Integrated Water Resource Management for the Cardrona River

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Foreword

Otago's rivers and streams are a major feature of any Otago landscape and help make the region what it is. The clean waters provide a rich ecological environment, serve rural and urban communities, and act as a tourist attraction. In many parts of the region, surface waters are vital for irrigation water, which enables or enhances primary production during the dry summer months. The future development and prosperity of Otago depends on water. However, much of Otago has long been recognised as a water-short area, and consequently the province is constantly at the forefront of water management in New Zealand.

A key thrust of the Regional Plan: Water is its emphasis on the progressive implementation of minimum flow regimes for streams and rivers throughout the region. The goal of these minimum flows is to maintain the stream's aquatic ecosystem and natural character during periods of low flow, while providing for the socio-economic and cultural values of the community. Furthermore, setting appropriate allocation limits for surface water and groundwater as well as promoting water-use efficiency are integral for ensuring reliable access to the water resource.

The Cardrona catchment drains into the Upper Clutha River/Mata-Au and the underlying aquifer includes parts of the Wanaka Township. This area has experienced recent substantial growth in residential development, expansion in tourism and agricultural intensification. The changes all bringing increased pressure on the surface and underground water resources. It is essential to fully understand the natural hydrology or an area before effective and efficient sustainable management decisions can be made for the future.

In Otago, surface water supplies are heavily allocated. Over abstraction can result in degradation of a stream's natural values and character. Therefore, careful management is required to keep rates of taking sustainable. The best way forward is to use this valuable water resource to our advantage and to implement allocation limits and minimum flows so that over abstraction does not occur.

This report has drawn together historical surface and groundwater information, along with a recent series of low flow gauging and an assessment of instream values to help in that decision making process. The selection of an appropriate minimum flow depends on evaluating instream values and attempting to balance these against flow management objectives that keep in mind the value of the water for other users.

Executive Summary

The water resources of the Cardrona River will potentially undergo a substantial shift in future water management for reasons which include:

- the proposed setting of the Cardrona River minimum flow;
- the proposed setting of the Wanaka – Cardrona Aquifer maximum allocation volume;
- establishment of surface water – groundwater management regime for the Cardrona Alluvial Ribbon Aquifer under Water Plan Change 1C; and,
- the transition from mining privilege water rights to conventional water permits.

To assist with these changes the Council has completed work which has improved the technical understanding of the Cardrona River, Cardrona Alluvial Ribbon Aquifer and the Wanaka – Cardrona Aquifer in terms of aquatic habitat, surface hydrology and groundwater hydrology.

The investigation of water resources both above and below ground are reported together recognising the strong interconnection between the surface and groundwater for future integrated management options. This report provides a technical description for any future water allocation and management regime and in turn, may provide mining privilege holders more certainty as to the eventual regulatory environment in transitioning to conventional water permits.

The Cardrona River catchment comprises the slopes and high altitude valley between the Cardrona and Criffell Ranges. Below The Larches Station, the Cardrona River empties out onto the Wanaka – Cardrona flats. From here the river flows over the Wanaka – Cardrona Aquifer before joining the Clutha River/Matau-Au at Albert Town.

The Cardrona River can be separated into three main hydrological sections; a neutral reach (upstream of The Larches), a losing reach in which surface water in lost to groundwater (between The Larches and SH6), and a gaining reach (downstream of SH6) in which surface flows are recharged from groundwater. Flow monitoring undertaken during the winter months (in the absence of surface water abstraction) indicates that approximately 0.7m^3/s of surface flow is the net loss to groundwater in the losing reach. When surface flows cease upstream of SH6, there is still a perennial base flow of approximately 0.3m^3/s in the Cardrona River at the Clutha River/Mata-Au confluence.

The Cardrona River in the vicinity of The Larches is turned out into four major water races managed within the mining privilege system under nine mining rights with at least two dozen shareholders. A legal potential take of 1.278m^3/s is apportioned to these rights. Although these represent the largest takes in the catchment they are not able to take their full allocation for the latter half of the irrigation season due to low flows in the Cardrona main stem.

There are 27 consumptive surface water takes upstream of The Larches, with a combined consented take of 1.13m^3/s. Many of these takes are from small tributaries that flow much less than consented rates of take during late summer, therefore it is likely that the actual take is significantly less than that consented for much of the irrigation season.

The river is well known for drying up in the reach between The Larches and State Highway 6 during distinct periods within Summer and Autumn. The onset of one such drying event was measured intensively by ORC at the end of January 2010. At this time $0.9m^3/s$ flowed past the Larches flow recorder from the upper valley, $0.5m^3/s$ was taken by water races around The Larches (after by-wash back to the river was accounted for) and the remaining $0.4m^3/s$ soaked into the river bed and aquifer downstream of the last water race intake.

The Wanaka – Cardrona Aquifer responds directly to changes in the rate of infiltration from the river to the aquifer. The aquifer water table drops up to 1.5m in the weeks following drying phases. However, the interaction between the river and aquifer upstream of Ballantyne Road is one-way, being infiltration through an unsaturated thickness of gravel. The lower Cardrona River downstream of State Highway 6 receives a steady augmentation from the aquifer of approximately $0.3m^3/s$ regardless of dry events in the upstream river. Changes in the water table can have a low to moderate effect on the rate of seepage to the lower river.

The Cardrona River is listed in the Regional Plan: Water as having a significant presence of eels, rare invertebrates and adult trout. In addition, there is significant habitat for juvenile trout and trout spawning. The Cardrona River supports four species of native fish (upland bully, longfin eel, koaro and Clutha flathead galaxias) and three species of introduced sports fish (brown trout, rainbow trout and brook char).

Upland bully are considered to be common and inhabit the edge habitat of the river where they are relatively unaffected by reductions in flow. Longfin eel are classified as being in "gradual decline", although the barriers to migration (Clyde and Roxburgh dams) have all but removed this species from the catchment. Clutha flathead galaxias are listed as being in gradual decline and are considered to be of high conservation importance, however they are not able to coexist with large trout and their distribution is limited to small tributaries were trout are absent. Because of this restriction in distribution, they will be relatively unaffected by a minimum flow set on the main stem of the Cardrona.

The middle and upper reaches of the Cardrona River supports a locally important brown trout fishery. Many trout from the upper Clutha River/Mata-Au remain in the Cardrona River throughout spring and are targeted by anglers early in the fishing season.

An Instream Flow Incremental Methodology (IFIM) study was undertaken in the Cardrona River in the vicinity of The Larches flow recorder. The survey reach was dominated by shallow riffles with very few runs and pools. IFIM measures changes in available habitat for fish species over a range of flows. Using IFIM, flows that provide optimum habitat have been identified as well as thresholds below which there is a significant increase in the rate of habitat reduction with decreasing flow (point of inflection). Where there is no clear point of inflection, the flow that provides 70% of the habitat available at MALF is used. The results of the IFIM study showed that there was very little available habitat for adult brown trout and adult longfin eels throughout the range of flows modelled, though a substantial amount of habitat is available for juvenile trout between $1m^3/s$ and $1.5m^3/s$. This is consistent with the riffle-dominated nature of the survey reach.

Among the options for future water management would be to reduce reliance on the water race system in favour of bore water supplies for irrigation. This option would maximise the amount of time that the Cardrona River was wet from headwaters to confluence and consequently the amount of river recharge to the aquifer. The bore water supplies, being piped at bore head, could be employed in higher efficiency methods of irrigation, thereby freeing up further water resource while sustaining the same level of agricultural production.

Management flow: Clutha River/Matau-Au confluence (m^3/s)	Predicted flow at SH6 bridge (m^3/s)	Predicted flow at The Larches (m^3/s)	Effects on instream values
0.7	0.4	1.1	Flows at SH6 are equal to the flow recommended to maintain a juvenile brown trout fishery. Flows at The Larches are close to MALF. Significant increase in recharge to Wanaka aquifer.
0.4	0.1	0.8	Flows at Clutha confluence are equal to the flow recommended to maintain a juvenile brown trout fishery. Flow continuity is maintained throughout the losing reach. Increase in recharge to Wanaka aquifer.

Based on this work a **Maximum Allocation Volume (MAV) of five million m^3/y** should be considered for the Wanaka – Cardrona Aquifer. Should it be shown that the options for management flows in the lower Cardrona River would definitively result in greater recharge to the aquifer, this may provide latitude to increase the MAV of the Wanaka – Cardrona Aquifer.

It is also suggested based on this work that the Cardrona Alluvial Ribbon Aquifer be managed in conjunction with the Cardrona River, including observance of any minimum flow and allocation limits.

Table of Contents

Otago Regional Council

Table of Figures

Table of Tables

1 Introduction

1.1 Background

The Cardrona River has a total catchment area of 337km^2 and flows northwest through the steep Cardrona Valley onto the Wanaka-Cardrona Flats before joining the Clutha River/Mata-Au at Albertown. The catchment is divided from the Wakatipu Catchment by the Crown Range, separated from adjoining Upper Clutha catchments of the Motutapu River by the Cardrona Range, and from Luggate Creek by the Criffell Range.

The Wanaka-Cardrona Flats sit astride a sedimentary basin characterised by glacial deposits and glacial outwash gravels. These deposits are defined in the Otago Groundwater Resource Management Scheme as the Wanaka Basin-Cardrona Gravel Aquifer (abbreviated hereafter to Wanaka-Cardrona Aquifer). This aquifer is responsible for the flow of Bullock Creek through Wanaka Township, the availability of groundwater in the rural areas, and the periodic drying-up of sections of the Cardrona River during summer.

In recent years, Wanaka Township and the Wanaka-Cardrona Flats have experienced substantial growth in residential development and land values. In the 2006 census, the population and the number of dwellings in the Wanaka area had almost doubled (93% and 88% increase, respectively) over the previous ten years[1]. Construction in the township on medium to high density residential and accommodation buildings has spiked significantly in the last five years. Several of these buildings have included underground car parks or utility rooms that imposed dewatering requirements during construction and post-construction. On the Wanaka-Cardrona Flats, rural residential construction, tourism facilities, crop diversification and agricultural intensification have been trends in the last 15 years. Snow and alpine tourism has also led to residential and hospitality development of the upper Cardrona River. Pastoral agriculture in the Cardrona Valley is also in transition from extensive pastoral systems to more intensive systems to increase production and surety of returns.

These developments have occurred against a backdrop of developing regional council water management and allocation planning documents. The Regional Plan: Water (RPW) came into operation in January 2004, bringing with it several groundwater policies. More recently, the proposed Plan Change 1C introduced more specialised groundwater allocation measures and surface water interaction provisions which are likely to come into operation in 2010. Otago Regional Council (ORC) has also announced that the Cardrona River is on a schedule for setting management flows to allow universal surface water allocation into primary and supplementary volumes. To date, ORC has issued groundwater take consents of up to 3.5 million m^3/y of groundwater for water supply and irrigation on the Wanaka -Cardrona Flats, and a further 5 million m^3/y for construction dewatering in Wanaka Township from the Wanaka-Cardrona Aquifer resource. Setting the technical specifics to these water management measures is the fundamental objective of this report.

1.2 Aims and objectives

This study is directed towards the following technical support objectives:

- identifying a management flow for the Cardrona River that caters for instream values.

[1] Source: Statistics New Zealand (StatsNZ) 2006 Census Data

- identifying the sustainable size of the aquifer’s water resource at a technical level
- supporting the future phases of consultation and decision making that are involved in setting a groundwater allocation limit for the aquifer
- other aspects of groundwater management that can be addressed concurrently, such as surface water interaction.

1.3 Previous studies

ORC has published two previous studies of the Cardrona catchment. The first study looked at surface water quality and covered the Cardrona and Lindis rivers (ORC, 2006). The second entailed a hydrological data review of the Cardrona and Bullock Creek catchments (ORC, 2007), and contained recommendations for intensified data gathering that were implemented to provide the basis for this study.

Studies into the groundwater conditions of the Wanaka-Cardrona Aquifer began in 1976. Thomson (1976) prepared an engineering geology report for the DSIR Geological Survey after visiting the Wanaka hatchery and reviewing available information on the geology of the Wanaka area. Subsequently, the Institute of Geological and Nuclear Science undertook a wider investigation of the water quality and flow dynamics of the Wanaka-Cardrona Flats (Rosen *et al*, 1997). ORC helped with this investigation, which included extensive water chemistry characterisation and the use of environmental isotopes to illuminate flow dynamics, such as groundwater source and residence time. ORC also surveyed bore heads and employed three water level surveys to draw up water table contour maps covering the basin. To consolidate the information obtained in the 1994 / 95 surveys, ORC undertook an analysis of all available field data for what became known as the Wanaka-Cardrona Aquifer in 2000 and 2001 (ORC, 2001). This analysis incorporated the accumulated data and utilised a steady-state computer model to develop a basin-wide water balance accounting for flows between surface water and the aquifer.

2 Setting

2.1 Location and topography

The Cardrona River catchment consists of a steep river valley at an elevation of between 300m at the confluence with the Clutha/Mata-Au River and 1000m at the top of the Crown Range. Tussock and low producing grassland is prevalent in the higher catchment, while in the lower catchment, high producing exotic grassland predominates. Sheep and beef farming on tussock dominates the catchment, with the high producing grasslands in the lower catchment supporting some deer farming.

The Wanaka-Cardrona Aquifer is set between Lake Wanaka, the Upper Clutha River/Mata-Au and the ranges to the south and west, namely Criffell Range and Mount Roy. The bedrock remnants termed *roche moutonnees* were formed during glaciation and represent gaps in the ice sheets, particularly at the confluence of two or more glaciers. Mount Iron and Mount Barker are recognised as prominent *roche moutonnees*, projecting above the surface of the glacial outwash gravels. The Mount Iron terminal moraine forms the backdrop to Wanaka Township and runs between Mount Iron and the western edge of the basin. Glacial outwash gravels and tills also form prominent terraces in the northwest and east of the aquifer area. Figure 1 shows the location of these features.

2.2 Climate and rainfall

Cardrona catchment lies between two contrasting climate zones: the drier Mediterranean climate of the Upper Clutha River/Mata-Au (represented by Wanaka Airport Automatic Weather Station-Wanaka AWS) and the mountain climate, which is affected by the spill-over rain which crosses the Main Divide (represented by Peat’s Hut). Figure 1 shows the location of the flow and rainfall sites used in this study.

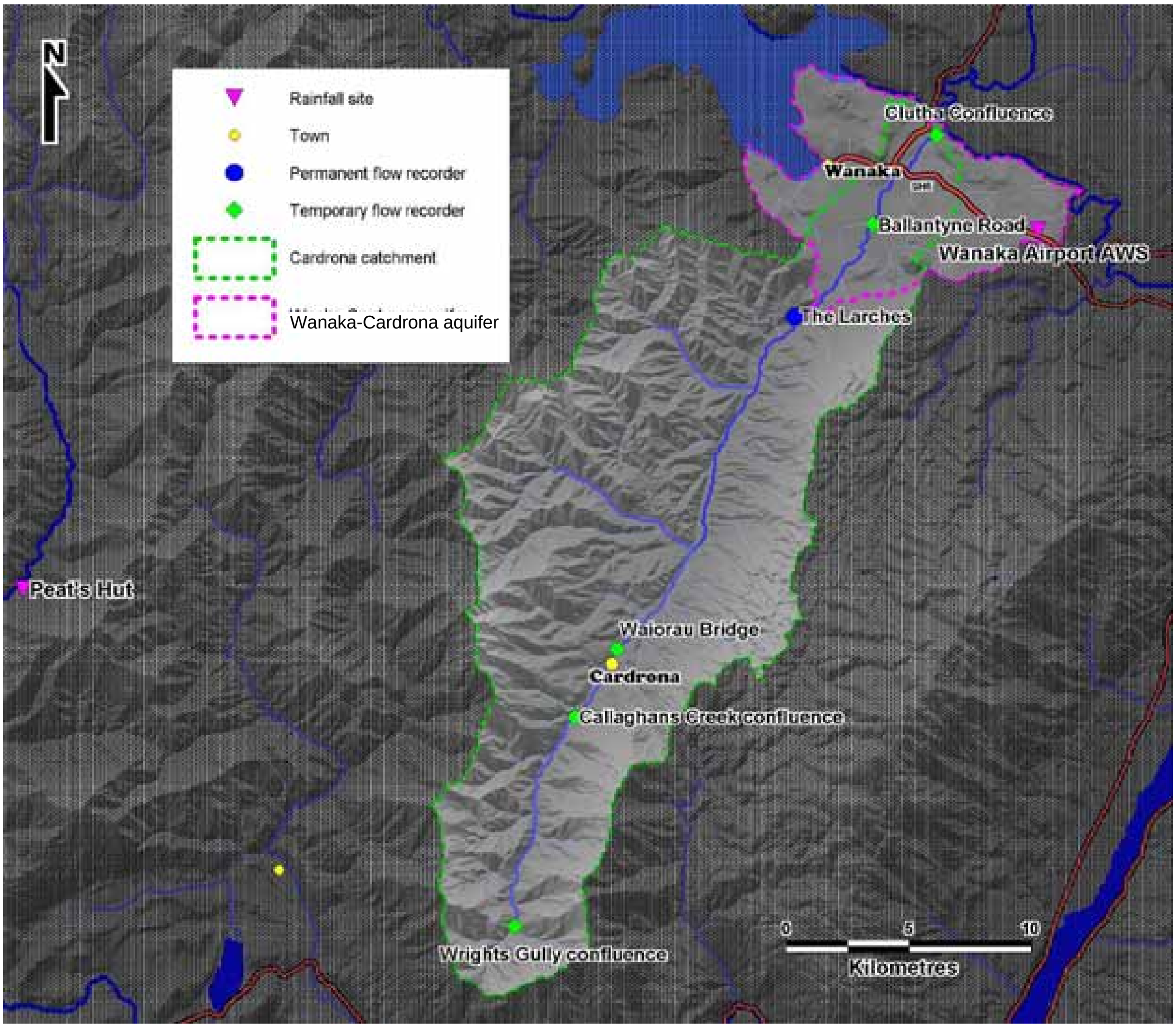

Figure 1: Catchment location, plus low flow and rainfall sites used in the Cardrona management flow study

The topography of the wider Wanaka area results in a number of climatic rain-shadow effects, where areas in the lee of mountains display lower precipitation totals. Spill-over rain during north-west airstream events that bring heavy rain to the West Coast on the far side of the Main Divide extends heavier rainfall to the Wanaka Basin.

Catchment potential evapotranspiration between January and March ranges from 2.5mm to 3.7mm, and averages 3.4mm/d across most of the lower Cardrona catchment. The annual mean daily evapo-transpiration in the wider catchment takes into account the cooler, wetter months of the year and approximates 1.1mm/d for the period 1975-2005. Annual mean air temperature for the lower Cardrona catchment is approximately 10.5^{0}C. Approximately 13 megajoules per square metres per day (MJ/m^2/d) of solar energy fall onto the surface of the lower Cardrona catchment. The first frost on lowlands typically occurs in early April and the latest frost typically occurs in early November.

Table 1 provides annual and seasonal summary rainfall statistics for the Wanaka AWS and Peat's Hut rainfall recorders. A "season", which refers to the irrigation season, is defined as being from October to April, inclusive.

Table 1: Annual and seasonal rainfall statistics for Wanaka AWS and Peat's Hut rainfall recorders

	Annual total rainfall statistics			Seasonal total rainfall statistics (Oct-Apr)		
Site	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Wanaka Aero AWS	863	358	605	659	206	353
Shotover at Peat's Hut	1075	666	900	628	381	490

The higher totals experienced by the Peat's Hut rainfall recorder are consistent with the greater exposure to spillover from westerly rainfall events.

A severe rainfall deficit occurs in the lower Cardrona catchment during summer, with January-April rainfall totals in the lower catchment generally ranging from 50 to 100mm (Figure 2). Potential evapotranspiration during this period is considerably higher, however, and ranges from 206 to 210mm (ORC, 2007). This summer moisture deficit leads to a high demand for irrigation water.

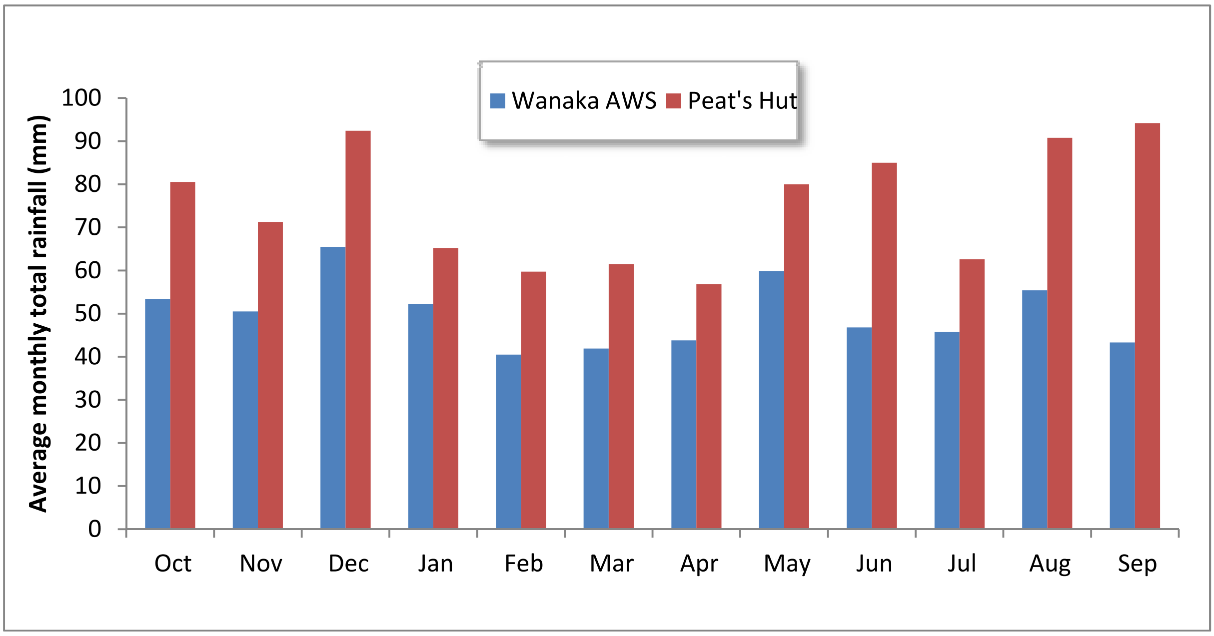

Figure 2: Average monthly rainfall totals for Wanaka AWS and Peat's Hut

Figure 2 shows that the lowest periods of rainfall occur between February and April, with some precipitation falling as snow between June and August.

Analysis of long-term annual and seasonal rainfall patterns has been undertaken for both Wanaka AWS and Peat's Hut rainfall recorders (Figure 3 and Figure 4).

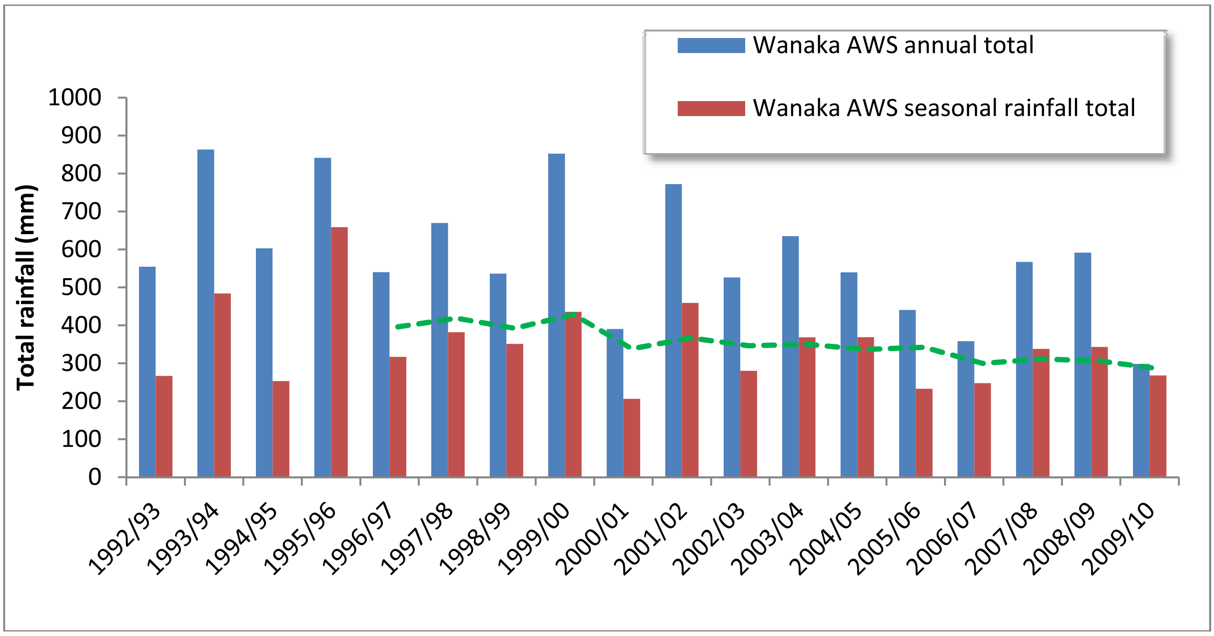

Figure 3: Long-term rainfall trends for Wanaka AWS

Figure 3 shows that there has been a slight downwards trend in seasonal rainfall at Wanaka AWS since 1992; however, this trend is skewed by unusually high rainfall early in the term of record. The 5-year moving average for seasonal rainfall has remained at approximately 350mm for the past decade, although there were some particularly dry irrigation seasons in 2005/06 and 2006/07.

