodology was discussed with and approved by Grant Webby, Principal Hydraulic Engineer at Opus International Consultants Ltd.

Calculated flows:

1) Wanaka outflow (Clutha River/Mata-Au): *1,285m³/s*

A partial duration analysis was used to calculate the frequency of flood flows at the outlet from Lake Wanaka using software developed for the ORC by Magdy Mohssen of Lincoln University. This analysis incorporates all flood peaks above a certain magnitude, rather than just the highest peak per year.

The dataset used to calculate flood frequency included:

- Continuous records from the Lake Wanaka at Roy's Bay site from 1933 to February 2013. This site has a stage to flow relationship with Lake Wanaka outflow, based on flow gaugings at the lake outlet.
- Historical peak lake level estimates from the largest events to occur in 1878, 1919, and 1929-1932 (6 events in total). The current stage to flow relationship (as used for 1) was used to determine flow at the lake outlet for each of these events. Other events that may have occurred between 1878 and 1932 were not able to be included in the analysis, as there are no records of these peaks.

This analysis found that a flow of 1,285m^3/s has an estimated return period of 100 years. Note that two events occurred between 1878 and 2013 which produced flows larger than this value – the 1878 flood is estimated at 1,711m^3/s (using the method described above), and the 1999 flood peaked at 1,444m^3/s.

2) Hawea River at Camphill Bridge: *200m^3/sec*

A flow of 200m^3/sec is used as the input from the Hawea River. This is the maximum flow that Contact Energy Limited (CEL) is consented to release from Lake Hawea via the Hawea Dam. CEL will normally attempt to limit the downstream effects of floods by holding back water during flood events.[18] This may not always be possible, however, as the ability to hold water back in Lake Hawea is related to antecedent lake levels. Larger events than 200m^3/sec have been recorded on the Hawea River - the largest on record being 346m^3/sec in July 1968, although this occurred prior to construction of the Hawea Dam. A credible situation could occur where the peak outflow from Lake Wanaka coincided with CEL having limited or no ability to hold back water in Lake Hawea, and having to release the maximum consented flow of 200m^3/sec. It is noted that this is not necessarily a worst case scenario.

3) Cardrona River at Albert Town: *136m^3/sec*

The flow for this site is the 100-year ARI flow calculated for the 'Cardrona River Floodplain Flood Hazard Study (GHD, 2010). This flow was estimated using the Generalised Extreme Event (GEV) probability distribution, using the flow record from 1979 to 2001 at the Cardrona River at Albert Town site.

4) Luggate Creek at Clutha Confluence *64m^3/s*

There is no flow or stage site located in the Luggate Creek catchment. There are one-off gaugings for Luggate Creek at SH6, although these are all at relatively low flows, the highest being 17.6m^3/sec. NIWA's WRENZ (Water Resource Explorer New Zealand) website estimates a 100-year ARI flow from Luggate Creek at the Clutha River/Mata-Au confluence to be 64.2m^3/sec.

5) Lindis River at Lindis Peak: *397m^3/sec*

A 35 year length of record between 1976 (when records commenced) and 2011 was used to produce a 100-year ARI flow of 397m^3/sec in the Lindis River at Lindis Peak site. This was determined in Hilltop Hydro using a Pearson's Type 3 distribution. The catchment area above the Lindis Peak site is 542km^2 which is approximately half the total catchment area. The 100-year ARI flow at Lindis Peak is considered to be indicative of the flow that may be experienced at the Clutha River/Mata-Au confluence for two reasons:

[18] For example, during the November 1999 event CEL were able to restrict outflow from Lake Hawea to 11m^3/sec during the peak of the flood.

- The catchment upstream of the Lindis Peak site is higher and closer to the Main Divide and, therefore, more likely to experience heavier rainfalls than the remainder of the catchment.
- Although a 100-year ARI flood in the Lindis River at the Clutha confluence may be bigger than 397m^3/sec (due to additional inflows from the catchment below Lindis Peak), it is unlikely that such a peak would occur at exactly the same time as the peak in the Clutha River/Mata-Au. Rather, it is more likely that the peak in the Clutha River/Mata-Au would coincide with the 'shoulder' of the flood hydrograph from the Lindis River.

