Update of scientific information for the Cardrona catchment: 2011-2017

September 2017

Otago Regional Council

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1. Introduction

The Otago Regional Council (ORC) has continued to measure flows in the Cardrona River since the publication of the report: “Integrated Water Resource Management for the Cardrona River” (Dale & Rekker 2011). This report presents updated hydrological analyses for the Cardrona River at the Mt. Barker hydrological site, including naturalised flows for 30 years as well as an updated instream habitat analysis based on this updated hydrological information.

The Cardrona River (catchment area: 337 km^2) has its headwaters in the Crown Range; it flows for 40 kilometres in a north-easterly direction, joining the Clutha River near the township of Albert Town. The Cardrona River flows through alluvial flats bordered by the Crown Range to the west and the Pisa and Criffel Ranges to the east. The river descends steeply from an elevation of 1200 metres to 300 metres at the confluence with the Clutha/Mata-au River.

The majority of the higher catchment is tussock and low production grassland while the lower catchment supports high producing exotic pasture. Sheep and beef farming on tussock dominate the catchment, with the high producing grasslands in the lower catchment supporting some deer farming (ORC 2011).

The climate of the Cardrona catchment is characterised as continental due to its distance from the moderating influence of the ocean (ORC 2016). Two distinct climate zones are spanned by the Cardrona; the lower catchment has a ‘cool dry’ climate whereas the upper reaches and high country has a ‘cool wet’ climate. The cool climate of the valley results in a short growing season.

Above Mt. Barker, the Cardrona Valley still has a degree of historic (undeveloped) atmosphere despite thousands of tourists passing through while traveling from Wanaka and Queenstown. Much of the atmosphere can be attributed to the Cardrona Hotel established in 1863. The hotel supported the many European and Chinese miners that once settled in the area as part of the 1860’s Central Otago Gold Rush.

At its peak in the early 1870’s the resident population reached 1000 with predominance of Chinese miners, who worked over claims abandoned by Europeans. Mine dredging started in the 1890’s and continued through to the twentieth century (Middleton 2006). In recent years, urban development has spread up the valley, with the Wanaka Township now occupying what was once farm land past Orchard Road.

There are 25 existing surface water-takes in the Cardrona River catchment, with a total allocation of an approximately 2.0 m^3/s, although the measured usage is considerably lower.

This report summarises the results and upgrades of the work undertaken since 2011 and discusses the implications for the minimum flow process in the Cardrona River catchment.

This information includes the following:

- hydrology and existing water allocation in the Cardrona River,
- aquatic in-stream values of the Cardrona River,

- presentation, analysis and interpretation of the results of instream flow and habitat modelling to maintain aquatic ecological values in the Cardrona River.

This report supersedes the findings of the previous surface water section in the report: “Integrated Water resource management for the Cardrona River” (2011). An additional assessment of the groundwater component of this study is being undertaken separately to this report.

2. Climate and Rainfall

The Cardrona River catchment consists of a steep river valley at an elevation of between 300 m at the confluence with the Clutha/Mata-Au River and 1200 m at the top of its headwaters in the Crown Range. Figure 2.1 shows the Cardrona catchment, including temperature, flow and rainfall monitoring sites.

Topography plays a large role in the rainfall distribution over the Cardrona catchment, with high rainfall in western, mountainous parts of the catchment and much lower rainfall in the lower elevation middle and lower parts of the catchment (Figure 2.2). The mean annual rainfall along the western edge of the Cardrona catchment is between 650and 750 mm, while the annual rainfall in the middle and lower parts of the catchment between Ballantyne Road and the confluence with the Clutha River is a relatively low 550 mm. The long-term mean annual rainfall for the Cardrona catchment is 634 mm.

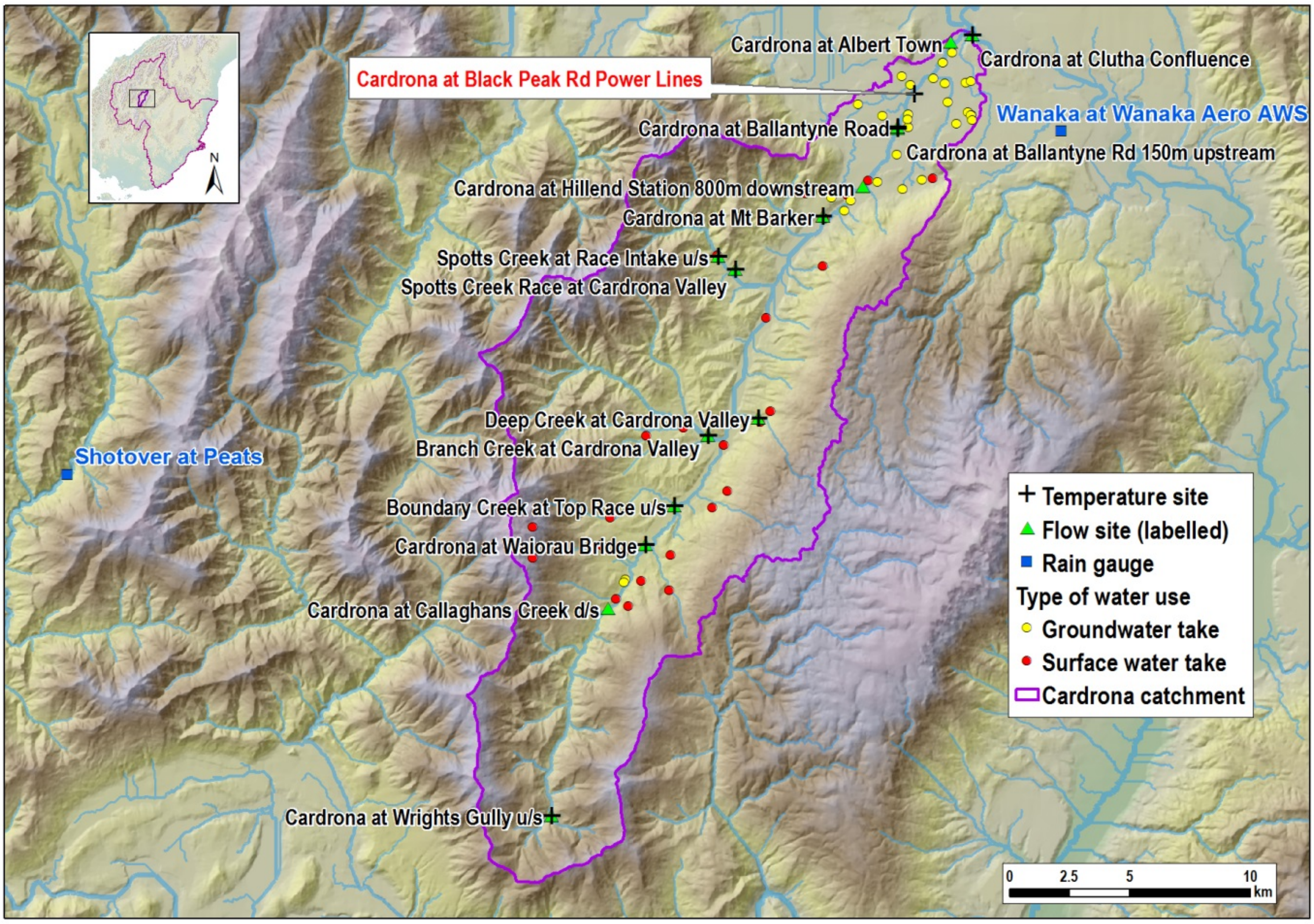

Figure 2.1 **The Cardrona catchment and the nearby temperature, flow and rain gaugesites**

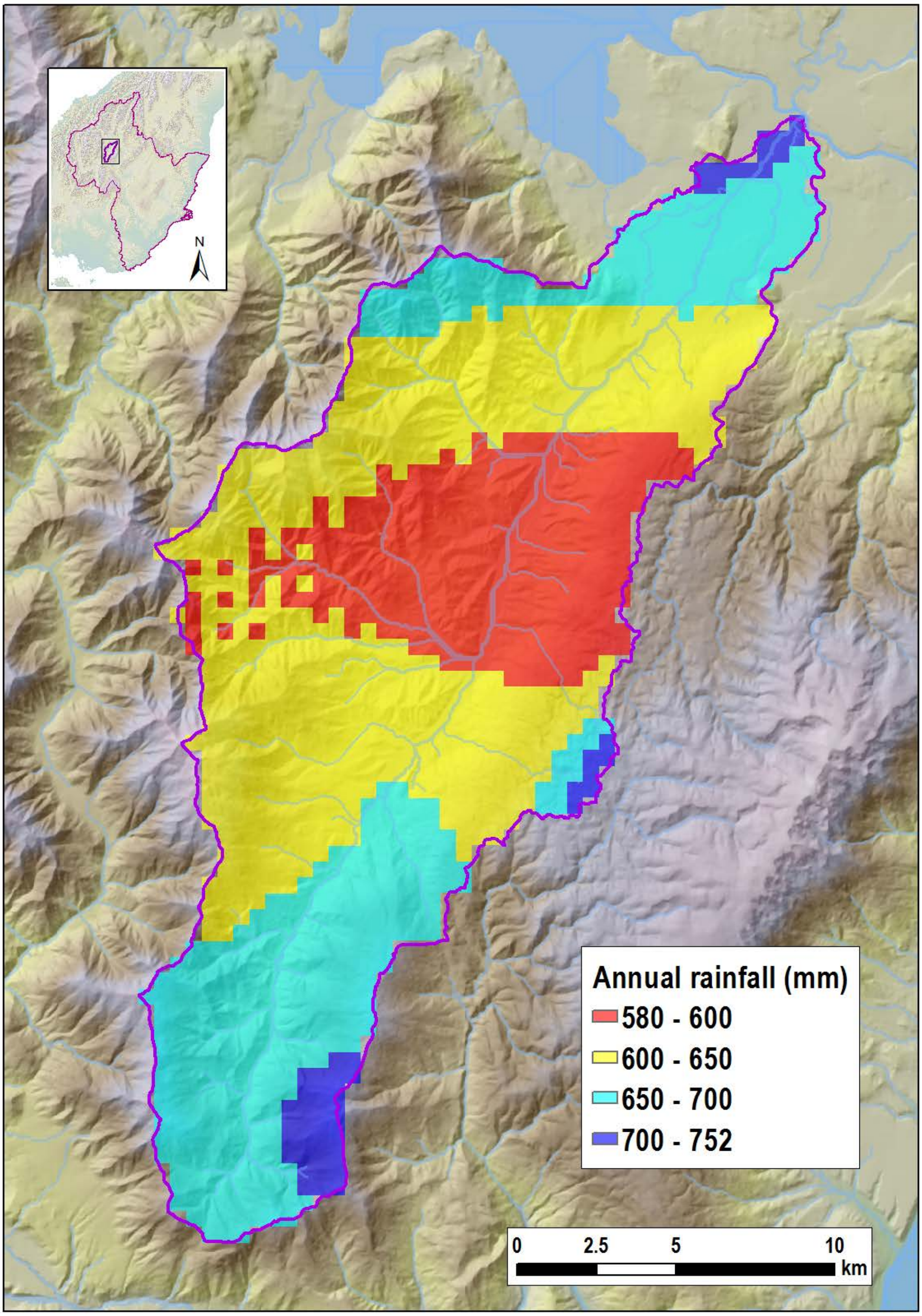

Figure 2.2 **The annual rainfall distribution around the Cardrona catchment (Tait, et al., 2006)**

3. River Hydrology

Hydrological monitoring in the Cardrona catchment has included a permanent flow recorder at Mt. Barker (1976 to present) and thirteen temporary flow recorders that have been located at the Clutha River/Mata-Au confluence, Albert Town, Ballantyne Road, Hillend Station, Spotts Creek, Deep Creek, Branch Creek, Boundary Creek, Waiorau Bridge, Callaghans Creek confluence and Wrights Gully confluence (Figure 2.1).

The three upper flow recorders (Waiorau Bridge, Callaghans Creek confluence and Wrights Gully confluence) were installed as part of a water resource study of the upper Cardrona catchment. Waiorau Bridge recorder was established in 2008 and removed 9 months later; the Callaghans Creek recorder was installed in 2008 and removed 14 months later and the Wrights Gully site was established in 2009 and removed 16 months later. These short-term recorders were not used in this study, which focuses on the hydrology of the lower catchment.

Currently, the Callaghans Creek flow recorder has been reinstalled as a reference flow site, capturing the natural flows for the upper catchment. The historic flow site located at Albert Town (Sep 1978 – Jan 2002) was managed by NIWA. Flows of the two newly-installed recorders (Dec 2016) at Ballantyne Road (150 m upstream) and Hillend Station, along with the water-take data, are used for estimating the surface water loss/gain along the Cardrona River between the two locations. Flow recorders installed at Deep Creek, Branch Creek, Spotts Creek and Boundary Creek record natural flows as there are no water-takes above these recorders. The flow recorder at Cardrona at Clutha Confluence was initiated in 2008 for monitoring the water level, and it became a permanent SOE water level recorder since March 2014.

A naturalised flow timeseries was created for the Cardrona above Mt. Barker based on Lindis peak. Details for the creation of this timeseries are provided in Appendix 1.

3.1. Naturalised flow statistics

Table 3.1 lists basic flow statistics summarised from both observed and estimated naturalised daily flow time series (see appendix 1) at Mt. Barker (available from 3/12/1976 to 3/5/2017). The low-flow frequency analysis was carried out by testing the goodness of fit for the three selected distributions, i.e., Gumbel, GEV, and GPareto. Based on goodness of fit tests, the low-flow frequency analysis from GEV distribution was used. Table 3.2 shows the daily flows at three different return periods (2, 5, and 10 years). This low-flow frequency analysis, provides a better understanding of low-flow regime for the Cardrona River and could assist in setting minimum flows for protection of instream habitats.

Table 3.1 The basic flow statistics summarised from both naturalised and observed flows at Mt. Barker

	Flow statistics (m^3/s)					
	Minimum	Median	Mean	7dMALF (Jul – Jun)	7dMALF (Oct – Apr)	7dMALF (May – Sep)
Naturalised flows	0.753	2.62	3.32	1.18	1.17	1.68
Observed flows	0.310	2.34	3.1	0.840	0.85	1.54

Table 3.2 The low flow frequency analysis for both naturalised and observed flows at Mt. Barker

	2-year low flow (m³/s)[1]	5-year low flow (m³/s)	10-year low flow (m³/s)
Naturalised flows	1.09	0.921	0.846
Observed flows	0.877	0.63	0.528

The low-flow frequency analysis was based on the naturalised daily flow time series at Mt. Barker. The low flows in Table 3.1 are expected to be lower if a finer temporal resolution is used (e.g., hourly).

Figure 3.1 shows flow duration curves for both naturalised and observed daily flow time series across the irrigation seasons (Oct – Apr, inclusive) at Mt. Barker, along with their corresponding 7dMALFs.

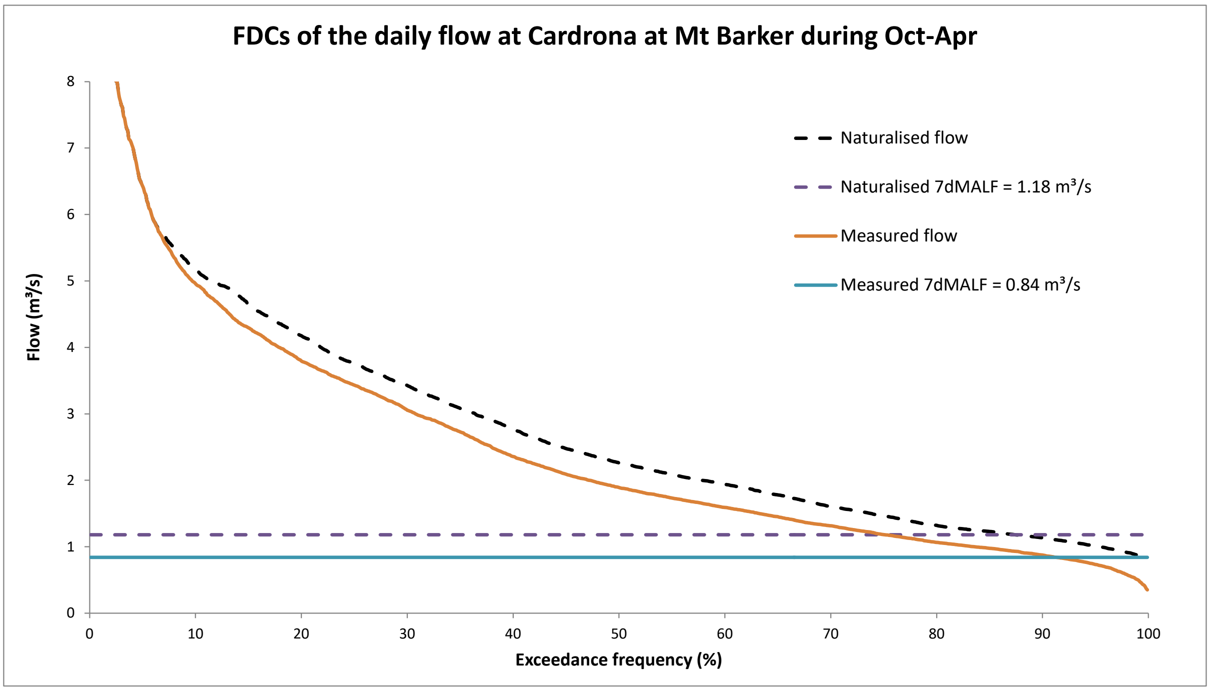

Figure 3.1 Flow duration curves of the daily flow at Mt. Barker during the irrigation season (October-April).