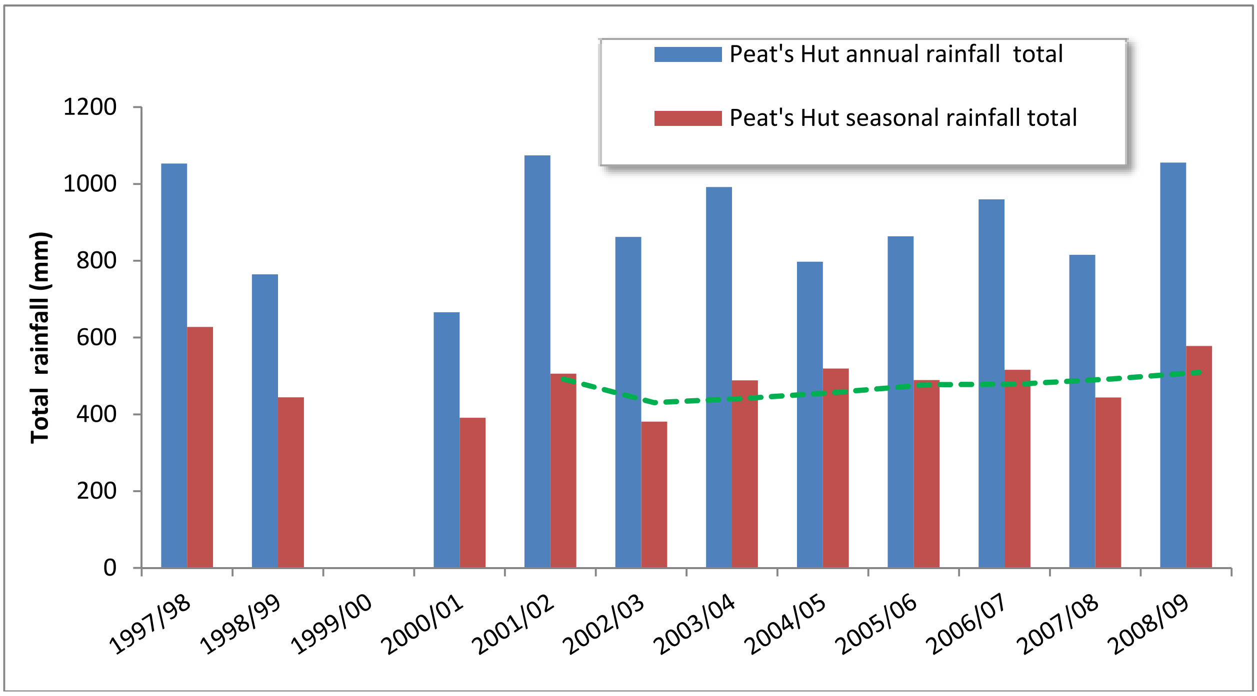

Figure 4: Long-term rainfall trends for Peat's Hut

Long-term trend analysis of rainfall is limited at Peat’s Hut, due to the relatively short period of record; however, seasonal rainfall totals have been relatively stable over this time, at around 450mm. As expected, annual and seasonal rainfall totals are significantly higher than that at Wanaka AWS (Figure 3).

2.3 Geology

The Wanaka Basin rests in the Haast Schist basement crustal unit. This regionally metamorphosed marine sedimentary sequence is several kilometres thick and has been subjected to profound and extremely rapid (by geological measures) deformation by folding and faulting in mountain-building periods, particularly during the last two million years (Ma). The Cardrona Valley coincides with the trace of the Cardrona-Nevis Fault system.

The flanks of the Cardrona Valley and floor of the Wanaka-Cardrona Flats are in-filled by tertiary lake sediments of the Manuherikia group. The Manuherikia group is a composite set of formations associated with lake, deltaic and river deposits dating from the Miocene geological era. The original deposits covered most of the underlying Haast schist basement rocks throughout the region, but have been subsequently disrupted and partially stripped away by crustal movements of the last 2Ma. The composition of the Manuherikia group sediments in the Wanaka Basin ranges from fine silty clay through silt to carbonaceous clay. A stratigraphic drilling project in 1979, near Luggate, encountered an 87m thickness of Manuherikia formation sediments; however, drilling was abandoned without hitting Haast schist basement. A test bore of similar depth located immediately to the east of Mt Barker penetrated 75m of silt and clay also without hitting basement. Manuherikia formation sediments are considerably thinner and often absent on the western side of the Cardrona-Nevis Fault (i.e. beneath Wanaka Township) that bisects the Wanaka Basin from the north-east to the south-west.

A rough terrace sequence is preserved in parts of the Cardrona Valley flanks. The course of the valley was initially formed in the presence of the Cardrona -Nevis Fault. The pre-history of the valley includes the possibility that the proto-Cardrona River flowed south-west into the Wakatipu catchment before reverting to its current pattern after the stabilisation of tectonics and drainage patterns. A sequence of fragmentary deposits have been left behind, including the Hawkdun group piedmont gravels, Early Quaternary deposits of the Lochar formation, Late Quaternary outwash and modern Cardrona River alluvium. Figure 5 shows that more than 80% of the Cardrona catchment consists of basement schist, coloured blue-grey; while the remainder is shown as being of various shades of yellow, indicating that there are glacial or alluvial deposits either side of the valley axis.

The Quaternary geology, in particular, the glacial processes and deposits of the last 2Ma, is very complex in the Wanaka Basin. At least four glacial periods have resulted in the Wanaka valley systems being filled with valley glaciers on separate occasions. In the aftermath of each glacial event, glacier retreat and riverine outwash tend to dominate landforms, with glacial deposits often having been re-worked and over-printed by the latest glacial event. The glacial and post-glacial geology of the Wanaka Township area comprise the following features:

- glacial till deposits, comprising sands, silts, clays and melt-water fine gravels
- glacial moraine deposits, particularly the Mt Iron Terminal Moraine
- post-glacial lake shore deposits associated with Lake Wanaka
- post-glacial outwash gravels resting atop terminal moraine

- younger alluvial deposits, associated with the Cardrona River flood plain
- melt-water deposits traversing the Wanaka-Cardrona Flats
- outwash gravels associated with the Clutha River/Mata-Au and Cardrona River also forming surfaces on the Wanaka-Cardrona Flat
- erosional and modern flood deposits of the Cardrona River to either side of its current course.

These features form a complex patchwork caused by the depositional environments and sediment supply available at the time of deposition. Figure 6 illustrates the distribution of principal geological formations in the Wanaka Basin.

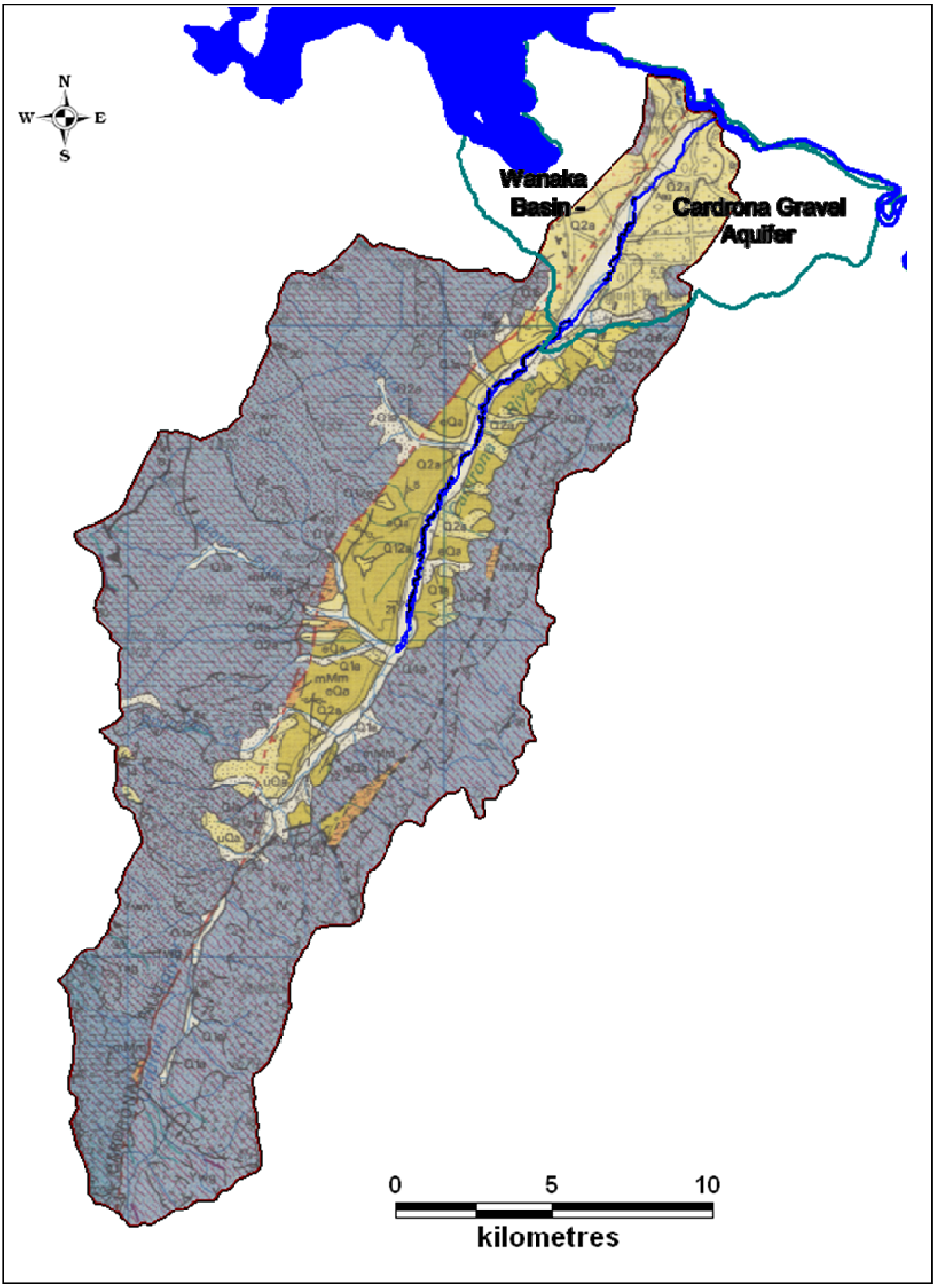

Figure 5: **Cardrona Catchment geology from 1:250,000 scale Geological and Nuclear Sciences QMap**

Figure 6: Outline geology of the Wanaka Basin

2.4 Hydrology

2.4.1 Cardrona River: Summary

Hydrological monitoring in the Cardrona catchment has consisted of a permanent flow recorder at The Larches (also known as “Mt Barker” flow recorder) and five temporary flow recorders, located at the Clutha River/Mata-Au confluence, Ballantyne Road, Waiorau Bridge, Callaghans Creek confluence and Wrights Gully confluence (Figure 7). 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, but were not used for the management flow study, which focused on the hydrology of the lower catchment.

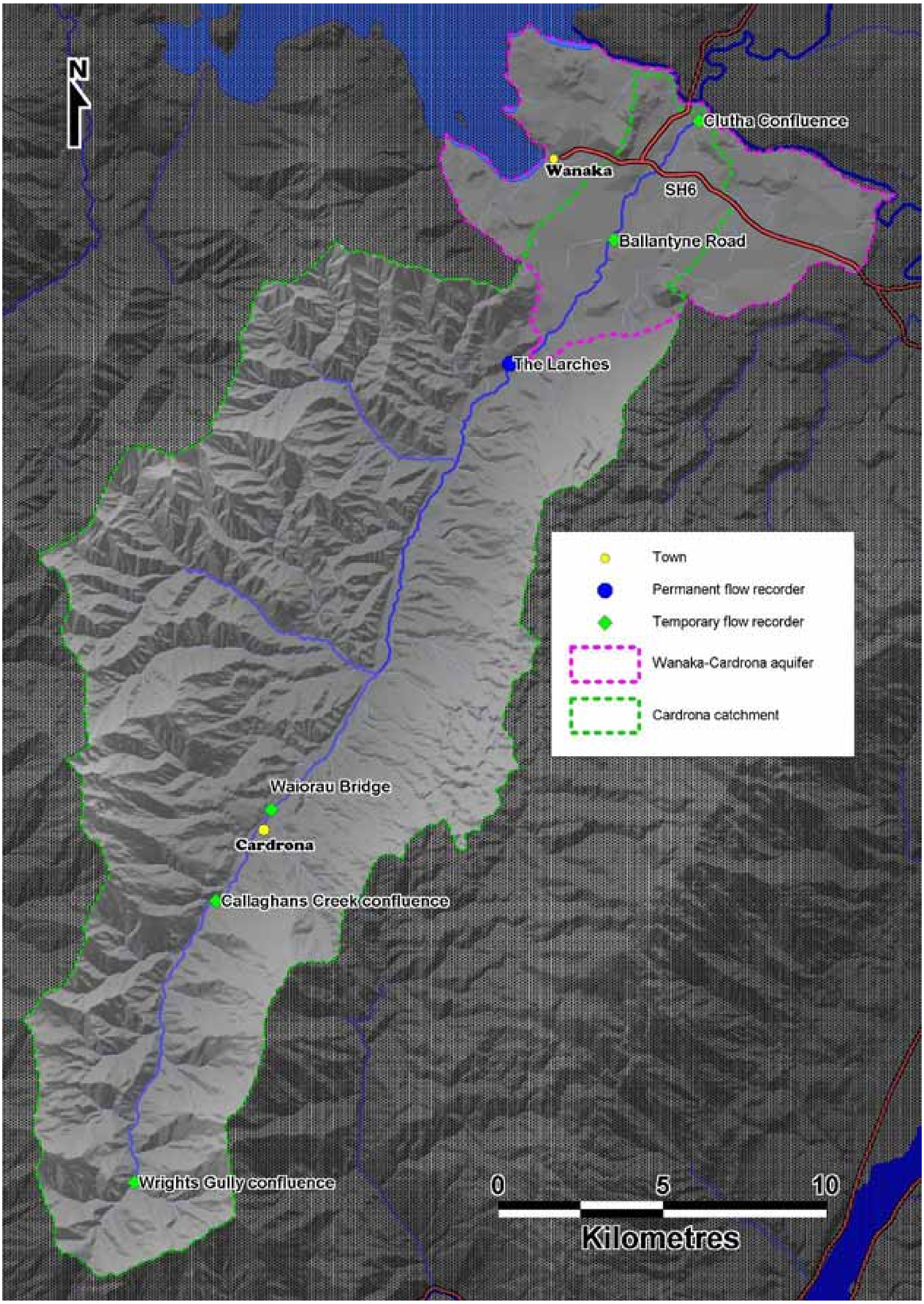

Figure 7: Flow recorders in the Cardrona catchment

2.4.2 Surface water/groundwater interactions

The Cardrona River can be separated into three main sections: a neutral reach (upstream of The Larches); a losing reach, in which surface water is lost to groundwater (between The Larches and SH6); and a gaining reach (downstream of SH6), in which surface flows are recharged from groundwater (Figure 8).

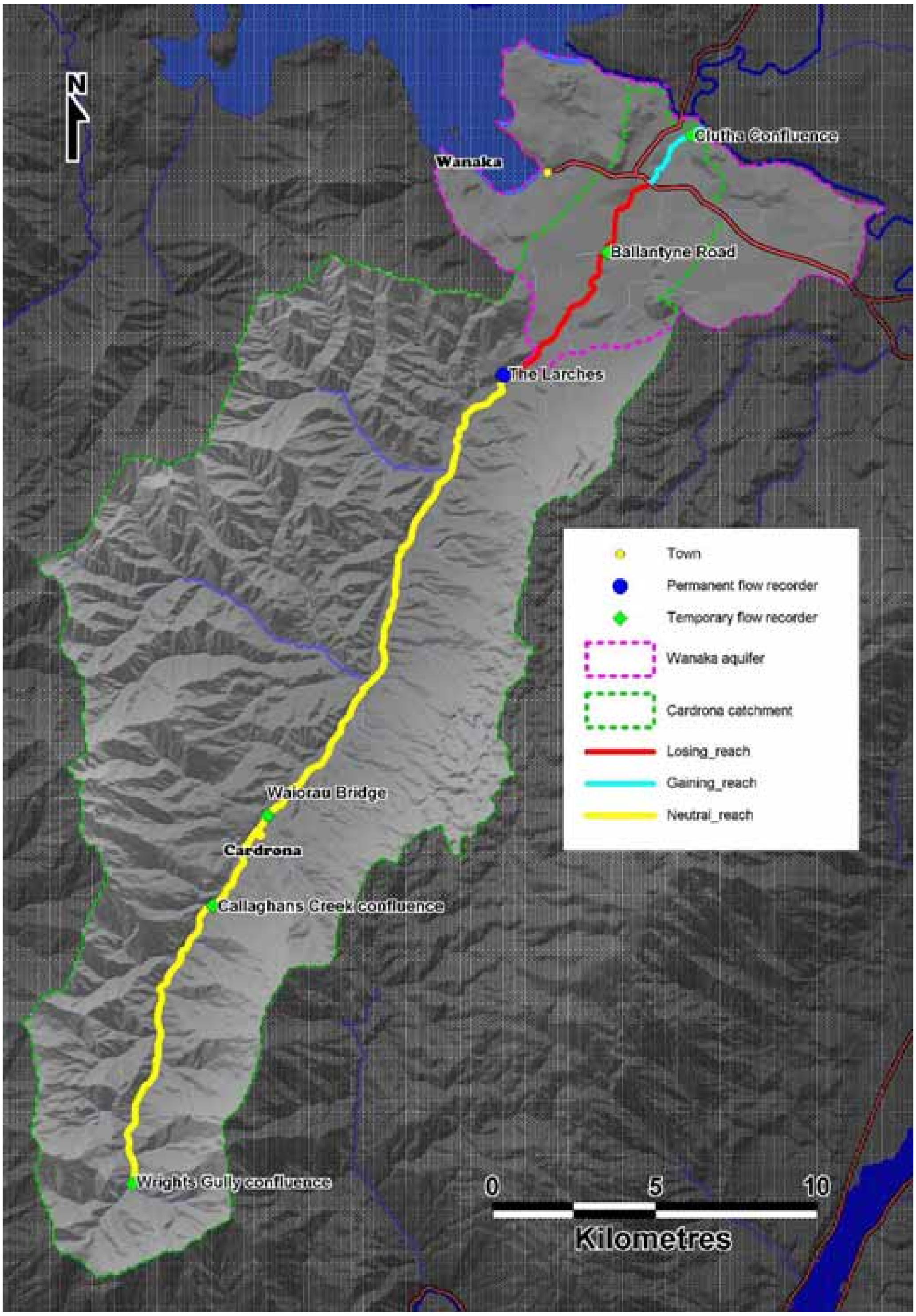

Figure 8: Neutral, losing and gaining reaches of the Cardrona River

A neutral reach occurs when the bed of the river is in equilibrium with the underlying ribbon aquifer, with no net exchange of water. The 'losing reach' is classed as a 'disconnected losing reach', and occurs when there is a continuous loss of surface flows to the groundwater, regardless of changes in groundwater level (Figure 9). Reduction of surface flow in a disconnected losing reach leads to a corresponding reduction in groundwater recharge.

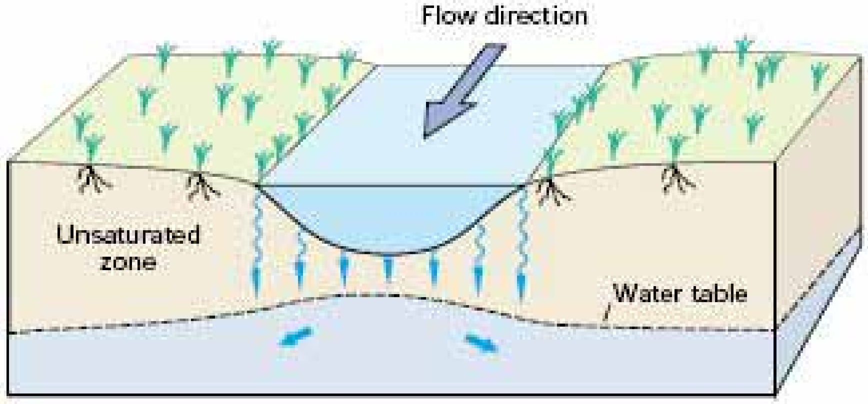

Figure 9: A disconnected loosing reach, where surface water and groundwater become decoupled and separated by an unsaturated zone (Winter *et al*, 1998)

An important feature of a disconnected losing reach is that continued pumping and subsequent reduction of groundwater levels do not cause a corresponding increase in surface water losses. Once groundwater and surface water become decoupled, the rate of surface flow loss is more consistent, although changes in river height and wetted perimeter would result in changed loss rate.

Flow monitoring undertaken during the winter months (in the absence of surface water abstraction) indicates that the net loss to groundwater in the losing reach is approximately $0.7m^3/s$ of surface flow. The loss is less over the summer because the size of the wetted channel is reduced, both laterally and longitudinally.

Gaining reaches occur when the stream gains water from the surrounding aquifer, and requires the aquifer to be higher in altitude than the surface of the stream channel (Figure 10).

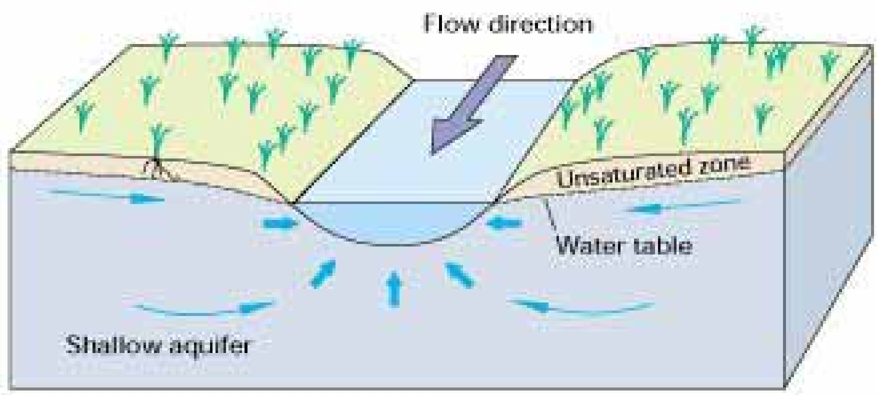

Figure 10: A gaining reach, where the stream gains water from a connected shallow aquifer (Winter *et al*, 1998)

When surface flows cease upstream of SH6, there is still a perennial base flow of approximately 0.3m^3/s in the Cardrona River at the Clutha River/Mata-Au confluence. Groundwater/surface water interactions are discussed further in the Groundwater Flow Pattern section (3.3).

2.4.3 *Flow statistics*

Information gathered from flow recorder sites at The Larches, Ballantyne Rd and the Clutha River/Mata-Au confluence have been analysed to provide stream flow statistics within the catchment (Table 2). Note that flow statistics for Ballantyne Rd and Clutha River/Mata-Au confluence are based on less than two years of data and are heavily influenced by surface water abstraction.

The Otago Catchment Board operated The Larches hydrological recorder site from 1976 to 1988; it then closed for several years before ORC re-opened it in February 2001. There are a large number of gaps in the early Larches record, most of which occurred during summer. These gaps comprise less than 1% of the record, however, and should therefore have only a minor effect on summer low flow calculations.

Table 2: Summary of annual statistics of the Cardrona River flow sites

Site Name	Catchment area (km^2)	Term of record (years)	Min recorded flow (m^3/s)	Max recorded flow (m^3/s)	Mean flow (m^3/s)
Cardrona at The Larches	293	22	0.308	145.299	3.137
Cardrona at Ballantyne Road	307	2	0	24.366	1.868
Cardrona at Clutha confluence	347	2	0.297	22.024	1.747

The Cardrona River downstream of The Larches is subject to losses due to groundwater recharge and abstractions for irrigation, and in most years, the Cardrona dries up along parts of its lower reach during summer. As of June 2006, 52% of the volume of the consented irrigation takes in the Cardrona catchment was below The Larches (1.44m^3/s). There was some recovery of flow by the time the river reached the Clutha River/Mata-Au confluence, as groundwater and excess irrigation water re-entered the river. Table 2 shows that the Clutha confluence recorder, which has been operating since 2008, did not record any periods of zero flow during this period.

Figure 11 shows surface flows during the 2009-10 irrigation season (October-April, inclusive) at The Larches, Ballantyne Road and the Clutha confluence flow recorders.

