Flood and erosion hazard in the Arrow River at Arrowtown

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Cover image: Arrow River and Arrowtown, sometime between 1867 and 1875.
(Source: Burton Brothers (photographers))

Technical summary

The township of Arrowtown has previously been affected by flooding and riverbank erosion associated with the Arrow River, which passes the town to the north. This report assesses the current flood-hazard characteristics of the Arrow River, including the extent and depth of floodwater during a 1:100-year flood event and the potential for bank erosion. The floodplain of the Arrow River near Arrowtown has been mapped using a geomorphological approach to identify land that may be affected by inundation, and which consists of sediments that have been transported by fluvial processes. In addition, the likely flood-hazard characteristics across the floodplain during a large flood event have been determined through the development of a hydraulic model. The model was used to estimate the depth of water and the area likely to be affected by a flood with an estimated return period of 100 years. An extensive recreational area, including a skate park, walkways, historic sites, public parks and car parks, has been developed on the true-right side of the floodplain between the Arrow River and Arrowtown. This study shows that much of this area is vulnerable to inundation and erosion hazard during large flood events, with water depths of 1m or more possible.

Changes in the channel morphology of the Arrow River next to Arrowtown have also been assessed using visual inspections, aerial and ground photography, cross-section surveys and hydraulic modelling. Between July 2001 and December 2011, the bed of the river fluctuated between aggradational and degradational phases, with there being an overall trend of bed degradation during this period. The degradational trend through this reach is likely to have resulted from a decrease in sediment availability, due to the cessation of mining activity in the upper catchment at the end of the nineteenth century.

As the mean bed level (MBL) degrades, the flood and erosion hazard for the Arrowtown business district and the recreational areas along the river's edge will decrease as the capacity of the river channel to carry flood flows increases.

A continuous bund, about 250m long and 2m high, and consisting of loosely sorted gravel, has been formed through this reach since 2005. Resource consent (2004.A16) is held by the Otago Regional Council (ORC) to maintain this bank. The bund is intended to provide separation between the Arrow River and Bush Creek, as well as containing small- to medium-sized flood events on the true-left (northern) side of the channel. However, flood events do have the potential to overtop or breach this feature, and occupy the full width of the channel, including the true-right (southern) bank.

This report is intended to help inform good decision making in relation to future and existing development within and adjacent to the Arrow River floodplain.

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1. Introduction

The township of Arrowtown has previously been affected by flooding and riverbank erosion associated with the Arrow River, which passes the town to the north. This report assesses the current flood-hazard characteristics of the Arrow River, including the extent and depth of floodwater during a 1:100-year flood event and the potential for bank erosion. Changes in the morphology[1] of the Arrow River are also described, using cross-section survey data obtained in December 2011. A comparison is made not only with previous bed-level surveys dating back to 1987, but also with historical information. The implications of ongoing changes in river-bed morphology on flood and erosion hazard are considered.

The study area is shown in Figure 1, encompassing a section of the Arrow River that would naturally have a braided form and a relatively wide floodplain. The locations of the cross-sections used to help inform this report are also shown.

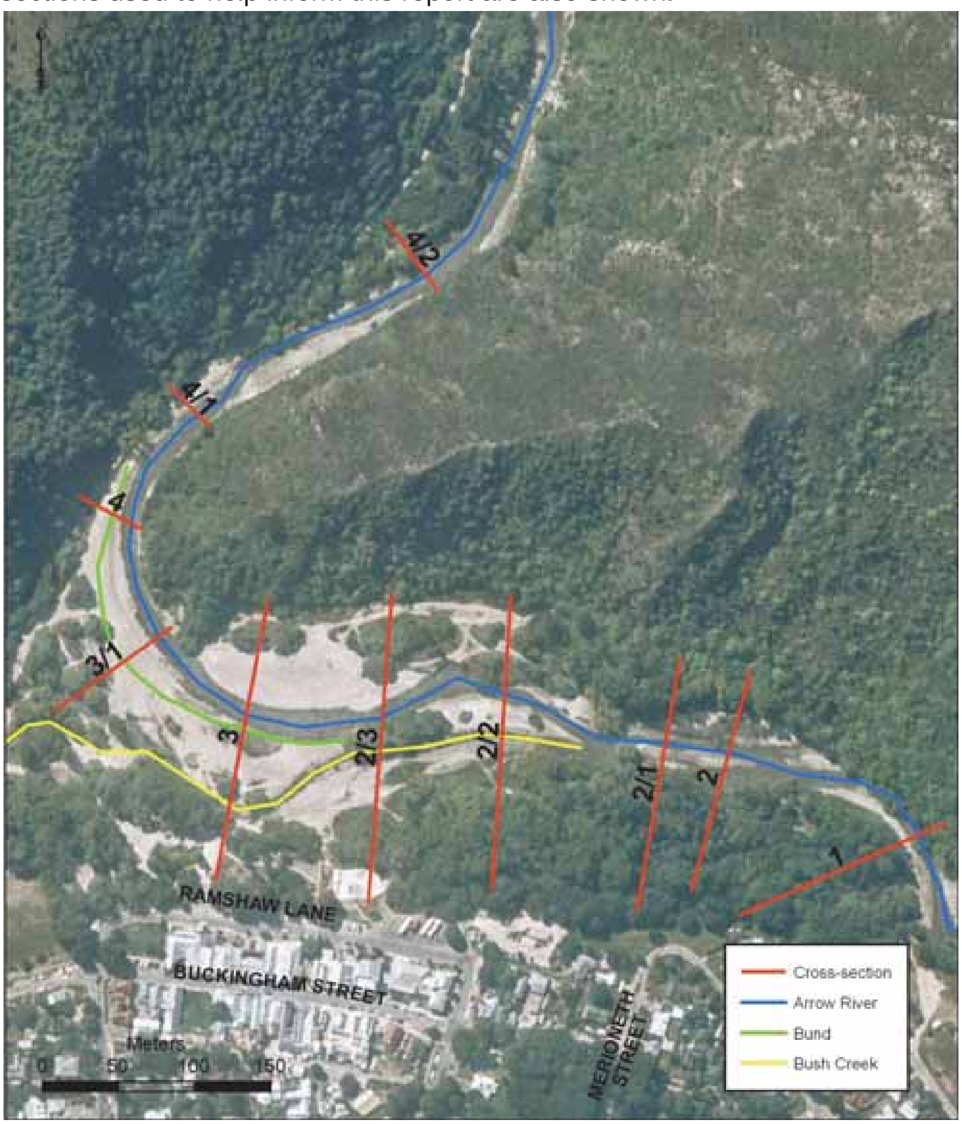

Figure 1. **Location of Arrow River cross-sections. These were established in 1987 and sections 4 to 2/2 were most recently surveyed in 2011 (Appendix 2).**

[1] The form or structure of topographical features within the river channel

1.1. Background

The Arrow River and its tributaries experienced a boom in gold-mining activity in 1861 and have been mined on various scales ever since. The most active gold-mining area was at Macetown, at the confluence of the Arrow River and the Rich Burn (Petchey, 2002) (Figure 3). Mining activity in the valley had an impact on sediment delivery, as sluicing of alluvial deposits is a main constituent of gold mining and can cause large amounts of sediment to enter the river system (Stevenson and Scarf, 1997; Black et al., 2004).

A large flood in July 1863 caused the loss of 20 lives when flood water from the Arrow River flowed through a mining encampment (Miller, 1973). This resulted in the Arrow River rising 4.9m above its ordinary banks and destroying several buildings in Arrowtown, including the Shamrock Hotel (Miller, 1973). The whole catchment was again affected by a large flood in 1878, which caused damage to the mining activities in the valley and destroyed several roads and bridges (Stratford, 1879), as well as causing metres of erosion to several properties next to the river (Griffiths, 1978). As a result of this flood, the town was reconstructed at its current, higher level and is considered safe from most floods (Johnstone, 1999) as it currently sits between 7m and 15m above the Arrow River.

The population of Arrowtown grew during the Gold Rush era of the mid-late 1800s when mining activities in the Arrow River valley led to a rapid influx of people. The population of Arrowtown has continued to grow in recent decades (Figure 4), and Statistics NZ predicts further population growth to occur. Arrowtown is also a popular tourist destination, and an extensive recreational area, including a skate park, walkways, historic sites, public parks, and car parks (Figure 2), has been developed on the floodplain between the Arrow River and Arrowtown.

Figure 2. **Assets and structures vulnarable to flood hazard. Top left: public toilet; top right: historic hut; bottom left: skatepark, Bottom right: public parking area (May 2012)**