Figure 3.1 shows on average, for 91% and 87% of the time the observed and naturalised daily average flows are above their respective 7dMALFs.

Figure 3.2 shows monthly average naturalised flows start receding in November and continue to do so through to the end of April, then start recovering again in May onwards. The February – April period is where flows are lowest with February being marginally drier than any other month.

[1] 2-year low flow (m³/s) is the low flow at a 1 in 2 chance or a 50 percent chance of occurring in any given year.

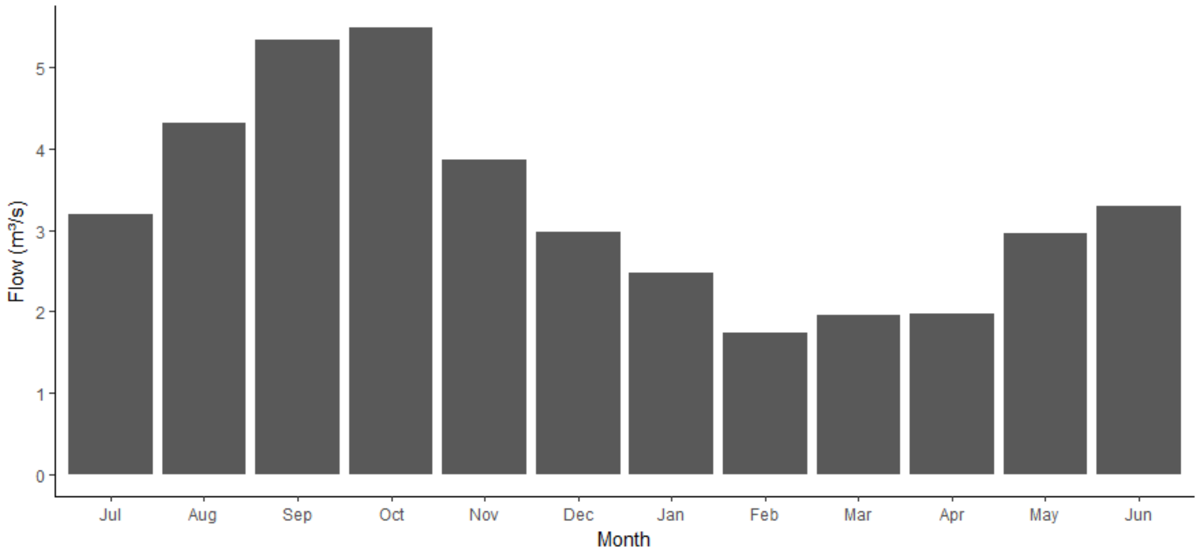

Figure 3.2 **Naturalised monthly average flows at Mt. Barker**

Table 3.3 presents the number of days and maximum consecutive number of days when the naturalised flows at Mt Barker were below its 7dMALF of 1.18 m^3/s for the period of October – April from 2000 to 2017. On average, there have been 35.5 days and 13.6 maximum consecutive days when the flows were below the 7dMALF, respectively.

Table 3.3 **The No. of days and maximum consecutive No. of days when the naturalised flows at Mt Barker were below 1.18 m^3/s for the period of October – April between 2000 and 2017**

Period October – April	**No. of days when flows were below 1.18 m^3/s**	**Maximum consecutive No. of days when flows were below 1.18 m^3/s**
2000 – 01	26	9
2001 – 02	15	11
2002 – 03	14	10
2003 – 04	3	3
2004 – 05	0	0
2005 – 06	100	39
2006 – 07	53	17
2007 – 08	72	35
2008 – 09	1	1
2009 – 10	76	30
2010 – 11	0	0
2011 – 12	0	0
2012 – 13	25	9
2013 – 14	49	16
2014 – 15	55	17
2015 – 16	105	28
2016 – 17	10	6
Average No. days	35.5	13.6

3.2. Surface water loss/gain for Mt. Barker- Hillend-Ballantyne Road

Flow connectivity is considered to be a key component of the natural character in a water way. Therefore, it is critical to understand whether the waterway dries naturally or due to water abstraction. As a result, a major objective of this study is to provide an understanding of surface and groundwater flow interactions to determine if the Cardrona River dries naturally and, if so, at what flows drying occurs.

The Cardrona River can be separated into three main sections: a neutral reach upstream of Mt. Barker; a losing reach, in which surface water is lost to ground between Mt. Barker and State Highway 6; and gaining reach in which surface flows are recharged from groundwater from State Highway 6 to the confluence with the Clutha River (Dale & Rekker 2011) (Figure 3.3).

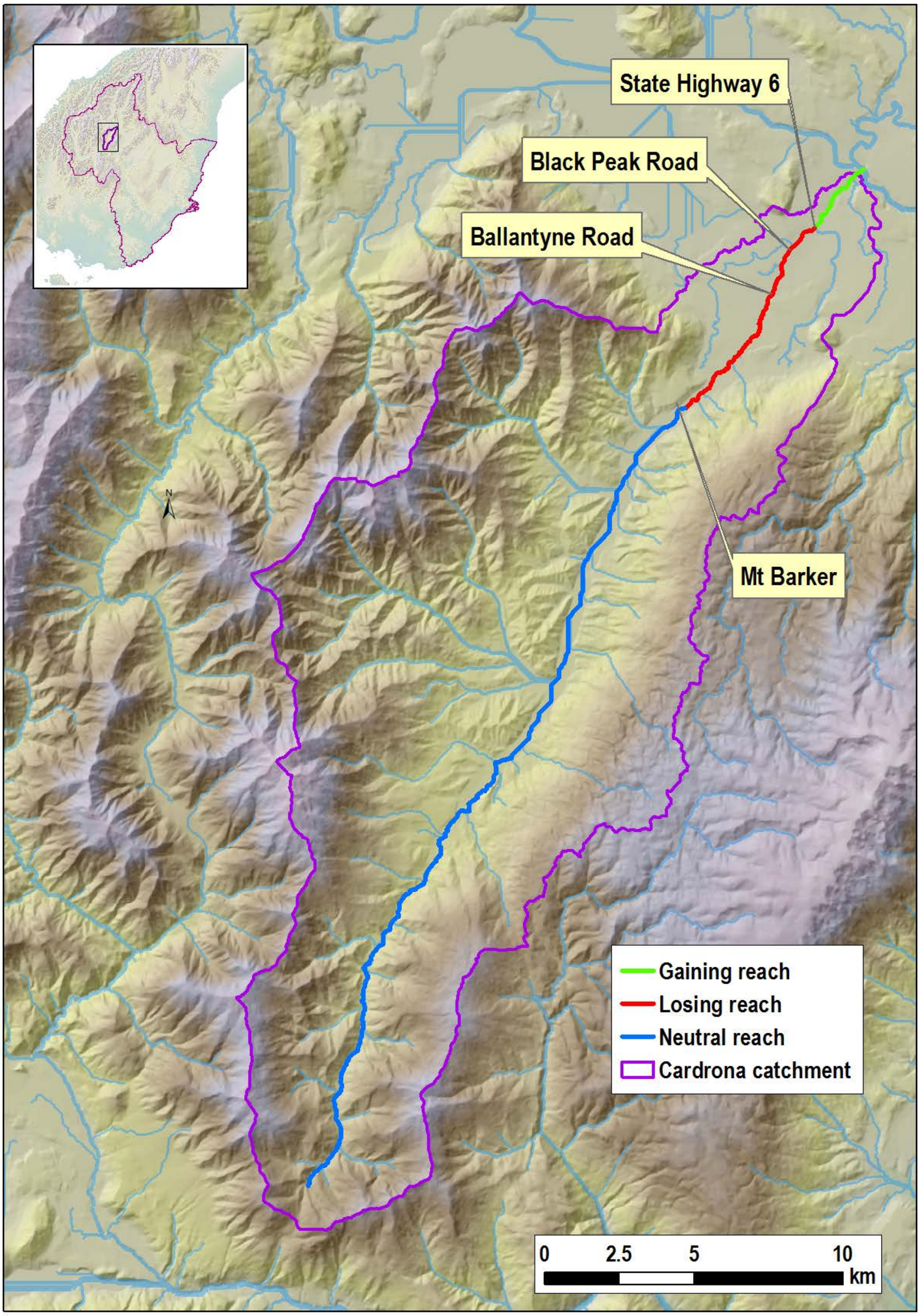

Figure 3.3 Location the three different hydrological reaches in the Cardrona River

3.2.1. Total water abstraction between Mt Barker and Ballantyne Road

Information was gathered from the permanent flow recorder site at Mt. Barker and a temporarily established flow recorder at Ballantyne Road which collected data from mid-December 2016 to May 2017. There are five abstraction points (listed in Table 3.4) located between the Mt. Barker and Ballantyne Road. These water-takes (99478, 97199.V1, 98370, 2001.A03, and RM14.345.01) were used to determine the amount of water lost to ground between the Mt. Barker and Ballantyne Road flow recorders.

Table 3.4 Summary of water takes between Mt Barker and Ballantyne Road

Site name	Consent ID	Start	End	Type	Maximum rate of take (l/s)
WM0583	99478	4/12/2012	17/07/2017	Surface take	250
WM0712	97199.V1 & 98370	8/05/2015	17/07/2017	Surface take	561.1
No meters[2]	96552, 96553 & 97129			Surface take	194.37
WM0203	2001.A03	6/11/2011	21/11/2016	Groundwater take	2.8
WM0987	RM14.345.01	19/01/2008	2/03/2015	Groundwater take	38

Based on water metering data, the total measured water-take data between Mt. Barker and Ballantyne Road can be derived and added to the flow at Ballantyne road to allow a calculation of loss to ground water (e.g. Flow at Mt. Barker – [Irrigation take between Mt. Barker and Ballantyne Rd + Flow at Ballantyne Rd] = Water loss). Figure 3.4 shows a box plot of the measured monthly rate of take along the Cardrona River between Mt Barker and Ballantyne Road during Feb 2014 – Jun 2017.

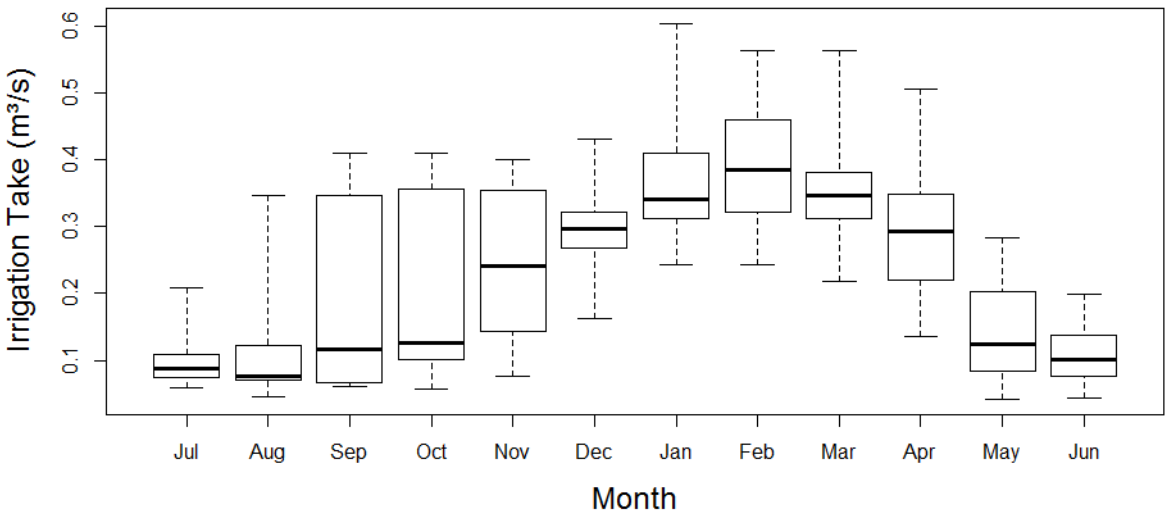

Figure 3.4 The box plot of the measured monthly rate of take along the Cardrona River between Mt Barker and Ballantyne Road (Figure 3.3) during Feb 2014 – Jun 2017.

[2] For the consents with no water meters being installed, the irrigators suggest that a consistent rate of 42 l/s is applied for a normal irrigation season.

3.2.2. Estimating losses to ground water

The relationship between flow at Mt. Barker and groundwater loss between Mt. Barker and Ballantyne Road was fitted with a quadratic relationship to account for potential saturation (Figure 3.5) and a maximum rate of loss to ground. When at or below naturalised 7dMALF, ground water loss between Mt Barker and Ballantyne Road ranges from approximately 0.52 m^3/s to 0.77 m^3/s (Figure 3.5). Above the naturalised 7dMALF, more water is lost to ground, but, as flows increase further, the rate of loss eventually starts to decrease resulting in a U-shaped curve. This U-shaped relationship likely occurs due to either groundwater saturation or a maximum rate of loss to ground. If groundwater is saturated or flows exceed this rate, surface flow would likely occur. The range of loss from Ballantyne Road to Black Peak Road powerlines is difficult to quantify as the amount of loss is dependent on the surface flows at Mt Barker.

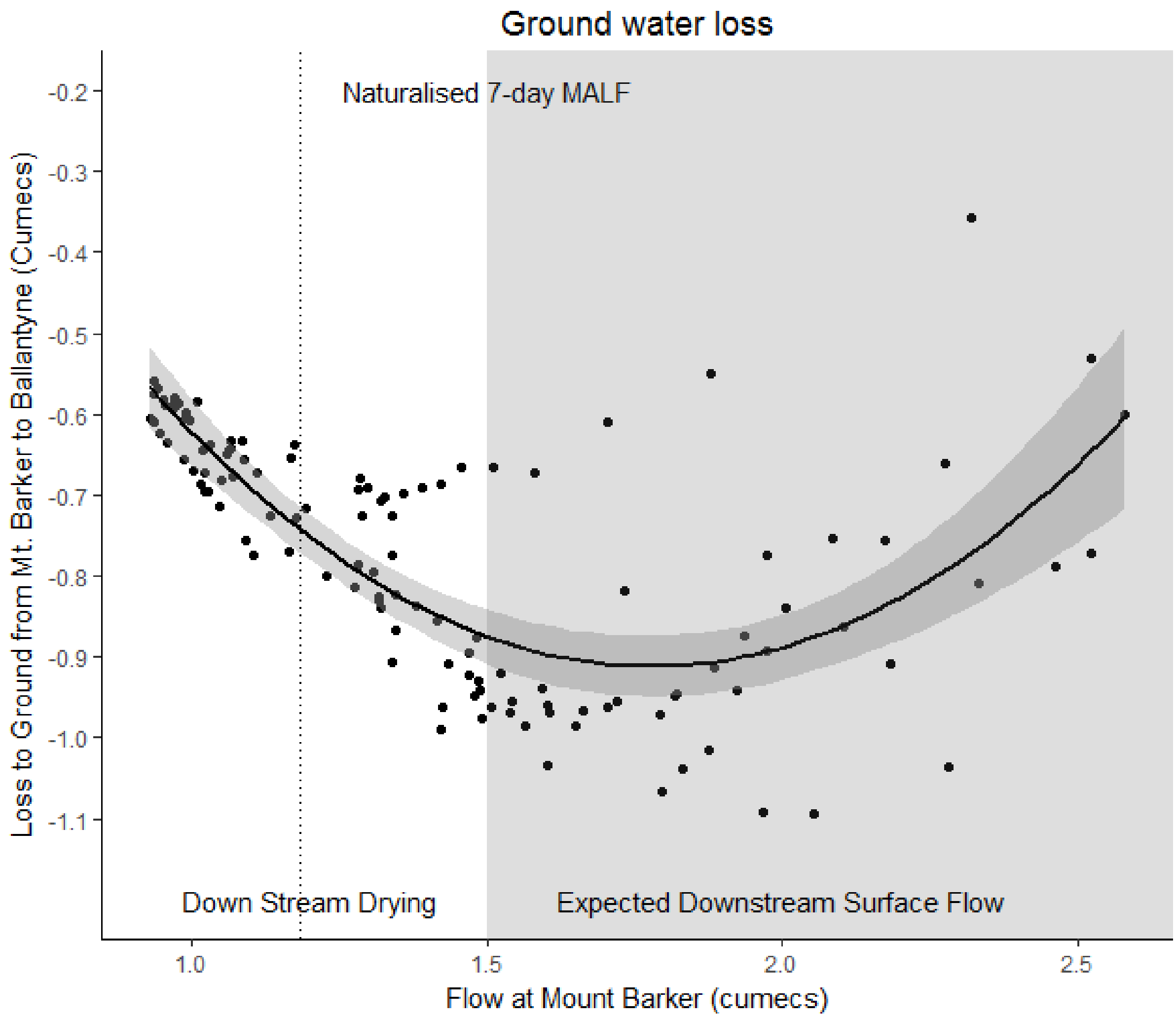

Figure 3.5 **Quadratic model fit of the relationship between flow at Mt. Barker and groundwater loss from Mt. Barker to Ballantyne Road with a shaded (grey) 99% confidence interval and naturalised minimum flow. Shaded expected downstream flow regions are based upon the inflection point of groundwater loss. When flow values exceed this point (1.5 cumecs), downstream surface connectivity is more likely to be maintained.**

Water temperature loggers were deployed between Mt Barker and the Clutha confluence to determine if sections of this reach went dry. A relatively small diurnal temperature range (e.g., ~10-25 °C) is characteristic of flowing water and a relatively large diurnal temperature range (e.g., ~5-45 °C) indicates water is not flowing and the reach is dry. Temperature data suggests that the river was flowing at Mt. Barker, Ballantyne Road and the Clutha confluence year-round while the Black Peak Road Power Lines site had periods of drying from January through to the end of March (Figure 3.6) Figure 2.1. The Black Peak Rd. Power Lines site was likely dry for at least 43 days and up to 69 days in the 2017 irrigation season. Temperature at this site does not show a gradual increase as seen in other catchments such as the Manuherikia (Olsen et al., 2016) but instead shows one of two states, either a relatively stable temperature, like that of Mt. Barker (Figure 3.6), or a drying reach with large temperature ranges. This suggests drying occurs relatively rapidly.