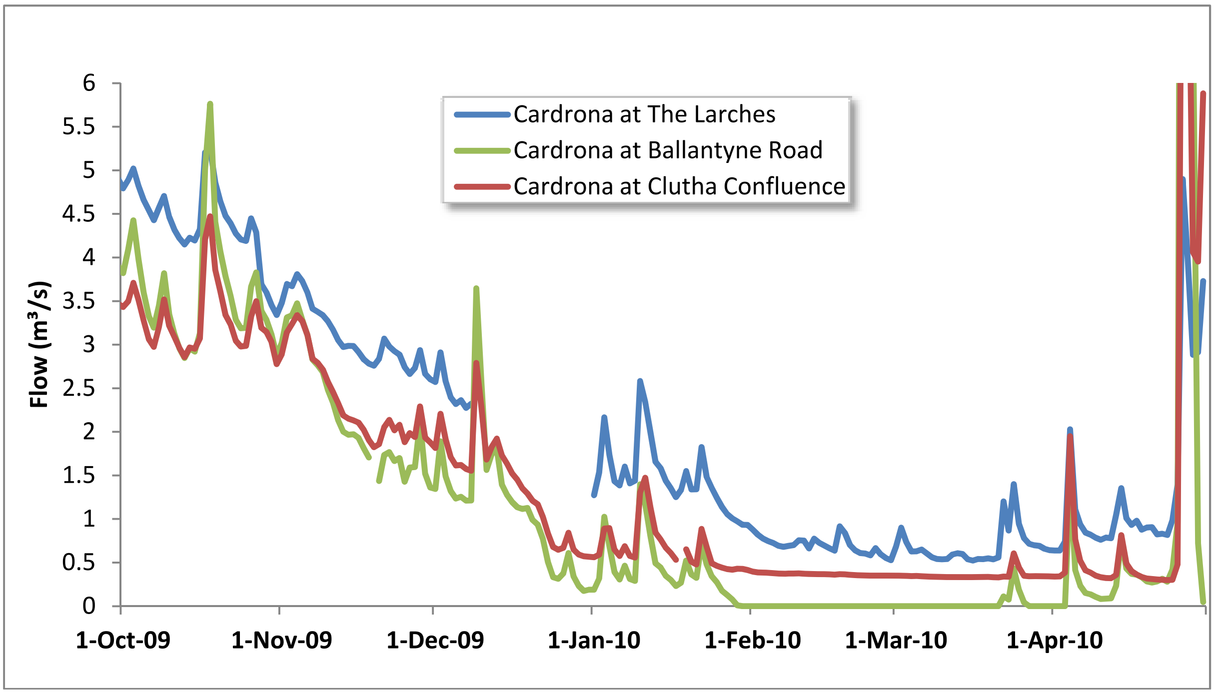

Figure 11: Surface flows in the lower Cardrona River during the 2009-10 irrigation season

The flow differential between The Larches and Ballantyne Road reveals that there is a significant loss of surface flows between these sites, due to abstraction and losses to groundwater. The steady base flow observed at the Clutha confluence is due to inflows from the Wanaka-Cardrona Aquifer downstream of State Highway 6.

2.4.4 Annual 7-day low flows and their frequency analyses

Mean annual 7-day low flows[2] (MALF), and the corresponding specific catchment yield at MALF[3] (SMALF) at the three flow recorder sites in the lower Cardrona catchment, are given in Table 3. The 7-day low flow in any year is the lowest average flow over a consecutive 7-day period. After this has been calculated for every year of record, the MALF is determined by adding the lowest 7-day low flows for every year of record and dividing by the number of years in the record.

The Larches flow recorder is prone to freezing during winter, giving false low flow readings and negatively skewing MALF and low flow return periods. To correct this, MALF and low flow return periods have also been calculated using data from October to April (inclusive). This data is also more applicable when considering management flows as it focuses on the period where demand for water resources is greatest.

[2] The mean of the lowest 7-day average flow for each hydrological year of record

[3] Specific discharge from 1km² of catchment area at MALF

Table 3: Summary of annual statistics in the Cardrona catchment flow sites

Site	Term of record	Catchment area (km²)	MALF (m^3/s)	SMALF ($l/s/km^2$)
Cardrona at The Larches	22	293	1.02	3.609
Cardrona at Ballantyne Road	2	307	0	0.000
Cardrona at Clutha confluence	2	347	0.331	0.954

Figure 12 compares the 7-day low flow and minimum recorded flows over the whole term of record for The Larches flow recorder.

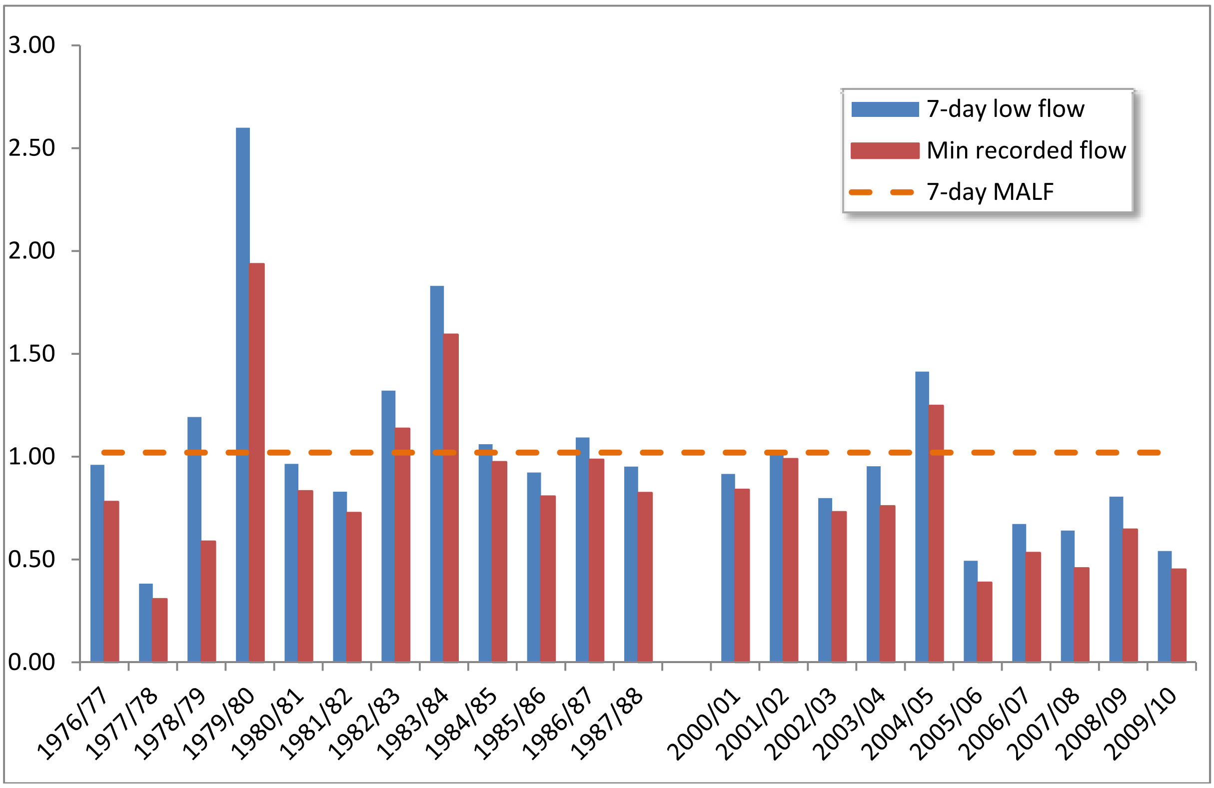

Figure 12: Comparison of annual 7-day low flows at The Larches flow recorder

As seen in Figure 9, there has been a significant reduction in low flows since the 2005/06 irrigation season. To investigate whether the reduction is due to lower rainfall over this period, or to other factors such as changes in land use or irrigation practice, a comparison has been made between 7-day low flows and rainfall totals at Wanaka airport AWS and Peat's Hut rainfall recorders (Figure 13 and Figure 14).

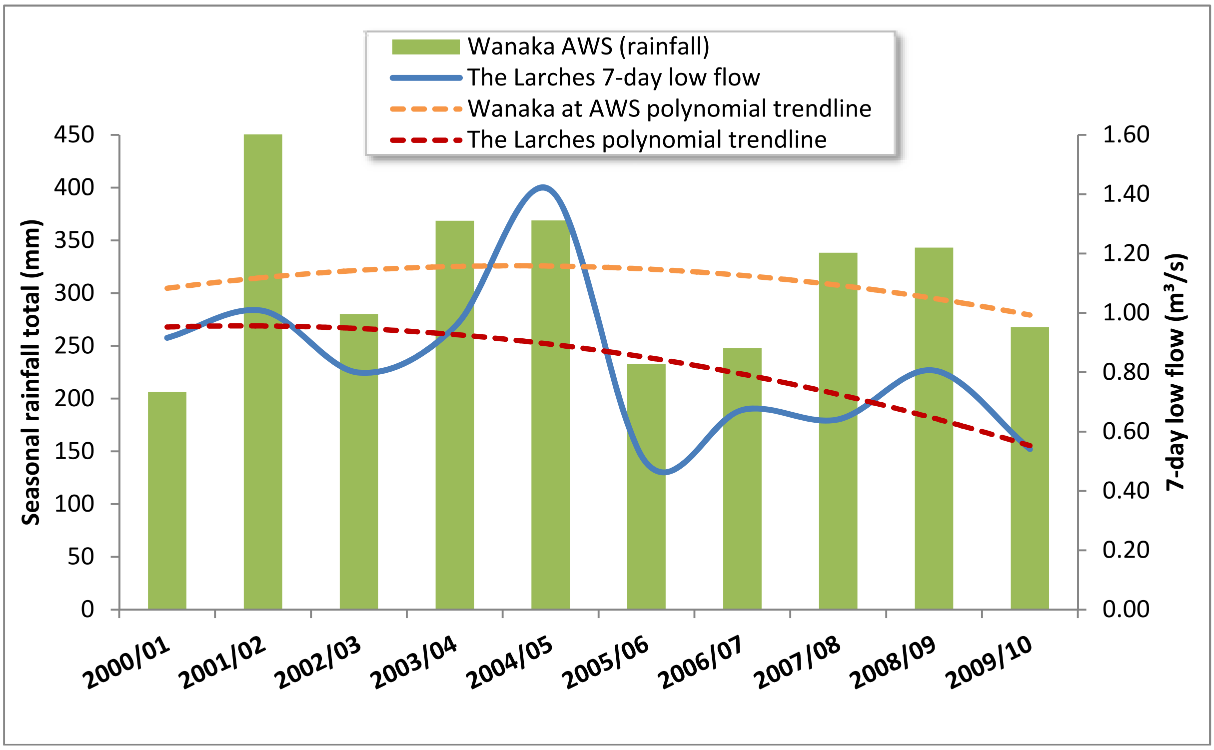

Figure 13: Comparison of flow and rainfall trends between The Larches flow recorder and Wanaka AWS rainfall site

Figure 13 shows that there has been a noticeable divergence between 7-day low flows at The Larches and seasonal rainfall totals at Wanaka AWS over the period in which the two data sets overlap.

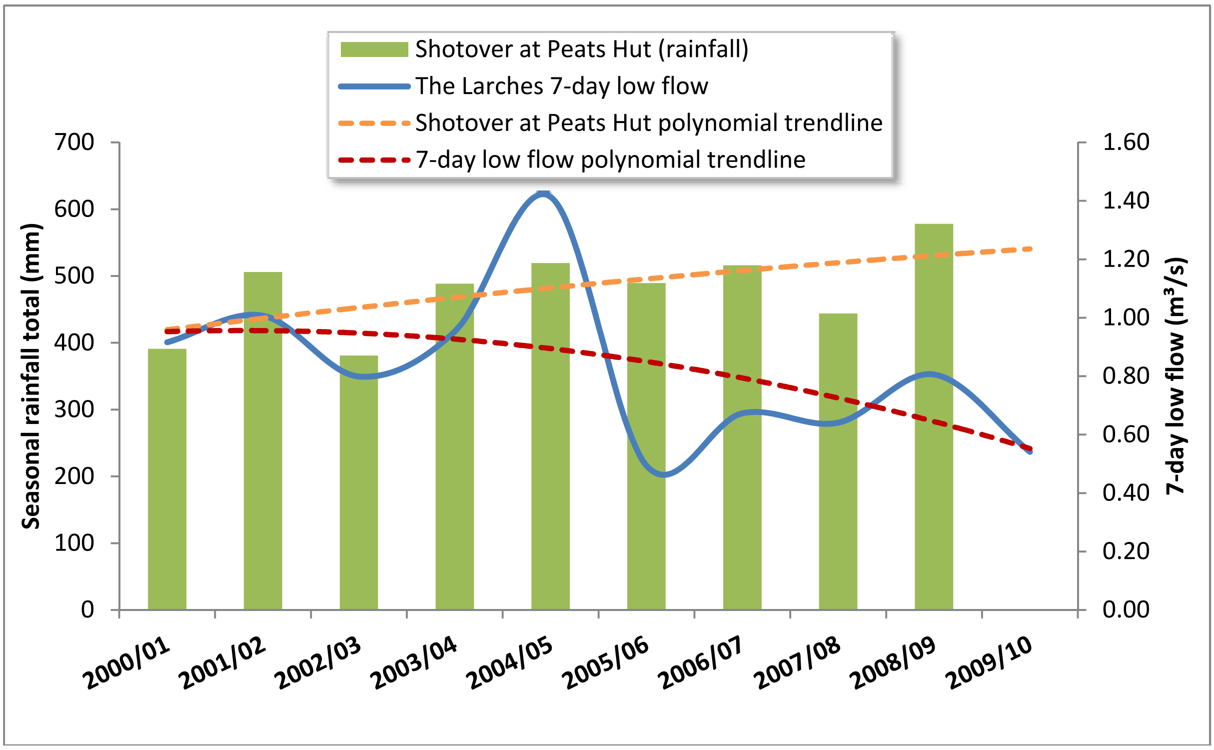

Figure 14: Comparison of flow and rainfall trends between The Larches flow recorder and Peat's Hut rainfall site

Figure 14 shows that while rainfall at Peat's Hut has increased slightly since 2000/01, 7-day low flows have exhibited a noticeable downward trend during the same period.

Several factors may contribute to base flow reductions in the Cardrona River. In the past 5-8 years, many irrigators have switched from flood to spray irrigation (I. Anderson & T Scurr, *pers comm.*). Although spray irrigation is a more efficient application technique, allowing more land to be irrigated using the same volume of water, this increased efficiency leads to a decrease in irrigation by-wash entering the river.

Another factor that contribute to declining base flows is the reduction in tussock cover, due to invasion of the pest plant, *Hieracium pilosella* (hawkweed). Snow tussock is well known for its ability to intercept and retain water (Mark & Rowley, 1976), contributing significantly, therefore, to catchment yields at low flows. Conversely, *Hieracium* is a flatweed that increases runoff and reduces water retention.

Changes in vegetation cover, including the replacement of snow tussock by *Hieracium,* have the potential to reduce base flows in the Cardrona catchment; however, the magnitude of this effect is unclear at this stage.

2.5 Water quality

2.5.1 Surface water quality

The water quality of the Upper Clutha River/Mata-Au is generally extremely good. Nutrient and microbiological parameters measured in the area's water show little indication of being compromised by human activity (ORC, 2006). The principal potential area for water quality degradation is that of the Cardrona Valley, where tourism and residential discharges are increasing due to the growth in population.

2.5.2 Groundwater quality

Groundwater quality in the Wanaka Basin is relatively good. Any detrimental water quality results have arisen from the presence of faecal coliforms or iron in excess of the drinking water standard of <1 CFU/100ml or $<0.2 g/m^3$, respectively. Over 86% of bore water samples taken in 1994 and 1995 were clear of any exceedence of the drinking water standard by either faecal coliforms or iron (Rosen *et al*, 1997). By most measures of comparison, the groundwater quality of the Wanaka-Cardrona Aquifer is very good.

Land application is the most common approach to waste disposal of tourism and residential premises treated wastewater. Much of the human wastewater and grey water disposal in the Wanaka-Cardrona Flats is primary treated and applied to land for sub-surface soakage. Wanaka Township's sewage effluent is treated in oxidation ponds adjacent to Riverbank Road and pumped to a land discharge site adjacent to Wanaka Airport. Consequently, the Wanaka - Cardrona Aquifer receives several tonnes of treated sewage effluent and principal contaminants every year.

3 Groundwater hydrology

3.1 Basin margins

Margins of a groundwater system are commonly termed ‘boundaries’. In the case of the Wanaka-Cardrona Aquifer, the margins are clearly defined at the Manuherikia formation or schist rock geological contacts. The Quaternary age gravels forming the aquifer overlie or lap onto the edges of these formations. Figure 6 shows the geological contacts of the older Quaternary gravels that comprise the Wanaka-Cardrona Aquifer: specifically, the Haast Schist basement, Pliocene sediments and hydrologic margins, which are principally found along Lake Wanaka and the Clutha River/Mata-Au. The schist rock *roche moutonnees* of Mount Iron and Mount Barker also protrude through the Quaternary outwash gravels and thus create impermeable plugs of rock in the aquifer.

3.2 Aquifer properties

The properties or parameters of permeability (or strictly speaking, hydraulic conductivity), transmissivity and storativity are those primarily considered in groundwater hydrology. The internal properties of the Wanaka-Cardrona Aquifer have been measured in a few instances by aquifer testing. In the south-west corner of the aquifer, there would appear to be two distinct outwash deposits with distinct aquifer properties. Thomson (2002) observed younger alluvium of moderate permeability and older alluvium of low permeability in drilling at the narrowing of the Cardrona Valley. The distinction was largely based on the silt/ clay matrix, which was higher in the older alluvium due to greater weathering. Thomson (2002) found that test flow rates during the drilling of pilot holes declined as the drill bit passed from the younger alluvium into the older alluvium. Aquifer testing of the younger alluvium, in bore F40/0335 on the opposite bank of the Cardrona River near Mt Barker, derived a transmissivity of 1200 square metres per day (m^2/d). ORC holds data for only ten aquifer tests undertaken in the Wanaka Basin-Cardrona Gravel Aquifer. Only a handful of the available aquifer tests provide values for transmissivity. The transmissivity values derived in interpreted aquifer tests ranged from $25m^2/d$ to $1,220m^2/d$. However, other aquifer tests for which transmissivity could not be quantitatively derived still point to high transmissivity, probably in the thousands of m^2/d.

Over a hundred specific capacity tests have been conducted at the conclusion of drilling bores in the aquifer. While specific capacity test results are subject to a wide range of potential interferences and inaccuracies, they are a general guide as to the permeability of the aquifer in the direct vicinity of the bore screen. Plotting the hundred or so specific capacity test results on the map of the aquifer reveals that very high values of specific capacity, say values in the thousands of cubic metres per day per metre of drawdown ($m^3/d/m$), lie in close proximity to low results of only tens of $m^3/d/m$. While such variability makes generalisation as to the aquifer properties more difficult, it is to be expected in a heterogeneous aquifer such as outwash gravels mixed with melt-water deposits and glacial till.

Bulk aquifer permeability was estimated from the results of specific capacity test available in 2001 (ORC, 2001). Zoning of the aquifer was undertaken in this manner with the lower end of the permeability range at 10 metres per day (m/d) and the upper end at 70m/d. The median permeability was inferred to lie at approximately 35m/d.

3.3 Groundwater flow pattern

The approximate groundwater flow pattern has been estimated by:

- developing contour maps of the water table from water table survey data
- observing areas where water infiltrates and other areas where water emerges from the aquifer
- using isotope data to infer the source and residence time of certain compartments of the aquifer.

Since 1994, these data sets have been obtained from a variety of field data sources. During the summer of 1994-95, three water level surveys were conducted using 45 bores for which the bore collar had been surveyed to mean sea level datum. In the summer of 2009-10, a reduced number of 25 bores was also measured on three occasions to observe the extent to which the water table changed across the summer time water table decline period. From each of these individual surveys, contour maps were prepared, which showed the broad contour arrangement and allowed inferences to be drawn as to the direction of flow in the aquifer.

Stream gauging can determine gross downstream changes in the flow of the Cardrona River and the dry-weather inflow from the aquifer to Bullock Creek. Several campaigns of stream gauging on the Cardrona River and Bullock Creek have been carried out since 2001, in addition to the installation of longer-term gauging sites on the Cardrona River, downstream of The Larches recorder. Environmental isotopes that throw light on the source waters or age of groundwater in the Wanaka-Cardrona Aquifer were examined in the mid-1990s (Rosen et al, 1997). Oxygen isotope ratios (18O), deuterium (2H) and tritium (3H) were analysed for a couple of dozen groundwater samples drawn from bores in the aquifer in 1995.

The inferred groundwater flow pattern, derived from these sources of information, points to the infiltration of Cardrona River water between The Larches recorder and Ballantyne Road crossing. Excess soil water from rainfall and irrigation water also augment this recharge of the aquifer. Incoming recharge pools below the water table, while moving steadily outwards towards the margins of the aquifer. The groundwater leaves the aquifer at the following discharge sites:

- Bullock Creek, Lakeside Drive and Ripponlea springs in Wanaka Township
- lower Cardrona River and the Cameron Creek tributary of the river
- springs scattered within Albert Town
- Lake Wanaka
- Clutha River/Mata-Au
- wells and bores tapping the aquifer.

This pattern of recharge and discharge to a variety of sites results in a splitting of the groundwater flow in the Mount Barker area between water flowing in the direction of Bullock Creek and Lake Wanaka, and water destined for the lower Cardrona River or Clutha River/Mata-Au.

Figure 15 illustrates the groundwater contours drawn from the 1995 water table survey. The direction of predominant groundwater flow is perpendicular to contour lines and arrows were added to Figure 15 to indicate the principal flow directions.

Figure 15: Water table contour map drawn from May 1995 measurements

The sites of recharge and discharge, and the patterns of isotopic depletion for ^{18}O and ^{2}H in the September 1995 survey (Rosen *et al*, 1997), confirmed this pattern of flow in the aquifer. The contouring of about 20 groundwater bores for their tritium (^{3}H) TR ratio indicated young groundwater at about 4 TR moving north-west and north-east away from the losing stretch of the Cardrona River towards Bullock Creek and the lower Cardrona River. Groundwater found displaying tritium ratios less than 2 TR tended to be restricted to the small sub-basin west of

Mount Barker and is likely to reflect the mixing of young groundwater with pre-bomb, older groundwater (Rosen *et al*, 1997). The results and interpretation of flow gauging in the Cardrona River and Bullock Creek confirm these patterns, with the added significance that a more substantial portion of river infiltration is destined for Bullock Creek than more easterly discharge sites (ORC, 2003). These patterns are further detailed in outlining the aquifer water balance.

3.4 Aquifer water balance

The Wanaka-Cardrona Aquifer extends from the Roy Bay arm of Lake Wanaka to the Clutha River/Mata-Au upstream of Luggate. The aquifer has become a parallel path for Cardrona River water to be channelled either into Lake Wanaka or the Clutha River/Mata-Au, as outlined in relation to groundwater flow patterns, and this channelling effect dominates the aquifer's water balance.

3.4.1 River recharge

The Cardrona River leaves the narrow Cardrona Valley and spills onto the Wanaka-Cardrona Flats. The transition is relatively sharp and includes a significant change in its Quaternary geology. The Cardrona Valley groundwater resources are characterised by most of the groundwater resource being contained within a thin veneer of alluvium, underlain at shallow depth by clay-rich Tertiary sediments that are effectively impermeable. The aquifer beneath the Wanaka-Cardrona Flats is substantially deeper and more permeable than the Cardrona Valley. This geological transition occurs near The Larches hydrological recorder site. Figure 16 shows a cross section of the bed elevation along the course of the Cardrona River from The Larches Recorder to the confluence with the Clutha River/Mata-Au. Figure 16 also shows the water table surface measured in the bores that fall near the river, but as interpolated in the contouring of 80 surveyed water bores in 1995. The contoured depth of the contact between the base of the outwash gravel aquifer and schist or Tertiary clay sediments is also shown in the cross section. Figure 16 reveals that the river and water table coincide near The Larches recorder and in bore F40/0300. The two surfaces diverge in the downstream direction as the water table declines sharply before stabilising between bores F40/0327 and F40/0151.