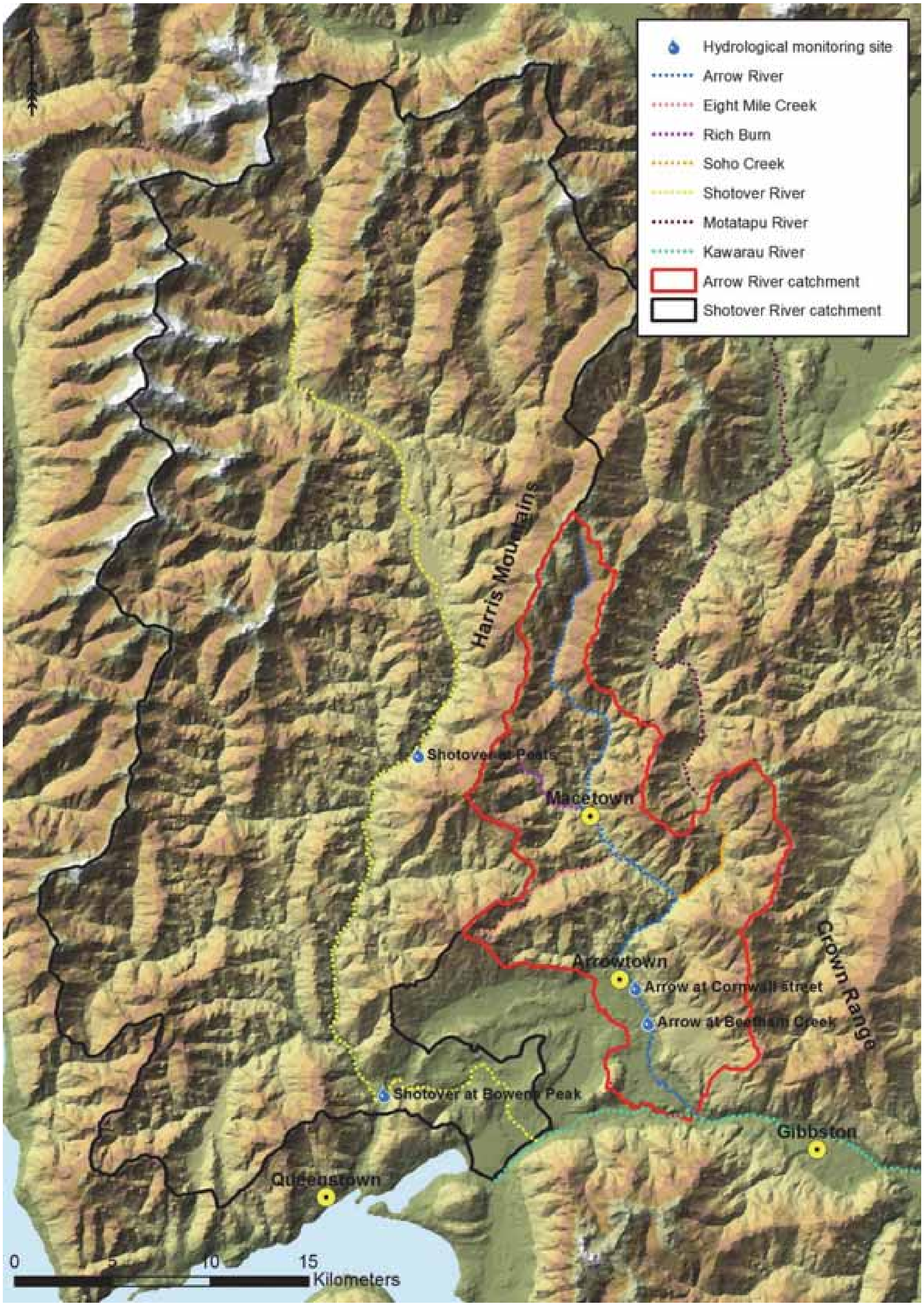

Figure 3. Arrow and Shotover River catchments

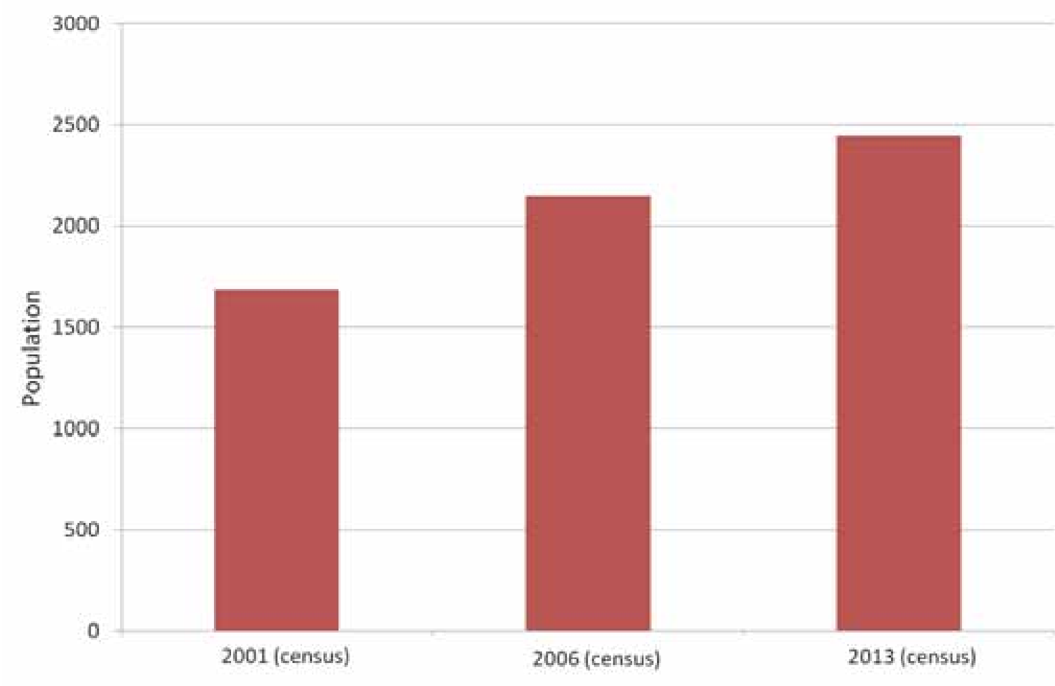

Figure 4. Population of Arrowtown from census data for 2001, 2006 and 2013

2. Environmental setting

The Arrow River catchment is about 42km long and 23km wide at its widest point, with a total catchment area of 237 km^2 (Figure 3). The Harris Mountains separate the western edge of the catchment from the Shotover River, while an unnamed mountain range forms the eastern edge, separating the Arrow from the south branch of the Motatapu River. The upper Arrow catchment (above Arrowtown) generally consists of rugged terrain, bordered by low mountain ranges. There are a number of tributaries, the most notable being Soho Creek, Eight Mile Creek and the Rich Burn (Figure 3).

The bed of the river displays a change in gradient to a shallower profile about 3km upstream of Arrowtown (Figure 5). The reduced gradient leads to a decrease in flow velocity, particularly where the river exits the gorge and turns sharply to the left. The reduced gradient, lower velocity and sharp bend in the river result in the section of the river next to Arrowtown being a natural sediment deposition zone (Figure 6).

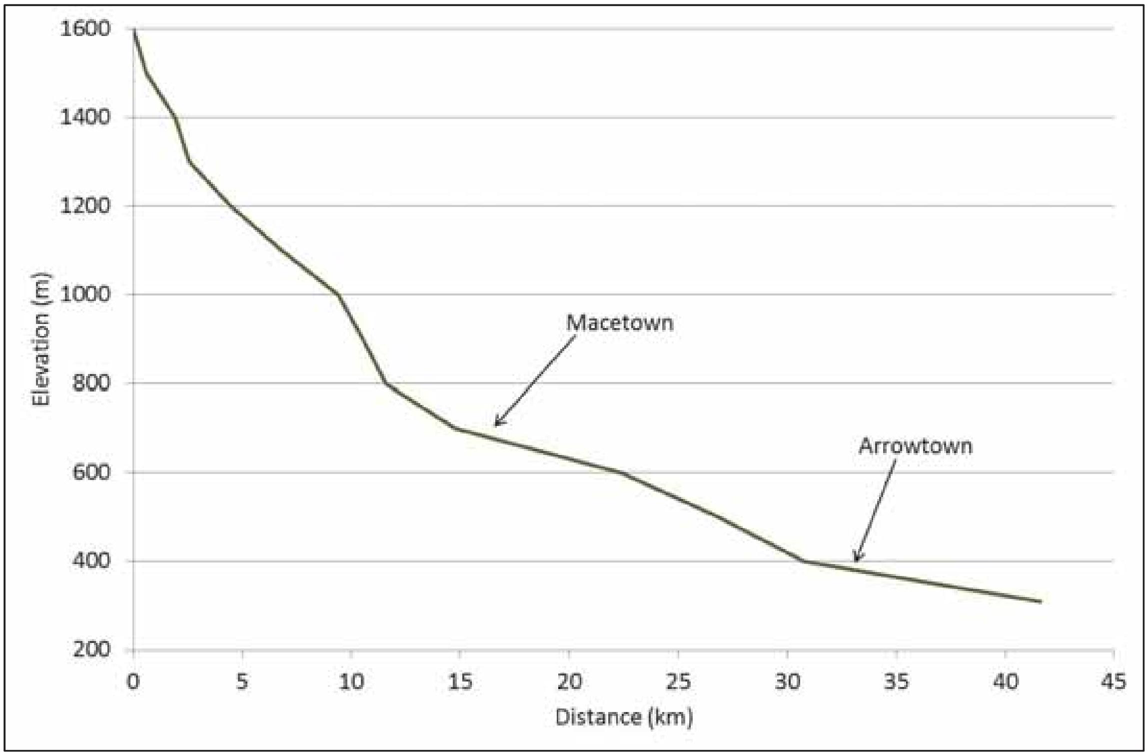

Figure 5. Longitudinal profile of the Arrow River (estimated from LINZ 1:50,000 topographical maps, F40, F41)

The morphology of the catchment also changes considerably where the Arrow River exits the steep hill country upstream and flows onto the more rolling hill country and terraces of the Wakatipu Basin. The reason for the river taking a hard turn to the left at this point is the presence of a raised terrace of outwash gravel (Barrell *et al*., 1994). The Arrowtown business district and residential areas are located on this terrace. Downstream of Arrowtown, the river flows southeast along the base of the Crown Range before it reaches its confluence with the Kawarau River, 8km downstream of Arrowtown (Figure 3).

Photos taken in the late 1800s/early 1900s show the river's natural tendency to occupy the true-right side of the floodplain where it exits the gorge, and to exhibit a relatively wide and braided form. Figure 6 shows Arrowtown sometime between 1867 and 1875,[2] while Figure 7 shows this same area sometime in the early 1900s.

The two older photographs highlight the large amount of freshly deposited sediment located at this site, compared to the current setting. This sediment may be associated with the mining activities occurring on the Arrow River and its tributaries at this time. Active erosion of the raised terrace upon which Arrowtown lies is visible in the oldest photo (Figure 6). Other changes are also evident in the two photos, including changes in vegetation cover and the steepness of the terrace riser (bank between the raised terrace and the river bed).

Figure 6. **Arrow River and Arrowtown, sometime between 1867 and 1875. A multi-storeyed building shown in the centre of this image is also visible in Figure 7. (Source: Burton Brothers (photographers))**

[2] This date range was determined by analysing information held by the Historic Places Trust and Queenstown Lakes District Council in regard to the construction date of historic and scheduled heritage buildings.

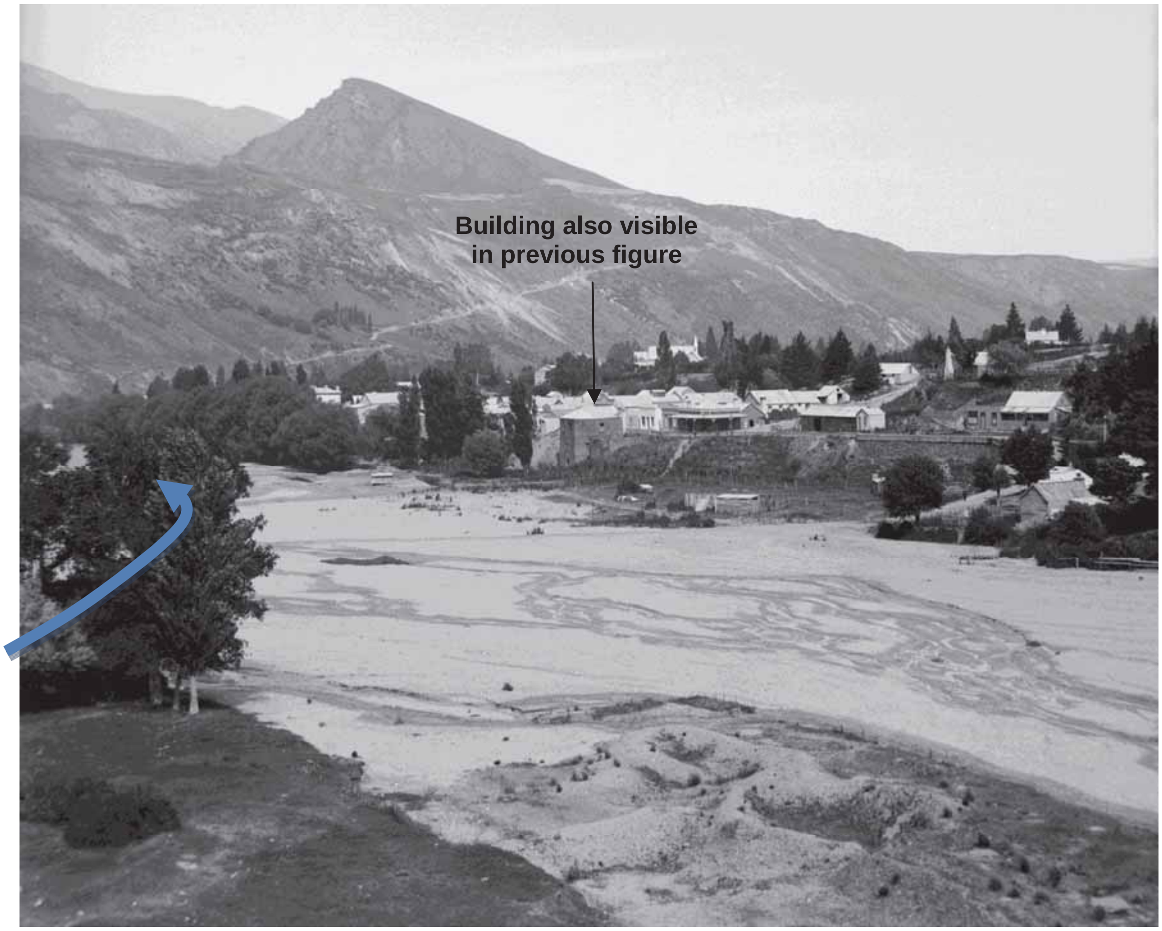

Figure 7. **View looking downstream of the Bush Creek/Arrow River confluence (the blue line indicates flow of Arrow River). A multi-storeyed building shown in the centre of this image is also visible in Figure 6. (Source: Williams (approximately 1900s))**

As it exits the gorge, the river is currently confined to the true left of the floodplain by a raised bund of loosely sorted river gravel (Figure 9, Figure 12). The ORC obtained resource consent (2004.A16) in 2005 to construct and maintain this bund, due to concerns raised by the local community. The consent for the bund expires in May 2015. The bund is intended to contain small- to medium-sized floods on the true-left (northern) side of the floodplain and prevent ongoing erosion or the deposition of fresh sediment at the base of the true-right terrace during such events. Before the construction of the bund, moderate-sized flood events could push the main channel towards the true-right side of the floodplain. An example is shown in Figure 8, where the main low-flow channel at cross-section 3 migrated 50m towards the right bank and filled in the previous channel between March 1995 and December 1996. This change is likely associated with the flood of December 1995 and helps to illustrate the dynamic nature of this part of the Arrow River floodplain.