There were three high flow events on the 19th, 22nd and 31st of January. These flows peaked at 5.38 m^3/s, 8.09 m^3/s and 5.69 m^3/s respectively. These high flow events may have provided connectivity in the lower reach but for relatively short duration (Figure 3.7). Field observations made at the time when flows were at 1.2 m^3/s (13th Feb 2017) confirmed there were no surface flows.

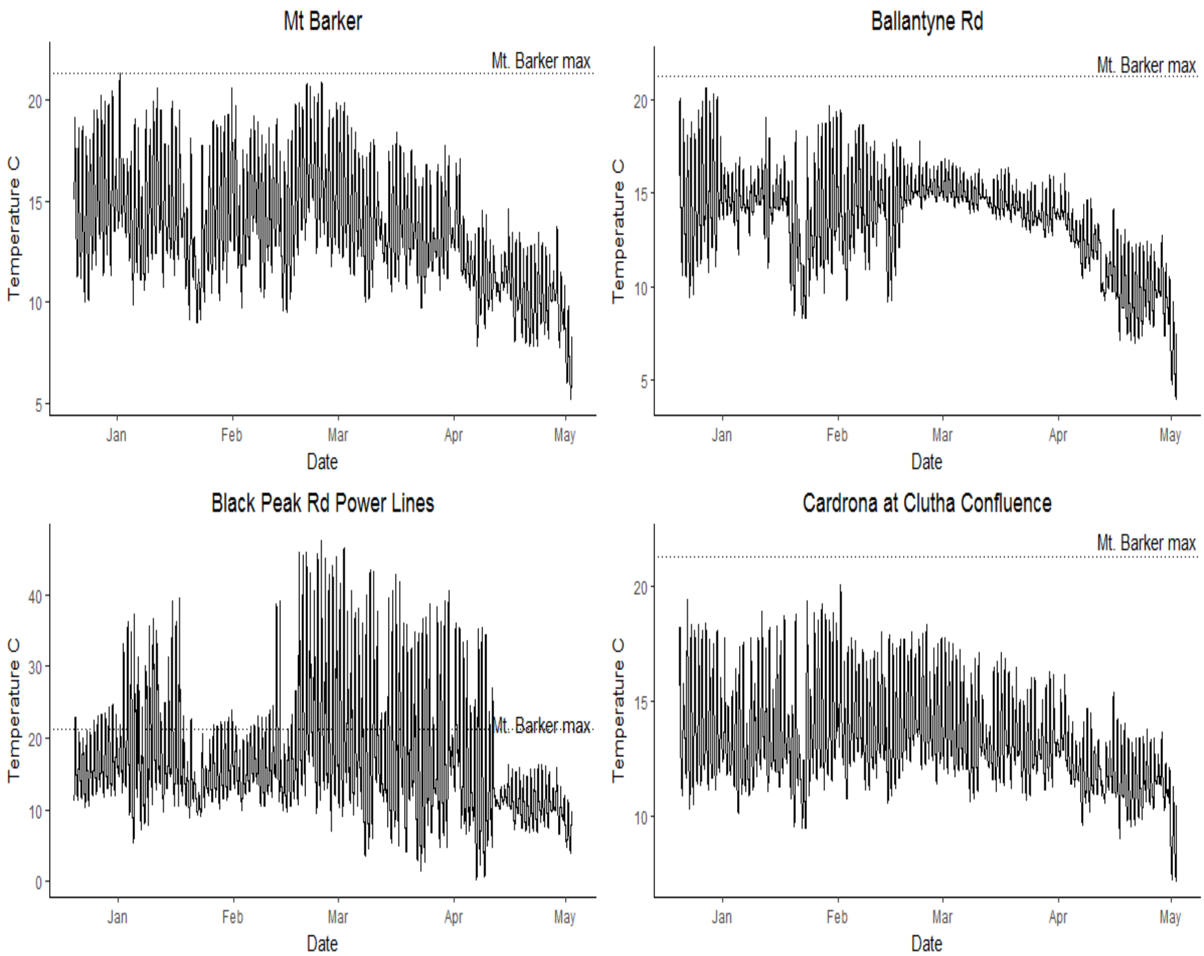

Figure 3.6 **Temperature graphs for four sites along the Cardrona River. Mt. Barker maintained flow and had a maximum daily temperature of 21.3 °C. Black Peak (note the greater y-axis scale) routinely exceeds this temperature by more than 10 °C suggesting a dry reach**

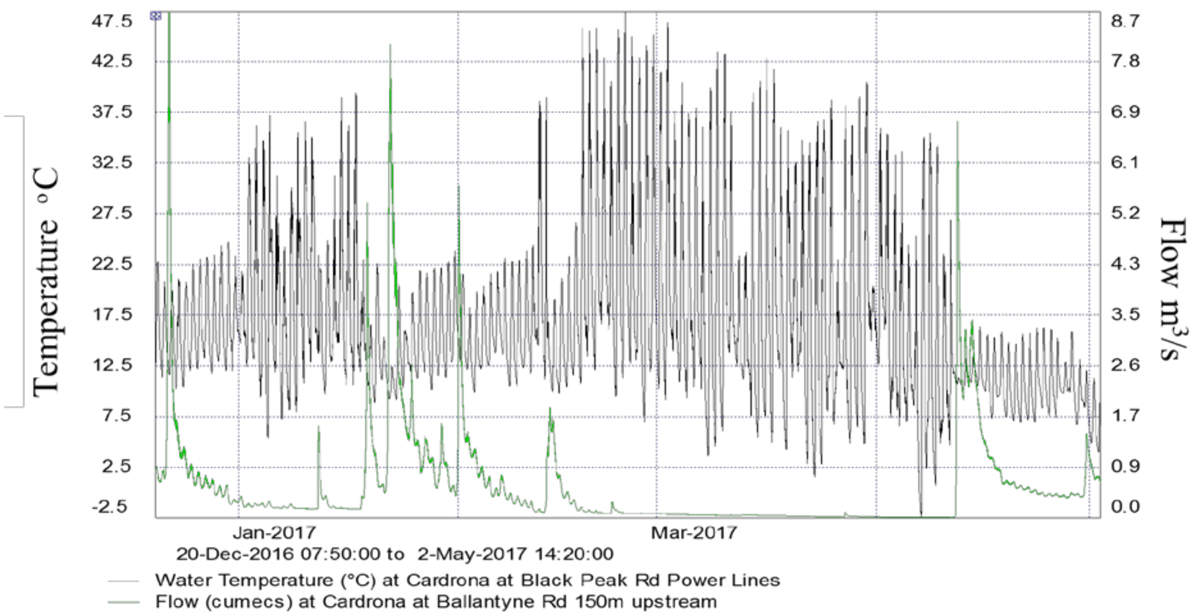

Figure 3.7 **Surface flows at Ballantyne Road and temperature at Black Peak Road powerlines**

To determine if the model in Figure 3.5 was meaningful in the context of downstream drying, the temperature of downstream sites was used as a proxy measure to determine if downstream reaches maintain surface connectivity at various flows. The relationship between flow at Mt. Barker and temperature range (Figure 3.8) at the Black Peak Rd. Power Lines shows when flows are below the range of the critical value (approximately 1.5 m^3/s) identified in Figure 3.5, temperature ranges have relatively high values whereas when flows are above 1.5 m^3/s temperature ranges are much less indicating the temperature logger likely remained submerged. Both drying and wetted temperature ranges are present from approximately 0.75 m^3/s to 1.75 m^3/s. This suggests surface flow may occur in downstream reaches when flows are less than 1.5 m^3/s if conditions, such as groundwater level, allow. Above 1.75 m^3/s, nearly all temperature ranges indicate surface flow. However, whether these flows maintain surface flow beyond the Black Peak Rd. Power Lines site to the Clutha confluence is unknown based on current data.

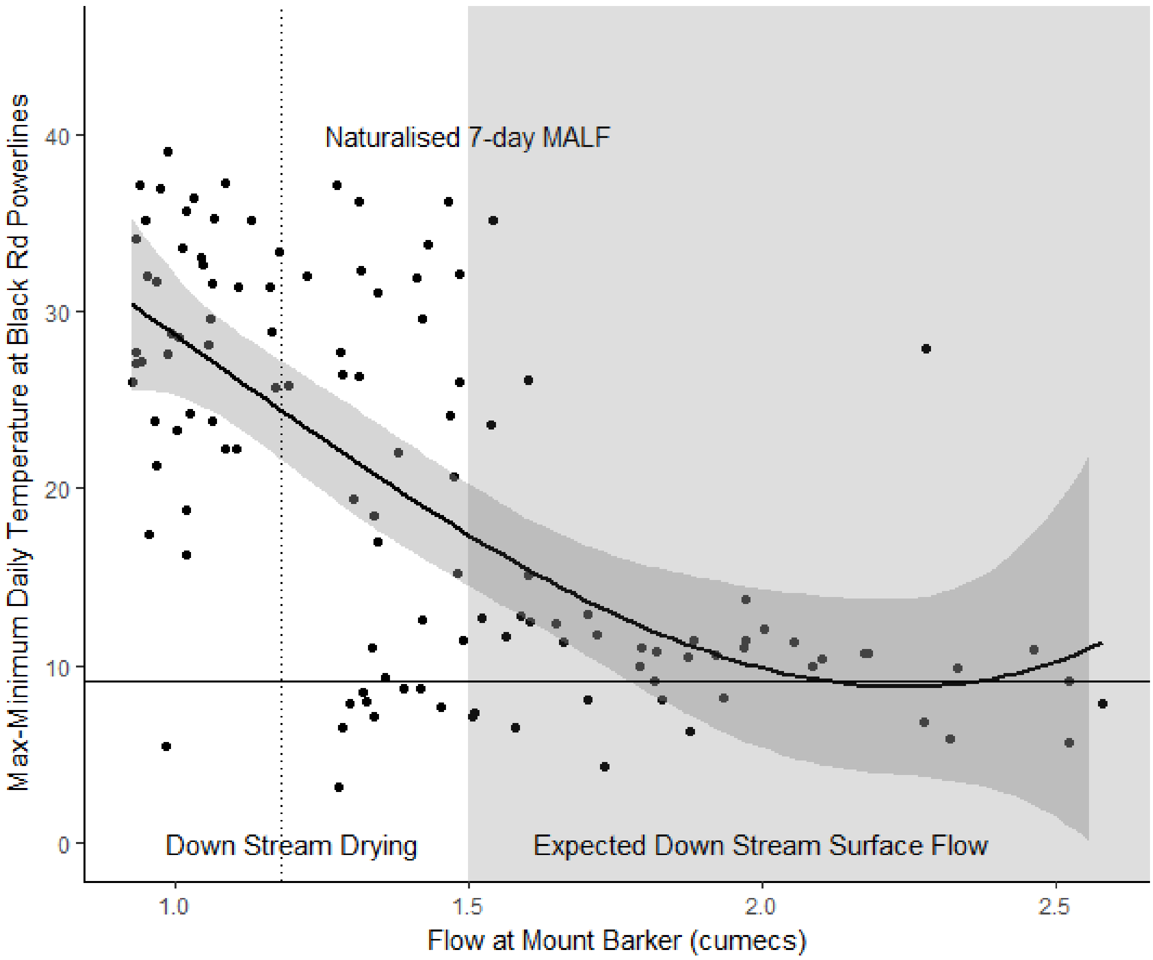

Figure 3.8 **Temperature range (daily maximum-daily minimum) at Black Peak Rd power lines and flow at Mt. Barker with 95% confidence interval. The shaded rectangle represents flows at which downstream connectivity is likely to occur based estimates from Figure 3.5**

Flow losses in the Cardrona River from Ballantyne Road to State Highway 6 were further established using ground-based surveys and aerial photography/satellite imagery. The analysis included three aerial photographs and/or satellite images of the reach immediately downstream of the Ballantyne Road flow recorder obtained from various sources (Otago Regional Council, Google Earthpro). Ground-based surveys involved marking drying reaches on five separate occasions from 5th January 2017 to 17th March 2017 using a hand-held GPS unit. These GPS points were imported to ArcGIS and the length of each section was determined.

To determine the length of the drying sections in the Cardrona River in relation to flows at Mt. Barker the following calculation was used: flows at Mt. Barker flow recorder minus measured water-take equals flow below the lowest point of take (Figure 3.9).

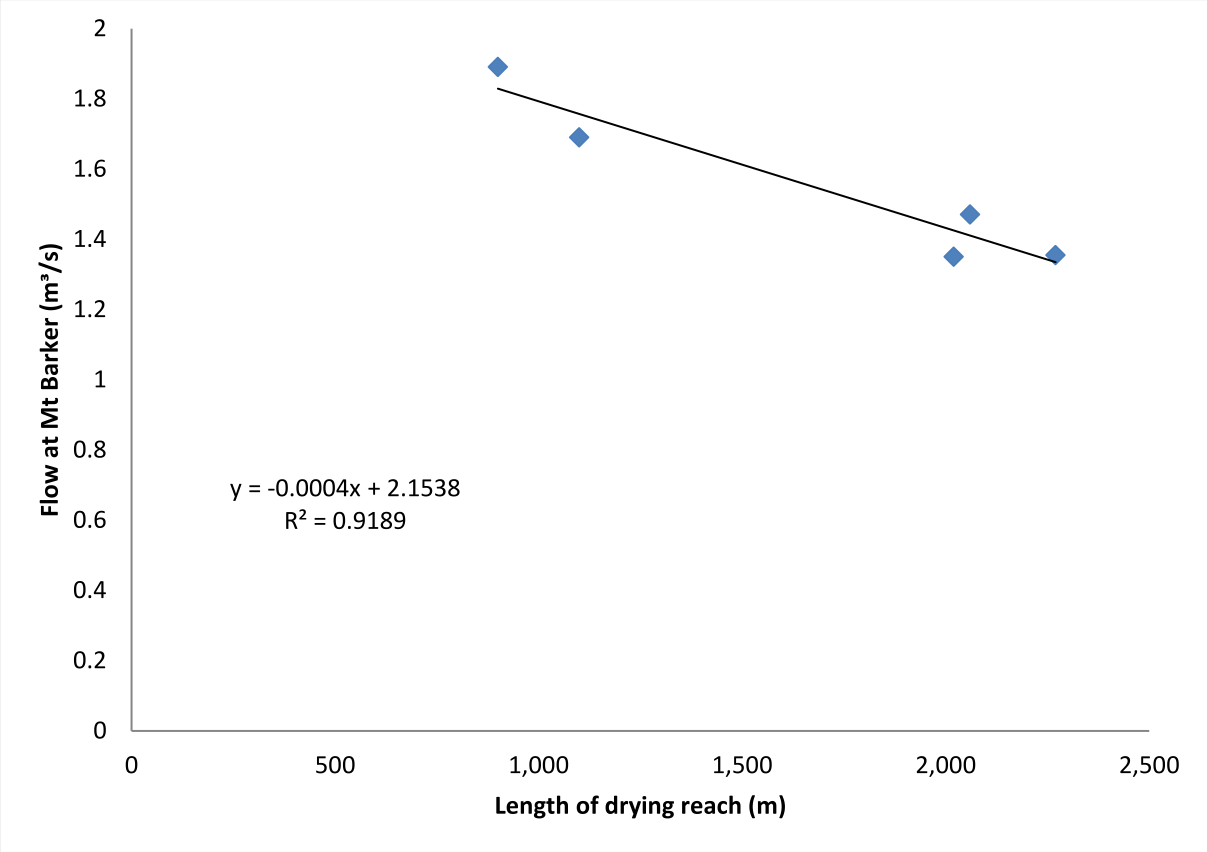

Figure 3.9 **Length of dry river bed in the Cardrona River in relation to actual flows at Mt. Barker minus water-take data**

The river consistently dries at Black Peak Rd Power Lines and recedes from this point upstream. The extent and the frequency of the drying reach are determined by surface flows and the interaction with ground water.