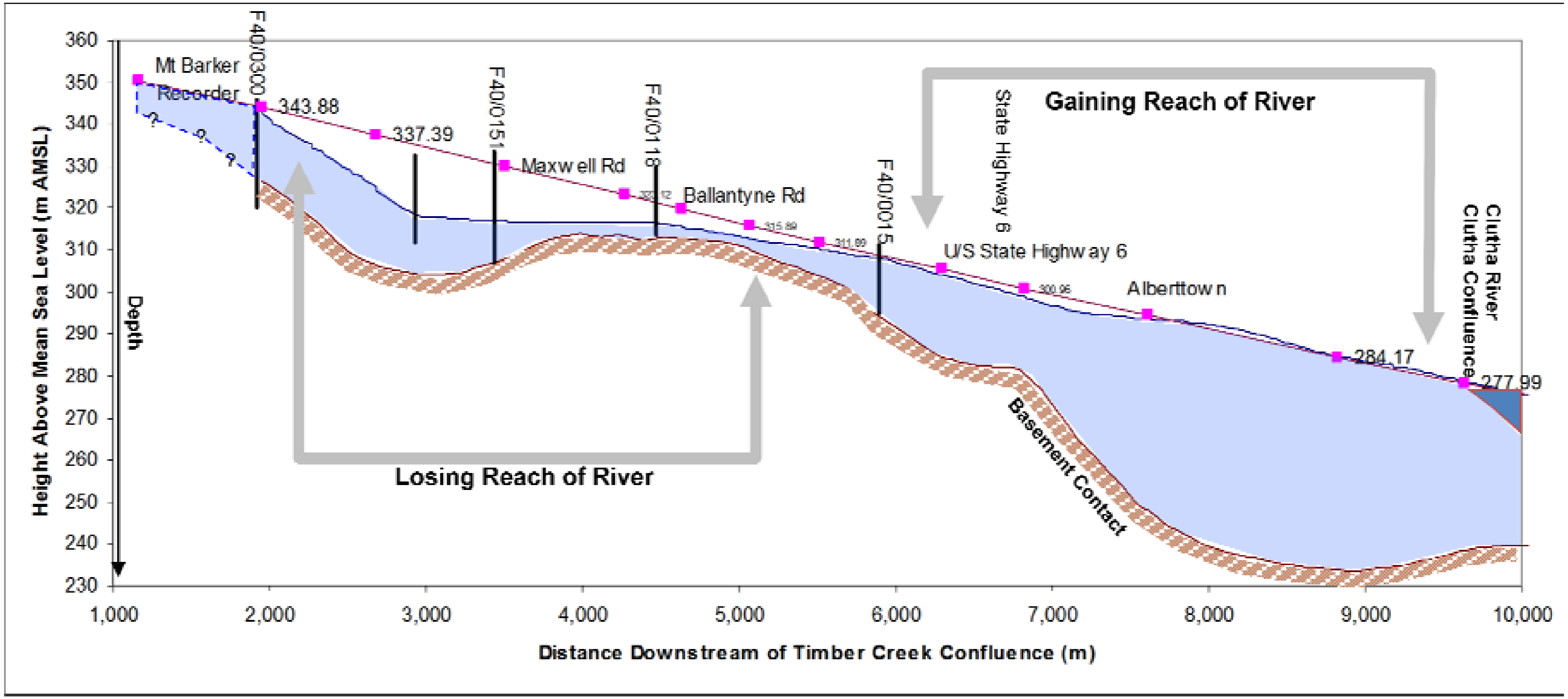

Figure 16: **Cross section along Cardrona River from The Larches recorder to Clutha confluence**

The consequence of the river-bed, water-table pattern, shown in Figure 16, is that as the river crosses the Wanaka-Cardrona Flats, it can be divided into *losing* and *gaining* reaches. The river loses water to the aquifer when the water table drops below the riverbed. This promotes a vertical infiltration gradient through the bed of the river. Once the relative levels are reversed, a vertical seepage gradient arises and the river gains groundwater. Figure 16 indicates where the inferred losing and gaining reaches of the Cardrona River lie in relation to the Ballantyne Road crossing.

The loss of surface flow in the Cardrona River has been observed since continuous flow recorder sites were installed at Mount Barker and Albert Town in 1978. While lower flows at the downstream recorder at Albert Town might be explained by the abstraction of river water during the summer irrigation months, this pattern of flow loss between The Larches and Albert Town continued into winter when the sole credible candidate for loss of river water was infiltration into the groundwater.

Multiple-site, same-day gaugings were carried out from 1999 to 2002. In May 2008, continuous recorder sites were installed at Ballantyne Road crossing and the Clutha confluence to extend the coverage of river flow sites across the Wanaka-Cardrona Flats. The data provided by these hydrological surveys allow quantification of the losses and gains for the Cardrona River. Figure 17 shows a similar river profile to that of Figure 16, but, in this case, the results of gauging carried out at four locations in March 1999 are overlain on the graph (ORC (2003)). The plot of flow rate trends in Figure 17 shows a distinct decline in flow from The Larches recorder to State Highway 6. However, downstream of State Highway 6 to the Clutha confluence, the river recovers part of the flow lost further upstream.

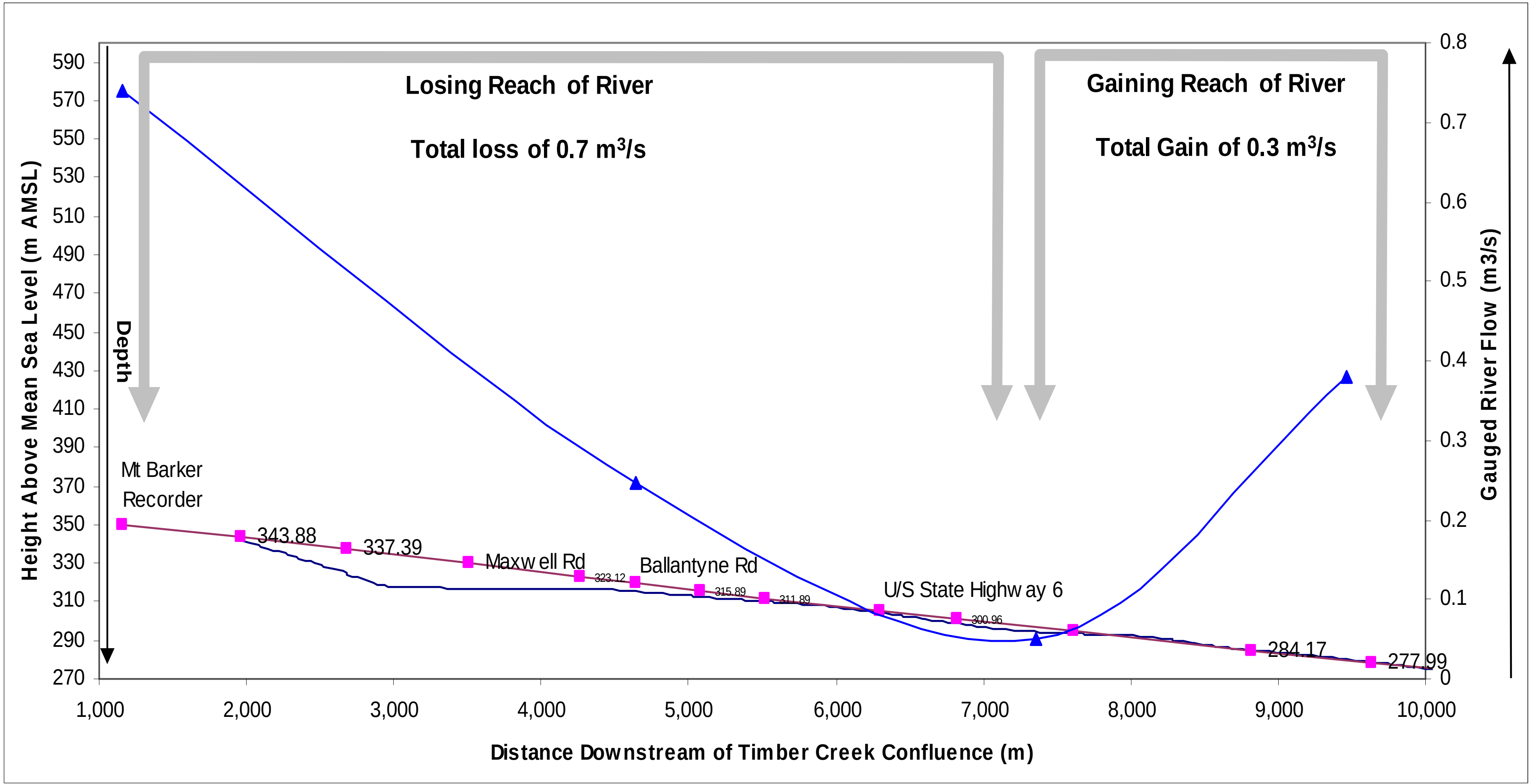

Figure 17: **Schematic profile of the lower Cardrona River, illustrating changes in flow rate on 31 March 1999 and inflocation of losing and gaining reaches of the river**

In summer low flows and during periods when surface water abstraction occurs, the Cardrona River is known to lose surface flow. Most of this losing reach and the site of water race intakes are located between The Larches recorder site and the Ballantyne Road crossing. As Figure 18 suggests, infiltration of river water extends a short distance downstream of Ballantyne Road. An instance of complete loss of surface flow occurred as a seven-week period in January-April 2010. Figure 18 shows the event as a combined plot of river flow at The Larches recorder, Ballantyne Road and the Clutha confluence, plus an over-plot of the groundwater level for the same period, as measured at the Envirowaste bore (F40/0014).

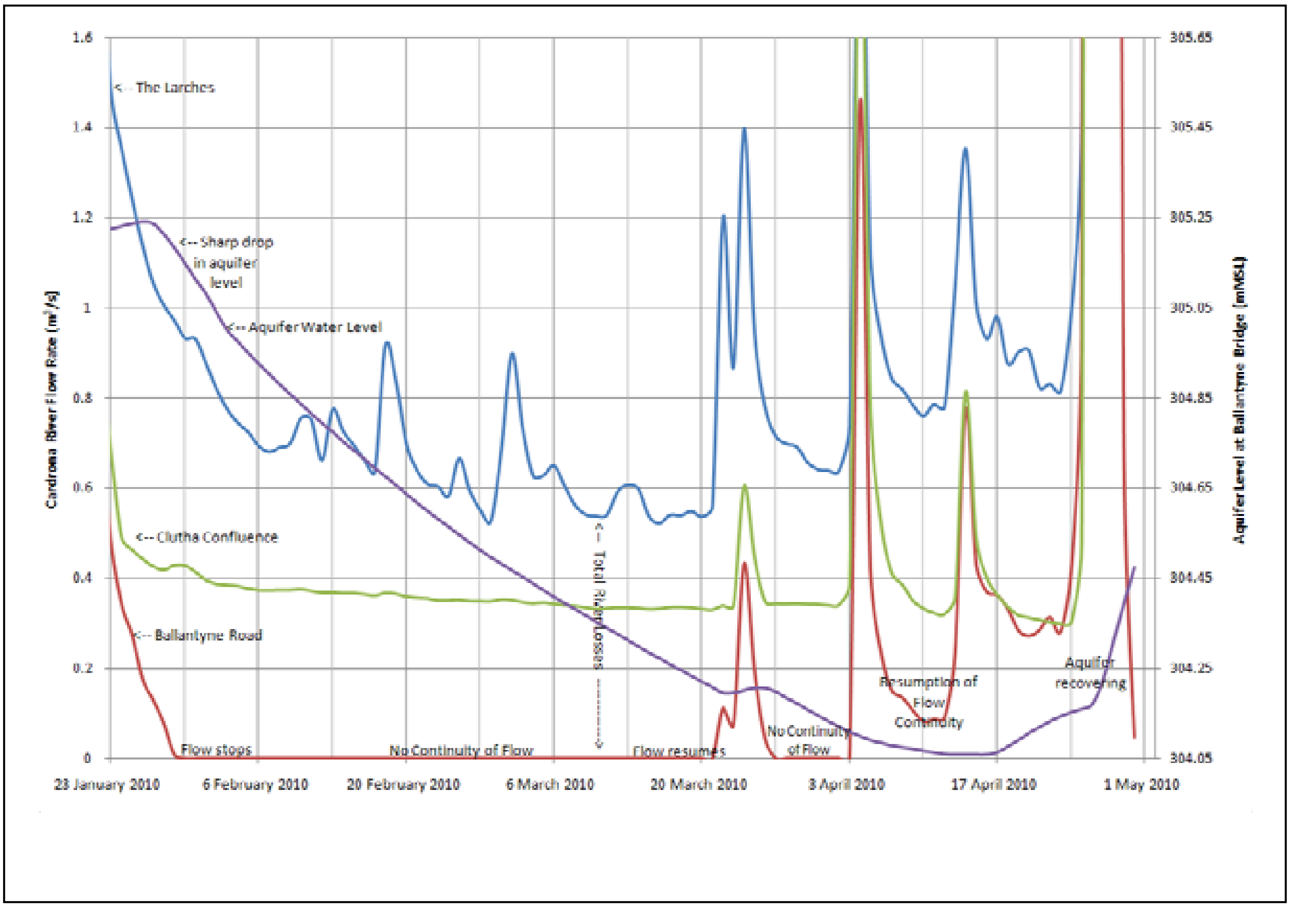

Figure 18: **Flow in the Cardrona River and groundwater level measured either side of Ballantyne Road, beginning in late January 2010, illustrating the effect of the river drying up in the middle reaches**

Figure 18 shows the flow at Ballantyne Road recorder site falling to zero in the first week of the low flow event. Interestingly, the flow measured at The Larches recorder declined gently and evenly, while the flow measured at the Clutha confluence remained relatively constant. The groundwater level recorded for the same period at Ballantyne Road, adjacent to the Cardrona River, displays a significant decline at the onset of river drying. In Figure 18, at the beginning of the seventh week, flow in the Cardrona River increases initially at The Larches recorder, followed by a sharp return of flow at Ballantyne Road that is passed on to the Clutha confluence. The response in the groundwater level is a distinct recovery.

Interpretation of the data evident in Figure 18 is that:

- low flows, water race abstraction and losses to groundwater exceed the flow capacity of the river inflow from the Cardrona Valley, as measured at The Larches recorder
- flow in the river ceased and pools soaked or dried up in the hours or day after the low flow threshold was reached
- the infiltration of groundwater for the reach of river closest to Ballantyne Road was thus curtailed abruptly
- groundwater level, which was previously in a dynamic equilibrium related to the steady inflow of river water, fell precipitously
- once a high flow rate from the Cardrona Valley rehydrated the full length of the river, flow resumed at Ballantyne Road and losses of river water to the aquifer restarted
- groundwater level at Ballantyne Road responded strongly to the resumption of river recharge of the aquifer by rising.

This event and multiple site observations of flow or groundwater level are highly illustrative of the relationships between the Cardrona River and the underlying aquifer. Groundwater levels in the aquifer are somewhat dependent on the losses of river water that pass through the riverbed and unsaturated zone on their way to the water table. The river's total losses, including the steady infiltration to groundwater and additional abstraction at water race intakes, can sometimes exceed the capacity of the river, resulting in the bed drying up between The Larches and Ballantyne Road. The marked symmetry of the groundwater level response to the cessation and resumption of river water infiltration indicates that the rate of infiltration is relatively constant, except for these rare interruptions. The constancy of the river losses to the aquifer could be explained by the fact that the rate of infiltration is governed by riverbed conductance and unsaturated zone hydraulic conductivity, two parameters that would be expected to remain relatively constant. In addition, the following interpretations were made about the general pattern of river-aquifer interaction:

- The river flow at Ballantyne Road is invariably lower than the Larches Recorder because of the infiltration losses to the aquifer in the magnitude of $0.7m^3/s$.
- At less than very high flows the river flow at Clutha Confluence is invariably higher than Ballantyne Road, not because there is any surface water tributary entering the river between these points, but because the aquifer water table intersects the base of the river in the vicinity of State Highway 6 crossing and allows seepage to augment river flow.
- The magnitude of the seepage augmentation to the lower river between SH6 and the Clutha Confluence is about $0.3m^3/s$.
- Between The Larches recorder and Clutha confluence, the river loses $0.7m^3/s$ and regains $0.3m^3/s$, so the net loss to the river (or viewed another way, the net gain to the aquifer) is up to $0.4m^3/s$.
- During higher river flows and floods when difference in flow between sites is more difficult to distinguish, the wetted perimeter of the river is larger and flow losses may be consequently larger.

3.4.2 Rainfall recharge

The Wanaka climate is classed as humid, semi-temperate and each year the climate will produce a net rainfall excess. Rain falling on the Wanaka-Cardrona Flats either runs off, evaporates, is transpired by plants or infiltrates to the underlying water table. The latter process is termed rainfall recharge.

Few ephemeral watercourses on the Wanaka-Cardrona Aquifer, and even fewer perennial creeks or streams, are not primarily augmented by groundwater seepage. Most watercourses are primarily conducting surface runoff from the surrounding ranges across the aquifer to a lake or river. This phenomenon suggests that there is little evidence that rain which falls on the aquifer sustains direct surface water runoff. Instead, the majority of any rainfall surplus would thus infiltrate to the underlying water table.

Modelling of the rainfall recharge rates, integrated rainfall, evapo-transpiration and soil properties in estimating the infiltration and runoff rates is covered in Appendix A. In summary, a soil moisture model is used with climate data and parameters consistent with the area's soil types to provide a time-series prediction of the groundwater recharge consistent with these temporal and static properties. Initially, the soil moisture model is calibrated using historical information and is subsequently used to project the recharge response to climate variation.

3.4.3 Irrigation recharge

Flood, border dyke, and more recently spray, irrigation is practised over the Wanaka-Cardrona Aquifer. Most of the water used for irrigation is taken from the Cardrona River via water race intake structures. These structures, and the water races that issue from them, are vestiges of the alluvial gold mining era of the area. The water races are now exclusively turned to pasture irrigation purposes and dominate the water management. Lesser additional surface water takes and groundwater takes are also used in pasture irrigation and occasionally in drip irrigation of grapes and olives.

An estimated total of 1.2m^3/s of irrigation water is applied to the surface of the aquifer in a manner whereby a portion would form groundwater recharge. When matched with the respective irrigated land areas, the daily application rate ranges from 33mm per day (mm/d), for the Wanaka race, to 8mm/d for the Studholme race. Modelling of the combined rainfall and irrigation recharge rates integrated rainfall, evapo-transpiration and soil properties in estimating the infiltration and runoff rates is covered in Appendix A.

3.4.4 Bullock Creek discharge

Aside from intermittent storm water runoff in Wanaka Township following rain, the small creek catchment of Bullock Creek is wholly fed by the discharge of groundwater from the Wanaka-Cardrona Aquifer. A series of springs are found at the toe of the terminal moraine facing the Wanaka lakeshore. These springs are strung together by the Bullock Creek watercourse and the creek carries the accumulated seepage to Lake Wanaka. The creek gathers substantial flow as it progresses, in the order of 0.16m^3/s per kilometre of creek length. At the creek confluence with Lake Wanaka, the measured rate of creek flow is between 0.3m^3/s and 0.5m^3/s (ORC, 2001; and ORC, 2007). In addition to Bullock Creek seepage, Ripponlea Spring discharges approximately 0.01m^3/s directly into Lake Wanaka (ORC, 2001). Other springs in the Marina area of the lakeshore discharge up to 0.1m^3/s.

3.4.5 Cardrona River discharge

The Cardrona River crossing the Wanaka-Cardrona Aquifer regains groundwater in its lower reaches where the regional water table intersects the riverbed. The lower reaches retain base flow even during periods when the river upstream has ceased flowing. Cameron Creek is a spring-fed tributary of the river and is sustained by the same seepage zone immediately downstream of the State Highway 6 crossing. The estimates of the steady base flow contributing to the lower, gaining reaches of the river and Cameron Creek are approximately 0.3m^3/s.

3.4.6 Clutha River/Mata-Au discharge

Although seepage discharge to the Clutha River/Mata-Au cannot be differentiated from the high flow rates of the main stem, the groundwater flow patterns suggest that the aquifer contributes groundwater to the Clutha River/Mata-Au as well.

3.4.7 Lake Wanaka discharge

In addition to the substantial groundwater discharge to Bullock Creek and springs fringing the lake, the groundwater flow pattern indicates that the aquifer contributes directly through the lake bed into Lake Wanaka.

3.4.8 Water balance: Summary

Table 4 lists the inflows and outflows for the Wanaka-Cardrona Aquifer. An aquifer water balance summarises the principal inputs and outputs, which helps characterise the sensitivity of a variety of different factors influencing the aquifer’s hydrology.

Table 4: Estimated Aquifer water balance for Wanaka-Cardrona Aquifer

	Inflow (+ Mm^3/y)*	**Outflow (- Mm^3/y)***
Cardrona River (Larches to SH6)	22.1	
Cardrona River (SH6 to confluence)		9.8
Rainfall recharge (natural)	6.7	
Irrigation recharge (additional)	9.7	
Bullock Creek		12.6
Clutha River/Mata-Au		8¥
Lake Wanaka		6.6¥
Groundwater takes		1.5
Total	38.5	38.5

* Mm^3/y = million cubic metres per annum
¥ These water balance terms are neither measured nor estimated using differencing.

4 Instream values of the Cardrona River

The Cardrona River is listed in the Regional Plan: Water as having a significant presence of eels, rare invertebrates and adult trout. It is also a significant habitat for juvenile trout and trout spawning.

4.1 Fish species

The Cardrona River supports four species of native fish and three species of introduced sports fish (NIWA Freshwater Fish Database). The spatial and temporal distribution of these species within the catchment is controlled by both reach specific hydrology and, in the case of Clutha flathead galaxias, predation from trout.

4.1.1 Native fish

Figure 19 shows the distribution of native fish in the Cardrona catchment, based on the New Zealand Freshwater Fish Database (NZFFD) and SOE monitoring.

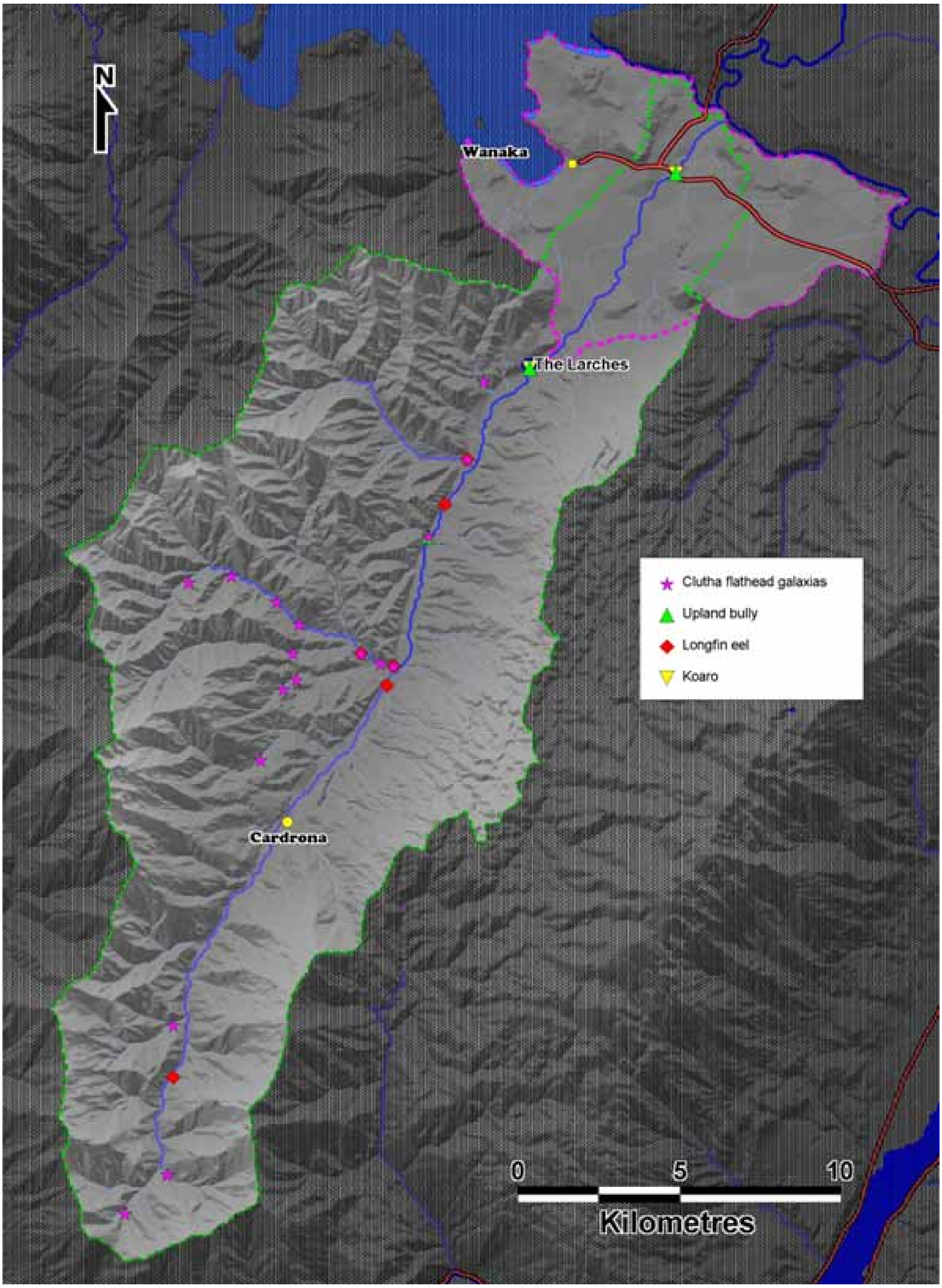

Figure 19: Distribution of native fish species in the Cardrona catchment

The presence of large trout in the main stem of the Cardrona River is likely to restrict distribution of Clutha flathead galaxias; therefore it is unlikely that a minimum flow on the main stem will have a significant impact on flathead galaxias.

State of the Environment (SOE) monitoring of the Cardrona River at The Larches flow recorder and at the SH6 bridge has identified upland bully and koaro. It is likely that koaro have only recently entered the Cardrona catchment after the establishment of a breeding population in Lake Dunstan following the construction of the Clyde Dam.

Upland bully and koaro are considered to be common (Hitchmough, *et al*, 2005) and inhabit the edge habitat of the river where they are relatively unaffected by reductions in flow. Although there have been several records on longfin eel in the Cardrona catchment, recruitment of this species is limited by the Clyde and Roxburgh dams, with a high mortality of adults as they move downstream through turbines, and because there are no fish ladders available for elvers migrating upstream. There has been no record of longfin eels in the Cardrona catchment since 1990; however, with an increase in the number of elvers being transported upstream of the dams, it is possible that a population will re-establish.