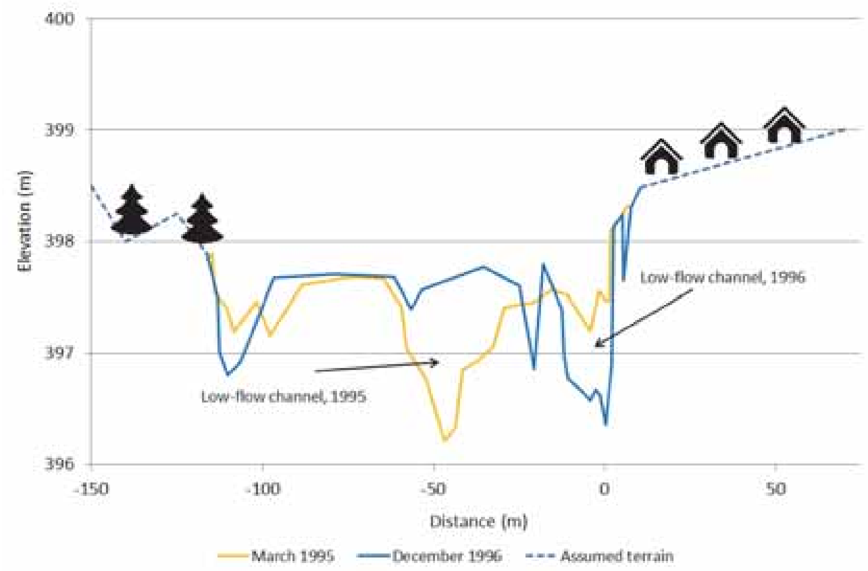

Figure 8. **Cross-section 3 showing migration of the main channel towards the true right between March 1995 and December 1996**

Flood flows may have the ability to overtop or breach this feature, and occupy the full width of the channel, including the true-right bank (as described in section 4.1). It is not an engineered floodbank, rather it is designed to maintain a low-flow channel on the true left and delay the onset of significant erosion/inundation on the true-right bank during larger flood events.

Maintenance of the bund is undertaken regularly (typically, annually), and involves the movement of sediment that has accumulated in the channel up onto the bund, particularly where erosion of the bund has occurred. The location and height of the bund on the floodplain has changed since it was initially established (Appendix 1).

The Arrow River continues to form a relatively wide (compared to the rest of the catchment) shingle bed as it exits the gorge upstream of Arrowtown. This shingle bed continues downstream for another 300m (Figure 9) before once again becoming more confined in the vicinity of Nairn Street (Figure 12). The true-right side of the floodplain is now well vegetated in parts and has a more stable appearance because of the smaller number of flood events that affect this area (due to the existence of the bund) and the work that has been undertaken to improve the recreational and visual amenity of this area (Figure 10).

Figure 9. **View downstream showing raised bund (right) and main channel (May 2012)**

Figure 10. View of the true-right side of the Arrow River floodplain, in the vicinity of the skate park (May 2012)

3. Hydrology

Median-annual rainfall is relatively high (up to 2,000mm/year) in the upper areas of the Arrow catchment compared with the lower reaches near Arrowtown (growOTAGO). The steep nature of the catchment and high-rainfall intensities in the upper reaches can lead to a rapid rise in river discharge and create a potential flood hazard downstream. At the hydrological site, 'Shotover at Peats', located 3km west of the Arrow River catchment (Figure 3), rainfall intensities of 50mm/day typically occur on an annual basis. The maximum observed rainfall over a 24-hour period at that site (since records began in December 1996) was 130mm in September 2002.

There have been two flow-monitoring sites on the Arrow River. The Beetham Creek site operated between 1981 and 1993, and the Cornwall Street site has been in operation since January 2011. Figure 3 shows the location of these sites, as well as the hydrological monitoring sites in the adjacent (and much larger) Shotover catchment. A comparison of the recent flow record from the Arrow River and the Shotover River at Bowens Peak (which has a continuous flow record dating back to 1967) shows that there is a relatively close relationship in the timing of high-flow events between these two catchments (Figure 11).

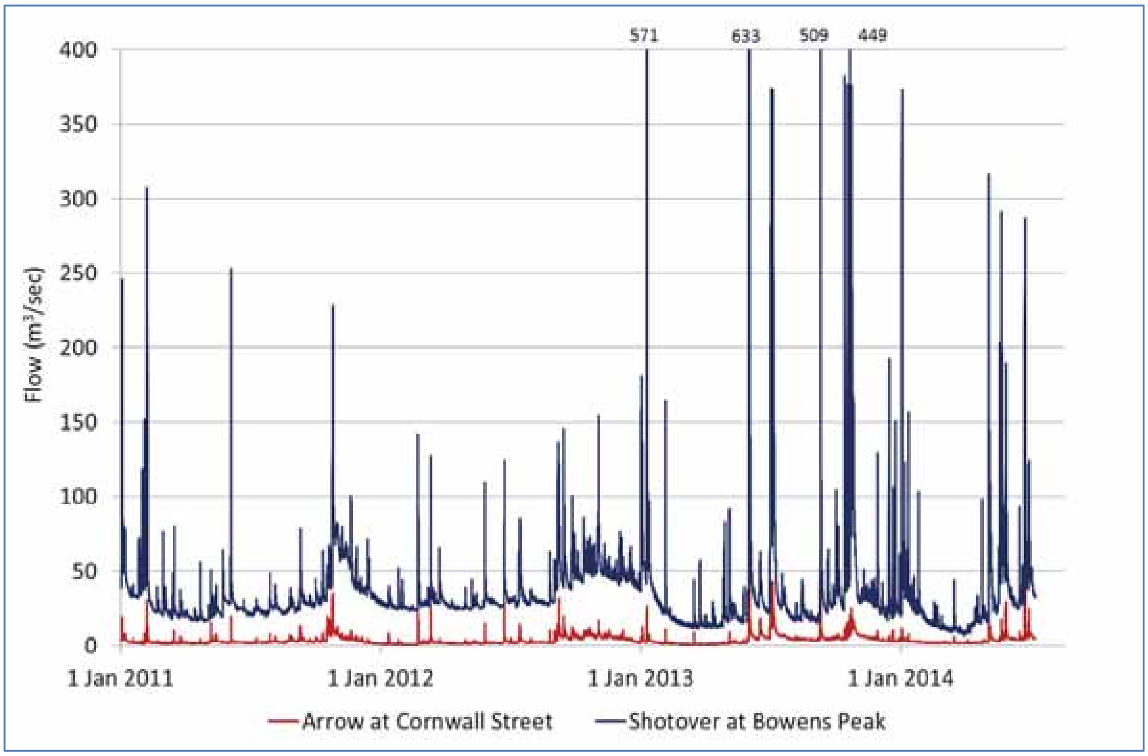

Figure 11. Comparison of flow in the Shotover River at Bowens Peak and the Arrow River at Cornwall Street. Flow peaks in the Shotover River > 400m^3/sec are labelled.

Over the past two decades, the Shotover and Arrow rivers have experienced significant flood events in 1994, 1995, 1999 and 2010, although no direct flow measurements of these flood events are available for the Arrow River. However, the effect of these events on river morphology can be observed to some extent by examining changes in the cross-sections through this period (see Figure 8, Section 4.2 and Appendix 1).

There is a lack of warning for flood events in the Arrow River, due to there being no hydrological monitoring sites in the upper catchment. The short and steep nature of the catchment allows flood water to quickly reach Arrowtown, rates of rise of about $30m^3/s$ in 30 minutes have been recorded.

4. Flood and erosion hazard

The Arrow River is, by nature, a dynamic system where flood events and the supply of sediment are the main factors that can influence the shape and form of the river bed and floodplain. Changes in morphology are occurring due to the effects of aggradation and degradation in the main channel, as well as the effects of artificial structures such as the bund described in Section 2.

This first part of this section describes the extent of the floodplain in this reach (sections 4.1 and 4.2) and the characteristics of flood and erosion hazards associated with the Arrow River at Arrowtown (sections 4.3 and 4.4). Secondly, the changes in the form of the bed that have occurred since monitoring commenced in 1987 are described, along with the implications of these changes for flood and erosion hazard (section 4.5).

4.1. Floodplain mapping

The floodplain of the Arrow River adjacent to Arrowtown extends from the mouth of the gorge to Nairn Street, while the Bush Creek floodplain extends upstream to Bush Creek Road (Figure 12). Bush Creek may also experience high flows during a flood event in the Arrow River. Depending on the relative height of each river during the event, flows from Bush Creek may back up for some distance upstream of the confluence and contribute to the overall flood hazard in the study area.

The floodplain area shown in Figure 12 was identified using a geomorphological approach to identify land that may be affected by inundation and consists of sediments that have been transported by fluvial processes.[3] Land that lies well above potential inundation areas has been excluded. The mapped area was verified with a field inspection in September 2014.

[3] Terrace risers and landforms that are composed primarily of unconsolidated alluvial material

Figure 12. **Arrow River/Bush Creek floodplain area, and the extent of the modelled 1:100-year flood level at each cross-section location**

4.2. Flood model: development

The likely flood-hazard characteristics across the floodplain during a large flood event were determined through the development of a simple computational hydraulic model.[4] The model was used to estimate the depth of water, and the area likely to be affected by a flood with an estimated return period of 100 years (the 'modelled flood event').[5] It is estimated that such a flood would result in a peak flow of 132m^3/s in the Arrow River at the lower end of the gorge and a peak flow of 148m^3/s downstream of the confluence with Bush Creek. Surveyed cross-sections (as surveyed in 2011), and 1m contour lines (generated from aerial photography), were used to determine the maximum extent of such an event. Figure 12 shows that the modelled flood event would extend across much of, but not the entire, floodplain area.[6]

Large quantities of sediment are deposited across the floodplain during flood events, due to the higher energy available. The amount of sediment moved and where it is deposited can vary considerably due to the complex process of sediment entrainment and deposition. To account for possible sedimentation during a flood event, the model was run with an increased bed level of 1m for the channels of both Bush Creek and the Arrow River. Similar increases in the level of the bed were observed following the November 1999 flood event; although additional material deposited during this event has since been re-worked downstream, and MBLs have continued to degrade during the following 12 years.

As noted, a bund is located within the floodplain that constrains flows on the true-left side during low-moderate flows. The bund is potentially prone to failure before overtopping occurs, as it is constructed of locally sourced material (gravel), is not compacted to any specification and lacks any vegetated surface cover. Due to the unconsolidated nature of the bund and uncertainty around its ability to constrain high-flow events (due to a breach or overtopping), it was not included in the modelled results (i.e. the bund was removed from the surveyed cross-sections when the model was run).

4.3. Flood hazard: characteristics

While the Arrowtown urban area is predominantly raised up above the Arrow River floodplain, there are still structures that can be inundated and damaged by flood water (Figure 2), including the local skate park, walkways, car-parks and the pipeline for the arrow irrigation scheme. Flood-protection work has been undertaken in the past on this section of the Arrow River, including reshaping of the channel to avoid erosion of the river banks and the management of willow trees along the bank (Strong, 2005). This work helps protect the car park and the recreational areas on the true right of the floodplain (Strong, 2005).