On the 5th January 2017, a 1,100-metre section of the Cardrona River was dry. At this time, the measured flow at Mt. Barker was 1.41 m^3/s; minus measured water abstraction which equates to a surface flow of 1.09 m^3/s entering the losing reach (Figure 3.9). The longest drying reach was 2,270 m recorded during the period 1st – 17th March. The dry reach extended from the power lines upstream to 30 metres above the Ballantyne Road Bridge. During this period, flows below the lowest point of take were 0.725 – 0.634 m^3/s. The highest flow at Mount Barker where a drying reach was observed was 1.78 m^3/s on 13th February 2017, when 900 m of river had no surface flows. This suggests drying flows are likely to occur when flows are below 1.5 m^3/s but may occur when flows are as high, or higher than, 1.78 m^3/s.

Figure 3.10 shows the flow duration curves for both naturalised and observed daily flow time series across the irrigation seasons (Oct – Apr, inclusive) at Mt. Barker, along with their corresponding 7dMALFs and threshold flows of 1.5 and 1.7 m^3/s when a dry reach is likely to occur.

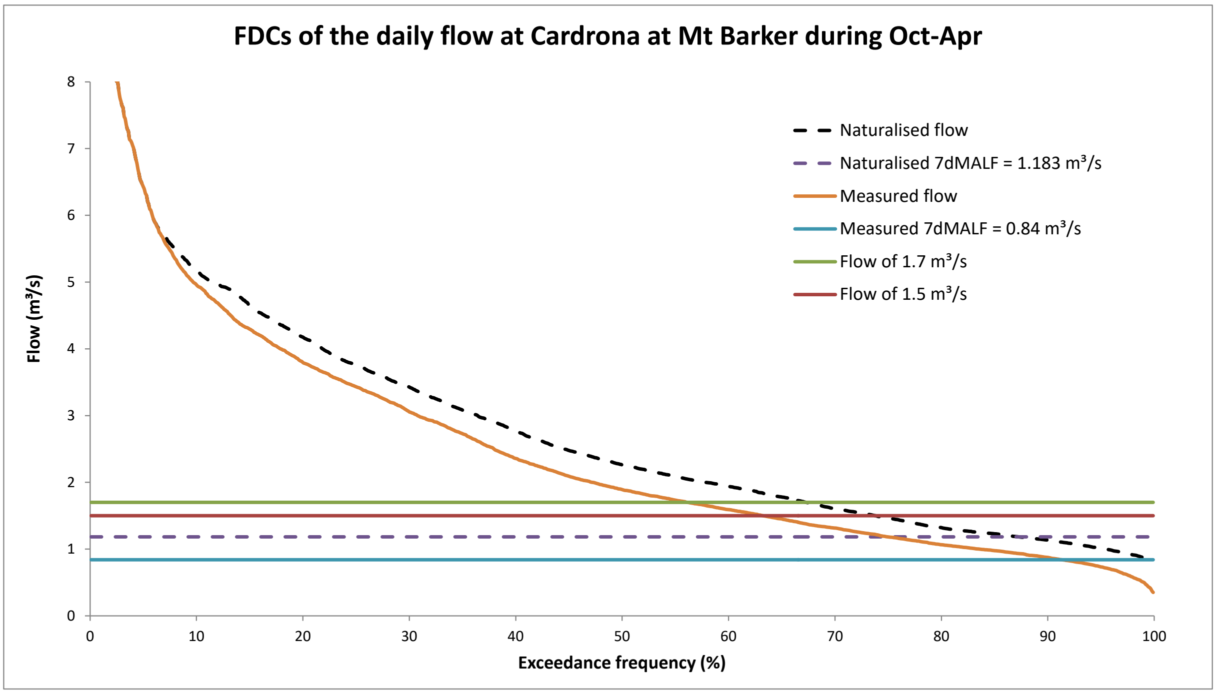

Figure 3.10 **Flow duration curves of the daily flow at Mt. Barker during the irrigation season (October-April).**

Figure 3.10, shows on average, for 91% and 87% of the time the observed and naturalised daily average flows are above their respective 7dMALFs. Naturalised flows are expected to be above 1.5 m^3/s and 1.7 m^3/s for 74 % and 67% of the time.

Table 3.5 presents the number of consecutive days when naturalised flows at Mt Barker were below three different flow rates. On average, there will 13.6 maximum consecutive days when flows are below 1.18 m^3/s; 31.8 maximum consecutive days/year when flows are below 1.5 m^3/s and 39.1 maximum consecutive days/year when flows are below 1.7 m^3/s.

From October to April and when flows are below 1.18 m^3/s we are likely to observe 35.5 days/year when flows are likely to be less than this. When flows are below 1.5 m^3/s and 1.7 m^3/s then, the number of days when flows will be less than this are 64.9 and 78.1, respectively.

Table 3.5 The maximum consecutive number of days where flows are below; <1.183 m^3/s; < 1.5 m^3/s; <1.7 m^3/s (Mt Barker)

Period October – April	No. of days when flows are < 1.183 m^3/s	Maximum consecutive No. of days < 1.183 m^3/s	No. of days when flows are < 1.5 m^3/s	Maximum consecutive No. of days < 1.5 m^3/s	No. of days when flows are < 1.7m^3/s	Maximum consecutive No. of days < 1.7 m^3/s
2000 – 01	26	9	64	32	64	32
2001 – 02	15	11	40	35	54	36
2002 – 03	14	10	77	28	87	34
2003 – 04	3	3	28	13	50	23
2004 – 05	0	0	0	0	0	0
2005 - 06	100	39	132	66	151	86
2006 – 07	53	17	79	40	89	47
2007 – 08	72	35	94	38	107	38
2008 – 09	1	1	28	10	55	27
2009 – 10	76	30	89	58	96	71
2010 – 11	0	0	10	7	14	14
2011 – 12	0	0	41	13	72	18
2012 – 13	25	9	69	37	83	42
2013 – 14	49	16	67	34	76	34
2014 – 15	55	17	96	48	112	49
2015 – 16	105	28	139	66	143	66
2016 - 17	10	6	51	15	75	48
Average No. days	35.5	13.6	64.9	31.8	78.1	39.1

3.3. Summary

The measured total take in the Cardrona River is highest in the December-March irrigation period, with an average of 0.54 m^3/s being abstracted. This period aligns with seasonal low flows. In addition to abstraction, a further portion of surface flow is lost to ground between Mt. Barker and Ballantyne Rd when flows at Mt. Barker are at or below 1.5 m^3/s. When at or below 7dMALF, this loss to ground ranges from 0.52 m^3/s to 0.77 m^3/s totalling in a 62-92% loss of the measured 7dMALF in this reach and 44-65% of loss of the naturalised 7dMALF in this reach alone.

The loss of surface flows continues within the reach from Ballantyne Road to Black Peak Road power lines. It is difficult to quantify the maximum rate of loss in this reach as it is dependent on surface flows at Mt Barker, groundwater levels and saturation. However, the range of loss that was observed varied from 0.01 m^3/s – 1.2 m^3/s. Temperatures downstream of Ballantyne Road show drying reaches occur when flows are at, or slightly above, 1.5 m^3/s at Mt Barker. Observations show up to 2,270 metres of river bed was dry when surface flows were 1.36 m^3/s at Mt. Barker and again 800 metres of river bed was dry when surface flows at Mt. Barker were 1.78 m^3/s.

Flows start receding in November and continue to do so through the end of April, before increasing again in May onwards. The February – April period is where flows are lowest with February being marginally drier than any other month.

The flow duration curves are summarised in Table 3.5 where the naturalised 7dMALF at Mt Barker is 1.18 m^3/s and likely to occur, on average, every 1.5 years. Flows of 1.5 m^3/s are likely to occur annually. In a typical season there will be a maximum of 13.6 consecutive days when flows are <1.18 m^3/s; a maximum of 31.8 consecutive days when flows are <1.5 m^3/s and a maximum of 39.1 consecutive days when flows are <1.7 m^3/s. On average there is likely to be 35.5 days, 64.9 days and 78.1 days per year when flows are less than the naturalised flows of 1.18 m^3/s, and threshold values of 1.5 m^3/s and 1.7 m^3/s respectively. These durations will be longer with the current flow regime.

Groundwater levels influence flow continuity during the period of October – April in the reach between Ballantyne Road and Black Peak Road Power Lines. The results of this study suggest surface reaches of the Cardrona River downstream of Ballantyne Road are expected to dry naturally in most years, even under naturalised conditions, due to losses to groundwater or the hyporheic zone.

4. Water temperature

Water temperature is a fundamental factor affecting all aspects of stream systems. It can directly affect fish populations by influencing survival, growth, spawning, egg development and migration. It can also affect fish populations indirectly, through effects on physicochemical conditions and food supplies (Olsen *et al.*, 2012).

Of all the fish in the Cardrona catchment, brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) are likely to be the most sensitive to high water temperatures. Their thermal requirements are relatively well understood, and Todd *et al.* (2008) calculated acute and chronic thermal criteria for both of these species. The objective of acute criteria is to protect species from the lethal effects of short-lived high temperatures. In this case, acute criteria are applied as the highest two-hour average water temperature measured within any 24-hour period (Todd *et al.*, 2008). In contrast, the intent of chronic criteria is to protect species from sub-lethal effects of prolonged periods of elevated temperatures. In this study, chronic criteria are expressed as the maximum weekly average temperature (Todd *et al.*, 2008). Most native fish species with available thermal tolerance data are more tolerant of high temperatures than trout (Olsen *et al.* 2012).

Water temperatures, recorded every five minutes, between Mt. Barker and Ballantyne Road suggest flow was maintained throughout the irrigation season. All temperatures are well within the acute and chronic thermal ranges of both brown and rainbow trout (Figure 4.1). This suggests that trout mortality in these reaches is unlikely to increase solely due to temperature. Drying reaches, as discussed in the previous section, are likely to pose a greater challenge to trout. Native species present in the main stem of the Cardrona River, such as longfin eel and bully species have a higher thermal tolerance than trout and therefore are unlikely to be negatively affected by temperature (Olsen *et al.* 2012).

4.1. Mt. Barker to Ballantyne Road

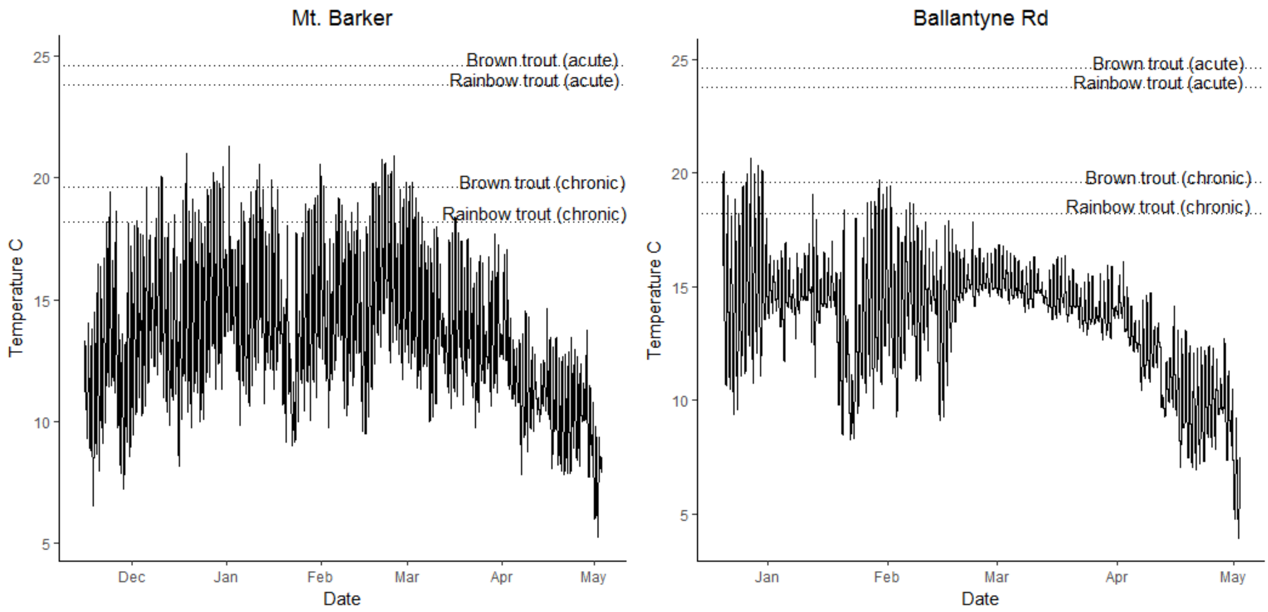

Figure 4.1 **Water temperature for the 2016-2017 irrigation season at Mt. Barker and Ballantyne Rd with chronic and acute temperatures for both brown and rainbow trout**

5. Aquatic ecosystem values of the Cardrona River

Schedule 1A of the Regional Plan: Water for Otago (RPW) outlines the natural and human use values of Otago's surface water bodies. The Cardrona River is identified as having the following values:

- Boulder, gravel and sand bed composition of importance to resident biota,
- presence of significant areas for fish spawning and development of juvenile trout,
- absence of aquatic pest plants identified in the Pest Plant Management Strategy for the Otago region,
- significant presence of trout,
- significant presence of eels,
- presence of indigenous fish species threatened with extinction,
- A high degree of naturalness above 900 m a.s.l.

5.1. Native fish

Native fish recorded from the catchment have included longfin eel, Clutha flathead galaxias (*Galaxias* sp. D), koaro, common and upland bully (NZFFD). The significant presence of Clutha flathead galaxias is listed as a value of the catchment in Schedule 1A of the RPW. Clutha flathead galaxias are classified as 'nationally critical' (the highest threat classification in the New Zealand threat classification system; Townsend *et al.* 2008) in the most recent assessment of the conservation status of freshwater fish in New Zealand, while longfin eel and koaro were classified as 'declining' (Goodman *et al.* 2014). Upland bullies are classified as 'not threatened' (Goodman *et al.* 2014).

Clutha flathead galaxias are restricted to remote headwater tributaries of the Cardrona, likely due to the presence of trout and potentially koaro. Koaro require a lake or ocean environment to successfully reproduce. Due to the establishment of Lake Dunstan downstream, koaro are now able to inhabit the Cardrona and may be further extirpating Clutha flathead galaxias, as koaro are known to be piscivorous and potentially adversely affect non-migratory galaxiids, through competition and potentially predation. Koaro, also known as the climbing galaxiid, can climb vertical surfaces and thus conventional barriers used to stop trout movement are unlikely to stop koaro.

It is probable that longfin eels would also be present in the Cardrona catchment if it were not for the presence of Roxburgh and Clyde Dams, which block upstream passage from the sea. Although a trap and transfer programme is operated at Roxburgh Dam, eel numbers in the upper Clutha catchment, (above Roxburgh Dam) have declined markedly since its construction. Commercial eel fishing has contributed to the decline in the overall numbers; however, construction of Roxburgh and Clyde Dams has accelerated the loss by preventing natural recruitment of young eels.

5.2. Sports fish

The Cardrona River supports a locally important sport fishery (Otago Fish & Game Council 2015). Angler use has increased over time and it has become more popular with fishing guides. Table 5.1 presents angler effort on the Cardrona River, recorded during National Angler Surveys conducted in 1994/95, 2007/08 and 2014/15. Overall angler usage is relatively low, with anglers targeting the early part of the fishing season, with 95% (Unwin, 2016) of angling effort being undertaken in the period from October to November, taking advantage of the adult sized trout. It's probable that these fish have remained in the river after spawning and will, overtime, move out of the catchment prior to December. However, there is a resident population of both brown and rainbow trout that remain within the catchment. These trout rarely obtain a catchable length and consequently provide little value to anglers.