4.1.2 Sports fish

There are three species of introduced sports fish present in the Cardrona River: brown trout, rainbow trout and brook char (Figure 20). However, there is only one record of brook char in the NZFFB.

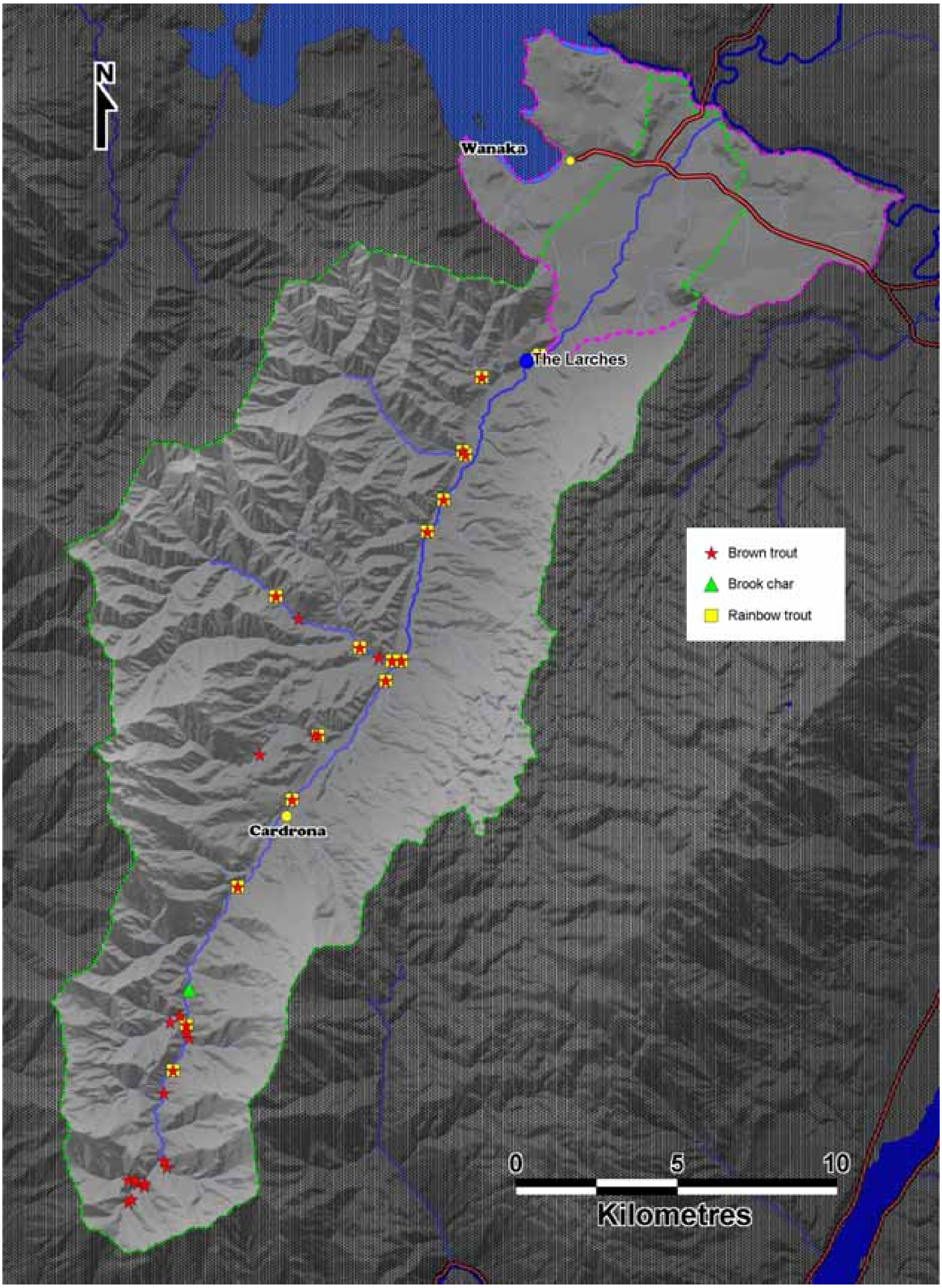

Figure 20: Distribution of introduced sports fish in the Cardrona catchment

Figure 19 shows that brown trout are spread throughout the Cardrona catchment, while rainbow trout tend to be restricted to the main stem. The perennial reaches of the Cardrona River support a significant population of resident adult brown trout, while the ephemeral lower reaches are dominated by juvenile brown and rainbow trout. Adult rainbow trout can be found in the main stem of the Cardrona throughout winter and spring, but remain only in low densities over summer and autumn, as most adults return to the Clutha River/Mata-Au.

The Cardrona River supports a small population of brook char in its upper reaches. This population has little or no recreational value because of their stunted size, due to the marginal conditions in which this population exists. The lower reaches of the Cardrona River provide spawning and juvenile rearing habitat for a large number of brown and rainbow trout from the upper Clutha and Lake Dunstan, and it is considered one of the most important sources of juvenile fish for those populations.

4.2 Natural values of the Cardrona River

The Cardrona River is recognised for both its scenic and biodiversity values. Schedule 1A of the Regional Plan: Water (RPW) recognises that the river has a high degree of naturalness above 900m and is free of pest macrophytes although its lower reaches are now infected with the invasive diatom *Didymosphenia geminata*. The RPW also recognises that the Cardrona River provides a significant habitat for flathead galaxias (Clutha flathead galaxias).

4.2.1 Sports fishery values

The middle and upper reaches of the Cardrona River support a locally important brown trout fishery (C. Halford, *pers comm.*), with fish averaging between 1 and 2kg, and, occasionally, over 3kg. The river supports an annual spawning migration of brown and rainbow trout from Lake Dunstan and the Clutha River/Mata-Au. Progeny from spawning is important for replenishing Cardrona River fish stocks and maintenance of the regionally and nationally recognised upper Clutha and Lake Dunstan fisheries (C. Halford, *pers comm.*). High numbers of migratory brown and rainbow trout from the upper Clutha and Lake Dunstan remain in the Cardrona River throughout spring and provide significant angling opportunities.

An angler survey undertaken in 2007/08 (Unwin, 2009) has shown that there were approximately 30 angler days on the Cardrona River during this period. This figure is low compared to the 1870 angler days spent on the nearby Makarora catchment during the same period.

4.2.2 Biodiversity values

The Cardrona River supports several populations of Clutha flathead galaxias, which is listed as being in gradual decline (Hitchmough, *et al*, 2005). A search of the New Zealand Freshwater Fish Database (NZFFD) shows that the largest population of Clutha flathead galaxias in the Cardrona catchment is located in the Branch Burn (Figure 19). It is likely that The Clutha flathead galaxias was once widely distributed throughout the Clutha catchment, but is now restricted almost exclusively to tributaries above trout barriers and in areas where flow conditions are not conducive to trout survival.

Most of the Clutha flathead galaxias populations in the Cardrona catchment occur upstream of physical barriers to trout migration and are unaffected by changes in flow regimes. However, Clutha flathead galaxias populations may exist without trout barriers where trout numbers are kept low due to sub-optimum conditions caused by surface water abstraction. This phenomenon has also been observed in the Manuherikia River in Central Otago (Leprieur, *et al* 2006).

5 Water management

5.1 Historic management

The issuing of mining privileges to water race owners to allow them to take and use surface water for gold sluicing was the means by which water in the Upper Clutha was originally managed. The Cardrona Valley was a goldfield for a short period, and the Pembroke and Cromwell warden's court was responsible for issuing mining privileges. After the waning of significant mining in the area, the warden's court continued to be used for the management of water rights to the pastoralists of the Upper Clutha until the Water & Soil Conservation Act 1967. Thereafter, mining privileges were 'grandfathered' over to the Act as 'mining rights'. With the coming of the Resource Management Act in 1991, mining privileges became 'deemed permits,' with a twilight extinction of thirty years which is due to expire on 1 October 2021. Sections of the Act provide for a transition from deemed permits to RMA water take resource consents. ORC's policy is to make an orderly transition from deemed permits to RMA consent before the ending date.

The first groundwater take consents were issued under the Water & Soil Conservation (W&SC) Act provisions as underground water rights, especially after the W&SC Amendment Act in 1981. Bore permits or consents became a requirement of the Otago Catchment Board after 1988.

5.2 Current management

5.2.1 Surface water

The Cardrona River near The Larches is turned out into four major water races, which are managed within the mining privilege system under nine mining rights, and have at least two dozen shareholders. A legal potential take of 1.278m³/s is apportioned to these rights. Although these are the largest takes in the catchment, they are not able to take their full allocation during the latter part of the irrigation season, because of low flows in the Cardrona main stem.

There are 27 consumptive surface water takes upstream of The Larches (i.e. within the upper catchment), with a combined consented take of 1.13m³/s. Many of these takes are from small tributaries that flow much less than consented rates of take during late summer; therefore, it is likely that the actual take is significantly less than that consented for much of the irrigation season.

5.2.2 Groundwater

Eighty-one groundwater take consents have been issued under the Resource Management Act 1991. A further five non-consumptive groundwater take consents have been issued since 2006 for construction dewatering. Since January 2004, when the Otago Regional Plan: Water (RPW) became operative, land disturbance consents have been required for any drilling activity greater than a metre in depth within the Wanaka-Cardrona Aquifer. In most other respects, there are few other groundwater management measures in place.

Use of groundwater within the Cardrona Alluvial Ribbon Aquifer is currently confined to communal water supply of consented 0.18 million m^3/y, with little scope for much else. The larger Wanaka-Cardrona Aquifer is currently exploited by 290 registered bores and 55 consented consumptive groundwater takes. The current Wanaka-Cardrona Aquifer allocation of groundwater by resource consents is between 3.5 and 4 million m^3/y. It is feasible to develop irrigation-capacity bore water supplies throughout much of the aquifer, although in the airport area, the water table is deep and any such development would need to remain within any future maximum annual volume limit.

The aquifer has **none** of the following declarations available in the RPW for the management of groundwater:

- water take restriction zone
- restriction levels
- groundwater protection zone(s).

No volumetric limit on the groundwater that can be allocated from the aquifer has been set yet. Changes to the RPW, brought in during 2010, allowed the setting of maximum annual allocation volumes.

5.2.3 Alluvial Ribbon Aquifer

The alluvial aquifer, adjoining the Cardrona River upstream of The Larches river recorder to Cardrona Village, is designated as an alluvial ribbon aquifer. This results in this section of alluvium groundwater being managed as the same hydrological unit as the Cardrona River. This management regime recognises the coupled hydrology of the two water bodies and that any significant depletion of groundwater results in the river being affected by an equivalent amount.

5.3 Current surface water management setting

Nine historic water race licences remain as deemed water permits taking water from the Cardrona River at or downstream of The Larches flow recorder. This arrangement has been rationalised into four water race intakes (“Wanaka Station”, “Studholme”, “Mt Barker” and “Farrant”). A legal potential take of $1.278 m^3/s$ is apportioned to these rights. Although these represent the largest takes in the catchment, they are not able to take their full allocation for the latter half of the irrigation season, due to low flows in the main stem of the Cardrona River (Figure 21).

Approximately 650 ha of land has been developed for surface water-based irrigation across the Wanaka-Cardrona Flats water races. The area of Wanaka-Cardrona Aquifer land surface under groundwater-based irrigation is approximately 550 ha in the ORC consent database. However, this consent database total is expected to contain substantial double counting and overlap with surface water-based irrigation land. The longest-standing means of pasture irrigation is also wild -flood and border dyke, primarily supplied from surface water races; however, an increasing number of properties in this area are upgrading to spray irrigation systems. Spray irrigation systems are dominated by either pivot or pod techniques.

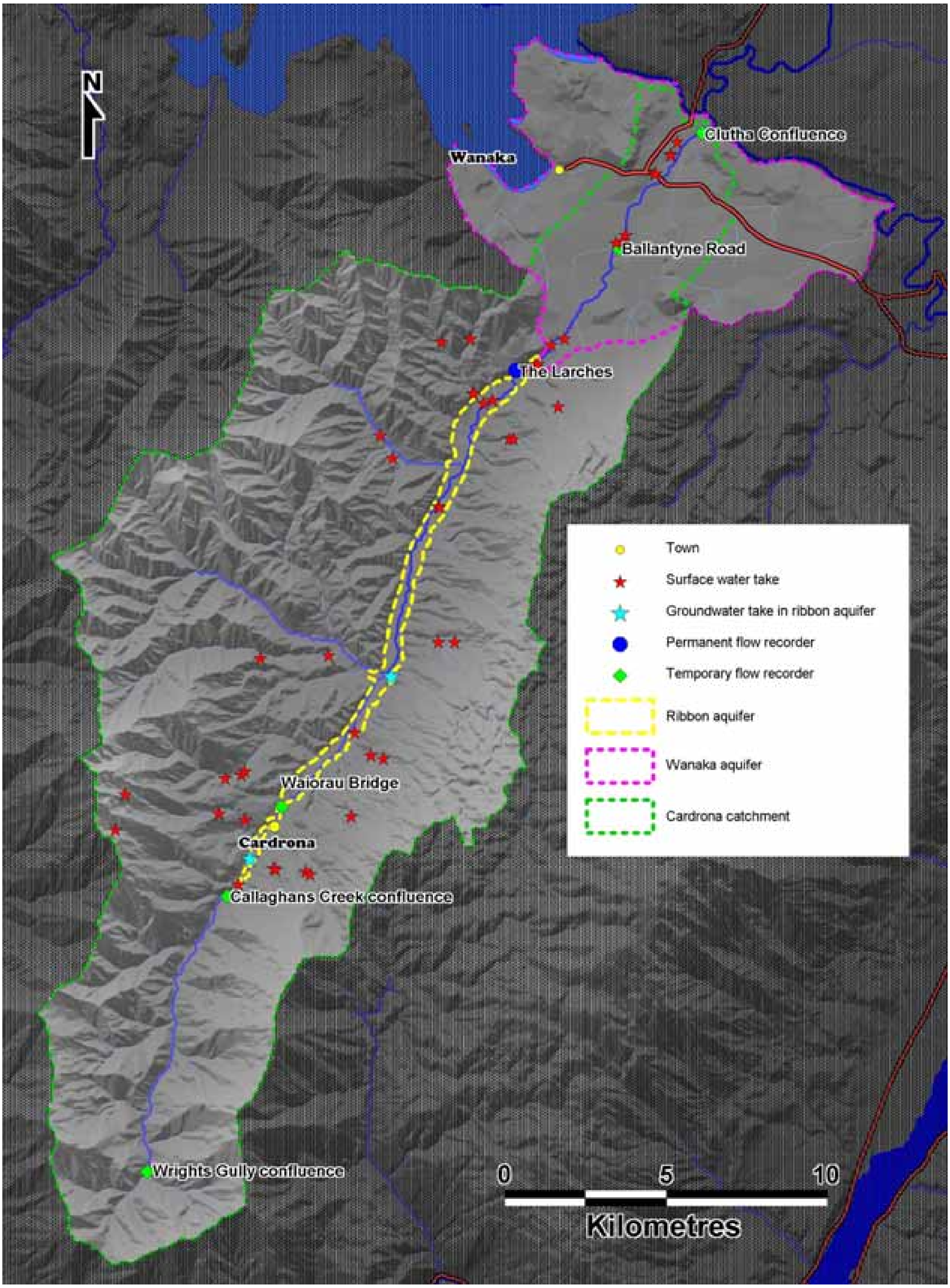

Figure 21: **Location of surface water takes in the Cardrona catchment**

Otago Regional Council

The Luggate Creek deemed permits continue to be operated by the Criffel Water Scheme. A weir was constructed in Luggate Creek in the mid-1900s, and a water race-tunnel system brings the abstracted creek water into the Wanaka-Cardrona Aquifer area. Deemed permits apportion up to $0.54m^3/s$ are issued from Luggate Creek into this weir, tunnel and race system.

6 Groundwater modelling

A computer groundwater model was developed to gain a better understanding of the behaviour of the Wanaka-Cardrona Aquifer and its interaction with water bodies such as the Cardrona River and Bullock Creek. Any similar computer model attempts to provide a simplified representation of the hydrological system concerned, which allows the model to be used in simulating past and future system behaviour. Appendix B details the technical development of the model and measures taken to achieve a highly representative model through calibration with measured data.

6.1 Model framework

The model was bounded by impermeable or low permeability boundaries, including schist bedrock and silty sediments, as outlined in the preceding discussion of geology. Lake Wanaka and the Clutha River/Mata-Au provided additional margins. The base of permeable gravel alluvium was modelled as a surface and formed the bottom of the modelled flow system. Finally, Mount Iron was specified as an impermeable plug within the model framework, as it was recognised that its constituent schist bedrock would not contribute to the main groundwater flow system.

6.2 Permeability and other parameters

The results of aquifer tests and bore pump testing were assessed for their ability to provide guidance on the range of aquifer permeability anticipated across the wider aquifer. However, due to the small scale of most tests and since few test results provided measurements of aquifer properties covering a small area, the bulk aquifer permeability values were manipulated within the calibration process to best match observed conditions.

6.3 Rainfall and irrigation

The recharge modelling method outlined in Appendix A was used to initialise aquifer recharge estimates. These values were applied across the aquifer surface and further manipulated in calibration, where justified by the data. An approximation of the current irrigation practice was made for the purposes of modelling groundwater recharge.

6.4 Interfaces with surface water

As outlined in discussion of groundwater hydrology, the Wanaka-Cardrona Aquifer system interfaces with the Cardrona River, Bullock Creek, Lake Wanaka and the Clutha River/Mata-Au. The model interfaces used to replicate the observed interaction are described in Appendix B.

Lake Wanaka and the Clutha River/Mata-Au are large, perennial water bodies that are strongly connected to the aquifer. Accordingly, specified level boundaries could be deployed in simulating these interfaces. The Cardrona River has a more complicated mode of interaction with the underlying aquifer, as previously described. So, the Cardrona River was simulated with a more sophisticated interface module in the groundwater model that allowed the flow of the river to be explicitly simulated, including the ability to cease loss of river water once available river water had been consumed by infiltration. A surface water-groundwater model of the lower Cardrona River as it crosses the aquifer was formulated in this fashion.

6.5 Calibration

6.5.1 Calibration data sets

Matching of computer model results with measured hydrological data formed the backbone of the calibration process. Two modes of calibration use distinct sets of measured groundwater levels, either distributed one-off water table surveys or time series of level measurements made over extended periods of time. The two modes of calibration, either static in time or time variant, are termed ‘steady-state’ or ‘transient’. In the case of the Wanaka-Cardrona Aquifer, several sets of distributed, one-off water table surveys were available, for the periods 1995-1996 and 2009-2010. One-off flow gaugings by ORC hydrologists were also available for Bullock Creek in Wanaka Township from October 2001 to April 2006.

Transient calibration data sets were available as a continuous time series from the following sites:

- groundwater level measured at the Envirowaste bore (F40/0014), from May 2001 to present;
- groundwater level measured at the Wilson bore (F40/0164), from November 1995 to September 2000.

As the calibration period of January 2006 to July 2009 was chosen, the Wilson bore could not be used in calibration. River flow data sets were used in setting transient interfaces. Therefore, the sole calibration data set was the Envirowaste bore.

6.5.2 Steady-state calibration

The first model calibration carried out used the calibration data set of 34 water table elevations, which were measured in May 1995. The results of calibration across the aquifer revealed a standard deviation in error of 1.18m (from -2.85m to +2.75m), with an altitudinal range across the aquifer of 65.3m. The standard deviation in calibration error divided by the range (Normalised Root Mean Squared Deviation, NRMSD) in the steady-state model settled at 0.018 or 1.8%. At this point, the steady-state calibration was concluded. A calibration solution is generally considered acceptable where the NRMSD is less than 0.05 or 5%. The flow rate of model interface simulating Bullock Creek of 0.3m^3/s was also comparable with the measured flow rate ranging ranged between 0.26m^3/s and 0.39m^3/s.

6.5.3 Transient calibration

The primary transient calibration data set was the four-year level record of 2006 to 2009 at the Envirowaste bore (F40/0014), near Ballantyne Road crossing. Matching the observed historic highs and lows on groundwater level at this site was the primary focus of transient calibration. Figure 22 shows the curve matching to historical level data graphically.

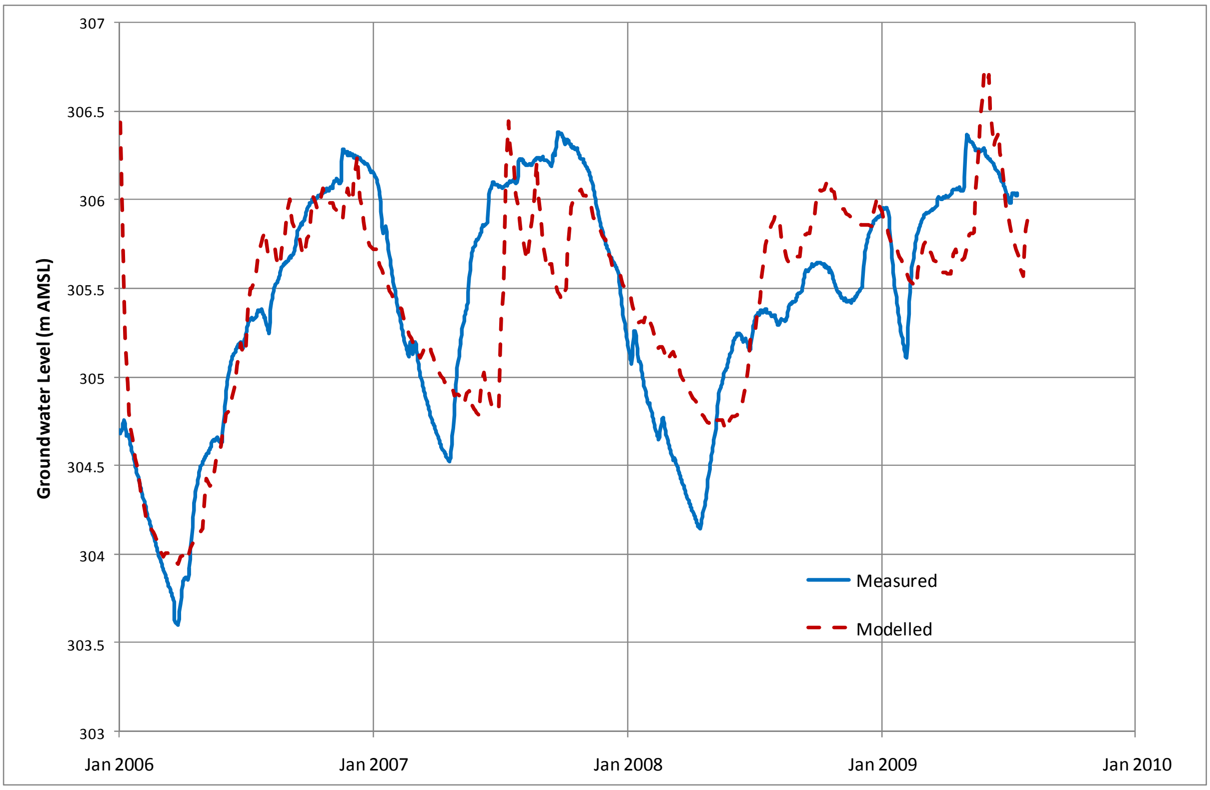

Figure 22: Measured vs modelled groundwater level for the Envirowaste bore (F40/0014) as part of transient calibration

An acceptable match with observed data was achieved and modelling progressed to scenario modelling.

6.6 Scenario modelling

Scenario modelling entails using a calibrated computer model to predict aquifer behaviour. This is sometimes termed as answering the "what if" questions. In this investigation, the primary questions to be answered involved the future groundwater extraction regime. Since this regime is managed primarily by limiting the combined annual groundwater allocation volumes, scenarios were devised to take fractions of the current allocation volume from the current distribution of bores throughout the Wanaka-Cardrona Aquifer. These scenarios are:

Scenario 0: No groundwater extraction from the aquifer

Scenario 1: **30%** of current allocation = **0.98 million m^3/y**

Scenario 2: **66%** of current allocation = **1.95 million m^3/y**

Scenario 3: **100%** of current allocation = **3.25 million m^3/y**

Scenario 4: **150%** of current allocation = **4.88 million m^3/y**

Scenario 5: **200%** of current allocation = **6.50 million m^3/y**

Scenario 6: **300%** of current allocation = **9.76 million m^3/y**

The "actual" volume of groundwater extraction in Otago aquifers is commonly thought to be 30% of the "paper" allocation volume. Thus, Scenario 1 can be thought of as representing the present day situation. However, it is useful to compare the 'extraction' scenarios to Scenario 0, which is the non-extractive scenario. In general, the higher the combined extraction rate, the larger the quantitative effects on the aquifer and connected water bodies. This proposition will be tested by comparing the various scenarios in computer modelling.