6) Clutha River/Mata-Au below Lindis confluence *2,082m^3/s*

This flow is the combination of all inflow above this point, as described in 1 – 5 above, and shown in Table A1 below.

7) Kawarau River *2,082m^3/s*

The hydraulic model developed by Opus requires an input flow for the Kawarau River, as the model finishes at the Clyde Dam and takes into account inflows into Lake Dunstan from both the Upper Clutha and Kawarau catchments. For the purposes of this investigation, it is assumed that during a flood in the wider Clutha catchment, 50% of the flow into Lake Dunstan will be from the Clutha River/Mata-Au and 50% will be from the Kawarau River. This appears reasonable, as observations from the November 1999 flood suggest that the peak inflows to Lake Dunstan from the Clutha and Kawarau catchments were both approximately 1,800m^3/s during that event (ORC, 2000). The input to the hydraulic model for the Kawarau River is therefore the same flow as that calculated for the Clutha River/Mata-Au at Lake Dunstan.

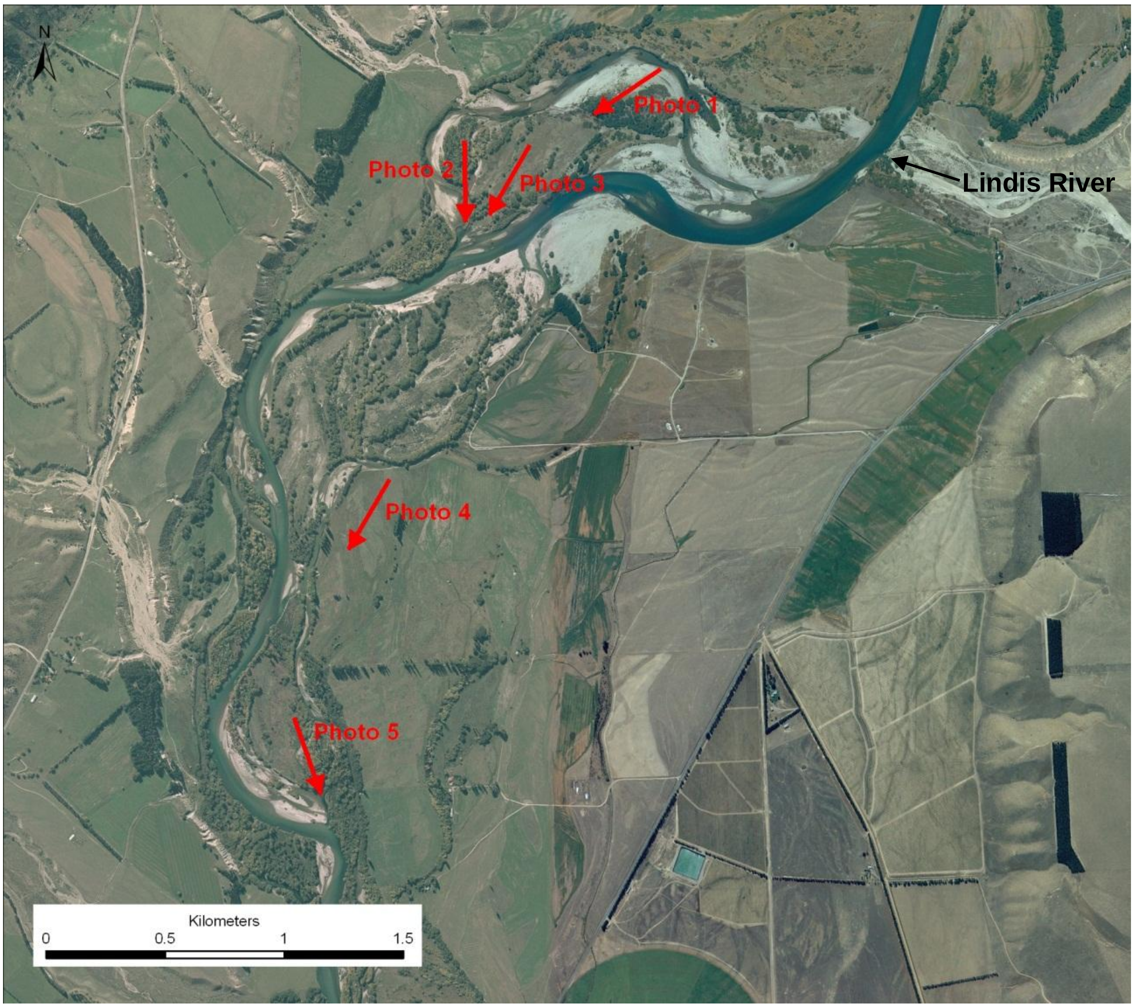
Table 3. Input river flows for the Clutha River/Mata-Au hydraulic model