Table 5.1 Angler effort on the Cardrona River based on the National Angler Survey (Unwin, 2016)

Source	Angler usage (angler days±SE)			
	1994/95	2001/02	2007/08	2014/15
NZ resident	30±30		30±30	200±+180

The Cardrona River provides juvenile recruitment for both the rainbow and brown trout fishery of the Upper Clutha system. The upper Clutha River sports fishery is nationally significant (Otago Fish & Game Council 2015).

Spawning of rainbow trout generally occurs within the Cardona River from late August to November but the key period is between October to November (pers. comm. Cliff Halford, Otago Fish and Game). Rainbows spawn throughout the catchment with densities of redds being higher in the upper catchment; the Branch Burn is known as a particularly significant spawning stream.

Brown trout spawn earlier than rainbow trout with the key spawning period being May to June. Brown trout redds have been observed throughout the catchment with the majority of spawning above Mt. Barker.

There is also a single record of brook char *(Salvelinus fontinalis)* which was observed 1991. There have been no observations of this species subsequently.

5.3. Summary of aquatic ecosystem values

The Cardrona River is a locally important brown and rainbow trout fishery based on the most recent angling survey. However, it also contributes to the recruitment of the nationally significant fishery in the upper Clutha River (Otago Fish & Game Council 2015). Koaro, longfin eel, upland bully, common bully and Clutha flathead galaxias comprise the native fish community. Clutha flathead galaxias is nationally critically endangered while koaro and longfin eel are both declining. Clutha flathead galaxias, are found within the reach of the main stem affected by flow alteration but are limited by presence of trout and potentially koaro, as opposed to habitat, and thus are not included in the instream habitat assessment. The values of the Cardrona River, and recommended level of habitat retention relative to the naturalised 7dMALF, are summarised in Table 5.2.

Table 5.2 Assessment of instream habitat values in the Cardrona River, with recommended levels of habitat retention (based on the approach of Jowett & Hayes, 2004). The % habtiat retention is expressed relative to the habitat at the naturalised 7dMALF.

Instream value	Fishery or conservation value	Recommended % habitat retention
Brown trout - adult	Locally significant†	70
Brown trout - juvenile	Locally significant†, recruitment to upper Clutha River*	90
Brown trout - spawning (May-August)	Locally significant†, recruitment to upper Clutha River*	90
Longfin eel	Declining‡	80
Koaro	Declining‡	80
Upland bully	Low	60

† Based on the assessment in Otago Fish & Game Council (2015).

* The fishery of the upper Clutha is assessed as being nationally significant (Otago Fish & Game Council 2015).

‡ Based on Goodman *et al.* (2014).

6. Instream habitat modelling

Instream habitat assessments were conducted for a single reach of the Cardrona River by ORC (2001). The study reach covered a 2 km reach downstream from Chinaman Gully, immediately upstream of the Mt. Barker flow recorder site. This reach is representative of much of the main-stem of the Cardrona River upstream of the Mt. Barker flow recorder.

6.1. Instream habitat modelling

Instream habitat modelling can be used to consider the effects of changes in flow on instream values, such as physical habitat, water temperature, water quality and sediment processes. The strength of instream habitat modelling lies in its ability to quantify the loss of habitat caused by changes in the flow regime, which helps to evaluate alternative flow proposals. However, for an assessment to be credible, it is essential to consider all factors that may affect the organism(s) of interest, such as food, shelter and living space, and to select appropriate habitat-suitability curves. Habitat modelling does not take a number of other factors into consideration, including the disturbance and mortality caused by flooding and biological interactions (such as predation), which can have a significant influence on the distribution of aquatic species.

Instream habitat modelling requires detailed hydraulic data, as well as knowledge of the ecosystem and the physical requirements of stream biota. The basic premise of habitat methods is that a given species cannot exist without a suitable physical habitat (Jowett & Wilding, 2003). However, if there is physical habitat available for that species, it may or may not be present in a survey reach, depending on other factors not directly related to flow or to flow-related factors that have operated in the past (e.g., floods). In other words, habitat methods can be used to set the outer envelope of suitable living conditions for the target biota (Jowett, 2005).

Instream habitat is expressed as Reach Area Weighted Suitability (RAWS), a measure of the total area of suitable habitat per metre of stream length. It is expressed as square metres per metre (m^2/m). The reach-averaged Combined Suitability Index (CSI) is another metric and is a measure of the average habitat quality provided at a particular flow. CSI is useful when considering the effects of changes in flow regime on periphyton where it is the percentage cover across the riverbed that is of interest, rather than the overall availability of habitat (such as for fish).

6.2. Habitat suitability curves

Habitat suitability curves (HSC) for a range of organisms present in the Cardrona catchment were modelled (Table 6.1) to understand the full range of potential effects of flow regime changes in the Cardrona catchment – from changes in the cover and type of periphyton, to changes in the availability of macroinvertebrate prey, and to changes in the habitat for native fish and trout. It should be noted that the HSC used in these analyses may differ from those presented in the original reports, as the analyses were re-run using the most up to date HSC.

Table 6.1 Habitat suitability curves used in instream habitat modelling in the Cardrona catchment.

Group	HSC name	HSC source
Periphyton	Cyanobacteria	Ex Heath *et al.* (2013)
	Diatoms	Unpublished NIWA data
	Didymo (Waitaki)	Jowett
	Long filamentous	Unpublished NIWA data
	Short filamentous	Unpublished NIWA data
Macro-invertebrates	Food producing	Waters (1976)
	Cased caddis fly (*Pycnocentrodes*)	Jowett *et al.* (1994)
	Mayfly nymphs *(Deleatidium*)	Jowett *et al.* (1994)
	Mayfly nymphs *(Deleatidium*) (Rainy)	Shearer *et al.* (2015)
	Net-spinning caddis fly (*Aoteapsyche*)	Jowett *et al.* (1994)
Fish	Brown trout adult	Hayes & Jowett (1994)
	Brown trout spawning	Shirvell & Dungey (1983)
	Brown trout Juvenile	Jowett & Richardson (2008)
	Juvenile trout T1	Wilding *et al.* (2014)
	Rainbow trout spawning	Jowett *et al.* (1996)

6.2.1. Periphyton

The periphyton community forms the slimy coating on the surface of stones and other substrates in freshwaters and can include a range of different types and forms. Periphyton is an integral part of many stream food webs; it captures energy from the sun and converts it, via photosynthesis, to energy sources available to macroinvertebrates, which feed on it. These, in turn, are fed on by other invertebrates and fish. However, periphyton can form nuisance blooms that can detrimentally affect other instream values, such as aesthetics, biodiversity, recreation (swimming and angling), water-takes (irrigation, stock/drinking water and industrial) and water quality.

The analyses presented in this report consider HSC for five classes of periphyton: cyanobacteria, diatoms, didymo (*Didymosphenia geminata*, an invasive non-native diatom), short filamentous algae and long filamentous algae (Figure 6.1). These periphyton classes were included in these analyses to consider how changes in flow may affect periphyton cover and composition, and the potential impacts on other instream values.

Cyanobacteria were included because some types may produce toxins that pose a health risk to humans and animals. These include toxins that affect the nervous system (neurotoxins), liver (hepatotoxins), and dermatotoxins that can cause severe irritation of the skin.

The presence of potentially toxic cyanobacteria is undesirable as it can affect the suitability of a waterway for drinking, recreation (swimming), dogs, stock drinking water and food-gathering (by affecting palatability or through accumulation of toxins in organs such as the liver). Cyanobacteria-produced neurotoxins have been implicated in the deaths of numerous dogs in New Zealand (Hamill, 2001; Wood *et al.*, 2007).

Native diatoms are generally considered a desirable component of the periphyton community, while didymo is an invasive, non-native diatom that can form dense, extensive mats (Figure 6.1) that can affect recreational and ecosystem values, as well as water use (ORC, 2007; Larned *et al.*, 2007).

Filamentous algae, and in particular long filamentous algae, can form nuisance blooms during periods of stable flows and under nutrient conditions. Such blooms can affect a range of instream values, including aesthetics, biodiversity, recreation (swimming and angling), water-takes (irrigation, stock/drinking water and industrial) and water quality.

Figure 6.1 **Periphyton types considered in these analyses: a) benthic cyanobacteria (*Phormidium*), b) native diatoms, c) underwater photograph showing an extensive growth of didymo in the Hawea River and d) long and short filamentous algae (and cyanobacteria).**

6.2.2. Macroinvertebrates

Macroinvertebrates are an important part of stream food webs, linking primary producers (periphyton and terrestrial leaf litter) to higher trophic levels (fish and birds), and were included in these analyses to consider how changes in flow in the modelled reaches may affect food availability for fish and birds. HSC for “food producing habitat” (conditions representative of the most productive habitats in rivers) and four widespread and common macroinvertebrate taxa were included in this analysis. Two HSC were run for the mayfly *Deleatidium*: one was produced using data from large rivers (Jowett *et al.* 1994), the other from a small river in Nelson (Rainy River; Shearer *et al.* 2015).

Figure 6.2 **Macroinvertebrate taxa considered in these analyses: a) a nymph of the common mayfly (Deleatidium), b) a larva of the net-spinning caddis fly (Aoteapsyche) and c) larvae of the sandy-cased caddis fly (Pycnocentrodes).**

6.2.3. Native fish

HSC are available for flathead galaxias, koaro and longfin eels. However, the habitat suitability curves available for koaro (Richardson & Jowett, 1995) were not included in these analyses, as they were based on data from steep cascade habitat in the Onekaka River (Golden Bay) and their applicability to the type of habitat present in the Cardrona River is uncertain.

Clutha flathead galaxias (*Galaxias* sp. D) are present in the Cardrona catchment, although numbers in the main stem are low, likely as a result of interactions with trout. It is likely that habitat is not the main factor currently affecting the distribution and abundance of Clutha flathead galaxias in the main stem of the Cardrona, but rather it is the presence of trout that is the main driver determining the presence and/or abundance of Clutha flathead galaxias in the Cardrona River. For this reason, habitat-flow relationships for Clutha flathead galaxias are not presented.

Habitat is also not currently the main factor affecting the distribution and abundance of longfin eels in the Cardrona catchment. Recruitment of longfin eels to the upper Clutha and Kawarau catchments is low due to the presence of Roxburgh and Clyde Dams.

6.2.4. Sports fish

Both brown and rainbow trout are found in the Cardrona catchment. Several HSC for different life stages of brown trout and for adult rainbow trout were included in these analyses to consider how changes in flow in the modelled reaches will affect habitat availability for sports fish.

6.3. Approaches to flow setting

There are a number of approaches to determining the appropriate flows to achieve management objectives. A simple approach is to identify the flow that provides the maximum (or optimum) habitat for a particular species. However, providing such flows is often unrealistic for flow-demanding species, as optimum habitat may occur at a flow well in excess of those commonly experienced. As a result, this approach is usually only applied when optimum habitat occurs at flows below the 7dMALF.

Another common approach is to identify the "tipping point", the flow below which the rate of habitat decline accelerates as flows reduce, often incorrectly referred to as the inflection point. A disadvantage of this approach is that it can be difficult to identify the exact point at which this occurs, and assessments can differ between practitioners.

Probably the most common, transparent and defensible method is to calculate the amount of habitat retained relative to some baseline flow. For fish species, this baseline flow is usually the naturalised 7dMALF.

6.4. Physical characteristics

The hydraulic component of instream habitat modelling made predictions about how water depth, channel width and water velocity will change with changes in flow (Figure 6.3). The most notable pattern is that there is a gradual decline in channel width, water velocity and depth with declining flows down to 0.40 m^3/s below which width and depth begin to drop more rapidly (Figure 6.3).

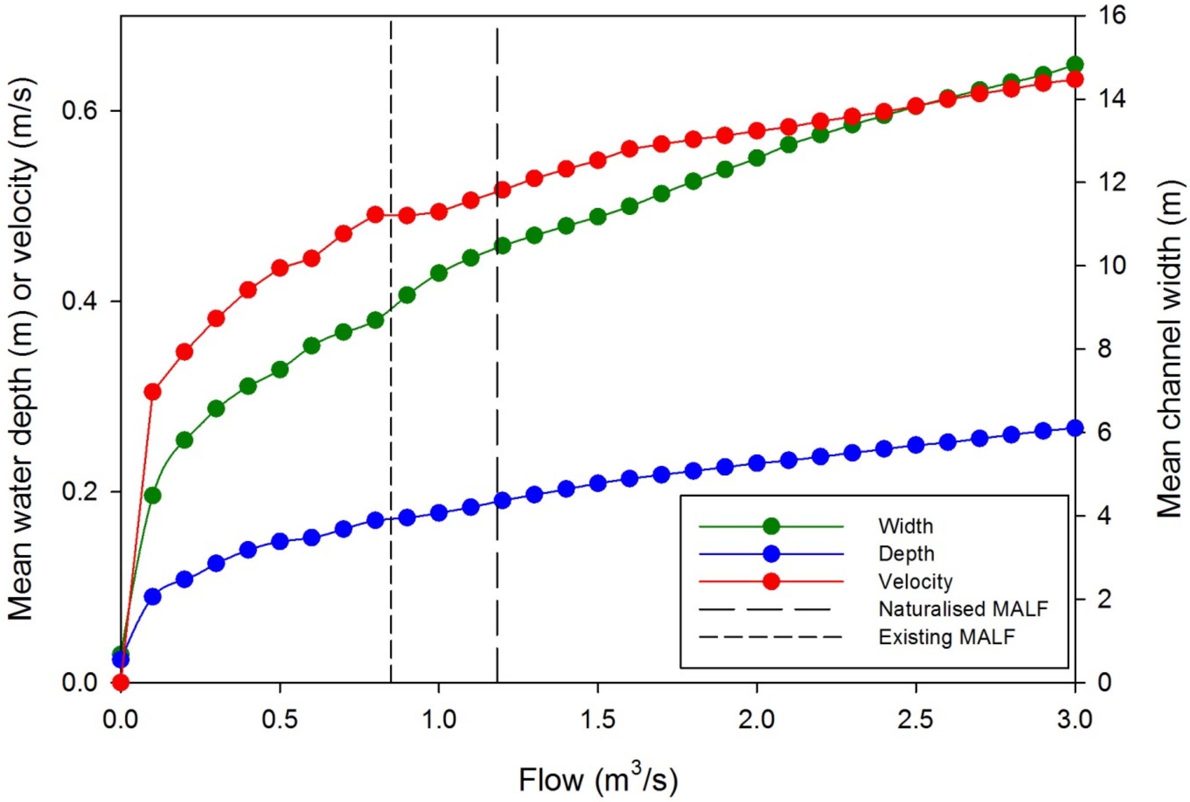

Figure 6.3 **Changes in mean channel width, wetted perimeter, mean water depth and mean water velocity with changes in flow in the Cardrona River.**

6.5. Periphyton

The main purpose of considering periphyton is to understand how changes in flow are likely to affect how much of the river bed is covered by periphyton, and the relative contribution of the different types of periphyton to the overall community. Given this, it is the percentage of the wetted channel covered by periphyton, not the total area of suitable habitat that is of interest. For this reason, the habitat suitability index (reach-averaged CSI) was used instead of weighted usable area (RAWS) in instream habitat analyses for periphyton.

Flow was predicted to have little effect on habitat quality for cyanobacteria (*Phormidium*) with habitat quality predicted to decline below 0.2 m^3/s (Figure 6.4). Flow was predicted to have little effect on habitat quality for didymo at flows between 0.5 m^3/s and 2 m^3/s, although habitat quality for didymo was predicted to decline as flows reduced below 0.5 m^3/s, or rose above 2.0 m^3/s (Figure 6.4). Habitat quality for native diatoms was predicted to increase with flow up to 2.0 m^3/s and remained constant at flows of between 2.0 m^3/s and 3.0 m^3/s (Figure 6.4). Habitat quality for short filamentous algae was predicted to increase with increasing flows to 0.5 m^3/s before declining as flows rose above 0.8 m^3/s, while habitat quality for long filamentous algae was predicted to be highest in the absence of flow and to decline as flows dropped to 0.7 m^3/s, with little change in habitat quality for long filamentous algae at higher flows (Figure 6.4).

This analysis suggests that when flows are less than 0.433 m^3/s in the Cardrona there is a significantly higher risk of proliferation of long filamentous algae, compared with the habitat available at the naturalised7dMALF, and this risk is predicted to rise further as flows drop below this value, with habitat quality for long filamentous algae at 0.26 m^3/s predicted to be approximately twice that at the naturalised 7dMALF (Table 6.2).