6.6.1 Groundwater levels

Groundwater level changes for the model scenarios were assessed at a number of points in the aquifer. The net reduction in groundwater levels at the Envirowaste bore (F40/0014) is listed in Table 5 below:

Table 5: Level reduction statistics for modelled increases in abstraction

	Scen01	Scen02	Scen03	Scen04	Scen05	Scen06
Proportion of current allocation	30%	60%	100%	150%	200%	300%
Mean reduction in level (m)	0.14	0.31	0.54	0.64	0.93	1.44
Median reduction in level (m)	0.14	0.30	0.51	0.55	0.8	1.21
Mean reduction in aquifer storage (million m^3)	1.0	2.2	3.8	4.6	6.7	10.3

The reduction in groundwater levels and net reduction in aquifer storage is broadly consistent with the level of additional abstraction envisaged. It is interesting to note that the mean groundwater level reduction at 100% of current allocation would be a generalised 0.5 m, while a tripling in allocation would entail 1.4m.

6.6.2 Aquifer outflows

Aquifer inflows as rainfall, irrigation and river losses have already been described and quantified for use in initialising the computer model. Aquifer outflows are the product of the computer simulation and changes in the outflows also indicate the net effect of groundwater extraction. The outflows in the Wanaka-Cardrona Aquifer context are described in the water balance section of the report, and include the following:

- seepage back into the lower Cardrona River
- seepage into Bullock Creek
- seepage into Lake Wanaka
- seepage into the Clutha River/Mata-Au
- net bore extraction from the aquifer.

Table 6 lists the change in outflows determined in computer modelling.

Table 6: Changes in modelled Wanaka-Cardrona Aquifer outflows for six scenarios of varying abstraction

	Scen01	**Scen02**	**Scen03**	**Scen04**	**Scen05**	**Scen06**
Proportion of Current Allocation	30%	60%	100%	150%	200%	300%
Bullock Creek						
Loss in outflow due to pumping (m^3/d)	249	486	632	898	1,227	1,941
Loss in outflow due to pumping (m^3/s)	0.003	0.006	0.007	0.010	0.014	0.022
Loss in outflow due to pumping (%)	1.3%	2.6%	3.3%	4.7%	6.5%	10.2%
Lake and Clutha River/Mata-Au						
Loss in outflow due to pumping (m^3/d)	1,761	3,604	5,673	6,946	9,724	14,099
Loss in outflow due to pumping (m^3/s)	0.020	0.042	0.066	0.080	0.113	0.163
Loss in outflow due to pumping (%)	3.4%	6.9%	10.9%	13.4%	18.7%	27.2%
Seepage Reach of Cardrona River						
Loss in outflow due to pumping (m^3/d)	2,045	4,200	6,553	8,194	9,896	12,876
Loss in outflow due to pumping (m^3/s)	0.024	0.049	0.076	0.095	0.115	0.149
Loss in outflow due to pumping (%)	10.3%	21.2%	33.1%	41.3%	49.9%	65.0%
Total						
Loss in outflow due to pumping (m^3/d)	4,055	8,290	12,857	16,037	20,846	28,915
Loss in outflow due to pumping (m^3/s)	0.047	0.096	0.149	0.186	0.241	0.335

The effect of extraction on Bullock Creek is relatively mild. Even Scenario 6, which is a tripling of current allocation, causes only a 10.2% loss in creek seepage. Bullock Creek could be considered relatively invulnerable to groundwater extraction. The loss of seepage to Lake Wanaka and the Upper Clutha River/Mata-Au is more significant, but these water bodies are largely insensitive to the reduction in seepage.

The water body found most prone to variation in abstraction was the gaining reach of the lower Cardrona River, with a reduction of 65% in seepage after a tripling of groundwater take allocation. This gaining reach of the lower Cardrona River would be most sensitive to such a reduction during periods when flow continuity has been lost and flow was entirely reliant on seepage from the aquifer.

7 Instream habitat requirements for flow

7.1 Physical habitat survey

The ORC contracted the National Institute for Water and Atmospheric research (NIWA) to carry out a study to determine the flows required to maintain acceptable habitat for the fish species present in the Cardrona River.

The primary aims of the study were to:

- conduct instream habitat surveys in critical reaches of the Cardrona River
- conduct a hydraulic analysis, using RHYHABSIM (Jowett, 1989) to determine how weighted usable area (WUA) for brown trout and native fish habitat varies with discharge
- assess flow requirements for the Cardrona River based on the habitat requirements of the native and introduced fish species.

7.2 Instream Flow Incremental Methodology (IFIM): Summary

The instream flow incremental methodology (IFIM; Bovee 1982) is a holistic way to assess flow regimes by considering the effects of flow changes on instream values. The IFIM strength lies in the ability to quantify the loss of habitat caused by changes in the natural flow regime, which helps the evaluation of alternative flow proposals (Jowett, 2004).

Assessing suitable physical habitat for aquatic organisms that live in a river is the ecological aim of IFIM assessments. The consequences of loss of habitat are well documented; the environmental bottom line is that if there is no suitable habitat for a species, it will cease to exist (Jowett, 2004). Habitat methods allow for a more focused flow assessment and can potentially result in improved allocation of resources (Jowett, 2004). However, it is essential to consider all aspects, such as food, shelter and living space, and to select appropriate habitat suitability curves for an assessment to be credible (Orth, 1987; Jowett, 1995, Biggs, 1996).

IFIM assumes that available habitat is the most important factor influencing fish abundance; however, it does not take into consideration physiochemical (such as temperature, dissolved oxygen, etc.) or biotic interactions (such as competition or predation). In situations where physical habitat is not the limiting factor, IFIM may not be the most appropriate method to determine the flows required for aquatic ecosystems. However, in the case of the lower Cardrona River, physical habitat is clearly limiting for most species, because much of this section is dewatered for a significant period every year.

7.2.1 Habitat preferences and suitability curves

The IFIM 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 if there is no suitable physical habitat for the given species, then they cannot exist. However, if there is physical habitat available for a given species, then that species 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, 2004).

Biological information is supplied in terms of habitat suitability curves for a particular species and life stage (Jowett, 2004). A suitability value is a quantification of how well suited a given depth, velocity or substrate is for the particular species and life stage (Jowett, 2004). The result of an instream habitat analysis is strongly influenced by the habitat criteria that are used. If these criteria specify deep water and high velocity requirements, maximum habitat will be provided by a relatively high flow. Conversely, if the habitat requirements specify shallow water and low velocities, maximum habitat will be provided by a relatively low flow, and habitat will decrease as the flow increases. The suitability curves developed in New Zealand for large, feeding adult brown trout (Hayes & Jowett, 1994) specify higher depth and velocities than curves for adult brown trout developed in the U.S. (Raleigh, *et al*, 1986). Whether this is due to differences in the sizes of fish has not been clarified. However, it is clear that it is important to use suitability curves appropriate to the river and that were developed for the same behaviour, size and life stage of fish as those to which they are applied.

The procedure in an instream habitat analysis is to select appropriate habitat suitability curves or criteria, and then to model the effects of a range of flows on the selected habitat variables in relation to these criteria. The area of suitable habitat, or weighted usable area (WUA), is calculated as a joint function of depth, velocity and substrate type for different flows. Instream habitat is expressed as the total area of suitable habitat (WUA (m^2/m). WUA (m^2/m) is the measure of the total area of suitable habitat per metre of stream.

Generally, native fish are found in similar habitats over a wide range of rivers. McDowall (1990) has described these habitats in descriptive terms. The quantitative approach taken in New Zealand has been to develop general habitat suitability criteria for species of interest by using data collected from several rivers. To date, general habitat suitability curves have been developed for several native fish species, some of which has been published (e.g. Jowett & Richardson, 1995), while some remains unpublished.

7.3 IFIM for the Cardrona River

Using IFIM, flows that provide optimum habitat have been identified, as have thresholds below which there is a significant increase in the rate of habitat reduction with decreasing flow (point of inflection). Where there is no clear point of inflection, the flow that provides 70% of the habitat available at MALF is used (Jowett & Hayes, 2004 (Appendix D)). The "inflection point" of an IFIM curve is essentially the point of diminishing return, where proportionally more habitat is lost with decreasing flow than is gained with increasing flow.

The IFIM survey reach for the Cardrona River was located upstream of The Larches flow recorder. The habitat in this reach is defined by a relatively unconfined channel with gravel substrate, alternating gravel bars, and varying river width. The survey reach was composed of 17.5% pools, 31% runs and 51.5% riffles (ORC, 2001b).

The habitat type of the survey reach is characteristic of the lower reaches of the Cardrona River, which provides a good habitat for juvenile brown and rainbow trout; however, relatively shallow depths restrict the available habitat for adult trout.

7.3.1 *Effects of changes in flow for available habitat for introduced sports fish*

Figure 23 shows the relationship between flow and available habitat for adult and juvenile rainbow and brown trout.

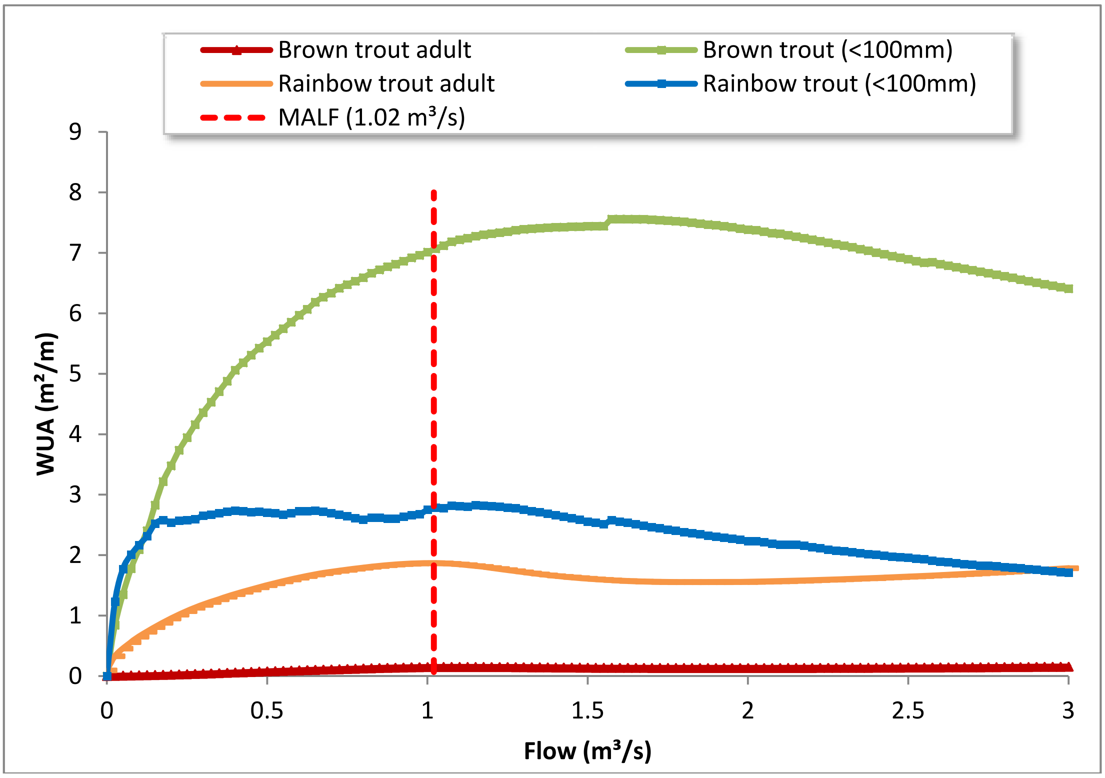

Figure 23: Variation of instream habitat in the Cardrona River for adult and juvenile trout

As shown in Figure 23, there is very little available habitat for adult brown trout throughout the range of flows modelled. Flows around 1m^3/s provide adult and juvenile rainbow trout with close to optimum habitat, although there is relatively little habitat available for adult rainbow trout, even at optimum flows. There is a significant amount of habitat available for juvenile brown trout at optimum flows (7.2m^2/m WUA at 1.57m^3/s)

Available habitat for trout spawning was also examined, and the results are shown in Figure 24.

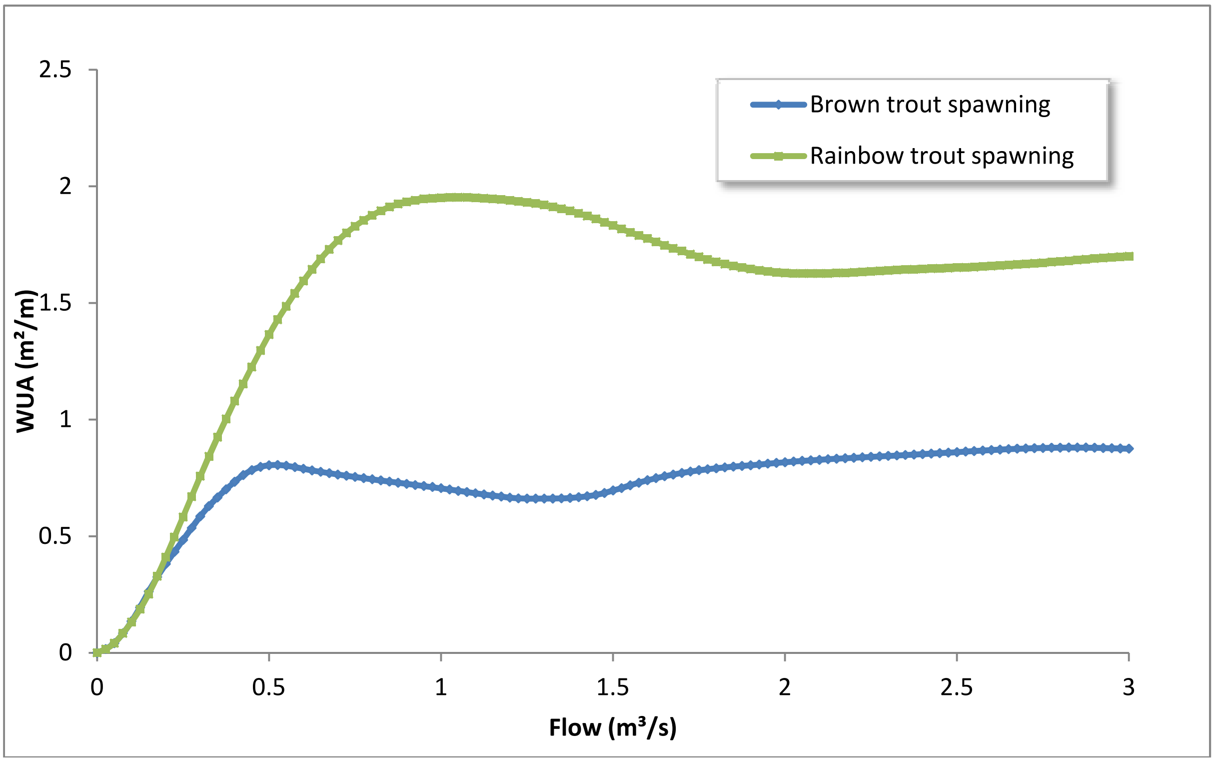

Figure 24: Variation of instream habitat in the Cardrona River for brown and rainbow trout spawning

Figure 24 shows that habitat for brown trout spawning peaks at 0.5m³/s and remains stable at approximately 0.75m²/m WUA throughout the range modelled. Available habitat for rainbow trout spawning peaks at 2m²/m WUA at a flow of 1m³/s.

Table 7 shows the optimum flows and points of inflection of available habitat for sports fish in the Cardrona River. Where no clear point of inflection is apparent, the flow which provides 70% of the habitat available at MALF is used in accordance with Jowett and Hayes (2004) (Appendix D).

Table 7: Critical thresholds for instream habitat for fish in the lower Cardrona River

	Brown trout adult	**Brown trout (<100mm)**	**Rainbow trout (<100mm)**	**Rainbow trout adult**	**Brown trout spawning**	**Rainbow trout spawning**
Optimum flow (m³/s)	NA	1.575	0.15 - 1.15	1.025	0.525	NA
Point of inflection (m³/s)	NA	NA	0.125	NA	0.35	NA
Flow at which 70% of available habitat at MALF occurs (m³/s)	0.675	0.4	NA	0.375	NA	0.5

Table 8 shows that the optimum flow for juvenile brown trout is 1.57m³/s, and without a clear point of inflection, the flow recommended to maintain a juvenile trout fishery is 0.4m³/s. A flow of 0.5m³/s provides for both brown and rainbow trout spawning.

The IFIM data supports the anecdotal evidence of the high value of the lower Cardrona River as a spawning and juvenile rearing habitat, and that available habitat is limited for adult trout by shallow water depths.

7.3.2 Effects of changes in flow for available habitat for native fish

Clutha flathead galaxias have been excluded from the IFIM analysis because they are absent from the main stem of the Cardrona River due to trout predation, and are not limited by available habitat in this reach.

The results of the IFIM study showed that there is very little available habitat for adult longfin eels throughout the range of flows modelled (Figure 25), although a substantial amount of habitat is available for juvenile eels at flows above 0.8m³/s. This is consistent with the riffle-dominated nature of the survey reach.

Although there is a significant amount of habitat available for juvenile longfin eels, recruitment for this species is severely limited by downstream migration barriers (Clyde and Roxburgh dams).

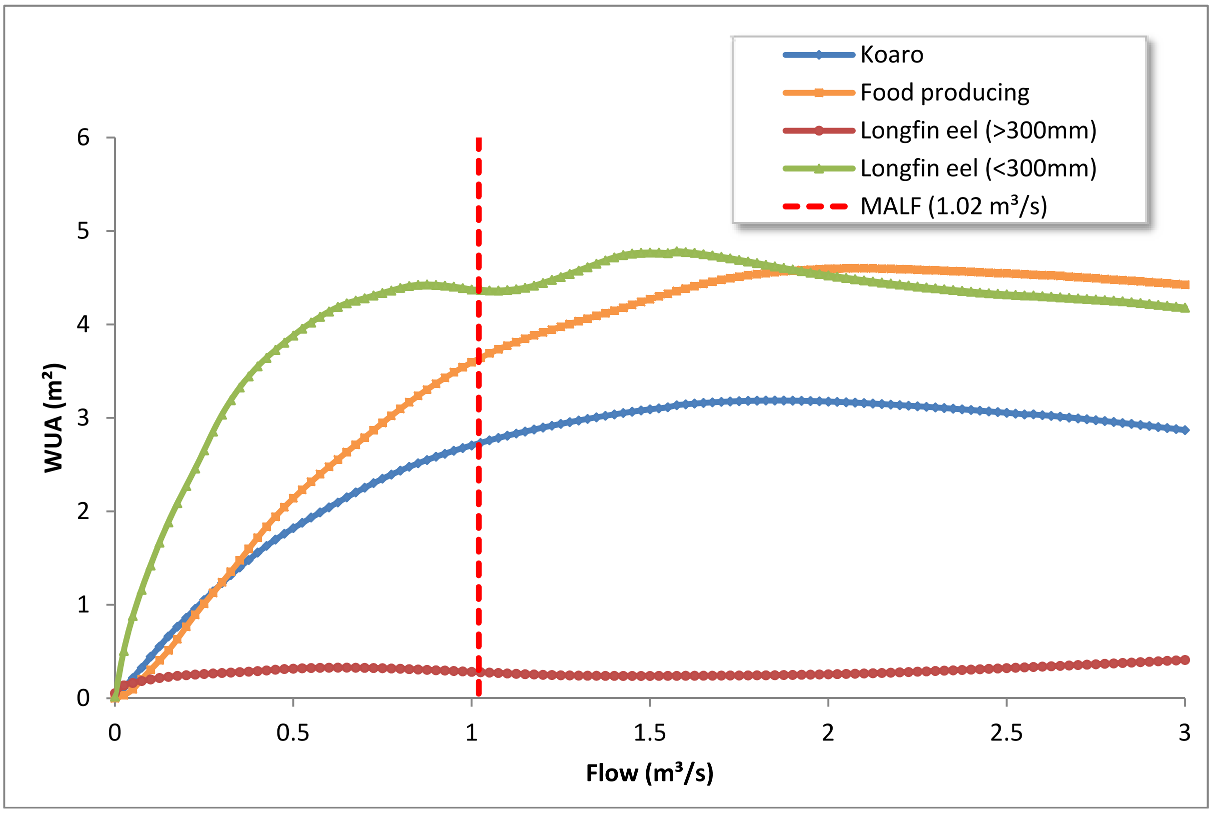

Figure 25: Variation of instream habitat in the Cardrona River for longfin eel, invertebrates and koaro

Available habitat for koaro and invertebrates ("food producing") peaks at 1.5m³/s and 2m³/s, respectively, with no clear point of inflection for either. Although koaro are able to coexist with trout more successfully than many other galaxias species, it is likely that the amount of physical habitat which koaro utilised is limited by trout predation, and this may have a greater influence on koaro abundance than simple habitat availability.

Table 8 shows the suggested flow requirements for native fish species of the Cardrona River. Where no clear point of inflection is apparent, the flow that provides 70% of the available habitat at MALF is used in accordance with Jowett and Hayes (2004) (Appendix D).

Table 8: Flows requirements for native fish and invertebrate habitat in the Cardrona River based on IFIM analysis

	Koaro	**Longfin eel (>300mm)**	**Longfin eel (<300mm)**	**Food producing**
Optimum flow (m^3/s)	1.75	NA	1.5	1.95
Point of inflection (m^3/s)	NA	NA	0.625	NA
Flow at which 70% of available habitat at MALF occurs (m^3/s)	0.55	0.1	NA	0.625

Table 8 shows that a flow of 1.95m^3/s provides optimum food-producing habitat. with a flow of 0.625m^3/s maintaining habitat for both invertebrates and juvenile longfin eels. A flow of 0.55m^3/s provides 70% of the available habitat at MALF for koaro, although, as noted previously, other factors than physical habitat probably limit this species in the Cardrona River main stem.

8 Evaluation of allocation and management options

Having undertaken extensive hydrological monitoring, instream habitat analysis, and a thorough assessment of biodiversity and recreational values, the following key instream values have been identified for the Cardrona River:

- flow continuity from The Larches to the Clutha River/Mata-Au confluence
- brown and rainbow trout spawning
- brown and rainbow trout juvenile rearing
- recharge of the Wanaka-Cardrona aquifer.

8.1 Suggested management flows and their effects on instream values

The environmental component of any minimum flow regime in the Cardrona River relies upon continuity of flow and maintaining the above values.

Table 9 discusses the effects of a number of management flow options on these values.

The “management flow seasons” shown in Table 9 are from November-April (summer) and May-October (winter), inclusive. These seasons differ from the standard “irrigation season” (October-April, May-September) and recognise the value of the Cardrona River as one of the most important brown and rainbow trout spawning tributary for the upper Clutha River/Mata-Au. Brown trout generally spawn between May and September, while rainbow trout spawn between July and October, inclusive.

Table 9. Suggested management flows for instream values in the Cardrona River

Season	Management flow at Clutha Confluence (m^3/s)	Predicted flow at SH6 bridge (m^3/s)	Predicted flow at The Larches (m^3/s)	Effects on instream values
November - April	0.7	0.4	1.1	Flows at SH6 are equal to the flow recommended to maintain a juvenile brown trout fishery. Flows at The Larches are close to MALF. Significant increase in recharge to Wanaka-Cardrona Aquifer.
November - April	0.4	0.1	0.8	Flows at Clutha confluence are equal to the flow recommended to maintain a juvenile brown trout fishery. Flows at SH6 are below that recommended to maintain a juvenile brown trout fishery. Flow continuity is maintained throughout the losing reach. Increase in recharge to Wanaka-Cardrona Aquifer.
May - October	0.8	0.5	1	Flows at SH6 are equal to the optimum flow for brown and rainbow trout spawning. Approx 0.7 m^3/s of recharge to the Wanaka/Cardrona Aquifer.

For each of the management flows options presented in Table 9, the corresponding naturalised flows at SH6 and The Larches flow recorders are given. These flow figures assume that there is a loss of $0.7m^3$ into the Wanaka-Cardrona Aquifer and that no water is being abstracted between the sites.

To manage surface water takes downstream of The Larches flow recorder through a minimum flow, there is a need to maintain a permanent flow site at the Cardrona River-Clutha River/Mata-Au confluence.

These suggested management flows are based on managing hydrological connectivity, instream habitat and groundwater recharge values, rather than indicating a preference for policy or regulation.

8.2 Relationship between suggested management flows and current flow conditions

To understand the potential effect of the proposed management flows on the hydrology of the Cardrona River, each management flow has been plotted alongside hydrographs for both the “winter” and “summer” periods (Figure 26 and Figure 27).

Figure 26 compares the suggested management flow options to recorded flows at the Cardrona River at the Clutha confluence for the 2009/10 “summer” season. Note that the management flows shown in Figure 26 relate only to the Cardrona at the Clutha confluence flow recorder (blue line).