Site	Flow (m^3/sec)	Method used (as described above)	Largest flood recorded (m^3/sec)
Wanaka Outflow	1,285	100 yr. ARI	1,444 (1999)[19]
Cardrona River at Albert Town	136	GHD (2010)	124 (1999)
Hawea River at Camphill Bridge	200	Maximum consented	346 (1968)
Luggate Creek at Clutha Confluence	64	WRENZ	64
Clutha River/Mata-Au at Queensberry	1,685		
Lindis River at Lindis Peak	397	Lindis Peak record	322 (1995)
Clutha River/Mata-Au below Lindis confluence	2,082		1,800 (1999)
Kawarau River input to Lake Dunstan	2,082		1,800 (1999)

[19] Lake Wanaka peaked at a higher level during the 1878 flood than in 1999. Using the current stage to flow relationship, this level would have resulted in a flow of 1,711m^3/s at the Lake Wanaka outlet.

Appendix 2. November 1999 Flood Photos

These photos show part of the study area during the November 1999 flood event. All photos are looking downstream towards Lake Dunstan. The exact date and time these photos were taken is not known, and was not necessarily at the peak of the flood. The river peaked at 1,617m^3/sec at 6:30pm on 17 November at the Clutha below Cardrona confluence flow site (Figure 9), and these photos appear to have been taken after the river had peaked. Map B1 shows the approximate location and direction of the photos.



Map B1. **Approximate location and direction of November 1999 flood photos**

November 1999 Flood Photo 1

November 1999 Flood Photo 2

November 1999 Flood Photo 3

November 1999 Flood Photo 4

November 1999 Flood Photo 5

Appendix 3. Estimating sedimentation at the Lake Dunstan mouth of the Clutha River/Mata-Au

Background

An investigation into flood and erosion hazard in the Clutha River/Mata-Au between Queensberry and Lake Dunstan is identified in the current Otago Regional Council Long Term Plan as an activity to be completed during the 2012-13 year. To help inform this investigation, Opus International Consultants Ltd has been engaged to develop a hydraulic model of this reach of the Clutha River/Mata-Au. The model will be used to provide a water level profile for a credible, high-magnitude flood event.

Future sediment accumulation in the channel and berm areas; and additional growth of the delta at the Lake Dunstan mouth of the Clutha River/Mata-Au will influence this flood water level profile, particularly in the lower reaches. This file note explains how the magnitude of future sediment accumulation has been estimated.

Discussion

A decision was made to estimate the amount of sediment accumulation likely to have been experienced in this section of the Clutha River/Mata-Au by 2030. Channel aggradation and delta growth will continue beyond this time, and a further assessment of these changes will need to be made in the future, based on additional information and knowledge as it becomes available.