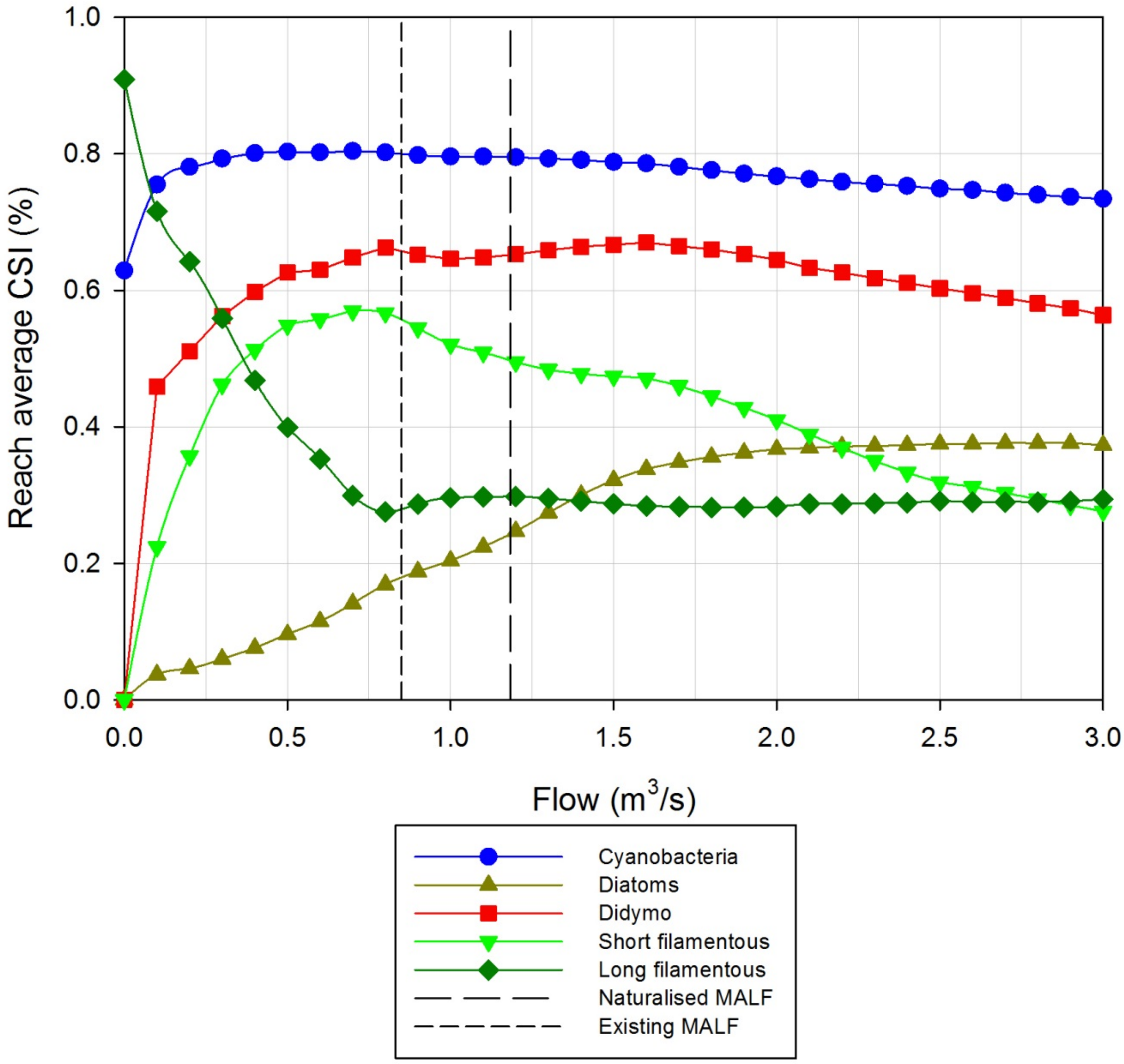

Figure 6.4 **Variation in instream habitat quality (reach-averaged CSI) for periphyton classes relative to flow in the Cardrona River. The long dash line represents the naturalised MALF.**

Table 6.2 **Flow requirements for periphyton habitat in the Cardrona River. Flows required for the various habitat retention values are given relative to the naturalised 7dMALF.**

Species	Optimum flow (m^3/s)	Flow below which habitat rapidly increases (m^3/s)	Flow at which % habitat retention occurs (m^3/s)		
			150%	200%	300%
Cyanobacteria	-	-	-	-	-
Diatoms	>2	-	-	-	-
Didymo	-	-	-	-	-
Short filamentous	0.70 -0.80	-	-	-	-
Long filamentous	0	0.80	0.433	0.258	0.009

6.6. Macroinvertebrates

Food producing habitat is predicted to increase with increasing flow to 2.1 m^3/s, above which habitat is predicted to decline (Figure 6.5). Habitat for net-spinning caddis fly larvae was predicted to increase with increasing flow across the modelled flow range (Figure 6.5). The habitat for the common mayfly *Deleatidium* is predicted to increase with increasing flow across the modelled flow range by the Jowett *et al.* (1994) HSC, while the small-river HSC of Shearer *et al.* (2015) predicted that habitat for *Deleatidium* would increase rapidly with increasing flows up to 0.7 m^3/s, after which habitat was predicted to rise more slowly with increasing flows up to 1.3 m^3/s and was then relatively consistent up to 3 m^3/s (Figure 6.5). Of these two sets of HSC, those of Jowett *et al.* (1994) are more conservative than those of Shearer *et al.* (2015). Habitat for the cased caddis *Pycnocentrodes* was predicted to rise with increasing flows, reaching a peak at 1.3 m^3/s, above which habitat was predicted to relatively consistent (Figure 6.5).

Flows of 0.7-0.8 m^3/s were predicted to retain 80% of the food producing (0.8 m^3/s) and *Pycnocentrodes* (0.711 m^3/s) habitat available in the lower Cardrona River relative to the habitat at the naturalised 7dMALF (Table 6.3). The flow requirement of the other species considered varied widely, from 0.595 m^3/s for the cased caddis fly *Pycnocentrodes* and 0.951 m^3/s for the net-spinning caddis fly *Aoteapsyche* (Table 6.3).

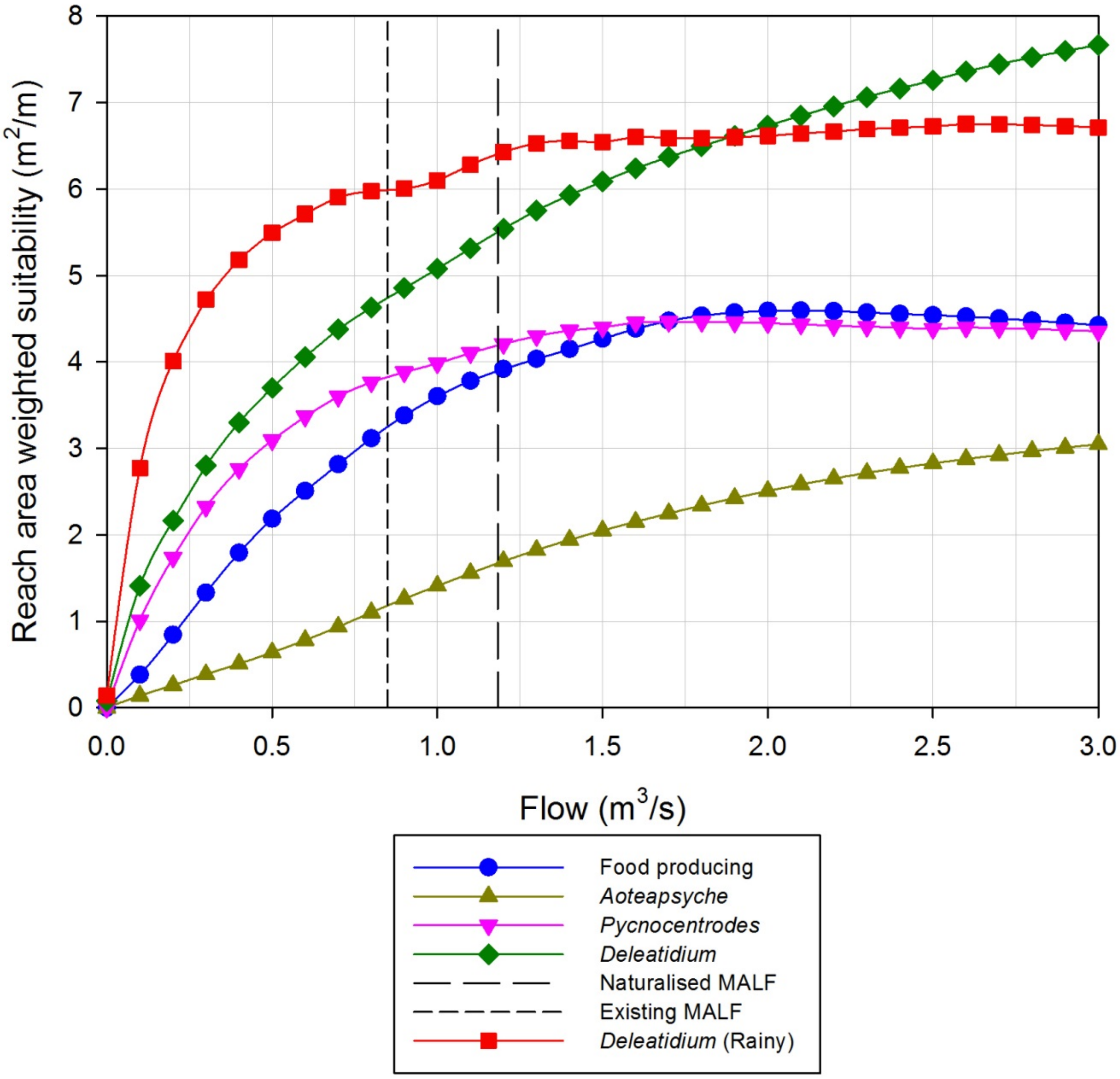

Figure 6.5 **Variation in instream habitat for common macroinvertebrates relative to flow in the survey reach of the Cardrona River. The long dashed line represents the naturalised MALF.**

Table 6.3 **Flow requirements for macroinvertebrate habitat in the Cardrona River. Flows required for the various habitat retention values are given relative to the naturalised 7dMALF (i.e., flows predicted in the absence of any abstraction).**

Species	Optimum flow (m^3/s)	Flow below which habitat rapidly declines (m^3/s)	Flow at which % habitat retention occurs (m^3/s)			
			60%	70%	80%	90%
Food producing	2.1	-	0.547	0.671	0.800	0.956
Mayfly nymphs *(Deleatidium)*	>3.0	-	0.401	0.542	0.711	0.944
Mayfly nymphs *(Deleatidium)* Rainy R	2.6	0.700	0.186	0.266	0.387	0.627
Net-spinning caddis fly *(Aoteapsyche)*	>3.0	-	0.740	0.843	0.951	1.07
Cased caddis fly (*Pycnocentrodes*)	1.750	-	0.344	0.452	0.595	0.806

6.7. Sports fish

Habitat for adult brown trout was predicted to increase with flows to 1 m^3/s, but remain relatively constant between flows of 1-3 m^3/s, while the adult trout (both brown and rainbow trout) curve of Wilding *et al.* (2014) predicted that habitat would increase with increasing flows across the modelled flow range (Figure 6.6). Habitat for juvenile brown and rainbow trout was also predicted to increase with flows across the modelled flow range, although the rate of increase was greatest up to 1 m^3/s (Figure 6.6). In contrast, the juvenile brown trout HSC of Jowett & Richardson (2008) predicted that habitat for juvenile brown trout would peak at a flow of 1.6 m^3/s before declining at higher flows (Figure 6.6). Predicted brown trout spawning habitat increased rapidly with increasing flows to reach an optimum at 0.5 m^3/s before declining as flows rise to 1.3 m^3/s before rising again with rising flows up to 2.9 m^3/s (Figure 6.6).

Flows of between 0.661 m^3/s (Hayes & Jowett 1994) and 0.789 m^3/s (Wilding *et al.* 2014, T1) were predicted to retain 70% of the adult trout habitat compared with habitat available at the naturalised 7dMALF in the lower Cardrona River, and flows of between 0.79m^3/s (Jowett & Richardson 2008) and 1.04 m^3/s (Wilding *et al.* 2014) were predicted to retain 90% of the juvenile trout habitat available compared with habitat available at the naturalised 7dMALF (Table 6.4).

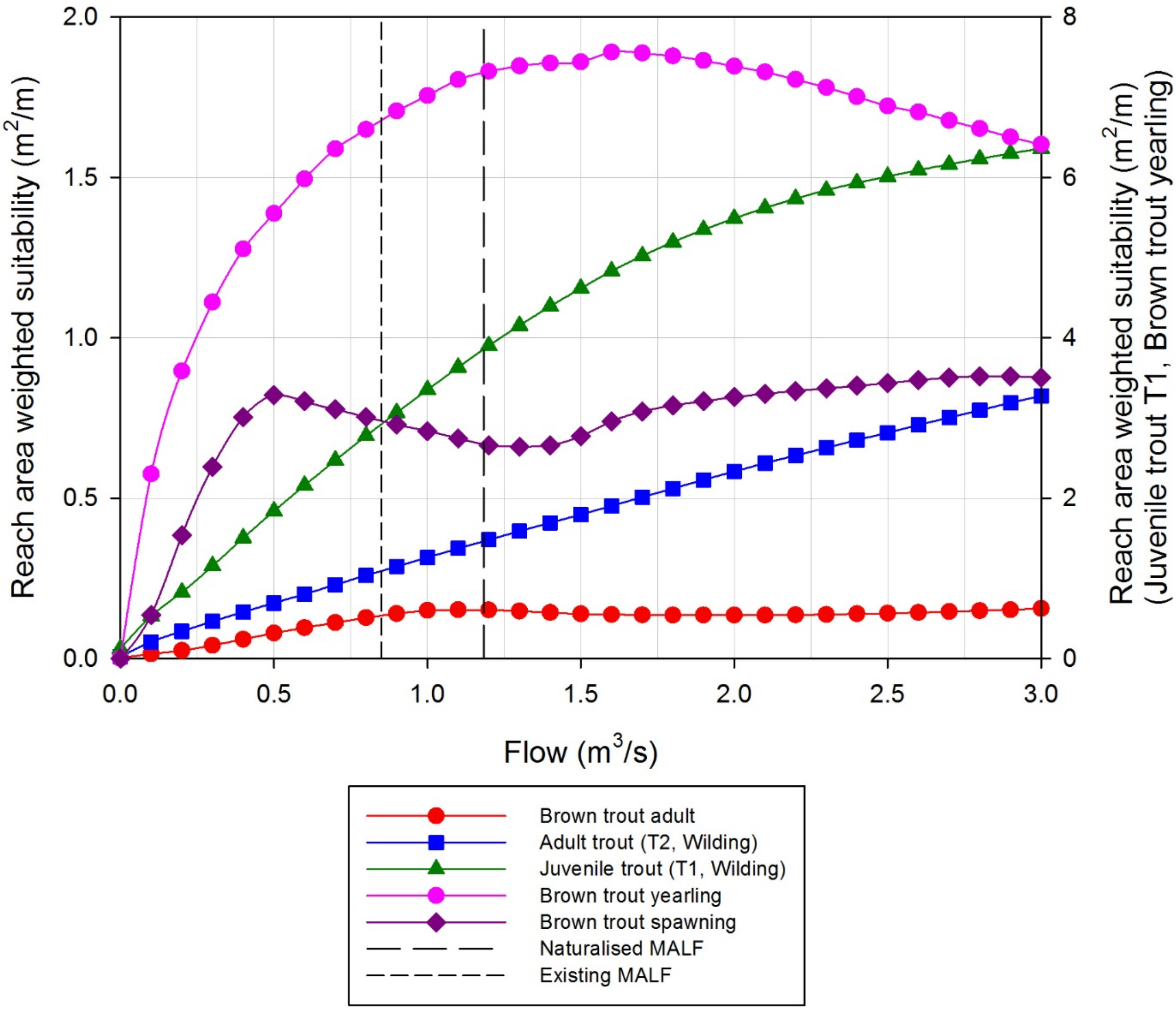

Figure 6.6 **Variation in instream habitat of various life stages of brown trout and rainbow trout relative to flow in the Cardrona River. The long dashed line represents the naturalised MALF.**

Table 6.4 **Flow requirements for trout habitat in the Cardrona River. Flows required for the various habitat retention values are given relative to the habitat available at the naturalised 7dMALF (i.e., flows predicted in the absence of all abstraction). Habitat retention levels for spawning are relative to naturalised mean annual winter (May-September) low flows.**

Species	Optimum flow (m^3/s)	Flow below which habitat rapidly declines (m^3/s)	Flow at which % habitat retention occurs (m^3/s)		
			70%	80%	90%
Brown trout adult (Hayes & Jowett)	>3	1	0.661	0.76	0.87
Adult trout (T2, Wilding)	>3	-	0.789	0.919	1.05
Brown trout juvenile	1.6	0.7	0.401	0.568	0.79
Juvenile trout (Wilding T1)	>3	1.7	0.775	0.906	1.04
Brown trout spawning (May-Sep)	0.5	0.4	0.22	0.248	0.277

6.8. Effects of existing flows

Water users in the Cardrona River are not currently subject to a minimum flow and the river is significantly over-allocated, at least in terms of consented maximum instantaneous rate of take, although measured use is significantly less than the consented use. The existing 7dMALF of the Cardrona River retains appropriate levels of habitat within the modelled reach (Table 6.5). However, it should be kept in mind that the existing 7dMALF represents average low flow conditions, not the low flows experienced in exceptionally dry years.