The water levels associated with the modelled flood event described above[7] are shown for each cross-section in Figure 13 to Figure 17 below. Once floodwater occupies the wider flood channel, it can move unpredictably across the flatter terrain, although the depth of water will be deeper in the main channels of the Arrow River and Bush Creek, and any older

[4] The model is described further in Appendix 2.
[5] Such a flood is not the biggest possible, having 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.
[6] The extent of the modelled flood event on the true right at cross-section 3/1 is not shown, due to uncertainties around the interaction of Arrow River/Bush Creek flood flows at this point.
[7] i.e. 1:100-year flood event, 1m of aggradation across the channel and removal of the bund from cross-sections

stream channels/depressions. As shown in the figures below, the depth of water across the floodplain during the modelled flood event ranges from shallow (e.g. 0.2m in the vicinity of the skate park at cross-section 2/3) to more than 1m deep (e.g. in the vicinity of the Bush Creek low-flow channel at cross-sections 3/1 and 3). Figure 18 shows that if floodwaters have minimal velocity, wading (for an adult) becomes unsafe at a depth of about 0.8m, and vehicles can become unstable at 0.3m. As velocity increases, the effects of flooding start to become significant for vehicles, people and structures at an even shallower depth.[8]

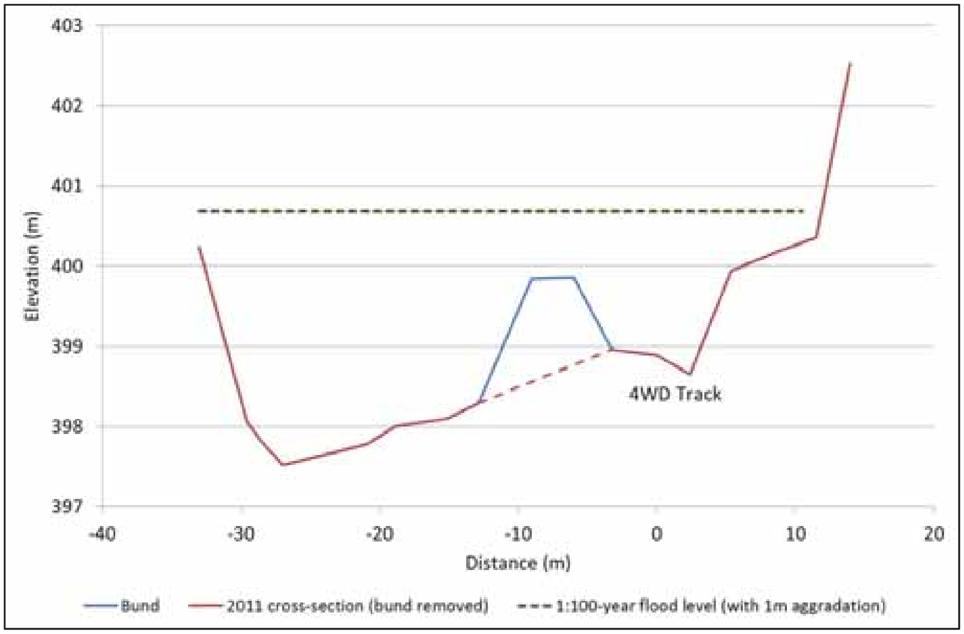

Figure 13. **Top: cross-section 4, looking downstream, showing the modelled 1:100-year flood level. Bottom: view upstream from cross-section 4, showing the bund and 4WD track (November 2011).**

[8] Average velocities at the cross-sections were modelled as being between 1-3m/sec

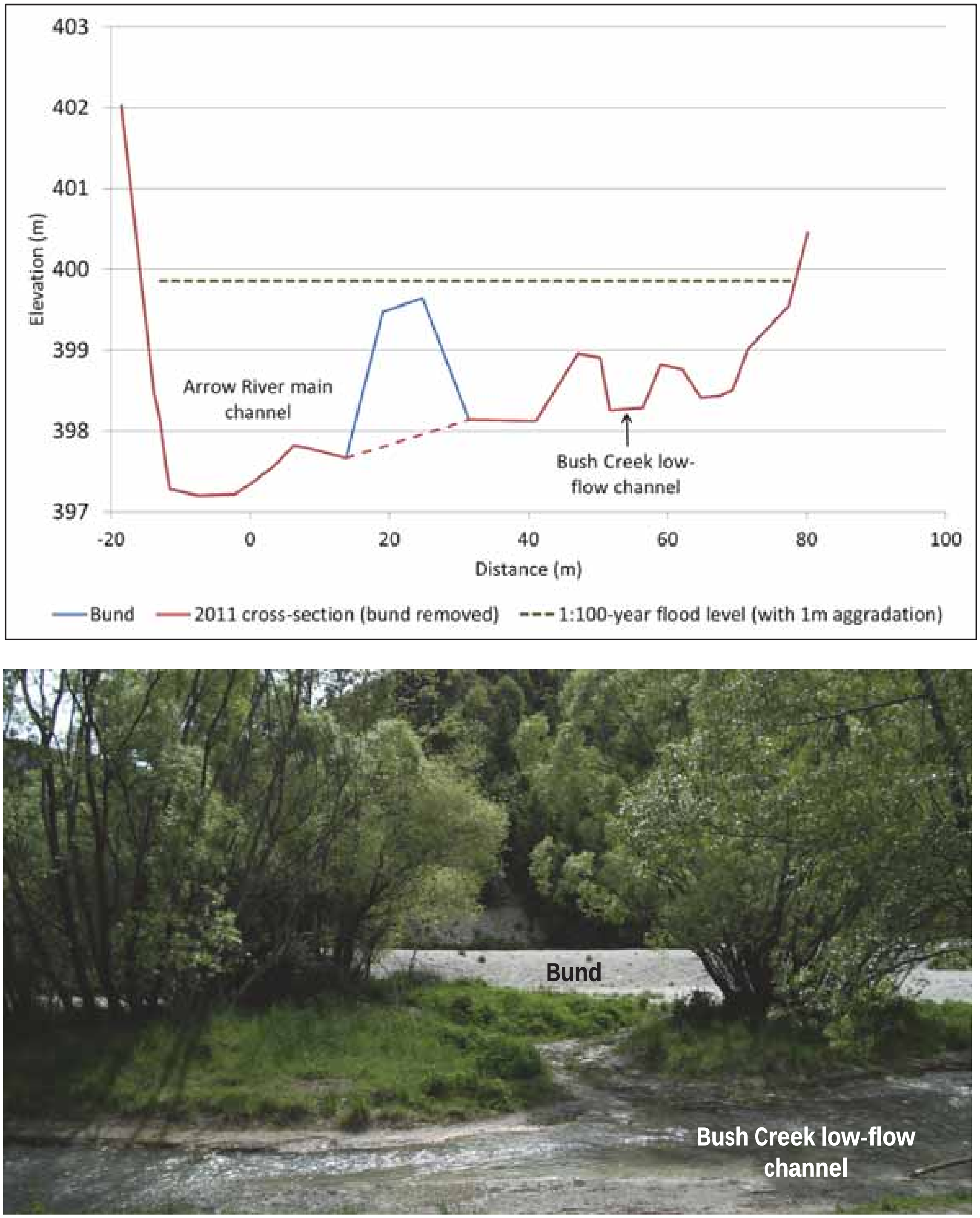

Figure 14. **Top: cross-section 3/1, looking downstream, showing the modelled 1:100-year flood level. Bottom: view from true right to true left at cross-section 3/1, showing the Bush Creek low-flow channel in the foreground (November 2011)**

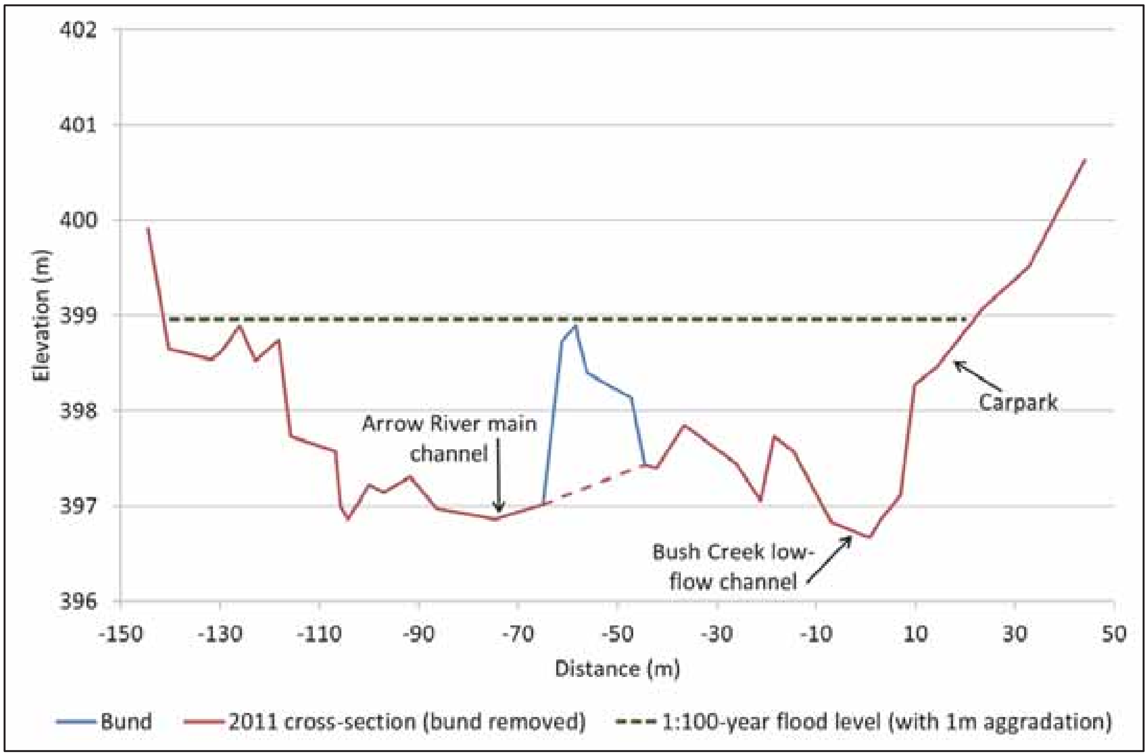

Figure 15. **Top: cross-section 3, looking downstream, showing the modelled 1:100-year flood level. Bottom: view from true right to true left at cross-section 3, showing the Bush Creek low-flow channel and the carpark (November 2011)**

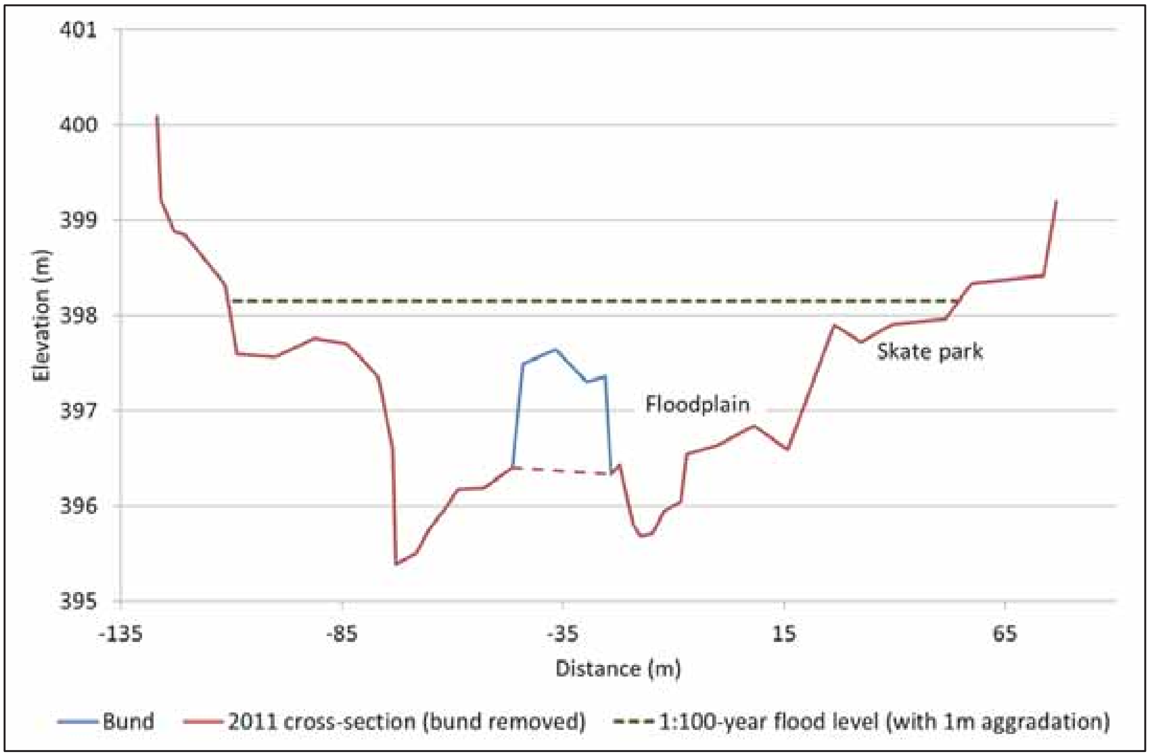

Figure 16. **Top: cross-section 2/3, looking downstream, showing the modelled 1:100-year flood level. Bottom: view from true right across the skate park, towards the true left at cross-section 2/3 (November 2011)**