The magnitude of sediment accumulation in 2030 was estimated by comparing historical rates of aggradation at three cross-section locations near the mouth of the Clutha River/Mata-Au (Figure C1). Cross-section survey data from 1995 and 2012[20] were overlaid (Figure C2 to Figure C4), and visually checked for accuracy (e.g. that the sections were completed at the same location, and cover the same extent of channel). The mean bed level (MBL) was calculated for both the 1995 and 2012 surveys. Due to limitations in the survey data, MBL was only able to be calculated for the active (low-flow) channel in XS4 and XS5 but did include the berm areas for XS3. The method for calculating the MBL follows that of Sriboonlue & Basher.[21]

The increase in MBL over the 17 year period between 1995 and 2012 at each cross-section location was calculated, and is shown in Table C1. This increase was then applied to the 2012 survey data, to show the average amount of aggradation likely to be experienced over the 17 years between 2012 and 2030. The estimated cross-section profiles in 2030 (i.e. the 2012 profile, with the values shown in Table C1 added on) are also shown in Figure C2 to Figure C4 below. It is noted that the actual shape of the channel in 2030 will differ significantly from these estimated cross-section profiles, due to lateral movement of the channel and other unforeseen changes.[22] However, it is thought that the estimate of the

[20] These are first and last sets of cross-section data available.
[21] Sriboonlue, S., Basher, L. 2003: Trends in bed level and gravel storage in the Motueka River 1957-2001: a progress report on results from analysis of river cross-section data from the upper and lower Motueka River, *Landcare ICM Report*, 2002-03/04.
[22] This is particularly true at cross-section 5, where the main channel became narrower between 1995 and 2012, due to sediment deposition at the distal margins of the Tindall Burn alluvial fan.

average level of the bed will be reasonably accurate, and it is this factor that will have the greatest influence on flood levels through this section of the Clutha River/Mata-Au.

Table C1. Changes in MBL at XS 3, 4 and 5, estimated using survey data collected in 1995 and 2012.

Cross-section	Change in MBL (m)
3	0.243
4	0.464
5	1.862

The hypothetical cross-section profiles were provided to Opus for inclusion into their hydraulic model, to enable the calculation of flood levels based on additional aggradation.