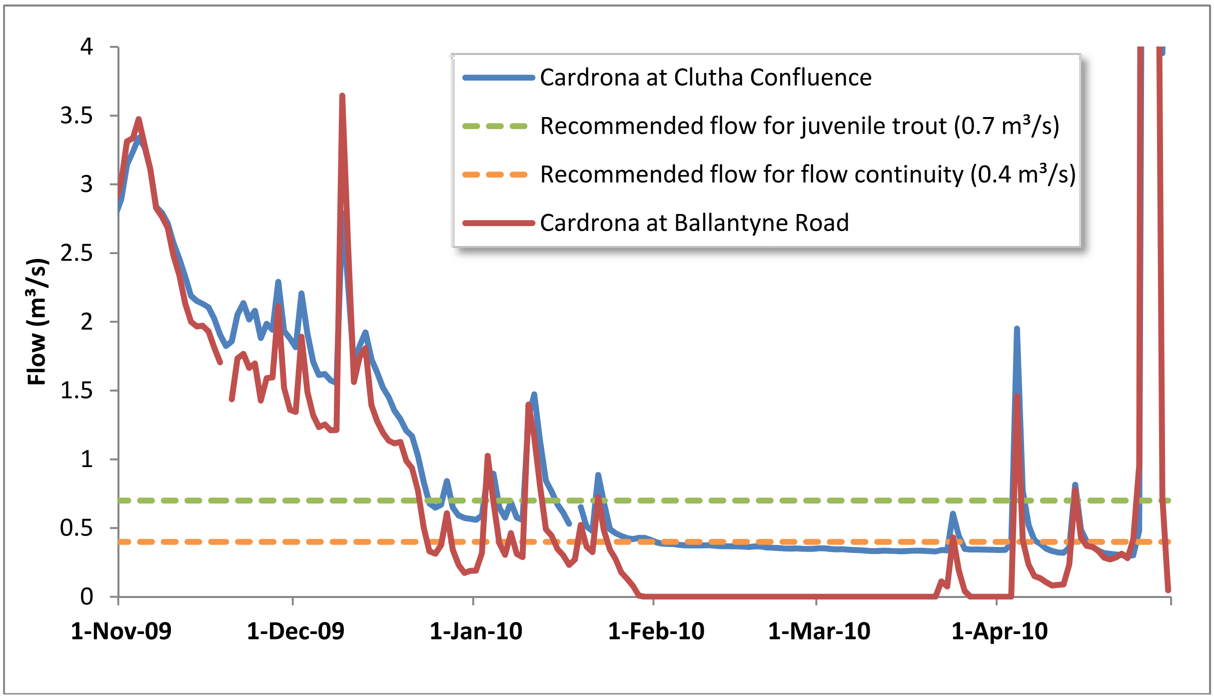

Figure 26: River flow alongside management flow options for juvenile trout and maintenance of flow continuity in the Cardrona River

Figure 26 shows that flow in the Cardrona at Clutha confluence were below the $0.4m^3/s$ management flow for approximately seven weeks during February and March and then intermittently throughout April. The time that flows at Clutha confluence are below $0.4m^3/s$ correspond well to those times when surface flows are lost at the Ballantyne Road flow recorder.

It is important to note that although the flows at the Cardrona- at Clutha confluence recorder were less than $0.05m^3/s$ below the $0.4m^3/s$ management flow throughout March, significantly more flow would be required to sustain losses to groundwater and reconnect surface flows in the lower Cardrona River to meet the management flow.

Figure 27 compares the suggested management flow options to recorded flows at the Cardrona River at the Clutha confluence for the 2008 "winter" season.

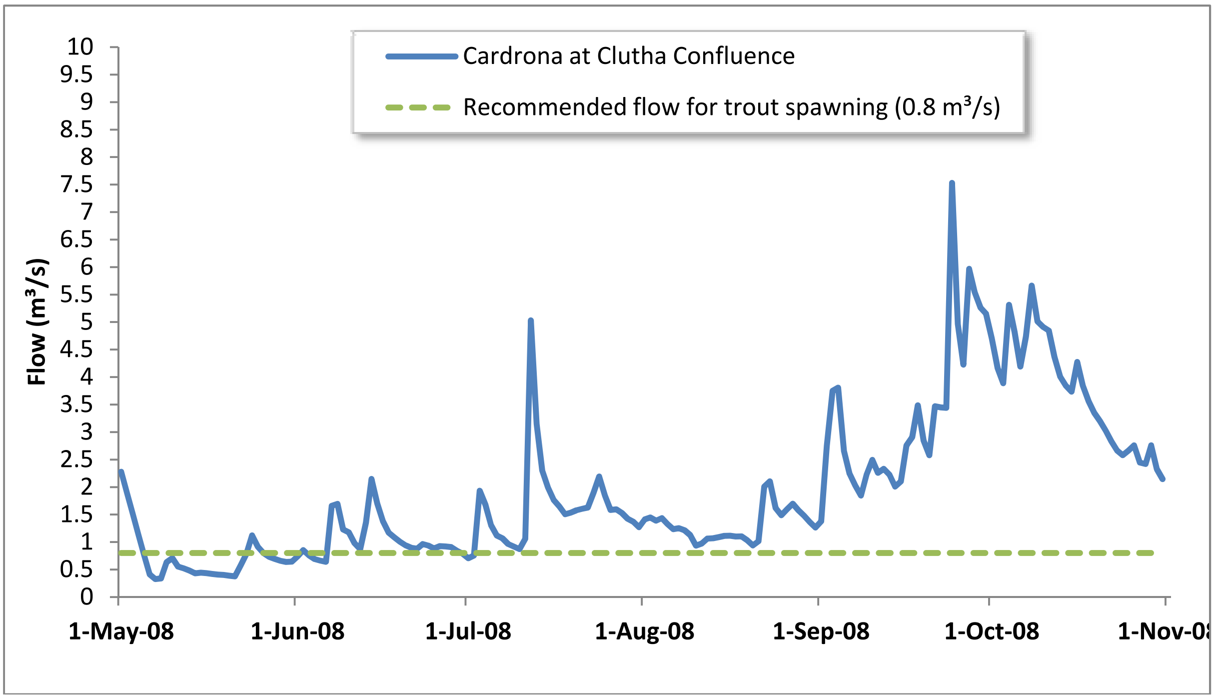

Figure 27: River flow, alongside management flow options for trout spawning

Figure 27 shows that flows in the Cardrona River at the Clutha confluence were below the $0.8 m^3/s$ winter management flow for more than two weeks in May and for brief periods in early June and July. These events were largely driven by natural catchment conditions because there was no abstraction for irrigation purposes.

9 Concluding discussion

9.1 Options for combined water management

The process of characterising and modelling the water resources of the catchment with the associated Wanaka-Cardrona Aquifer has suggested that surface water and groundwater are closely linked. The water resources on the surface and in the ground are linked in both their hydrology and the manner in which they are used, or could be used in the future. This insight leads to the following conclusion:

Surface and groundwater resources should be considered as a combined water resource and managed accordingly.

This realisation stems principally from the following conclusions drawn from the hydrology of the combined water resource:

The alluvial ribbon aquifer upstream of The Larches is effectively in full hydraulic connection with the Cardrona River.

The volume of groundwater resource in the Wanaka-Cardrona River is determined primarily by riverbed losses downstream, between The Larches and SH6 crossing.

The volume of water recruited to the aquifer in this manner is governed by the flow of the Cardrona River through this section, mainly as a function of flow continuity and wetted width of the river.

The amount and timing of abstraction into water races has a large influence on the river water available for infiltration to the aquifer.

The amount and timing of abstraction into water races has the primary influence on the habitat available for juvenile fish species and fish passage for the full length of the river.

The diversion of river water into races near The Larches has a major influence on the past and present-day groundwater recharge and habitat condition of the lower catchment. Water races are used to harvest water for the dry months when irrigation water is required. This process of taking water for irrigation reduces the river-wetted width, which consequently reduces the groundwater recharge and results in the complete drying of the river, as was observed in 2009 and 2010.

Should management flows be applied in the future, the amount of abstraction at the water race intakes could be manipulated to increase overall groundwater recharge, and maintain instream values. This highlights the following conclusions:

The implementation of the suggested management flows will result in an increase in recharge of the Wanaka-Cardrona aquifer.

The ability to extract water more reliably from the aquifer may offset, to some extent, the reduction of current surface water abstraction from the Cardrona River.

Already one irrigator has surrendered a deemed permit to the lower river and switched to groundwater based irrigation by transferring the surface take consent to groundwater. The original deemed permit was for 96l/s, with 24 l/s being transferred to a groundwater take. This move stands to provide 100% security of supply, which offsets the additional pumping and infrastructure cost, compared to the old gravity-fed race system. As well as improving reliability by removing any physical restriction on water supply, this irrigator has also removed the need to observe any future minimum flow for the Cardrona catchment. The beneficial aspects of a well-recharged aquifer would also benefit natural values for water at Bullock Creek, Lower Cardrona River and other spring zones.

The combined water resources approach allows the use of integrated catchment management with surface water and groundwater management tools. The corresponding groundwater management instruments are suggested, as follows:

Based on the results of this study, a **Maximum Allocation Volume (MAV) of five million m^3/y** should be considered for the Wanaka-Cardrona Aquifer. The results of computer modelling and the values of beneficial seepage and maintenance of access to groundwater resources were the primary considerations assessed in this suggested volume. Should it be shown that the options for management flows in the lower Cardrona River would definitively result in greater recharge to the aquifer, then this may provide latitude to increase the MAV of the Wanaka-Cardrona Aquifer.

The results of the present study also suggest that the Cardrona Alluvial Ribbon Aquifer would be better managed in conjunction with the Cardrona River; this management includes the observance of any minimum flow and allocation limits.

Finally, it is recommended that a permanent flow site is installed at the Cardrona River-Clutha confluence because it is crucial to the implementation of the proposed management flows.

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Appendix A: Recharge modelling

A.1 Method chosen

Spreadsheet calculations for soil moisture balance have been set up to follow the algorithms given in the appendix of Rushton *et al* (2006). The calculation involves four steps:

The calculation of runoff using the USDA SCS runoff method.

The calculation of infiltration to the soil zone (*In*), and near surface soil storage for the end of the current day (*SOILSTOR*). Infiltration (*In*) as specified by the Rushton algorithms is infiltration (Rainfall-Runoff) and *SOILSTOR* from the previous day.

The estimation of actual evapotranspiration (AET) was utilising the PET derived using the Penman (1963) equation. A crop coefficient is not applied since the crop is assumed to be pasture. Most pastures in New Zealand behave like the reference crop for most of the year (Scotter and Heng, 2003).

The calculation of soil moisture deficit and groundwater recharge. Recharge occurs only when the soil moisture deficit is negative (i.e. there is surplus water in the soil moisture reservoir). The soil moisture deficit for the first day of the model is assumed to be zero.

The steps outlined above partition soil moisture between near surface soil storage for the following day, AET, and the soil moisture deficit/reservoir, respectively.

A.2 Required parameters

In addition to rainfall and PET, the soil moisture balance model requires four different input parameters to calculate daily soil moisture deficit. These parameters are described below.

A.2.1 SCS curve number

This curve number relates to the tendency for a soil to allow or promote surface runoff. A curve number needs to be estimated for each soil, which is then used to calculate maximum soil retention of runoff. (This is the same method used for the HortResearch SPASMO model.) Lower curve numbers result in higher soil retention thresholds, which induce less runoff. Pasture in good condition on free draining soil has a low curve number (40). Pasture in poor condition on a poorly drained soil has a high curve number (90). Additional values are given in Table 5.5.1 (Rawls *et al* (1992)). The SCS runoff calculation also has the capacity to incorporate slope and soil moisture (Williams, 1991). The Wanaka-Cardrona model assumes that slope is always less than 5 degrees, and soil moisture is not considered.

A.2.2 Profile Available Water (PAW)

PAW is calculated from field capacity, wilting point and rooting depth data.

A.2.3 Profile Readily Available Water (PRAW)

PRAW is related to PAW by a depletion Factor, *p*. The depletion factor is the average fraction of PAW that can be depleted from the root zone before moisture stress (reduction in ET). For NZ conditions, *p* should be around 0.4 to 0.6, typically 0.5 for grass.

A.2.4 Fracstor

Fracstor is the near-surface soil retention, and values are estimated. Typical values are 0 for a coarse sandy soil, 0.4 for a sandy loam, and 0.75 for a clay loam (Rushton, 2006).

A.2.5 Field capacity (FC)

Field capacity is the volume of water which is the maximum that a soil can hold in its pores after excess water has drained away. Field capacity is also the state of a soil in this condition, when the only water that remains is water retained by the soil particles through surface tension.

A.2.6 Wilting point (WP)

Wilting point occurs when soil moisture has reached the point where it is insufficient to meet a plant's need and it wilts permanently.

A.3 Methods of defining additional parameters

The data for field capacity (FC), wilting point (WP), profile available water (PAW) and profile readily available water (PRAW) were derived from the New Zealand Soils Database for individual horizons. Data which Rickard & Cossens (1968) collected were also included.

A number of steps were required to define these additional parameters:

Match the soil series with the same series, or with similar soil series, within the database.

Determine the average FC and WP as percentages for these series to 1 m depth.

Multiply the percentage FC and WP values by the estimated rooting depth of the soils, for soils with rooting depth less than 1 m. (Moderately deep soils were estimated to have and average rooting depth of 0.7m, shallow soils 0.45m, stony soils 0.35m and very stony soils 0.2m.)

The above figures provide an estimate of FC and WP in mm for the profile.

PAW is determined by subtracting WP from FC.

The PAW range indicates the likely variability of PAW across the map unit, taking into account the likely variation in the depth of fines over gravels.

PRAW is determined by multiplying PAW by a ratio of PRAW/PAW found from the database for similar soils. In the case of shallow and stony soils, the ratio is modified according to expert opinion. As soils become shallower, the percentage of PRAW/PAW becomes larger.

To assign HSG classes, each soil map unit was matched with the description provided in the National Engineering Handbook (SCS, 1967). Soil profiles can be assigned to one of the four classes in this system.

The SCS number is possibly derived from a combination of soil permeability and soil water storage in the moist condition (air capacity). The SCS number is not static but varies with antecedent moisture condition and with land use. Soils were rated according to tables in SCS (1967) for land under pasture in a moist antecedent state. Soils in the middle of the HSG class were rated first, and then the curve number was either increased or decreased for other soils, according to their relative permeability and air capacity.

A.4 Recharge model inputs

A.4.1 Rainfall

There is relative uniformity of rainfall patterns across the Wanaka-Cardrona Flats. GrowOtago's contouring of median rainfall indicates that annual rainfall totals tend to fall within the range of 600 to 750mm/a. The area east of the Wanaka-Cardrona Flats is known to experience lower rainfall than the west; the proximity to hills appears to control this phenomenon. Mount Iron and Mount Barker both attract slightly higher rainfall, up to 750mm/a, but these peaks do not contribute to alluvial groundwater recharge. After an analysis of the various rainfall-recording sites across the study area, a short-list of historical and operational sites was compiled:

- Department of Conservation rain gauge, Ardmore Street, Wanaka
- Wanaka Airport weather station, SH6, between Wanaka and Luggate
- Mount Barker Station rain gauge.

Mount Barker Station was chosen because of the continuity and length of its rainfall record. Mount Barker Station also sits in a position that is close to the 'centre of gravity' for the rainfall variation across the Flats. The Mount Barker rain gauge (Site I49712) has a relatively continuous 30-year length of record, with the retention of 91.4% of daily measurements occurring during that period.

A.4.2 Potential Evapo-Transpiration (PET)

As a rule, measurements of evapo-transpiration are undertaken at climate stations and are thus sparsely distributed throughout Otago. The closest climate station to Wanaka is Cromwell, which is located in a climate zone that has more in common with the Upper Clutha Valley basins. More distant climate stations are located at Clyde (I59239), Alexandra (I59234/I5923B) and Lauder (I59065). Analysis of the evaporation records for these four climate sites within the Upper Clutha-Central Otago climate region indicated that there was a strong correlation between the Cromwell and Lauder climate site evaporation records (R^2 = 0.89). The Lauder evaporation data also extends from October 1985 to the present and is, therefore, a more complete record. Accordingly, the Lauder evaportation (Penman evapotranspiration) record was chosen for use in soil water balance modelling.

A.4.3 Soil properties

Soil moisture balance modelling requires knowledge of the spatial distribution of principal soil types, as well as a knowledge of their physical properties in terms of their ability to retain water. For this study, Landcare Research was commissioned to provide an evaluation of the soils within the project area, based upon the New Zealand Soils Database.
The table below provides a summary of properties assigned to the six dominant soil classes in the study area, and Figure B-4 is a map showing the soil zones.

Table 10: Soil properties used in the Rushton soil moisture balance model. Soil zones represent an amalgamation to eight predominant types

Soil property zone	Field capacity	Wilting point	Rooting depth (mm)	Depletion Factor, p	SCS curve number	FRACSTOR	TAW	RAW	Mean Recharge Rate (mm/a)
1	40	10	300	0.35	45	0.9	30	21	131.7
2	70	20	300	0.35	65	0.9	50	30	154.0
3	80	30	150	0.35	40	0.9	50	30	159.6
4	25	10	300	0.35	40	0.9	15	10	208.5
5	110	30	300	0.35	50	0.9	80	48	129.5
6	180	40	600	0.35	55	0.9	140	84	81.0
7	160	40	600	0.35	60	0.9	120	72	93.6
8	230	70	600	0.35	60	0.9	160	96	68.0

This table also shows the percentage of annual rainfall that becomes groundwater recharge, as calculated by the Rushton spreadsheet model. The proportions of mean annual recharge represent the annual average for the 24-year model period (Sept 1985-Aug 2009).

A.5 Recharge model outputs

Calculated recharge inputs for the 24-year model period (Sept 1985-Aug 2009) for the predominant Soil Zones 1 and 2, which cover the Wanaka-Cardrona Aquifer surface, are shown in the time series plots below. These plots illustrate the influence of soil properties on daily modelled recharge. Soil Zone 8 has the area’s highest field capacity and RAW, and consequently it has the lowest modelled recharge rates as well. This is due to the retention of more soil moisture that it will use later in transpiration and evaporation rather than shed in recharge and runoff. By contrast, Soil Zone 4 allows a significantly higher quantum of recharge through the soil due to the area’s lowest field capacity and RAW. Indicative water level time series for the continuous groundwater level recorders in the Wanaka-Cardrona Aquifer are included, to illustrate the tendency of high or low recharge to punctuate rises or falls of the water table.

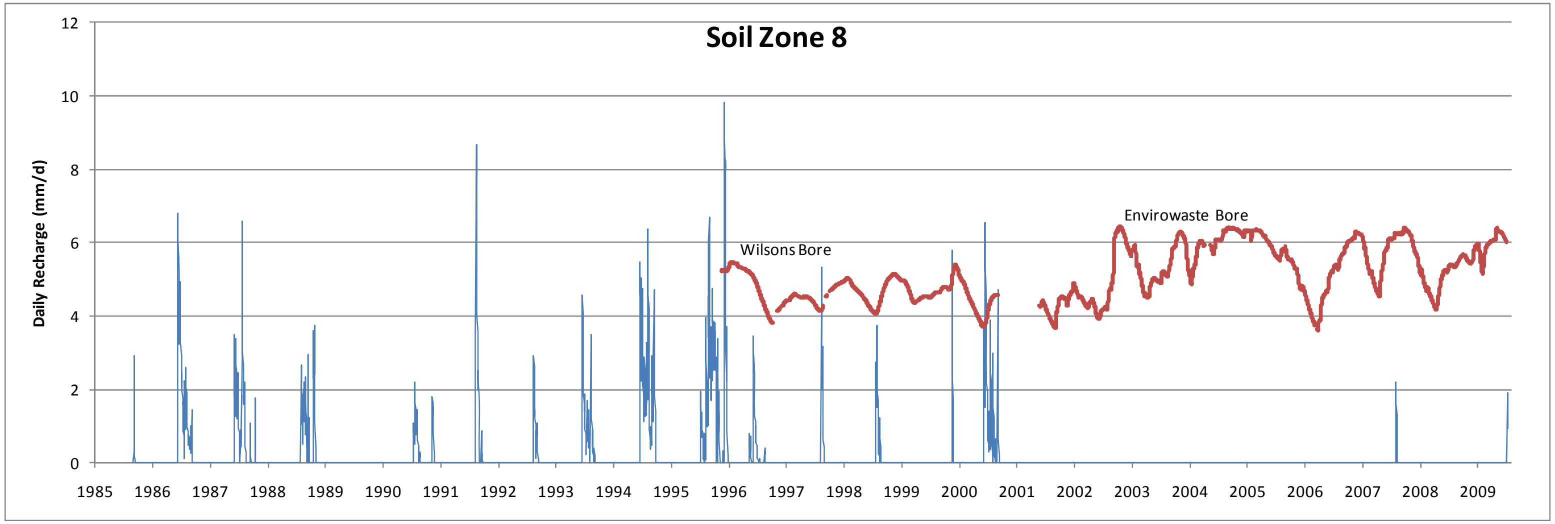

Figure 28: Modelled recharge response for Soil Zone 8

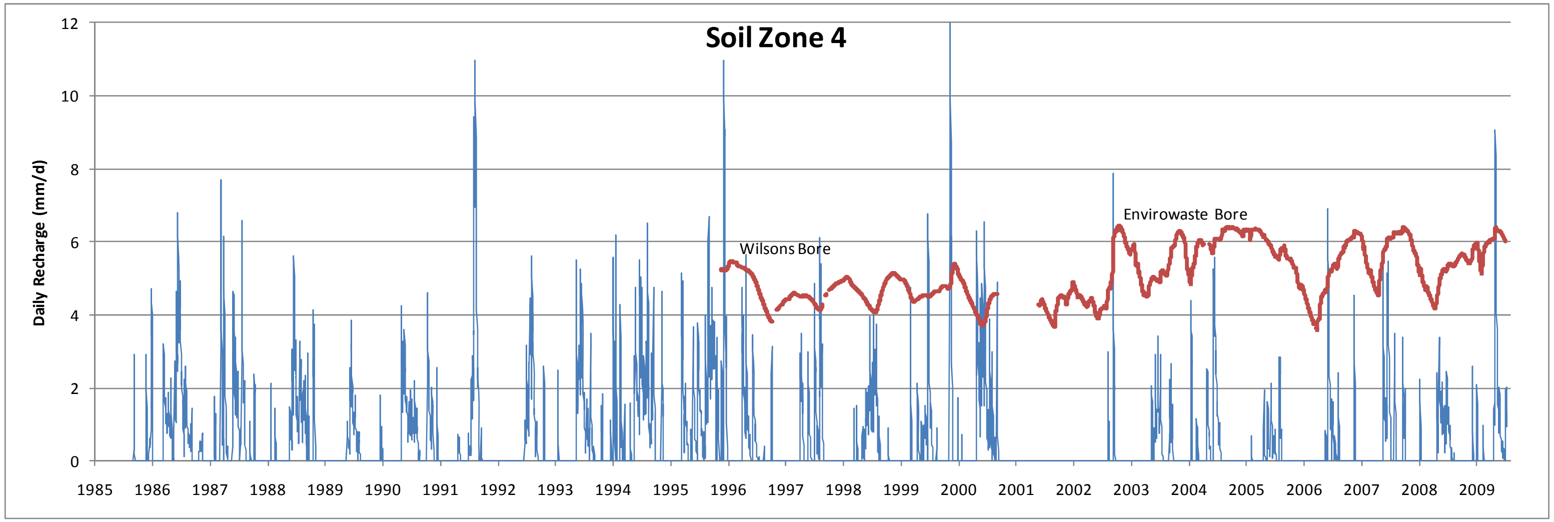

Figure 29: Modelled recharge response for Soil Zone 4

Appendix B: Groundwater modelling: Technical development

B.1 Model objectives

The objectives for the Wanaka-Cardrona Aquifer model are as follows:
Establish a transient-flow numerical model based upon the conceptualised groundwater system and calibrated under transient system stresses (although steady state simulation is a transition to transient simulation).

Determine the mass-balance for the aquifer system including temporal variation in aquifer fluxes and levels under a range of climatic conditions and river flow rates.

Simulate the aquifers response to difference abstraction scenarios as a basis for developing allocation and aquifer management policy.

B.2 Model code selection

The USGS finite difference numerical code MODFLOW (Harbaugh *et al*, 2000) was used to model the Wanaka-Cardrona aquifer. The 'Groundwater Vistas' data processing interface software (Environmental Simulations Inc., 2007) was used to build the model, assist with the calibration process, including parameter optimisation, and process the output data.

B.3 Grid design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centered multi-layered spatial grid. The Wanaka-Cardrona aquifer model was built within a grid domain of 12 x 17km, with a non-uniform cell size ranging from 10 ha to 50.6 ha. The grid spacing was refined by mesh refinement within the principal area of interest around the Cardrona River. The model grid has 5,660 active cells, including 95 stream (STR) cells simulating the Cardrona River.

The grid has not been rotated since the geometry did not favour any particular re-orientation. The model has been constructed using one layer. The rationale behind the layer structure is discussed below.

The active model domain is delineated by the basal contact of the Wanaka-Cardrona Aquifer with underlying formations or major structures.

B.4 Conceptual hydrogeology and numerical adaptation

B.4.1 Outer model boundaries

The lateral boundaries of the Wanaka-Cardrona Aquifer model are largely set to coincide with the basement rocks and sediment, such as the Otago Schist and Manuherikia formation mudstones. However, the very strong hydrologic boundaries imposed by Lake Wanaka and the upper Clutha River/Mata-Au are also used in the model to divide the Wanaka-Cardrona Aquifer from the Hawea Basin Aquifer on the northern bank of the Clutha River/Mata-Au. Only one flow divide has been set as a Head-No-Flow boundary. This is the inferred groundwater flow divide just back from the edge of the outwash terrace overlooking the Luggate area.