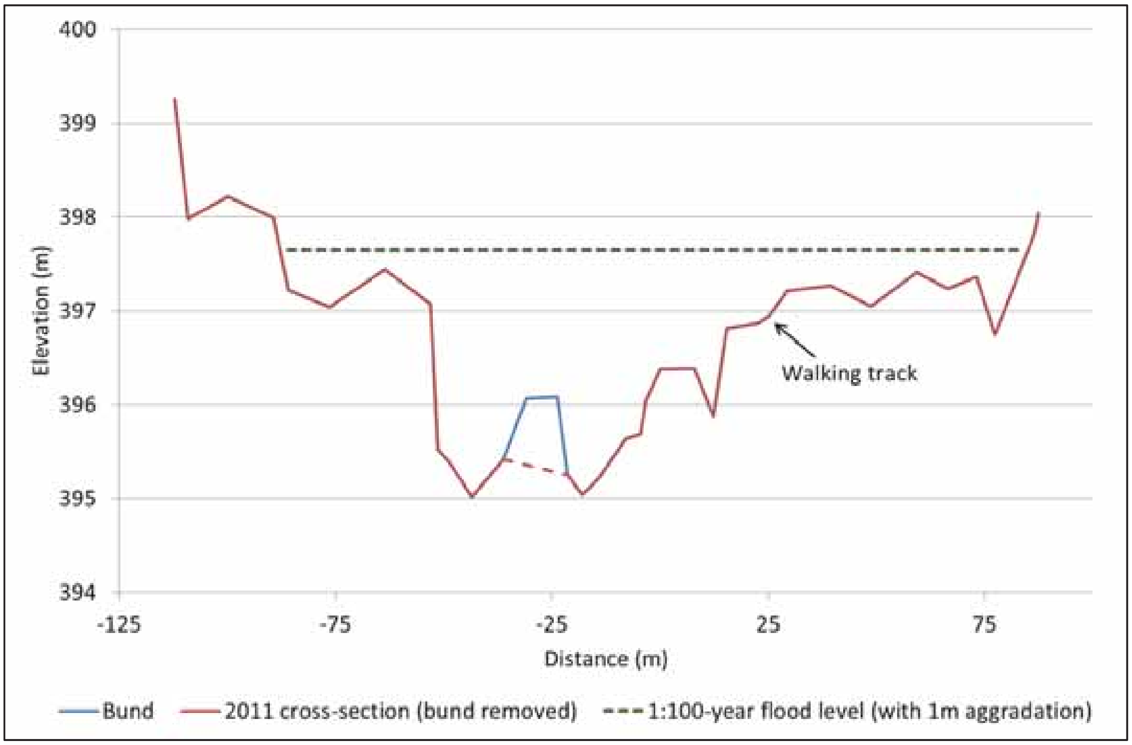

Figure 17. **Top: cross-section 2/2, looking downstream, showing the modelled 1:100-year flood level. Bottom: view upstream from cross-section 2/2, showing the walking track (November 2011)**

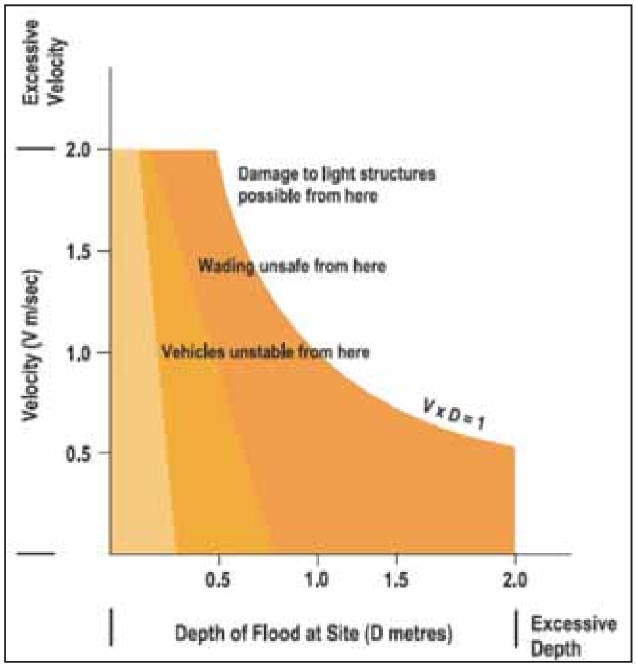

Figure 18. Example of flood-hazard classification, based on the product of the velocity and depth (NSW Government, 2005)

4.4. Erosion hazard

In the past, the Arrow River has occupied the true-right side of the floodplain, and actively eroded the terrace riser (Figure 6, Figure 7), suggesting that the natural tendency of the river is to flow in this location. Bush Creek may also contribute to erosion of the terrace during a flood event due to its close proximity to the terrace riser.

As described in Section 1.1, the business district and residential areas of Arrowtown are now located on a raised terrace, 7 to 15m above the floodplain, and are therefore unlikely to be inundated during a flood event. Parts of the town closest to the river may still be vulnerable to erosion hazard during extreme flood events. However, water depths along the margins of the raised terrace upon which Arrowtown sits are generally quite shallow during the modelled 1:100-year flood event (Figure 15 to Figure 17). Recreational and carpark areas on the true-right side of the floodplain are more vulnerable to erosion, as they lie closer to the deeper and faster flowing main channel of the Arrow River and Bush Creek.

Several factors and processes have changed in the Arrow River that have led to a change from the historical erosion hazard environment. The presence of a raised bund prevents ongoing erosion of the terrace riser by confining the Arrow River to the true-left side of the floodplain for low-moderate flows. This has allowed vegetation to become established along the true-right side of the floodplain, and the terrace riser now has a more gradual slope than shown in earlier photos of the study area (Figure 6, Figure 7). There has also been a reduction in the supply of sediment to this reach since the 19th century, and the effects of this are described in Section 4.2.

4.5. Bed-level change

Changes in the MBL of the Arrow River floodplain can influence the flood and erosion hazard at Arrowtown.[9] The surveys undertaken at the cross-sections shown in Figure 1 show a general degradational trend (i.e. an overall lowering of MBL) since they were first surveyed in 1987. Over time, this may lead to a reduction in flood and erosion hazard, as the Arrow River channel is cutting deeper into its bed, increasing channel area and therefore the amount of water that can be transported during a flood event. The river can still experience aggradation across the channel and wider floodplain during major flood events, although this additional sediment is generally re-worked downstream in subsequent years.

Figure 19 shows recent changes in MBL at the five cross-sections surveyed in 2011. Between 2001 and 2011, there was a net decrease in MBL at all five cross-sections. During the most recent survey period (2006 to 2011), MBL also decreased at all sections, except at 3/1, which experienced minor aggradation of 0.08m. The largest decrease in MBL between 2001 and 2011 was at cross-section 3, due to a significant decrease in the level of the main channel of the Arrow River (Figure 30).

A more detailed explanation of changes in the shape of channel and floodplain since 1987 and during more recent surveys is provided in Appendix 1.

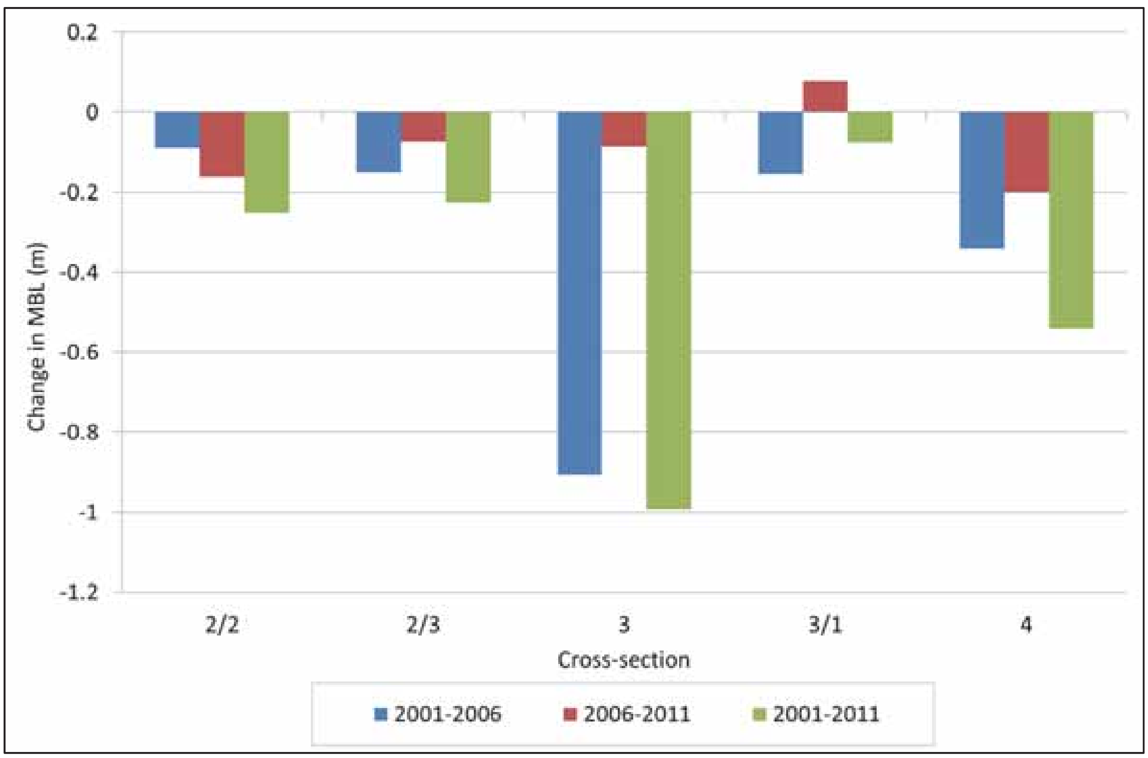

Figure 19. Change in MBL between Jan. 2001 and Nov. 2006 and Nov. 2006 and Nov. 2011. The net change in MBL over the entire period is also shown.

[9] The method used to determine MBL is outlined in Appendix 2.

5. Summary

This report describes observed changes in channel morphology and the implications of those changes for flood and erosion hazard in the Arrow River adjacent to Arrowtown. It is intended to help inform decision making in relation to future and existing development within this area. 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.

Most of the Arrowtown urban area is located above the Arrow River on a raised terrace, 7m to 15m higher than the adjacent floodplain. Recreational areas on the true-right floodplain are exposed to flood hazard, however modelling undertaken for this study shows that floodwater depths of 1m or more are possible during a large (1:100-year) flood event.

The terrace riser that separates the town from the recreational areas appears to have a low risk of further erosion, due to a number of factors, including:

- the presence of an artificial unconsolidated gravel bund that limits ongoing erosion of the terrace riser by confining the Arrow River to the true-left side of the floodplain during low-moderate flows
- the establishment of vegetation along the true-right side of the floodplain
- the terrace riser now having a more gradual slope.
- the reduction in the supply of sediment to this reach and the associated decline in MBL.

Recreational areas at the base of the terrace riser are more likely to be exposed to erosion as they lie closer to the deeper and faster flowing main channel of the Arrow River. It is noted that Bush Creek may also contribute to erosion and flooding of the terrace during a large flood event.

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Appendix 1. Arrow River cross-sections: summaries

Arrow River cross-section: 4

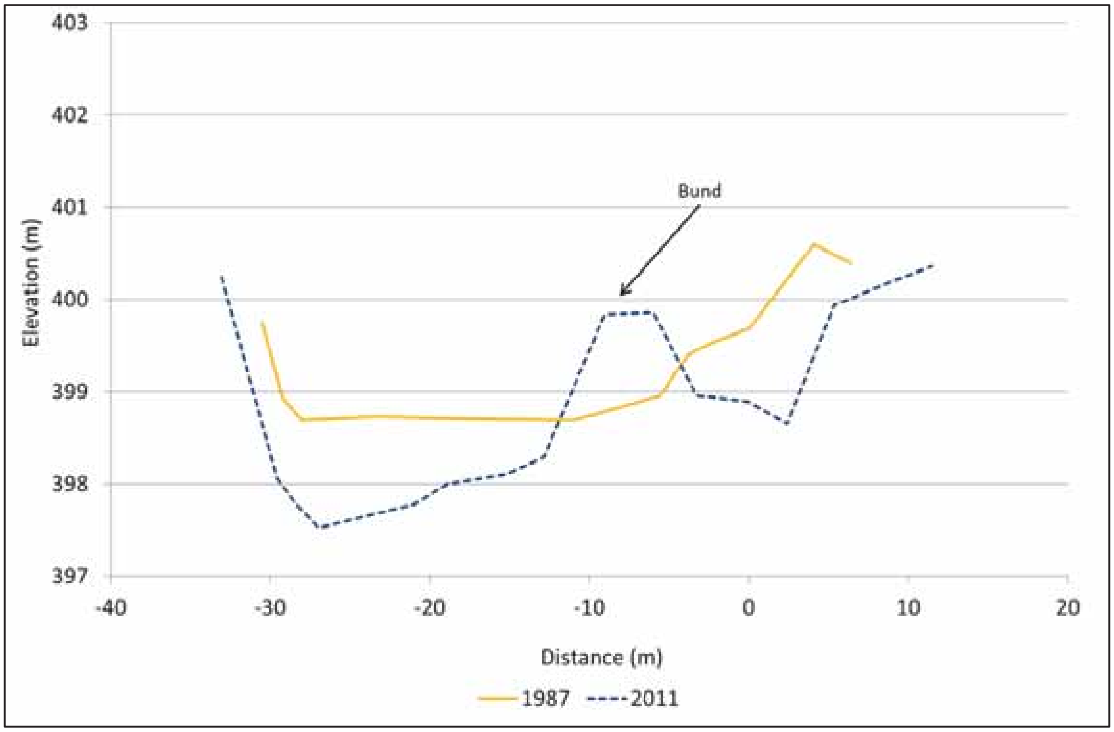

Figure 20. **Cross-section 4, looking downstream, showing first (1987) and last (2011) survey data**