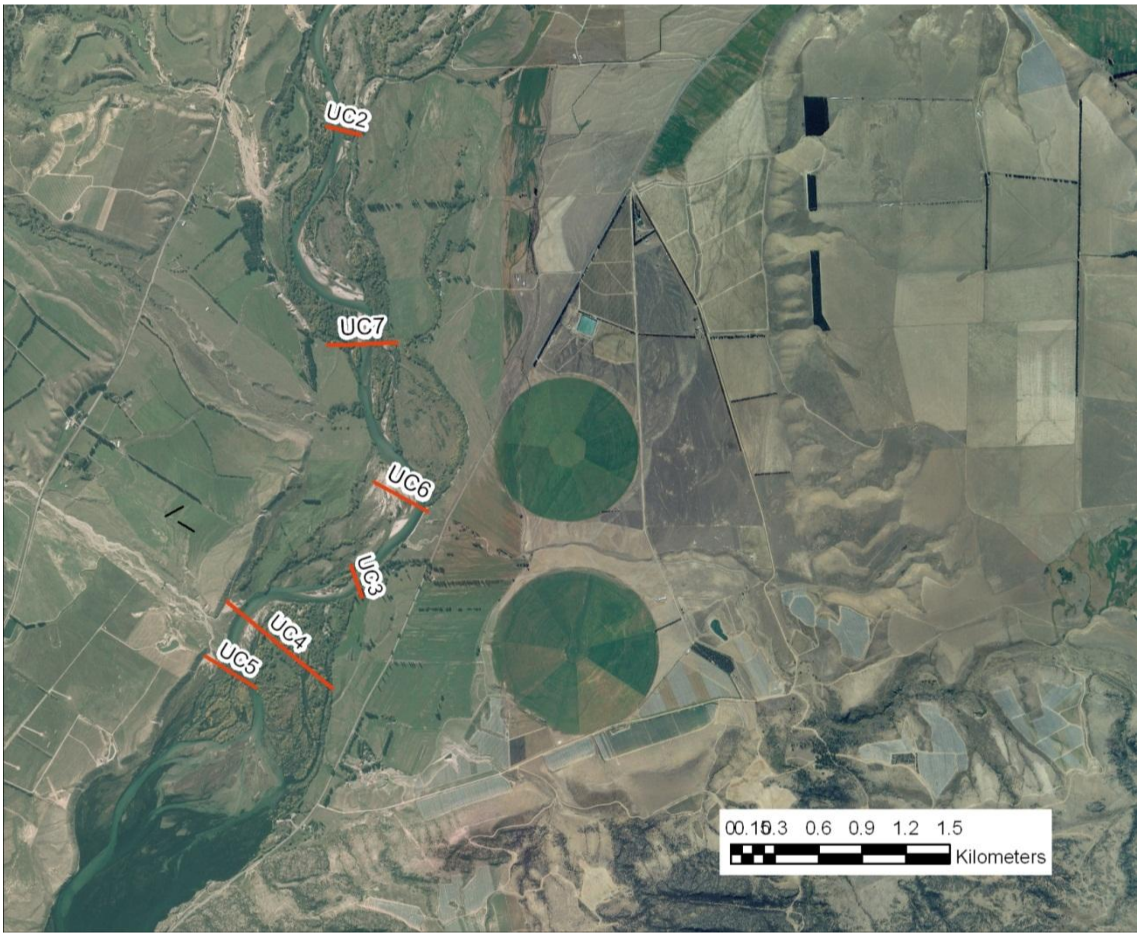


Figure C1. Location of cross-sections on the Clutha River/Mata-Au. Sediment accumulation was estimated for cross-sections 3, 4 and 5 (labelled UC3, UC4 and UC5 respectively).