B.4.2 Model base

Head-No-Flow boundary and layer base elevations are used to simulate the finite depth of the Wanaka-Cardrona Aquifer. Without vertical exaggeration, the Wanaka-Cardrona Aquifer is a relatively thin "onion skin" layer overlying the Manuherikia formation sediments and the Otago Schist. The contact elevations between the Quaternary outwash and underlying schist or mudstone were determined from bore logs in the ORC wells database. These elevations were plotted as spot elevations on the basal contact surface. Subsequently, the spot elevations were contoured to a coherent surface within the Wanaka-Cardrona Aquifer model.

B.4.3 Model top

The land surface elevation surface was used to provide the model top. Since the model considered the aquifer to be unconfined, a free water table surface was provided between the model base and the model top.

B.4.4 Layers

As previously stated, the conceptual model did not provide sufficient justification to include multiple layers within the numerical simulation. A single model layer was employed in model development.

B.5 Boundary conditions

B.5.1 Modflow stream boundaries (STR1)

The Cardrona River has a complex interaction with the underlying Wanaka-Cardrona Aquifer. Consequently, the more sophisticated stream boundary was used in simulating the river. This also allowed the addition of a weekly flow record for the river in the transient simulation.
The STR boundary type requires data to be specified for:

- hydraulic conductivity, width and depth of the river channel
- bed roughness as a Manning's N ratio
- dynamic water level
- dynamic flow rate.

The following sources provided the data and dimensions:

- GHD flood plain hazard study, including 20 river profiles of the Cardrona River crossing the Wanaka – Cardrona Flats (GHD, 2009)
- bed roughness estimates (GHD, 2009; Hicks & Mason, 1991)
- river stage ratings at The Larches flow recorder site (ORC data on Hilltop database).

B.5.2 Springs: Modflow drain boundaries (DRN)

Drain (DRN) boundaries were applied with the computer model to simulate the presence of Bullock Creek in the Wanaka-Cardrona Aquifer. Such boundaries act to drain groundwater out of the aquifer concerned, but cannot inject water back in if the vertical gradient reverses itself. This type of boundary is equivalent to Bullock Creek, since this water body is more like a series of joined up springs than a true creek.

The alignment of the creek that follows the foot of the Mount Iron terminal moraine catches the majority of groundwater seepage. As the creek reach leaves the moraine towards Lake Wanaka, it is less likely to receive significant seepage. Typical bed conductances were specified and these were further calibration in parameter optimisation. These conductances were not likely to be sensitive.

B.6 Aquifer properties

Initially, six parameter zones were specified, with contrasting hydraulic conductivity (horizontal and vertical). After a sensitivity analysis and parameter optimisation runs, two further parameter zones were added to differentiate areas of the aquifer with clearly contrasting properties. Storage parameters (storativity and specific yield) were not zoned because it was considered that the environmental variability of storage parameters was substantially less sensitive than those of permeability parameters. The table below shows the final calibrated hydraulic conductivities with the model. Zones arranged within the core of the model, such as Zones 2, 6 and 7, tended to have higher permeability. The lower permeabilities tended to be clustered around the margins.

Table 11: Groundwater model zones and hydraulic conductivities

	Horizontal hydraulic conductivity (m/d)
Zone 1	1000
Zone 2	144.9
Zone 3	0.74
Zone 4	0.31
Zone 5	0.88
Zone 6	246.2
Zone 7	247.5
Zone 8	0.31

B.7 Rainfall recharge modelling

The spreadsheet modelling of soil water moisture and the derivation of transient groundwater recharge rates were described in Appendix A. Weekly recharge averages were used in the transient model for each of the 187 stress periods of 7-day length (January 2006 to August 2009). Ten recharge zones were specified, which included nine areas of contrasting soil properties, plus a tenth zone specifying the average of recharge under irrigation for all soil zones irrigated. This simplification was considered justified because:

- an unwieldy complexity would otherwise develop with six soil property zones under irrigation

- with overlapping and intersecting irrigated and non-irrigated zones, the complexity of contrasting recharge would overwhelm the available resolution within the model cell network
- of the dominant influence of the additional irrigation water infiltration over the small influence of soil-water properties.

These reasons were considered sufficiently pertinent to average the response to irrigation within irrigated areas. Thus, a single ‘irrigation’ recharge zone was specified in the midst of nine natural recharge zones.

B.8 Groundwater abstraction

Thirty-eight groundwater extraction bores were considered to be significant enough to be included in the computer model. All were consented irrigation takes. No domestic or stock water bores were simulated, due to their extremely small scale of extraction. Construction site dewatering was not included because of its position on the seepage periphery of the Wanaka-Cardrona Aquifer and its tendency to respond to groundwater level fluctuations rather than to drive them.

The modelled groundwater bores were specified by position within the model and their nominal rate of groundwater take. Due to the single aquifer layer and relatively thin aquifer cancelling vertical head distributions, there was no requirement to specify the depth of extraction.

B.9 Model calibration

The basic calibration approach was to conduct steady state calibration using a May groundwater survey for a broad spatial alignment of the model to observed data. Once steady-state calibration achieved an acceptable result or diminishing returns to parameter optimisation effort, the calibration focus would be shifted to transient calibration.

B.9.1 Steady-state simulation

The first model calibration undertaken used the calibration data set of 34 water table elevations measured in May 1995. This data set was chosen because of the bores’ wide geographical spread and the fact that the month of May occupied a period of relative quiescence in terms of recharge, lack of irrigation and stability of surface water flow. Steady-state calibration is aided by the use of data collected in reasonably stable conditions. The calibration process included trial-and-error calibration, where model parameters were manipulated manually each simulation, and calibrated automatically (by PEST parameter optimisation), where selected parameters were taken through a range of values and combinations with other parameters to optimise the calibration result. The magnitude of errors (the residual between modelled and measured target values) progressively declined until a clump of remaining errors was left that further calibration could not improve on.

The results of calibration across the aquifer revealed a standard deviation in error of 1.18m (from -2.85m to +2.75m), with an altitudinal range across the aquifer of 65.3m. The standard deviation in calibration error divided by the range (Normalised Root Mean Squared Deviation, NRMSD) in the steady-state model settled at 0.018 or 1.8%. At this point, the steady-state calibration was concluded. A calibration solution is generally considered acceptable where the NRMSD is less than 0.05 or 5%. The flow rate of model interface simulating Bullock Creek was also compared with the measured flow rate. The model following steady-state calibration simulated a rate of $0.3m^3/s$. The measured flow rate at Helwick Street between March 2002 and April 2006 ranged between 0.26 m^3/s and 0.39 m^3/s, which brackets the modelled flow value.

- ***Steady-state mass balance***

The table below lists the steady state mass balance.

Table 12: Steady state mass balance

Units: million m^3/y	**Outflows**	**Inflows**	**Error**
Lake, Clutha River/Mata-Au & upper Cardrona River crossing aquifer	20.8	4.7	
Bullock Creek drainage	11.9		
Cardrona River	17.5	33.8	
Recharge		11.8	
Total	50.2	50.3	0.1

The model mass balance differs from the conceptual mass balance, partly due to the model having a larger extent than the declared extent of the Wanaka-Cardrona Aquifer and higher flux rates for the Cardrona River. The differences in Cardrona River flux rates were rectified in transient modelling.

- ***Steady-state sensitivity analysis***

Sensitivity analysis to identify the sensitivity of input parameters was conducted, which assisted in the steady-state calibration process. The graph below shows an example of such analysis for horizontal hydraulic conductivity.

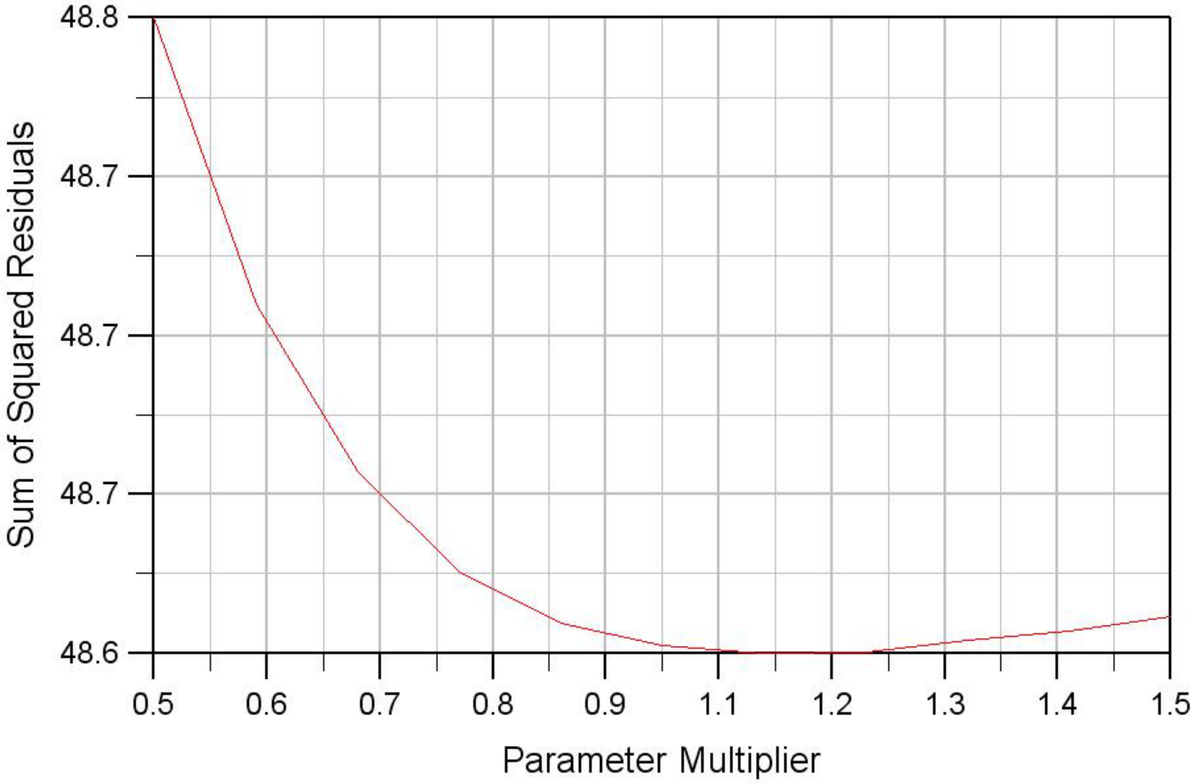

Figure 30: Steady state model sensitivity to horizontal hydraulic conductivity

The graph above reveals that the model simulation is more sensitive to lower hydraulic conductivity than higher hydraulic conductivity. The graph below shows a similar sensitivity plot, but relating to the bed conductance of the stream boundary simulating the lower Cardrona River.

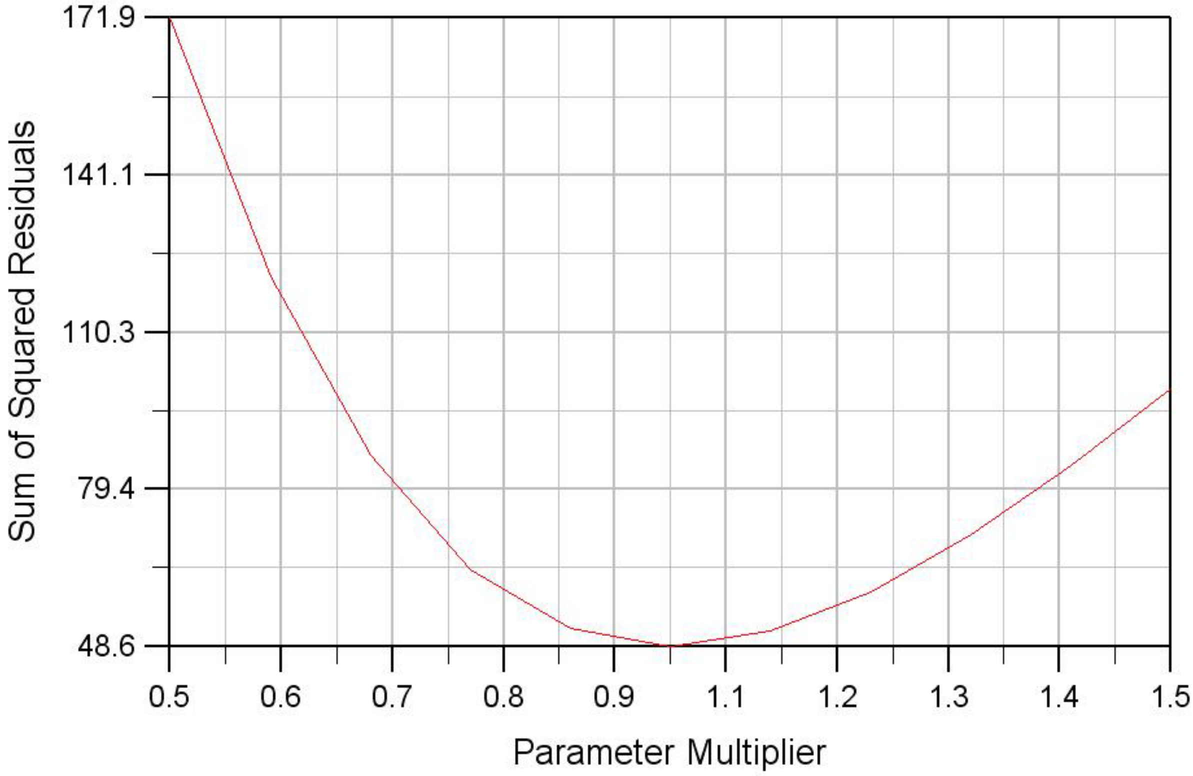

Figure 31: Steady state model sensitivity to Cardrona river bed conductance

This graph reveals that sensitivity to change in the stream conductance is more even from decrease to increase. It also shows that the impact of a 50% change in conductance is more than three times that for a 50% change in hydraulic conductivity of the aquifer. Therefore, riverbed conductance is a more sensitive parameter by a factor of at least three.

B.9.2 Transient modelling

- ***Transient model design, calibration targets and initial inputs***

Since the transient calibration process had only one groundwater level record site, its ability to provide model calibration for properties such as permeability across the full extent of the model was compromised. Consequently, transient calibration was used to refine the storage parameters and Cardrona River STR boundary operation.

Transient data sets were assembled in accordance with the requirements of the model stress period set-up. The recharge model output was compressed accordingly. The 15 minute flow and stage height record for the Cardrona River was similarly compressed to the 7-day stress period.

- ***Transient calibration***

The goodness of fit between the modelled and observed groundwater levels in transient model calibration was largely conducted by overlaying the modelled and observed levels on a graph plot. In that way, the undulation of the levels and modelling and record could be observed in a simultaneous fashion. Once again, automated parameter optimisation was undertaken using the PEST module. The figure below illustrates the final calibration match between observed and modelled transient groundwater level at Envirowaste bore (F40/0014).

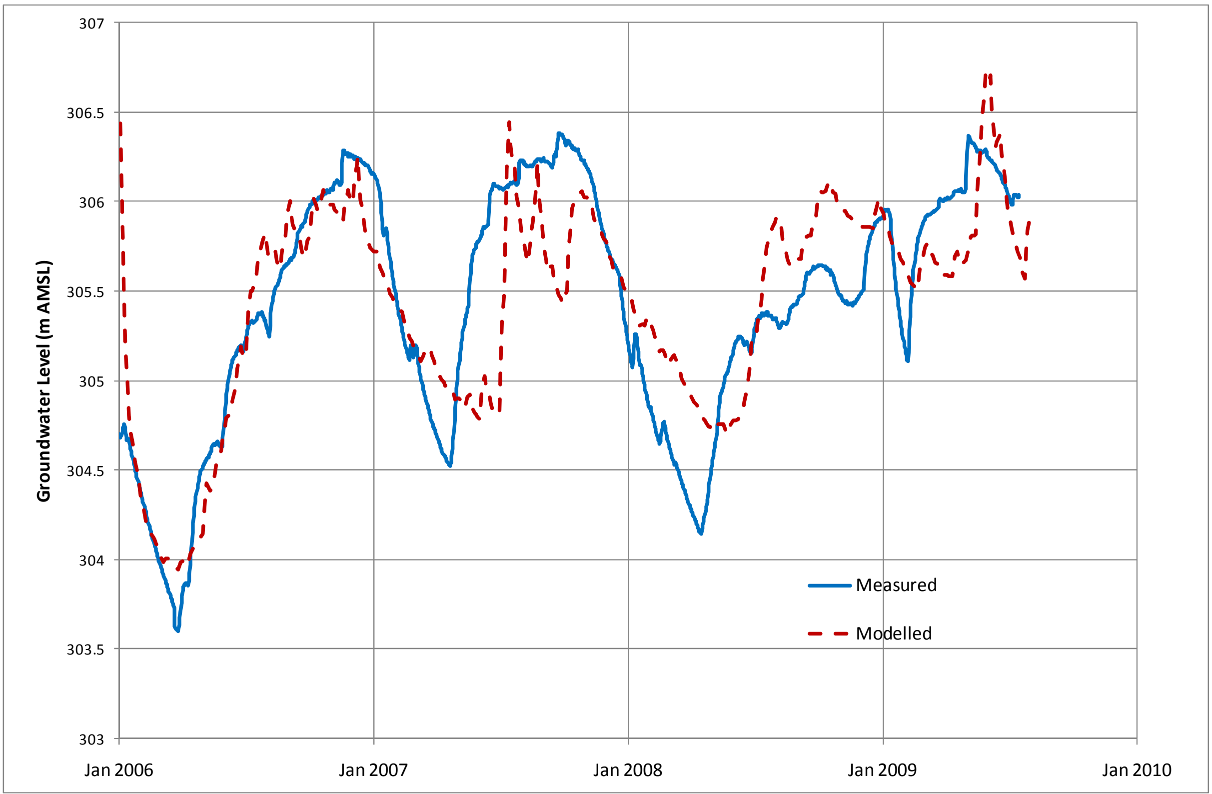

Figure 32: Final calibration history matching (calibration) to Envirowaste bore record

The primary transient calibration data set was the 4-year level record of 2006 to 2009 taken at the Envirowaste bore (F40/0014), near Ballantyne Road crossing. Matching the observed historic highs and lows on groundwater level at this site was the primary focus of transient calibration. Major swings in groundwater level between modelled and observed records were replicated and the broader state of aquifer storage was maintained from the start to the end of the model period. Finer scale errors between modelled and observed groundwater level may reflect the difficulty of precisely simulating the Cardrona River interchange, unsaturated zone recharge damping or the lack of information as to the exact timing of irrigation affecting summer recharge. An acceptable match with observed data was thus achieved and modelling progressed to scenario modelling.

B.10 References

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Appendix C: Consented groundwater takes within the Wanaka-Cardrona Aquifer and Cardrona Alluvial Ribbon Aquifer

Well number	Consent number	Easting	Northing	Annual allocation (m^3/yr)	Irrigation area (ha)	Maximum daily quantity (m^3)	Maximum monthly volume (m^3)	Use
F40/0128	2000.125	2205700	5601700	40,000	5	1,987.2	5,000	Irrigation
N/S	2000.388	2207832	5603852	13,500	22	150		Winery; irrigation; accommodation
F40/0221	2001.791	2209370	5603054	171,000	50	1,900	57,000	Irrigation; domestic supply to facilities
N/S	2001.848	2206300	5604600	116,640	104	2,860	85,800	Irrigation; communal domestic
F40/0250	2001.953	2207163	5600729	23,328	6	259.2		Irrigation; communal domestic
F40/0244	2001.956	2203574	5602914	32,000	4	475	4,000	N/S
F40/0213	2002.030	2203625	5605201	59,220		288	8,640	Irrigation
N/S	2002.057	2204671	5605190	45,000	7	500	10,500	Irrigation
N/S	2002.171	2203800	5600700	65,700		180		Communal domestic
N/S	2002.336	2207936	5602972	45,000	11	500	6,622	Irrigation; community supply
N/S	2002.337	2201100	5604800	23,691		78	2,418	Commercial water supply
N/S	2003.271	2210419	5603495	304,080	28.16	1,267	38,010	Irrigation
N/S	2003.291	2206838	5600820	9,624		82.3	1,308	Irrigation; community supply
N/S	2003.315	2207151	5604879	18,980	2	52	1,612	Single stockwater; irrigation; communal domestic
N/S	2003.328	2207562	5605568	402,000	50	1,650	49,500	Irrigation; communal domestic
G40/0189	2003.586	2211615	5604215	26,752		80	2,229	Community supply
F40/0269	2004.554	2205967	5600320	16,942		143		Irrigation; community supply; communal stockwater
F40/0206	2004.886	2207931	5604404	143,000		907	20,500	Irrigation
F40/0208	2004.887	2208500	5604600	143,000	40	907	20,500	Irrigation
N/S	2005.222	2207685	5604686	210,000		1,188	36,157	Irrigation; domestic supply to facilities
N/S	2006.151	2204000	5605000				77,760	Dewatering

Well number	Consent number	Easting	Northing	Annual allocation (m^3/yr)	Irrigation area (ha)	Maximum daily quantity (m^3)	Maximum monthly volume (m^3)	Use
N/S	2006.241	2203800	5605700				222,307	Dewatering
N/S	2006.293	2203800	5605700				222,307	Dewatering
N/S	2007.100	2203700	5605800			2,592		Dewatering
N/S	2008.277	2209500	5603400	24,990	4.2	160	3,124	Single stockwater; domestic
N/S	2009.087	2202788	5606936			8,640		Dewatering
N/S	2009.106	2204877	5600613	237,353		2,160	64,733	Irrigation
N/S	2009.296	2205060	5603350	18,000		75	2,100	Irrigation
N/S	2009.440	2203961	5605538			432	12,960	Dewatering
N/S	2009.467	2204426	5603819	27,900		100	3,100	Dust control
N/S	2010.075	2208624	5603509	119,369		850	25,765	Irrigation
N/S	2010.107	2203855	5606442	62050		170		Irrigation
N/S	95613	2205900	5600300	1,460		4		Communal domestic
F40/0125	95734	2207444	5600548	5,475		15		Communal domestic
N/S	95846	2207100	5600400	2,190		6		Communal domestic
N/S	95936	2207600	5602800	7,300		20		Communal domestic
N/S	95937	2206111	5603186	2,700		30		Irrigation; communal domestic
N/S	96015	2206700	5605100	31,104	2	346		Irrigation
N/S	96199	2204100	5604800	45,000		500		Irrigation
F40/0111	96307	2203887	5606200	27,000		300		Irrigation
N/S	96330	2206400	5600700	1,800	6.6	20		Irrigation; communal domestic
N/S	96624	2208500	5603200	116,640	31.6	1,296	20,000	Single domestic; Irrigation
N/S	96724	2208747	5604727	31,050	27	345		Irrigation; communal domestic
N/S	97011	2205382	5605487	25,920	2.04	288		Irrigation
F40/0069	97204	2209800	5603200	6,300		70		Irrigation; communal domestic
N/S	98044	2207000	5600600	2,920		8		Communal domestic
F40/0191	98393	2203749	5599816	295,488	85	3,283.2	50,000	Irrigation
N/S	98507	2208300	5603100	30,171	9.9	335.2	4,125	Irrigation; communal domestic

Well number	**Consent number**	**Easting**	**Northing**	**Annual allocation (m^3/yr)**	**Irrigation area (ha)**	**Maximum daily quantity (m^3)**	**Maximum monthly volume (m^3)**	**Use**
N/S	98651	2201900	5604500	9,125		25		Commercial water supply
N/S	99164	2203900	5603200	20,075		55		Communal domestic
N/S	99165	2205600	5601500	6,570		18		Communal domestic
N/S	99209	2208000	5606100	311,040	40	3,456	30,200	Single domestic; irrigation
G40/0103	99378	2212500	5602600	21,600	4.8	240		Single domestic; irrigation
N/S	99506	2203300	5603200	38,880	9	432	1,170	Irrigation; communal domestic
N/S	99522	2204762	5602730	11,498		31.5		Community supply
N/S	99524	2204021	5603324	14,490		161		Irrigation; communal domestic
N/S	99528	2203300	5602800	17,520		48		Communal domestic
N/S	2001.A00	2203600	5602700	27,180	4.2	302	8,472	N/S
N/S	2001.A03	2203450	5599432	21,700	2	100	3,100	Irrigation
N/S	2001.A07	2206148	5602855	6,750		75		Irrigation
Cardrona Alluvial Ribbon Aquifer								
N/S	2003.293	2194364	5584098	N/S		500		Community supply
N/S	2000.332	2198735	5589731	N/S		2,400		Mining; dewatering and process supply

Note: N/S = Not Specified.

In some instances the annual allocation is not specified in the consent, instead it is calculated from instantaneous, daily or monthly limits.

Appendix D: Guidelines of habitat retention required for instream values (Jowett & Hayes, 2004)

Critical value	Fishery value	Significance ranking	Recommended % of habitat retention
Large adult trout - perennial fishery	High	1	90
Diadromous galaxiid	High	1	90
Trout spawning/juvenile rearing	High	2	80
Non-diadromous galaxiid	-	3	70
Large adult trout-perennial fishery	Low	3	70
Diadromous galaxiid	Low	3	70
Trout spawning/juvenile rearing	Low	5	60
Bully species	-	5	60