Figure 21. **Bedrock banks on the true-left bank, cross-section 4, May 2012**

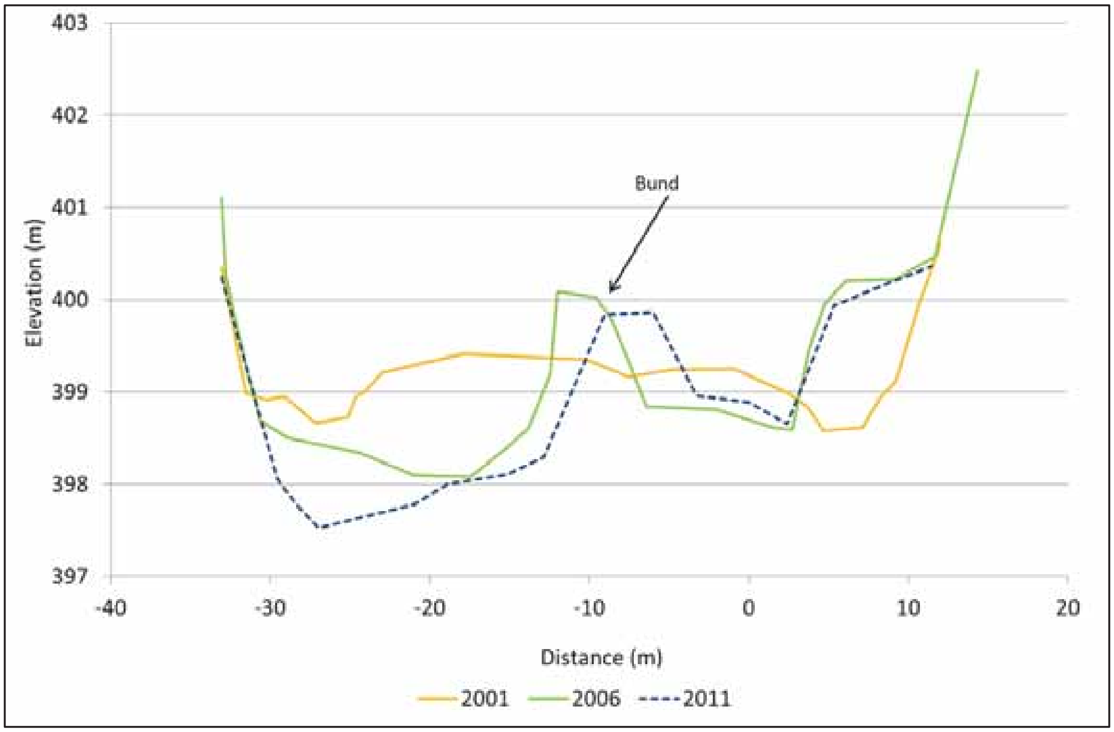

Figure 22. **Cross-section 4, looking downstream, showing data from the three most recent surveys**

Figure 23. **Looking downstream from cross-section 4, November 2011**

MBL at cross-section 4 lowered by about 0.2m between 2006 and 2011, continuing the trend that has been observed since 1987. The bund moved to the right by about 2.6m and has lowered to about 0.25m over the same period. There has been minimal bank erosion at this location due to the river being confined between steep bedrock banks as its exits the gorge onto the wider floodplain.

Arrow River cross-section: 3/1

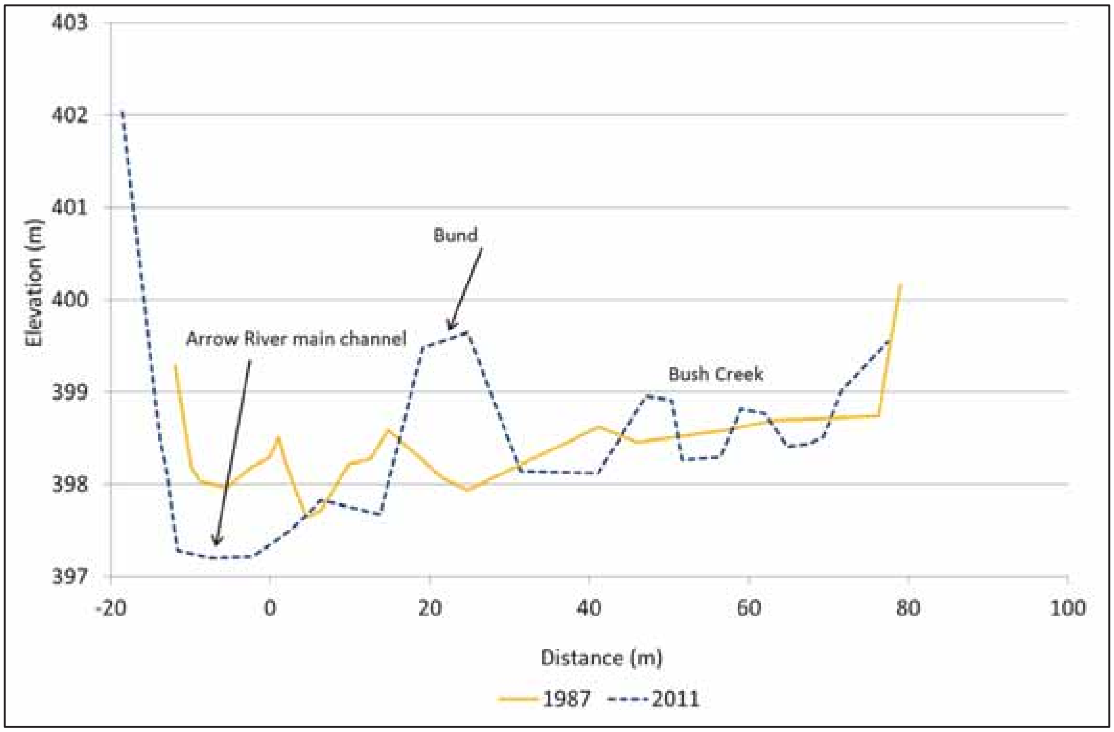

Figure 24. **Cross-section 3/1, looking downstream, showing first (1987) and last (2011) survey data**

Figure 25. **Cross-section 3/1 looking upstream, November 2011**

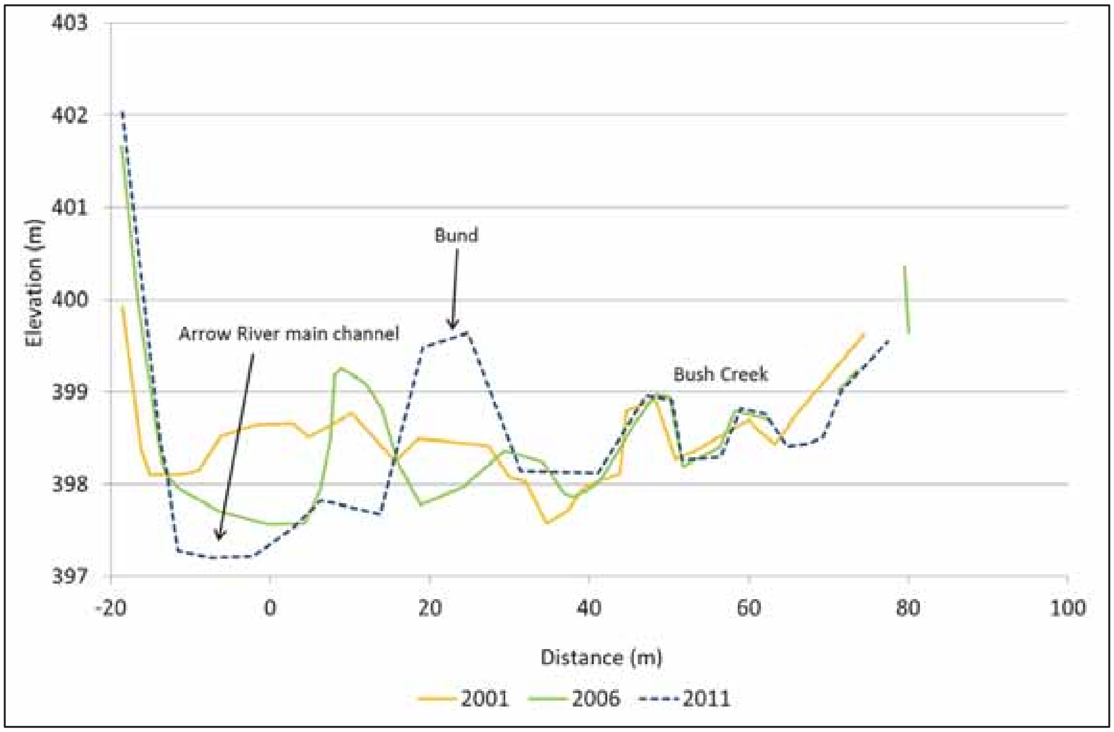

Figure 26. **Cross-section 3/1, looking downstream, showing data from the three most recent surveys**

The artificial bund was created in 2005 forcing the Arrow River to the true left of the floodplain. The channel has widened towards the right bank between 2006 and 2011 due to the bund being reshaped. There was an overall trend of bed-level degradation in the Arrow River between 2001 and 2011, and there was limited bank erosion of the true-left and true-right banks.

Figure 27. **Cross-section 3/1, looking from the true-left to true-right bank, November 2011**

Arrow River cross-section: 3

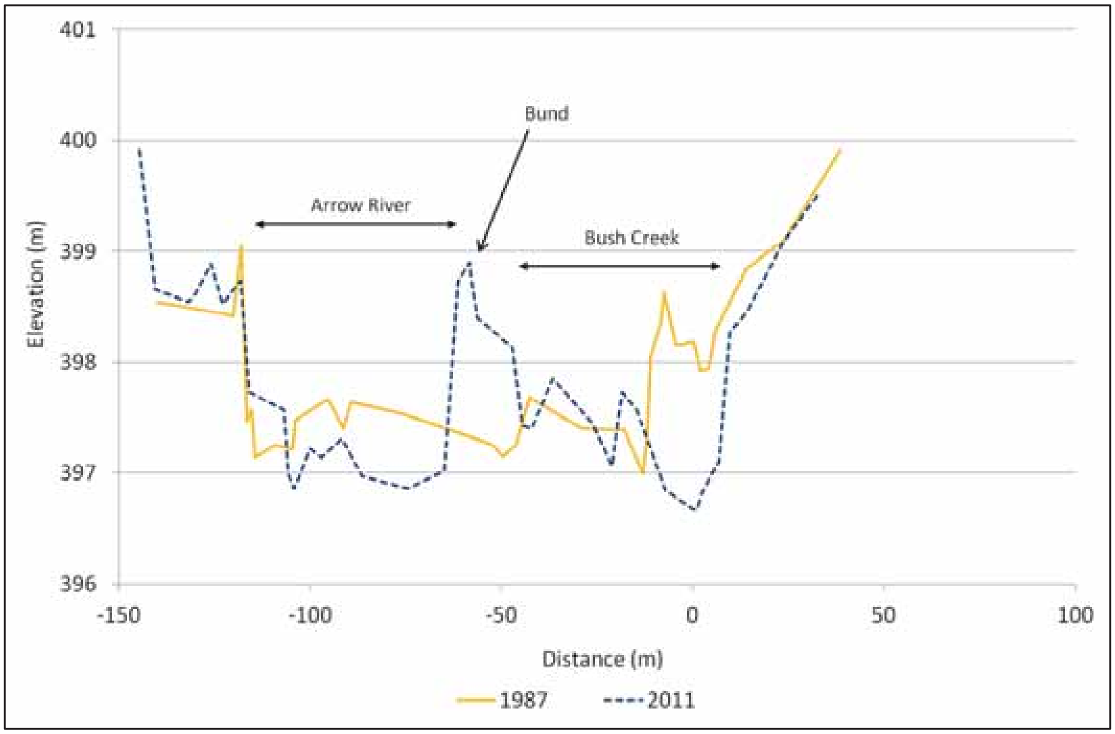

Figure 28. **Cross-section 3, looking downstream, showing first (1987) and last (2011) survey data**