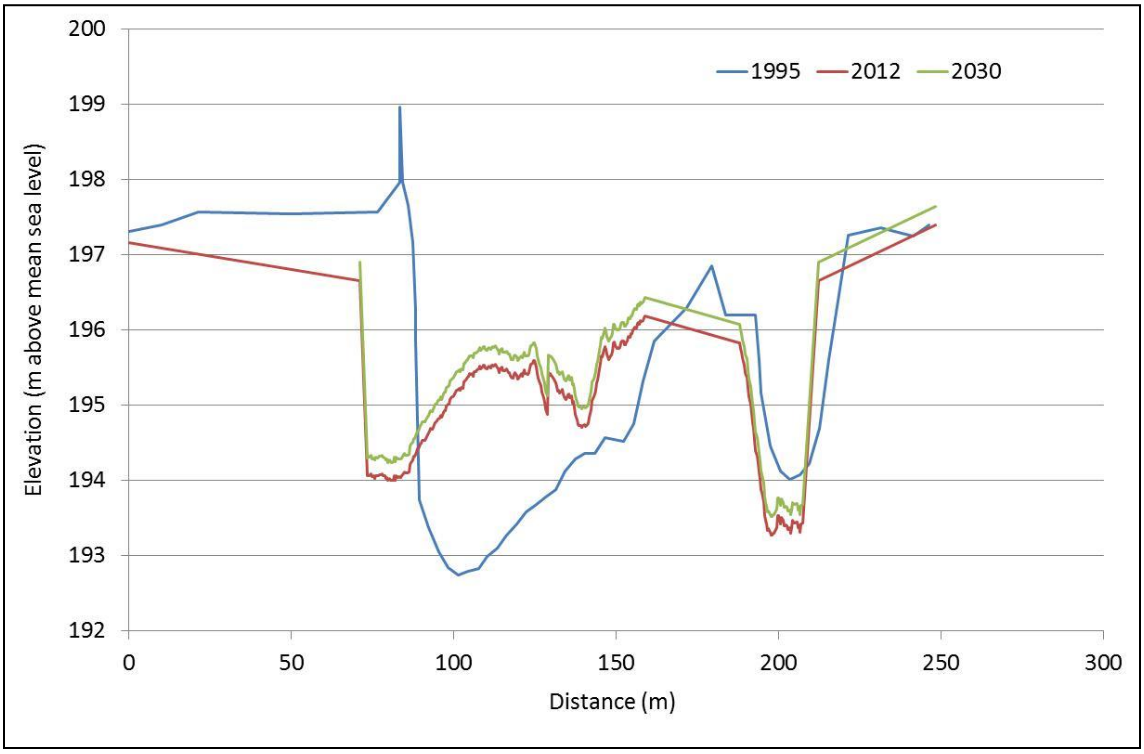


Figure C2. **Observed and predicted profiles for cross-section 3**

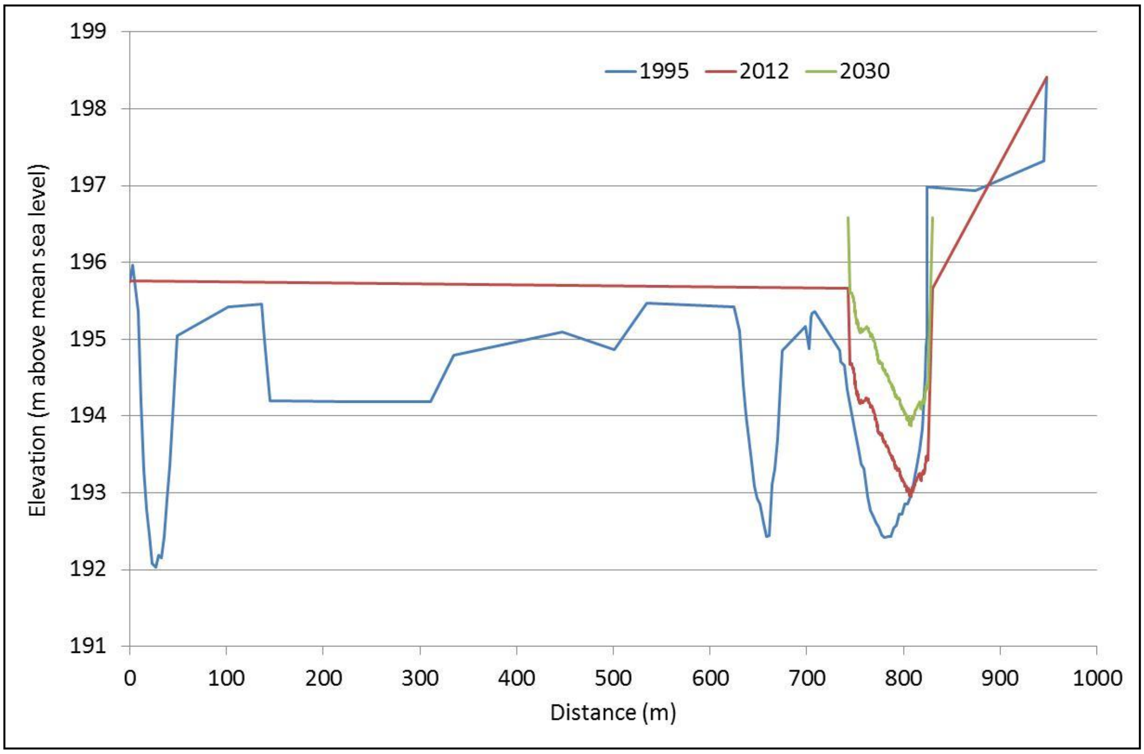


Figure C3. **Observed and predicted profiles for cross-section 4**

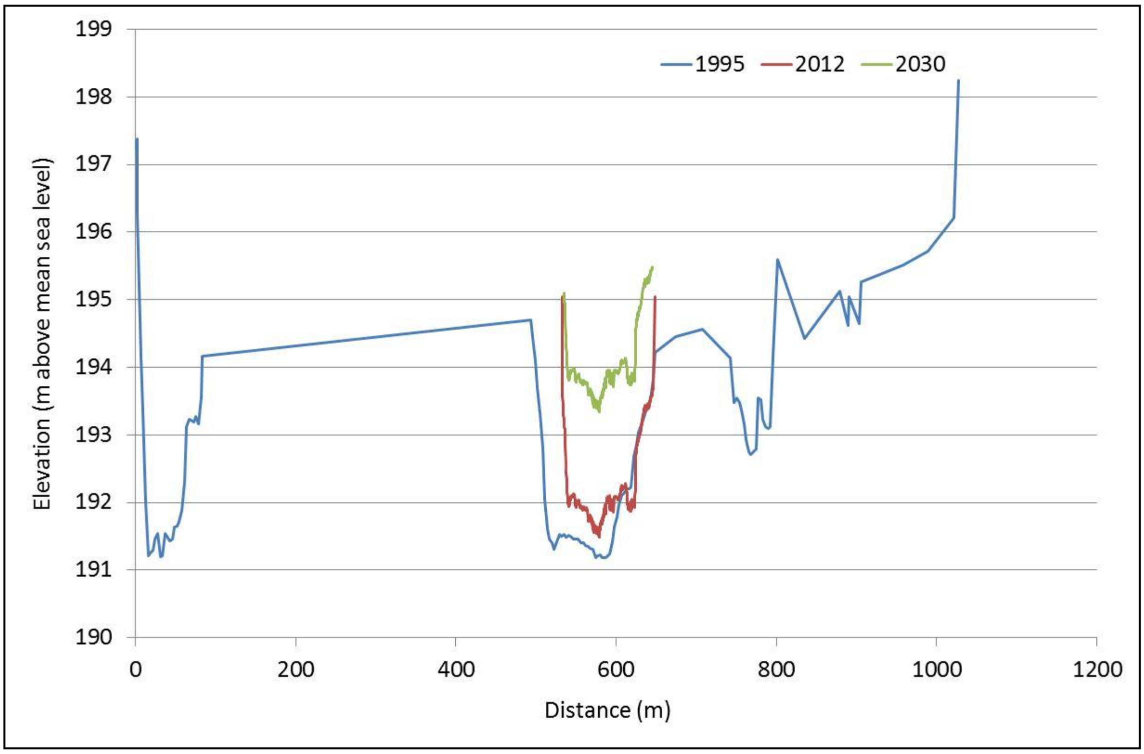


Figure C4. **Observed and predicted profiles for cross-section 5**

Appendix 4. Sensitivity check on flood extent

Table 4. **Sensitivity check on flood extent showing a change in distance from the original boundary as an increase (+) or decrease (-), distance measurements could not be completed for all cross-sections due to the LiDAR extent (the locations are shown in 12)**

Cross-section	Flood level for a flow of 1,685m^3/sec	Flow of 1,348m^3/sec (decrease of 20%)			Flow of 2,022m^3/sec (increase of 20%)		
		Flood level	Distance from original flood extent (m) (left bank)	Distance from original flood extent (m) (right bank)	Flood level	Distance from original flood extent (m) (left bank)	Distance from original flood extent (m) (right bank)
UC12	219.894	219.005	-10.7	-14.2	220.1	+1.3	+4.2
UC11	217.891	217.342	-3	-0.7	218.364	+1.7	+0.6
UC10	215.017	214.659	-3.7	-0.6	215.332	+1.8	+0.5
UC9	213.58	213.359	-3		213.779	+1.2	
77	211.781	211.601	-7.2	-0.8	211.946	+1.8	+1.5
UC8	208.416	208.197	-0.3	-3.2	208.585	+0.7	+2
76	204.579	204.433	-1.4	-0.5	204.717	+1.8	+0.3
UC7	201.538	201.285	-1.5	-33	201.748	+1.3	+2.4
UC6	199.428	199.231	-0.4	-12.9	199.614	+0.3	+4.8
75	198.492	198.285			198.691		
74	198.09	197.883			198.291		
73	197.647	197.513			197.785		