Table 6.5 Habitat retention in the Cardrona River under the existing 7dMALF relative to the naturalised 7dMALF

Group	HSC name	% retention under existing 7dMALF compared with naturalised 7dMALF
Periphyton	Cyanobacteria	101%
	Diatoms	80%
	Didymo (Waitaki)	101%
	Long filamentous	95%
	Short filamentous	109%
Macro-invertebrates	Food producing	83%
	Mayfly nymphs *(Deleatidium)*	86%
	Mayfly nymphs *(Deleatidium)* Rainy	94%
	Net-spinning caddis fly (*Aoteapsyche*)	71%
	Cased caddis fly (*Pycnocentrodes*)	91%
Fish	Brown trout adult	88%
	Adult trout (T2, Wilding)	75%
	Rainbow trout feeding	82%
	Brown trout Juvenile	92%
	Juvenile trout (T1, Wilding)	76%
	Brown trout spawning	111%

6.9. Summary of instream habitat assessments

The Cardrona River dries naturally within the reach from Ballantyne Road and Black Peak Road power lines. Therefore, the following conclusion is for the reach of the river above Mt Barker.

Appropriate objectives for the management of the aquatic ecosystems of the Cardrona River include maintaining the locally-significant trout fishery and to protect its life-supporting capacity including macroinvertebrate populations and limiting the risk of periphyton proliferation. In addition, the Cardrona River contributes to the recruitment of the nationally significant fishery in the upper Clutha River (Otago Fish & Game Council 2015).

A flow of 1 m^3/s in the Cardrona would provide 90% habitat retention (relative to the natural 7dMALF) for adult and juvenile trout, as well as providing excellent amounts of habitat for macroinvertebrates and keeping the risk of periphyton proliferation at a level similar to that at present (Table 6.6). In comparison, a flow of 0.9 m^3/s in the Cardrona would provide 80% habitat retention (relative to the natural 7dMALF) for adult and juvenile trout, whilst also providing excellent amounts of habitat for macroinvertebrates and keeping the risk of periphyton proliferation at a level similar to that at present (Table 6.6).

Flows of 0.9 m^3/s or 1 m^3/s are predicted to maintain existing trout spawning habitat. However, given that demand for water is expected to be low in winter, it is likely that any minimum flow would have minimal effect on winter flows (Table 6.6).

Table 6.6 Flow requirements to maintain the values of the Cardrona River based on the instream habitat model of Jowett & Wilding (2003)

Instream value	Season	Fishery or conservation value	Recomm. % habitat retention	Flow to maintain suggested habitat retention (m^3/s)	Flow below which habitat rapidly declines (m^3/s)	Optimum flow (m^3/s)
Adult trout - adult	All year	Locally significant†	70%	0.789	-	>3
Juvenile trout	All year	Locally significant†	90%	1.04	1.7	>3
Brown trout - spawning (May-Sep)	Winter	Locally significant†	90%	0.277	0.4	-
Food producing	All year	Life supporting capacity	70%	0.671	-	2.1
Long filamentous algae	Summer	Nuisance	<150%	>0.433	0.8	-

† Based on the assessment in Otago Fish & Game Council (2015).

7. Conclusions: Flow requirements for aquatic ecosystems in the Cardrona catchment

Under the Water Plan, rivers will have minimum flows set to provide for the maintenance of aquatic ecosystems and natural character under low-flow conditions. Similarly, residual flows can be imposed on resource consents for water-takes from tributary streams for the same reasons. The purpose of this report is to update the previous Cardrona report and provide information on the Cardrona catchment that assists in setting minimum flows including the existing use of water resources, the values present in the catchment, and the flows required to maintain instream habitat, based on instream habitat modelling.

There are three distinct hydrological reaches in the Cardrona River; the upper reach from the headwaters to Mt. Barker is a neutral reach, a losing reach from Mt. Barker to State Highway 6 and a gaining reach from this point downstream to the confluence with the Clutha River.

Twenty-five existing surface water-takes are present in the Cardrona catchment, with a total allocation of approximately 2.0 m^3/s although the measured usage is considerably lower than this, especially at low flows. There is a reasonably high level of water allocation, and a long history of water use and flow alteration.

Naturalised low-flow statistics were estimated by building a relationship between the Mt. Barker flow site and the Lindis Peak flow site. Analysis was conducted comparing the relationship between to the two sites at low flows from the same event low flow event. Results indicate a strong correlation between the two sites, (R^2=0.9097).

Table 7.1 provides the findings of this analysis which indicates that the measured 7dMALF at Mt. Barker was 0.84 m^3/s whereas the naturalised 7dMALF was 1.18 m^3/s.

Table 7.1 The basic flow statistics summarised for both naturalised and measured flows at Mt. Barker

Mt. Barker	Minimum flow (m^3/s)	Median flow (m^3/s)	Mean (m^3/s)	7dMALF (m^3/s)
Naturalised flows	0.753	2.62	3.32	1.18
Observed flows	0.310	2.34	3.1	0.84

In a typical year, flows are at their lowest from January through to the end of April (Figure 3.2), with February marginally the month where flows are at the lowest. The flow duration curves (Figure 3.1) indicate that on average, 91% and 87% of time the observed and naturalised daily average flows are above their respective 7dMALFs at Mt. Barker. When flow parameters are 1.5 m^3/s and 1.7 m^3/s respectively then naturalised flows were shown to be exceeded for 74 % and 67% of the time meaning a dry reach is likely to be present.

The low flow frequency time series analysis (Table 3.2) show there is a 1 in 2, or 50%, chance of naturalised flow of 1.1 m^3/s occurring in a given year; 1/5 (20%) chance of flows 0.92 m^3/s occurring in a given year, and 1/10 (10%) chance of flows of 0.85 m^3/s occurring in a given year.

The findings of this study established a relationship between the loss of surface flows to groundwater between Mt. Barker and Ballantyne Road. When flows were at or below 7dMALF of 1.18 m^3/s at Mt Barker, the loss to ground water between Mt Barker and Ballantyne Road ranged from approximately 0.52 m^3/s to 0.77 m^3/s (Figure 3.5). There was no consistent relationship between the losses to groundwater with the increase in surface flows above 1.18 m^3/s. The rate of loss to groundwater is highly dependent on groundwater level and other ground water related factors which cannot be addressed by this study.

The river consistently dries at Black Peak Road Power Lines and recedes from this point upstream generally to Ballantyne Road. The extent and the frequency of the drying reach are determined by high or low surface flows and losses to ground. The surface loss within this reach ranged between 0.01 m^3/s and 1.2 m^3/s. Water temperature data collected during the 2016–17 period from Black Peak Road Power Lines site indicated that surface flows ceased for 43–69 days. Temperature data shows that flow connectivity was likely when flows were at or above 1.5 m^3/s (Figure 3.8). However, the measured distance of the drying reach suggested that flow disconnection can occur even when flows were as high as1.78 m^3/s. The flow where disconnection occurs is influenced by groundwater levels and therefore is variable. However, based on this study, the best estimate of when flow disconnection likely to occur is 1.5 m^3/s, which is much higher than the naturalised 7dMALF of 1.18 m^3/s.

Flow connectivity is considered to be a key component of the natural character in a water way. Therefore, it is critical to understand whether the waterway dries naturally or due to water abstraction. The data gathered during the summer of 2016-17, indicates that the Cardrona River would go dry naturally between Ballantyne Road and State Highway 6. Flow continuity will cease at times during the October to April period within the naturalised flow range of 1.18 m^3/s (7dMALF) to 1.5 m^3/s. In a typical summer, the river will be dry for 35.5 days (max. 13.6 consecutive days) and when flows are below 1.18 m^3/s and 64.9 days (31.8 maximum consecutive days) when flows are below 1.5 m^3/s (Table 3.5). These drying periods are likely to be even longer under the current flow regime.

There are five native fish species recorded in the Cardrona catchment. Clutha flathead galaxias is classified as “nationally critical”, the highest threat classification available (Goodman *et al.*, 2014). The galaxiid still persists in isolated pockets within the main-stem and occasionally in a small number of tributaries but, overall, it has disappeared from much of its historic range within the Cardrona catchment. Koaro and longfin eels are also present in the catchment and are listed as “At Risk and Declining” in the most recent threat classification (Goodman *et al.*, 2014). Longfin eels have not appeared in a survey since 1992, whereas koaro numbers have increased since the formation of Lake Dunstan. There two species from the bully, common and upland neither of these two species are threatened.

In addition, koura and freshwater mussels have been recorded in several tributaries (NZFFD) but there is doubt whether they actually are present; they have a threat classification of “at risk, declining” (Granger *et al.*, 2014).

The Cardrona River supports a locally important brown and rainbow trout fishery, with the majority of the angling effort occurring in the early part of the season (Unwin, 2016). Adult rainbow and brown trout spawn throughout the Cardrona catchment with the majority of spawning activity occurring above Mt. Barker.

Table 6.6 provides flow requirements to maintain instream values that are located above Mt Barker, based on the instream habitat model of Jowett et al. (2004). Modelling recommends that a flow of 1 m^3/s would provide 90% habitat retention (relative to the natural 7dMALF) for adult and juvenile trout, as well as providing excellent amounts of habitat for macroinvertebrates and keeping the risk of periphyton proliferation at a level similar to that of current conditions. Flows of 0.9 m^3/s or 1 m^3/s are predicted to maintain existing trout spawning habitat.

This report shows the Cardrona dries naturally. A loss of connectivity has implications for fish passage, particularly during the out-migration season of juvenile salmonids (November-December). As the river likely dries naturally from December-January onwards; the setting of two minimum flow thresholds could be considered. A higher minimum flow threshold for the period leading into January which recognises the need to maintain fish passage through the critical drying reaches for as long as possible and second minimum flow beginning in January that recognises that in a typical year, the reach of river below Ballantyne Road will dry naturally.

8. Glossary

Catchment
The area of land drained by a river or body of water.

Existing flows
The flows observed in a river under current water usage and with current water storage and transport.

Habitat suitability curves (HSC)
Representations of the suitability of different water depths, velocities and substrate types for a particular species or life stage of a species. Values vary from 0 (not suitable) to ideal (1). HSC are used in instream habitat modelling to predict the amount of suitable habitat for a species/life stage.

Instream habitat modelling
An instream habitat model is used to assess the relationship between flow and available physical habitat for fish and invertebrates.

Irrigation
The artificial application of water to the soil, usually to assist with the growing of crops and pasture.

Mean flow
The average flow of a watercourse (i.e., the total volume of water measured divided by the number of sampling intervals).

Minimum flow
The flow below which the holder of any resource consent to take water must cease taking water from that river.

Natural flows
The flows that occur in a river in the absence of any water-takes or any other flow modification.

Naturalised flows
Synthetic flows created to simulate the natural flows of a river by removing the effect of water-takes or other flow modifications.

Reach

A specific section of a stream or river.

River
A continually or intermittently flowing body of fresh water that includes a stream and modified watercourse, but does not include any artificial watercourse (such as an irrigation canal, water-supply race, farm drainage canal or canal for the supply of water for electricity power generation).

Seven-day low flow
The lowest seven-day low flow in any year is determined by calculating the average flow over seven consecutive days for every seven-consecutive-day period in the year, and then choosing the lowest of these averages.

Seven-day Mean Annual Low Flow (7-d MALF)

The average of the lowest seven-day low flow for each year of record. Most MALF values reported here are calculated using flows from the irrigation season (October–April) only. This is to avoid the effect of winter low flows that may occur due to water being “locked up” in snow and ice in the upper catchment. However, if significant winter low flows do not occur, estimates of 7-d MALF calculated using data from the full hydrological year or from the irrigation season should be very similar.

Taking

The process of abstracting water for any purpose and for any period of time.

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Appendix: Flow Naturalisation

Naturalised seven-day mean annual low flow (7dMALF) for the Cardrona River at Mt. Barker

The flows of the Cardrona River at Mt. Barker are modified by upstream water-takes. To understand the natural character of the Cardrona River, an estimate of what the river flow would have been like prior to any water abstractions is needed. This section details the flow naturalisation process at Mt. Barker.

Table A.1 lists the flow data used to estimate naturalised flows for the Cardrona River at Mt. Barker, while Table A. 2 summarises the availability of water-take time series data for water takes upstream of Mt. Barker.

Table A.1 Flow data used to naturalise flows for the Cardrona at Mt. Barker

Flow site	Type of flow time series	Start	End
Lindis at Lindis Peak	Assumed natural	25/09/1976	21/03/2017
Cardrona at Mt. Barker	Modified by water-take during irrigation seasons (Oct – Apr, inclusive), flows during Jun-Aug are assumed natural	3/12/1976	4/05/2017

Table A. 2 Water-take time series data for water takes located in the Cardrona catchment upstream of the at Mt. Barker flow site

Site name	Consent ID	Max rate of take (l/s)	Start	End	Length (year)	Gap (day)
WM0325	2003.293.V1	8.33	19/10/2016	18/07/2017	0.7	0
WM0553	97199.V1	50	22/02/2014	18/07/2017	3.4	0
WM0555	RM12.259.01	13.9	3/11/2012	30/03/2017	4.4	0
WM0562	RM14.155.01 & RM14.161.01	27.77	22/10/2014	18/07/2017	2.7	0
WM0570	99151.V3	5	2/05/2007	18/07/2017	10.2	0
WM0571	99151B.V2	5	11/03/2007	18/07/2017	10.4	0
WM0577	99356	55.55	6/12/2013	18/07/2017	3.6	3
WM0629	RM12.254.01	24	22/01/2013	18/07/2017	4.5	0
WM0630	RM12.255.01	10	23/10/2014	18/07/2017	2.7	0
WM0638	RM12.473.01	28	3/09/2014	17/07/2017	2.9	0
WM0639	RM12.512.02	35.5	16/11/2013	29/06/2016	2.6	0
WM0726	2009.191.V1 & 2009.435.V1	45	5/05/2015	18/07/2017	2.2	0
WM0827	2005.493.V1	5.8	2/06/2011	30/07/2014	3.2	298
WM0832	2005.604.V1	0.35	1/06/2011	30/07/2014	3.2	207
WM0865	2006.377.V1	2.08	25/12/2007	15/08/2016	8.6	564
WM1002	99339.V1	56	2/01/2010	29/08/2016	6.7	0
WM1080	RM12.258.01	146	2/07/2015	17/07/2017	2.0	49

WM1102	99356	55.55	2/07/2015	28/06/2017	2.0	0
WM1184	95677.V1, 98058 & 99129	97.2	16/04/2016	18/07/2017	1.3	0
WM1233	98494	27.77	11/03/2007	18/07/2017	10.4	0
WM1239	99357 & 99358	152.774	12/12/2015	29/06/2017	1.5	0
WM1256	95677.V1 & 99129	83.32	21/09/2016	18/07/2017	0.8	0
WM1316	RM12.438.01	16.8	20/12/2016	18/07/2017	0.6	0
No meter	93390	41.66				
No meter	98181	5				

Due to the relatively short records of water use, long-term naturalised flows at Mt. Barker cannot be estimated by totalling all measured upstream water abstractions and observed flows, thus alternative methods must be used. These are outlined in the following sections.

Estimating long-term naturalised low flow statistics

Flows in the Lindis River at Lindis Peak are almost natural, as there are very few takes upstream of this site (Figure A.1). In addition, the Lindis Peak site has a sufficiently long record of flow data, which would result in a more reliable estimate of its seven-day Mean Annual Low Flow (7dMALF). Winter flows (June, July and August) are assumed to be natural as no irrigation is expected during this period. Therefore, flows during June-August between Lindis Peak and Mt. Barker have been analysed to establish a relationship between the flows of the two sites (with focus on low flows).