Figure 29. **The Bush Creek low flow channel part of cross-section 3, looking downstream, November 2011**

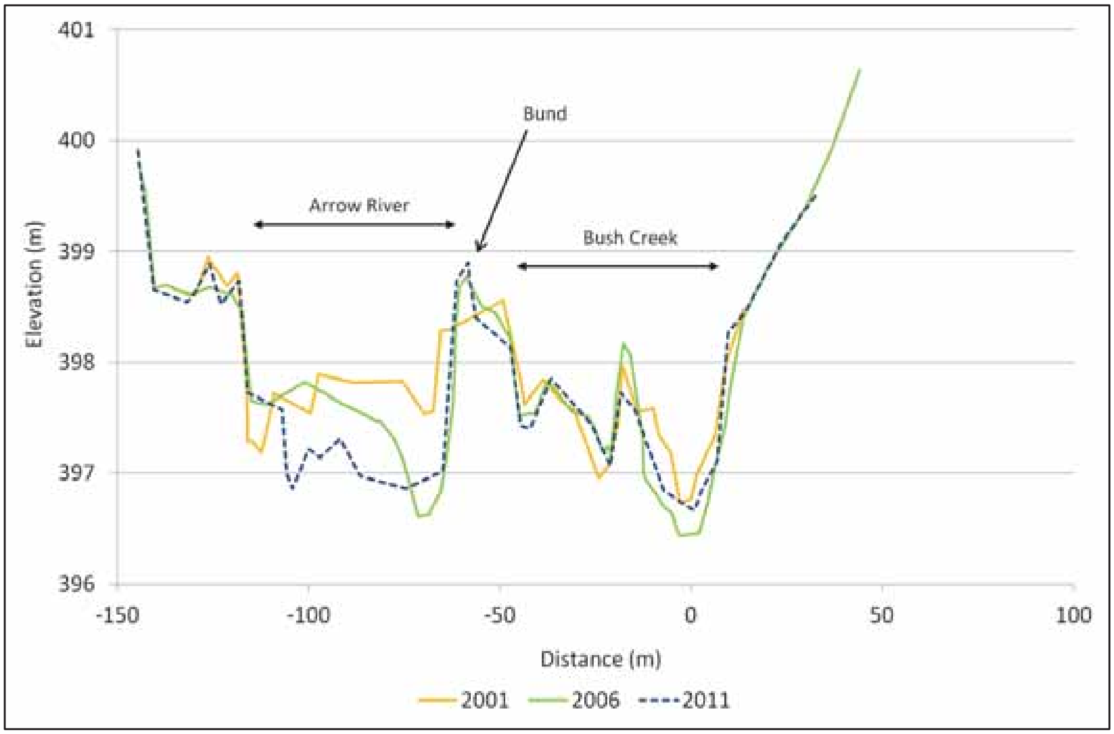

Figure 30. **Cross-section 3, looking downstream, showing data from the three most recent surveys**

Figure 31. **The Bush Creek low-flow channel part of cross-section 3, looking upstream, September 2014**

There has been degradation of the Arrow River channel between 2001 and 2011 at cross-section 3. A decrease in MBL of 1m occurred between 2001 and 2011, indicating long-term degradational processes. The bund was increased in height by about 0.25m between 2001 and 2011, and limited bank erosion was observed during this time.

Arrow River cross-section: 2/3

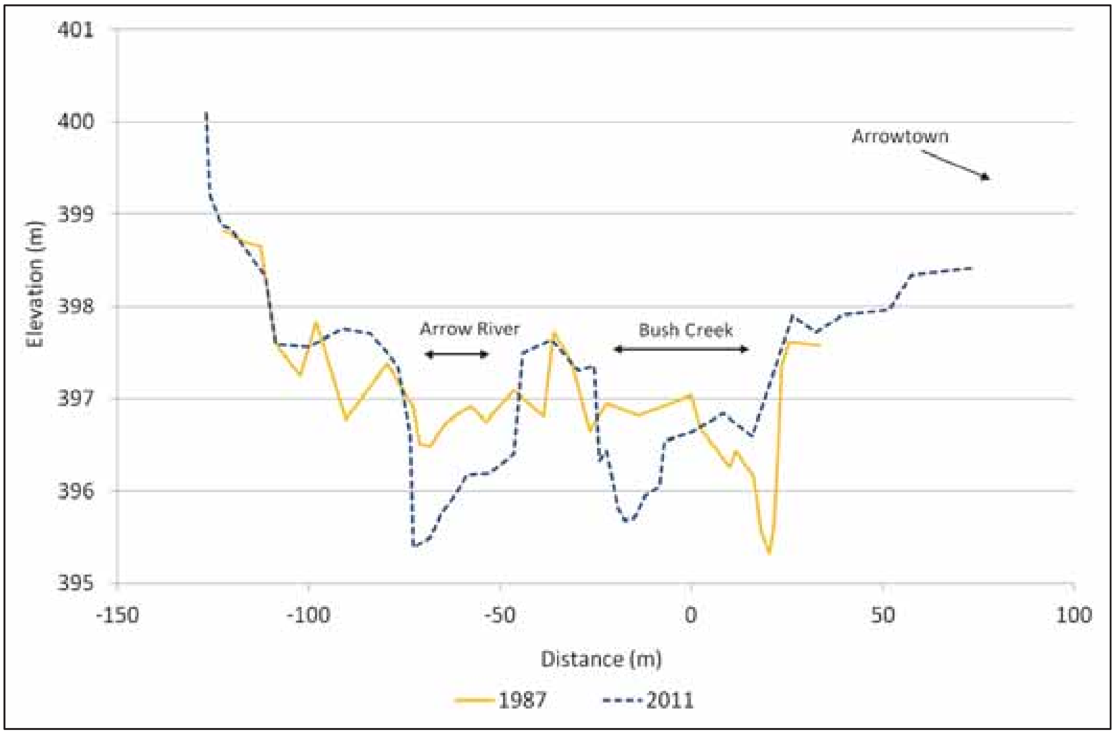

Figure 32. **Cross-section 2/3, looking downstream, showing first (1987) and last (2011) survey data**

Figure 33. **The Bush Creek low-flow channel part of cross-section 2/3, looking upstream, November 2011**

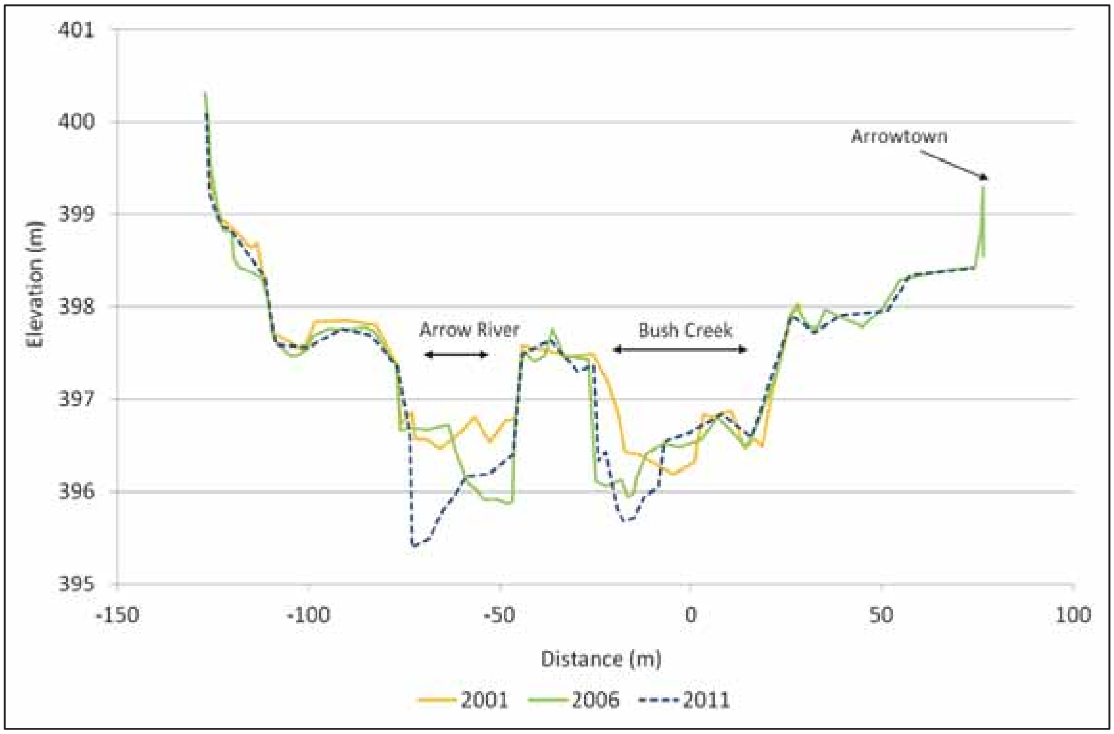

Figure 34. Cross-section 2/3, looking downstream, showing data from the three most recent surveys

At cross-section 2/3, the main Arrow River and Bush Creek channels degraded between 2001 and 2011, with the MBL decreasing by 0.22m over this time. An overall degradational trend has also been observed since 1987 at this site. Figure 34 shows that the Arrow River thalweg (lowest point of the channel) lowered and shifted towards the left bank between 2006 and 2011. There was limited erosion of the left and right banks between 2001 and 2011.

Arrow River cross-section: 2/2

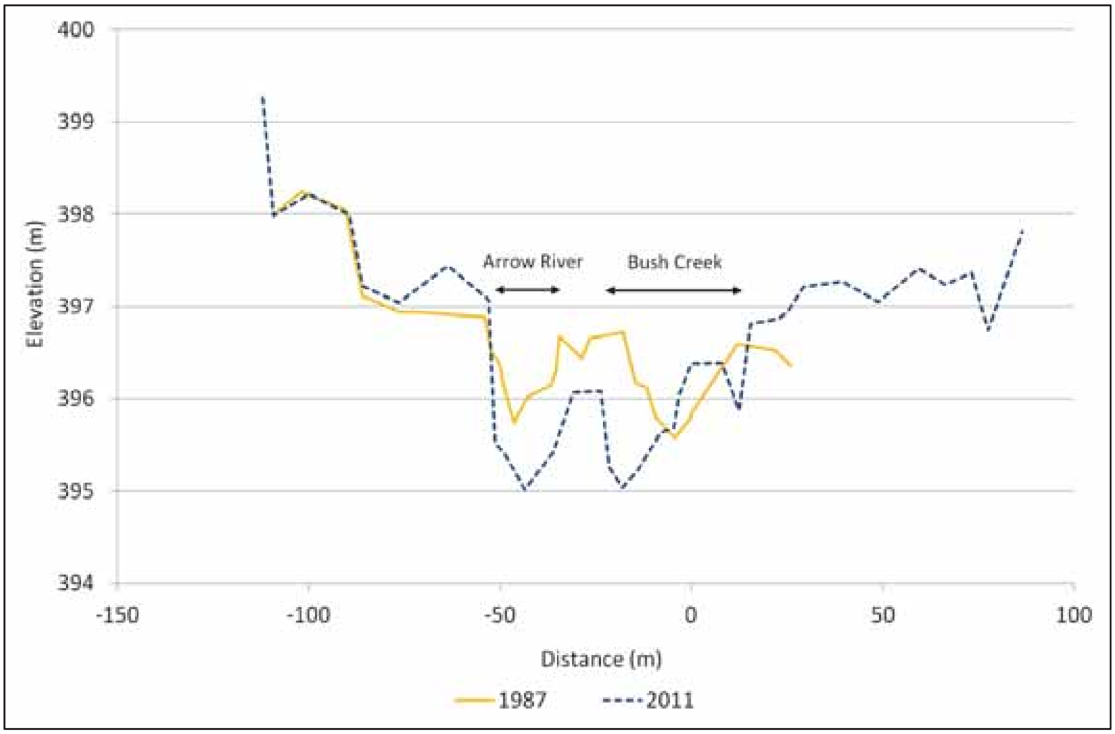

Figure 35. **Cross-section 2/2, looking downstream, showing first (1987) and last (2011) survey data**