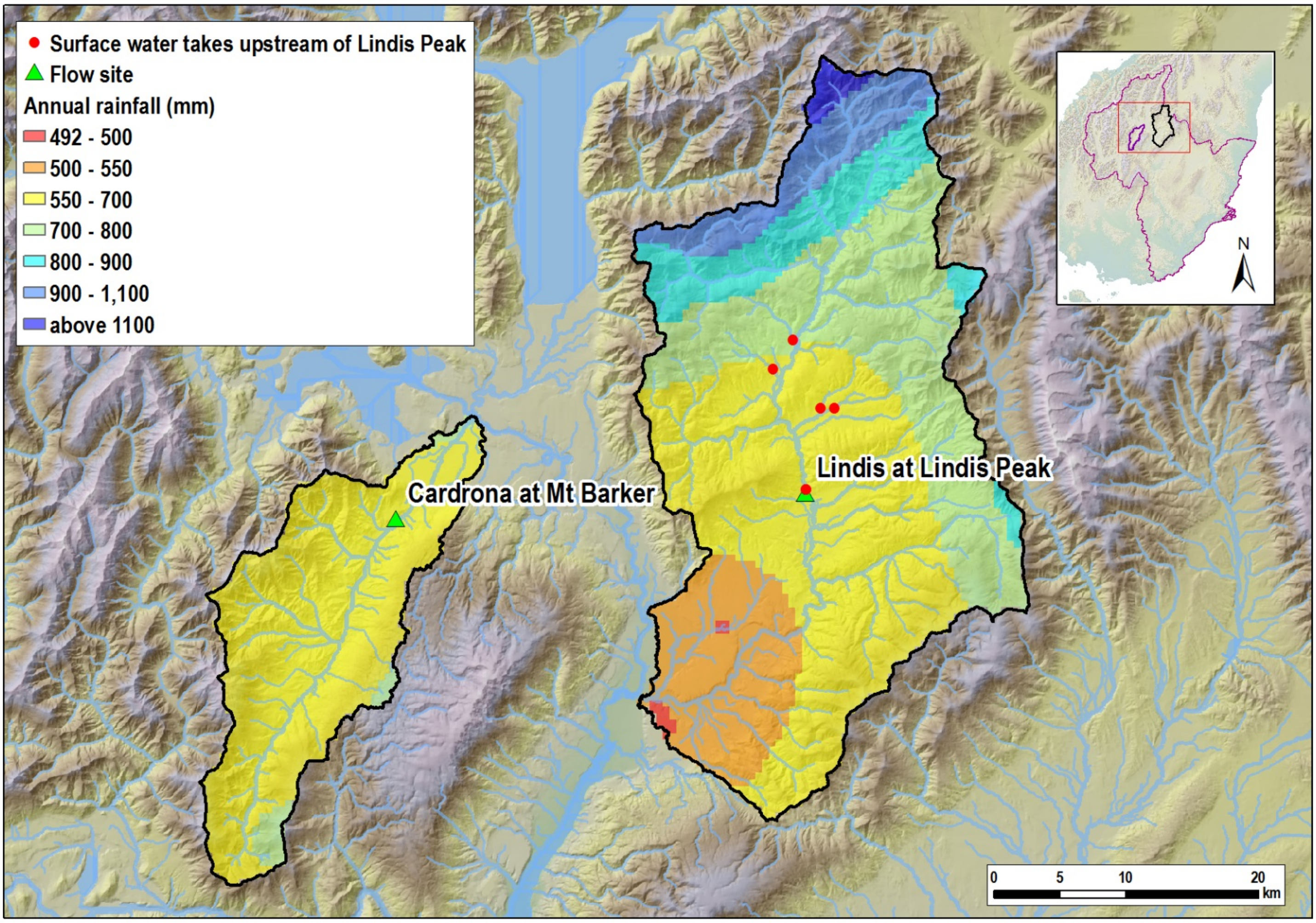

Figure A.1 **The relative locations of the two flow recorders – Lindis at Lindis Peak and Cardrona at Mt Barker with long-term annual rainfall distribution (Tait et al., 2006)**

Relationship based on seven-day moving averages (7dMA) of low flow events

To develop a relationship between flows of the Lindis River at Lindis Peak and the Cardrona River at Mount Barker flow site, 7dMA flow time series for Lindis Peak and Mt. Barker were calculated. Eighty-one independent flow events[3] (with focus on low flows) were identified during the June – August period and the minimum 7dMAs at Lindis Peak and Mt. Barker for each flow event were identified. The lag time between the minimum flows of Lindis Peak and Mt. Barker was estimated by comparing the hydrographs. Figure A.2(a) shows the relationships based on all eighty-one 7dMA low-flow events and Figure A.2(b) shows the relationship based on the selected thirty 7dMA flow events with a lag time of 280-480 minutes, which constitutes the prevailing lag time between flows at the two sites.

[3] As for the selection of the low flows from Lindis at Lindis Peak between June and August, there is possibility of a sudden flow drop with fluctuation for several days during these winter months. Most likely, this would be the case of low flows under an extremely cold weather condition. For this analysis, the described low flows in these cases were ignored.

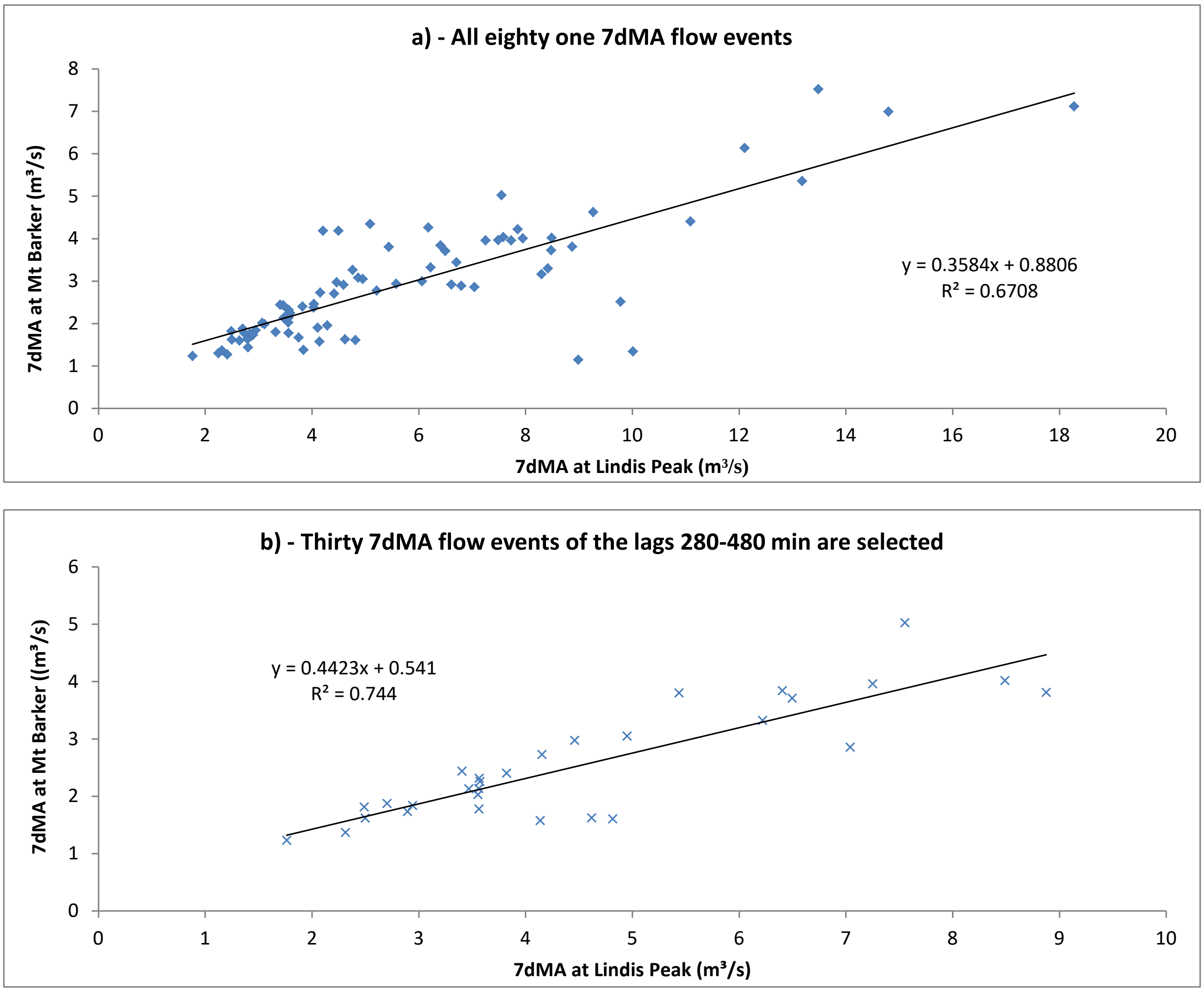

Figure A.2 **The relationships from (a) all eighty-one minimum 7dMAs and (b) selected thirty minimum 7dMAs with lag time of 280-480 minutes**

When compared with Figure A.2(a), Figure A.2(b) shows a better relationship for the low 7dMA. Based on this relationship, the naturalised 7dMALF at Mt. Barker was calculated as 1.18 m³/s (naturalised 7dMALF at Lindis Peak is 1.45 m³/s).

Naturalised flow time series for the Cardrona River at Mt. Barker

Building a relationship between daily flow time series of Lindis Peak and Mt. Barker

Selected flows (from flow events which exclude flows during recession periods after rainfall events and focuses on low flows) for Lindis Peak and Mt. Barker were analysed. A relationship was established, with a focus on the flows at Mt Barker below 4.9 m³/s. Table A.3 shows basic flow statistics for Cardrona at Mt Barker and Lindis at Lindis Peak. Most of the chosen flow events were lower than the average flows for their corresponding flow sites. However, flows above the mean flow were also included so that this relationship is applicable to flows up to 4.9 m³/s at Mt Barker.

There was a strong relationship (R^2 = 0.9097) between the paired daily flows during the corresponding flow events at both sites (Figure A.3). As shown in Figure A.3, this relationship is only applicable for the flows at Mt. Barker between 1 and 4.9 m³/s, as this is the flow range for Cardrona at Mt Barker for all the selected paired daily flows for this relation.

Table A.3 The basic flow statistics for the recorded daily flows at Cardrona a Mt Barker and Lindis at Lindis Peak

Flow site	Availability	Minimum (m³/s)	Maximum (m³/s)	Median (m³/s)	Mean (m³/s)
Cardrona at Mt Barker	3/12/1976 - 3/5/2017	0.310	77.4	2.34	3.1
Lindis at Lindis Peak	25/9/1976 - 21/3/2017	0.672	223	4.15	6.02

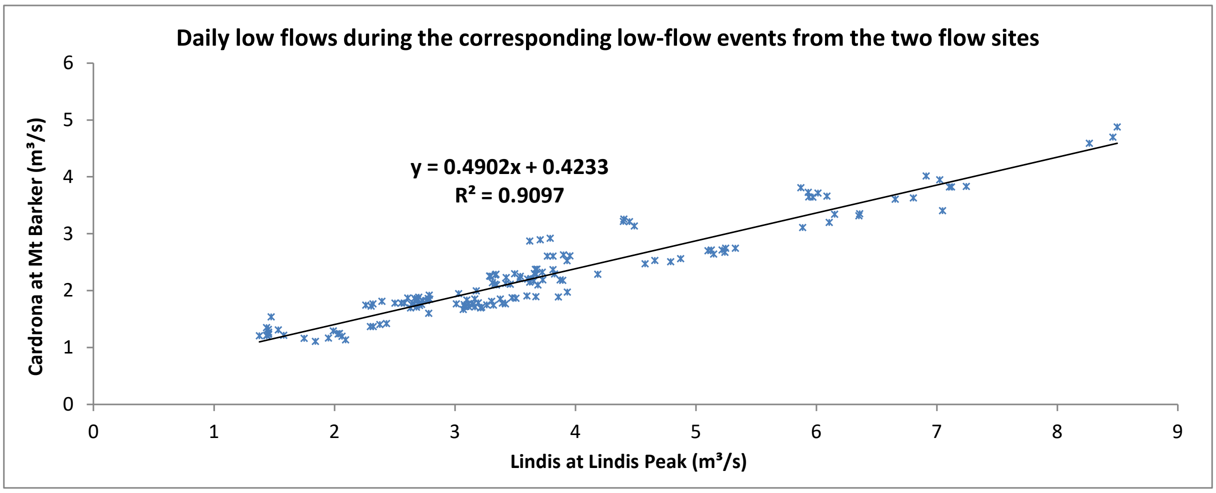

Figure A.3 The relationship between Mt Barker and Lindis Peak selected daily flows during selected flow events with focus on low flows

Daily flows above 4.9 m³/s at Mt. Barker were assumed to be natural as high flows are usually associated with rainfall events, and such events are assumed to reduce the need for irrigation. Thus, when measured flows are greater than 4.9 m³/s, flows at Mt Barker were considered to more accurately describe natural flows than flows correlated with those at Lindis Peak.

Using water-take data to refine the naturalised flow timeseries

Naturalised flow at Mt Barker cannot be estimated by adding water abstraction to measured flow as water take data is primarily short term and often has missing values. However, the water abstraction data can be used to create the long-term naturalised flow timeseries (refer below). Instead of using daily abstraction data, the monthly average rate of abstraction for the total take above the Mt Barker flow site can be estimated. This estimated total monthly take allows bridging of the periods with missing data and is assumed to apply to the periods with no available abstraction measurements. The details are presented in this section.

Measured total water-take and consented allocations upstream of Mt. Barker were analysed and used along with measured flows at Mt. Barker to refine and improve the quality of the naturalised flows calculated for this site. This included two thresholds for the naturalised flows during irrigation seasons:

1. The lower threshold for the naturalised flows at Mt. Barker is the sum of its observed flows, F, and the measured water-takes (expressed as percentage of the total consented allocation above Mt. Barker WT of 0.998 m^3/s, i.e., %·WT). This lower threshold (LT) can be expressed as:
   $LT = F + \%\cdot WT$

2. Naturalised flows at Mt. Barker should not be higher than the sum of its observed flows F and the total consented takes WT (when applicable), and this is used as an upper threshold:

   $UT = F + WT$

The next step is to estimate how much water is used above Mt. Barker on average. Average ratios of monthly measured total water-take to the total consented allocations above Mt. Barker were estimated from the available water use data listed in Table A. 2 as percentages (%), as shown in Table A.4.

Table A.4 **Monthly average ratios (as percentages %) of the measured total take to the total consented during irrigation seasons from September to May**

Month	Average ratio (%) of the measured to the consented
Jan	22.1%
Feb	21.9%
Mar	24.6%
Apr	14.7%
May	6.9%
Sep	9.9%
Oct	14.1%
Nov	15.1%
Dec	20.3%

In summary, the following steps are followed to generate the estimated naturalised daily flow time series at Mt. Barker:

1. The observed daily flows during winter "June – August" ($F_{Jun\text{-}Aug}$) at Mt. Barker are assumed natural.

2. As for the measured flows during other months (September – May), if measured flows are above 4.873 m^3/s, they are assumed natural and labelled as ($F_{Sep\text{-}May} > 4.873$)

3. Measured flows below 4.873 m³/s during Sept – May are labelled as (***$F_{Sep\text{-}May}$≤4.873***), the modelled naturalised flows at Mt. Barker were calculated by the relationship presented in **Error! Reference source not found.**. i.e., (***Flow@Lindis Peak$_{Sep\text{-}May}$,*** labelled as ***LP***) ***× 0.4902 + 0.4233*** when the ***Flow@Lindis Peak$_{Sep\text{-}May}$*** is available (i.e., no data gaps). If ***Flow@Lindis Peak$_{Sep\text{-}May}$*** is not available, the lower threshold ***LT*** (***$F_{Sep\text{-}May}$*** + ***%·WT***) will be used. The calculated flows from both conditions in this step are labelled as ***$MF_{Sep\text{-}May}$*** and it can be expressed as:

$$MF_{Sep-May} = \begin{cases} LP \times 0.4902 + 0.4233, & LP\ is\ available \\ LT, & LP\ is\ a\ gap \end{cases}$$

4. Compare ***$MF_{Sep\text{-}May}$*** with the lower threshold ***LT*** (***$F_{Sep\text{-}May}$*** + ***%·WT***) and ***UT*** (***$F_{Sep\text{-}May}$*** + ***WT***). The naturalised flows at Mt. Barker during Sep – May, ***$NF_{Sep\text{-}May}$*** can be conceptually calculated as:

$$NF_{Sep-May} = \begin{cases} LT, & MF_{Sep-May} < LT \\ MF_{Sep-May}, & LT \leq MF_{Sep-May} \leq UT \\ UT, & MF_{Sep-May} > UT \end{cases}$$

Therefore, the estimated naturalised daily flow time series at Mt. Barker NF are the union of the following:

NF = Union of ***$F_{Jun\text{-}Aug}$, $F_{Sep\text{-}May}$>4.873,*** and ***$NF_{Sep\text{-}May}$***

Limitations which restricted the use of water-takes to produce naturalised flows at Mt. Barker

1 There are no overlapping periods for the available water use time series. Therefore, it was not possible to estimate the measured total water-take time series above Mt. Barker. The average monthly total water-take was applied instead.

2 Available water-take time series are very short for most water-takes. Only 18% of water-takes have available records of more than 5 years, and no records are available for more than 10.4 years. In addition, the quality of the available daily take values is poor, but these values can be averaged across a month to obtain a more reliable record of abstraction. Thus, a regression formula had to be used to estimate the long record of the naturalised flows at Mt. Barker based on the natural flows at Lindis Peak. Measured water-takes were then used to revise and improve the synthesized naturalised flows.

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