Figure 36. **Looking downstream from below cross-section 2/2, May 2012**

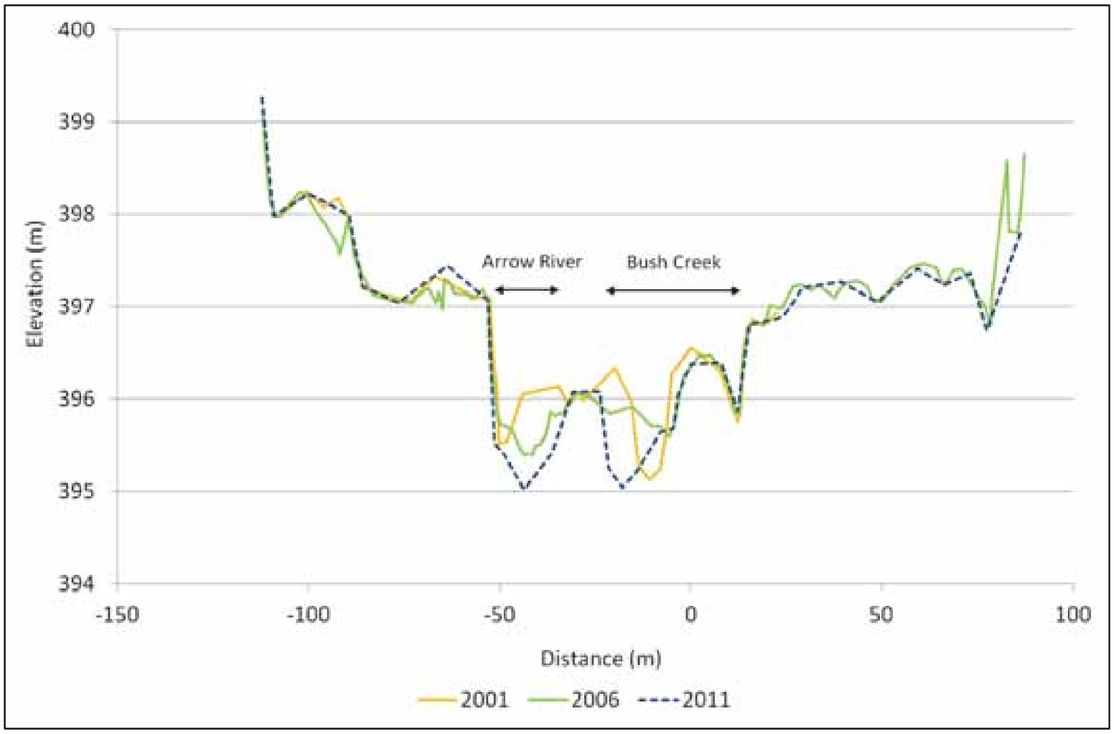

Figure 37. **Arrow River cross-section 2/2, looking downstream**

Figure 38. **View of the well-vegetated, true-right part of the floodplain at cross-section 2/2, November 2011**

As at cross-section 2/3 upstream, the Arrow River and Bush Creek channels degraded between 2001 and 2011 at section 2/2, continuing a trend that has been observed since 1987 and indicating that long-term degradation is taking place at this location. There has been little lateral movement in the Arrow River thalweg between 2006 and 2011. However, the Bush Creek thalweg has moved to the left of its active channel. There was limited bank erosion between 2001 and 2011.

Appendix 2. Timing of cross-section surveys in the Arrow River

A blank space indicates a cross-section was not surveyed that year.

Table 1. Surveyed cross-sections for the Arrow River

Cross-section	Mar. 1987	Oct. 1989	Mar. 1995	Dec. 1996	Jul. 2001	Nov. 2006	Nov. 2011
4/2	X		X		X	X	
4/1	X		X		X	X	
4	X		X		X	X	X
3/1	X		X	X	X	X	X
3	X	X	X	X	X	X	X
2/3	X		X	X	X	X	X
2/2	X	X	X		X	X	X
2/1	X	X	X		X	X	
2	X		X		X	X	
1	X		X		X	X	

Appendix 3. Methods

ORC has collected cross-section survey information on the Arrow River in the vicinity of Arrowtown since 1987. A comprehensive survey of all the existing cross-sections was undertaken in March 1987, March 1995, July 2001 and November 2006. This analysis is intended to show the changes in morphology that have occurred between 2011 and the last comprehensive survey that was undertaken in 2006.

Parameters

The MBL of the channel at each cross-section was calculated using the MBL function algorithm in the XSECT program. XSECT compiles a list of widths and their associated elevation for each cross-section and survey period. XSECT calculates all output information (minimum, maximum and MBL) from the respective widths and elevations.

MBL represents a 'horizontal straight line across the channel, positioned so there is as much bed above the line as below it' (Griffiths, 1979).To calculate the MBL, the lateral margins of the channel were identified as being either:

- the point where flood water would begin to overtop the channel and spill out onto the wider floodplain,[10] or
- the widest extent of the survey data, where such a point was not obvious.

The cross-section data collected in 2011 were used to define these lateral margins (Table 2). The MBL was calculated from the 2011 survey data, and also for the two previous surveys (using the same lateral margins). An example of how the MBL was calculated is shown in Figure 39.

A reduction in the MBL between survey periods does not necessarily mean that the level of the low-flow channel or thalweg has reduced. Rather, it shows that the average level of the whole channel has reduced. This may be a result of significant bank erosion rather than a decline in the level of the thalweg (Figure 39). The MBL values are shown in graphical form, and changes between survey periods are discussed in Section 4.5.

Table 2. The lateral margins of channel cross-sections used to calculate the MBL

Cross-section	Left bank	Right bank
4	-33.050	5.350
3/1	-18.540	71.580
3	-125.980	9.810
2/3	-91.360	26.4
2/2	-63.630	15.390

[10] In many cases, the cross-section extends beyond this point, onto the adjacent floodplain.

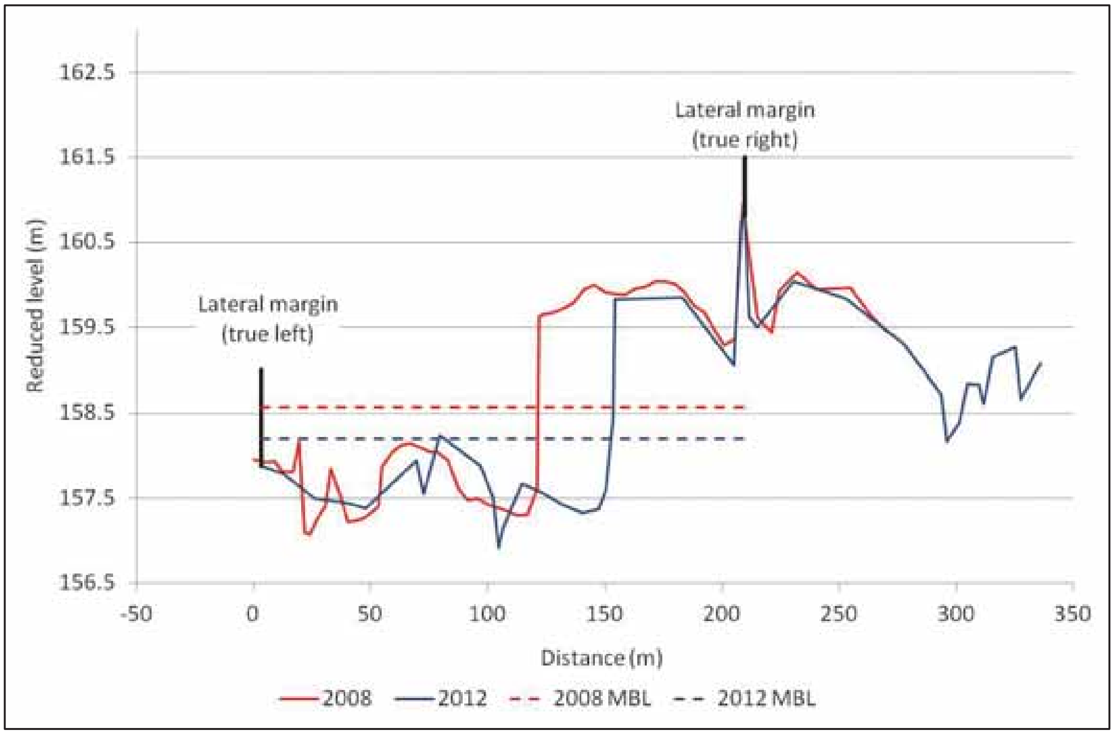

Figure 39. **Change in the MBL at a cross-section. The MBL was calculated for that part of the channel within the true-left and true-right lateral margins.**

Limitations

A limitation of the cross-section data is that it shows the river as it was at the time the survey was undertaken. Therefore, it provides a snapshot view of the river morphology for that particular time and place. Furthermore, survey methods involve taking an elevation and distance measurement at every major break in slope. This method has limitations in terms of transect resolution. The interpretations should therefore be viewed within the context that the data were collected.

All the cross-section graphs are looking downstream, with the true left of the river being on the left side of the graph. All reduced level measurements are expressed relative to mean sea level (MSL).

Hydraulic model

Introduction

A one-dimensional steady state computational hydraulic model (MIKE11) was developed to calculate flood levels in the Arrow River near Arrowtown (between the gorge and the corner of Merioneth and Bedford Street) for a 1:100-year flood event and for a 1:100-year flood event with channel aggradation of 1m. To account for aggradation of 1m, the elevation of the 2006/2011 cross-sections were increased by 1m. This was restricted to the channel and lower banks of the Arrow River and Bush Creek. The bund was removed. The model extends from approximately 500m upstream of Arrowtown to downstream to Narin Street.

Topographic data

Surveyed cross-sections of the Arrow River and Bush Creek from 1987, 2006 and 2011 were used. One metre contours collected from aerial photography were provided by QLDC. This was used to extend the modelled flood levels across the wider floodplain.

Boundary conditions

A 1:100-year flood flow of 132m^3/sec for the Arrow River and 15.56m^3/sec for Bush Creek were used as the upstream inputs into the model. The flow value for the Arrow River is based off regional flood frequency analysis (McKercher and Pearson, 1989) using a q100 (1:100-year flood coefficient) of 2.75 and a Qav/A^0.8 (annual rainfall quantity coefficient) of 0.8. The flow value for Bush Creek is based off the rational method from the NIWA Stream Explorer (http://stream-explorer.niwa.co.nz/) with a C-value (runoff coefficient value) of 0.25. This value corresponds to a surface type of bush and scrub cover (DBH, 2011).

The downstream boundary was a copy of the last measured cross-section, with a reduced elevation for each point of 0.92m. This reduction in elevation is based off the slope for the 2011/2006 cross-sections of 0.0082, measured from the most upstream cross-section (4/2) to the most downstream cross-section (1). The water level was set at 492.9m, for the modelled 1:100-year flood, and 495.48m for the 1:100-year flood, with 1m of sedimentation, at the downstream boundary cross-section. The water level was calculated using a slope, area calculation for a flow of 147.56m^3/sec for the two modelled scenarios.

Calibration and verification

Flood levels were surveyed after the March 1987 flood near Arrowtown. These levels were used to provide validation of the model. The model was run using the 1987 cross-sections, with an input flow of 83.1m^3/sec for the Arrow River and a point source inflow of 10.5m^3/sec for Bush Creek. The flows are based off the peak measured flow at the hydrological site, Arrow at Beetham Creek, for the March 1987 flood event of 93.6m^3/sec.

The flood levels predicted by the model for the 1987 flood event closely match the recorded flood marks and provide reasonable confidence in the setup of the model for use in other modelled scenarios (1:100-year flood event). The cross-sections surveyed in 2011 did not cover all of the established cross-sections. The 2006 cross-sections were used for the sections that were not surveyed in 2011.

Manning's roughness coefficient

The Manning's roughness coefficient (0.05) was derived from a simplified calibration process, using debris mark levels surveyed after the March 1987 event. The estimated coefficient was also checked against typical values for similar rivers.

Limitation of the modelling approach

The model uses a steady-state flow (i.e. a constant flow and not a hydrograph that is only useful in peak flood level estimations). The model does not take into account any floodplain storage, and it is based off cross-sections that were collected in 2011 that may not reflect the current topography of the Arrow River and Bush Creek floodplains.