Cromwell Terrace Aquifer Study

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Overview

Background

The Otago Regional Council (ORC) is responsible for managing Otago's groundwater and surface water resources. Before this study ORC hadn't investigated how much groundwater resource there was under the terraces surrounding Cromwell. This investigation assesses how much of the groundwater can be assigned for irrigation or other large uses of water that require consents. Assigning volumes of water in consents is termed 'allocation'.

Why is allocation of groundwater necessary?

Groundwater is less transient and more vulnerable to over-exploitation than surface water. It may takes years or decades to find out if the underground water resource is being over-used. The setting of a limit on the amount of groundwater which can be taken from an aquifer helps prevent over-exploitation from being experienced in the first place.

What this study found

The aquifer was found to be replenished by rainfall and irrigation returns percolating through the ground, and the seepage of water from Lake Dunstan into the aquifer. The aquifer was seen to respond immediately and completely to the filling of Lake Dunstan in the early 1990s, and from this we know that they are strongly connected by exchanges of water.

We were able to account for the water exchanges that the aquifer makes with its surroundings, including the net rainfall that soaks into the ground; the irrigation from the lake and pumped from the aquifer that also soaks in; and the inflows and outflows with the lake. A computer model of the aquifer was also used to firm up the specifics of these exchanges, especially those that could not be measured directly. In this manner, we found that the average yearly contribution from the surface and lake was 2.4 million cubic metres per year (or approximately 1000 Olympic sized swimming pools every year). Of this volume, the Water Plan says that we can allocate 50%, or 1.2 million cubic metres per year, until a tailored volume is set. It should be noted that the groundwater allocated in existing resource consents is already 1.7 million cubic metres per year.

We think that the default allocation of 1.2 million cubic metres per year is overly restrictive and that the ability of the lake to compensate for the extraction of groundwater should be recognized in a tailored allocation volume for the aquifer at Cromwell.

What should be done next?

The recommendations from this report should be discussed with the local community and other stakeholders. A new allocation regime would then be determined and be included in a future Water Plan change.

Technical Summary

As a shallow, unconfined, outwash aquifer adjoining Lake Dunstan, the Cromwell Terrace Aquifer is closely connected by land surface and surface water influences on its geo-hydrology. At 22 km^2 the Cromwell Terrace is relatively small in extent, compared to other Clutha catchment groundwater systems, but its water resource is of great significance to the people of the area.

The building of a conceptual model describing the aquifer was based on a detailed review of the area's geology, soils, hydrology and monitoring data. The aquifer is formed from at least three glacial outwash terraces that coalesced in the Cromwell confluence area, and include gravel formations from both the Upper Clutha and Kawarau catchments. The outwash generally rests upon relatively impermeable mudstone of the Manuherikia Group lignite measures, and locally on schist. The overlying soils formed on the terrace surface are sandy, with relatively low water retention capacity. The hydrology of the fringing river systems was profoundly altered with the filling of Lake Dunstan behind the concrete gravity dam at Clyde in 1993. The measured mean rise in the aquifer's water table after lake filling was 10.5 metres. Consequently, the post-filling aquifer holds a substantially enhanced water resource. Aquifer testing at completed bores indicated generally high, to extremely high, transmissivity in the Cromwell township area.

Quantitative analysis of the aquifer's water balance using recharge modelling and groundwater modelling indicated the following major inputs and outputs on a mean annual basis.

	Aquifer Inflows (Mm^3/y)	**Aquifer Outflows (Mm^3/y)**
Bore extraction ('Actual')		0.4
Net rainfall recharge	0.7	
Net irrigation recharge*	0.9	
Infiltration from Lake Dunstan	0.8	
Seepage into Lake Dunstan		2.0
Totals	2.4	2.4

* Irrigation includes bore water and water pumped from Lake Dunstan.

The aquifer is in dynamic equilibrium with Lake Dunstan, receiving a modest volume of infiltration in the Ripponvale area and discharging the bulk of its excess further downstream. Due to its high transmissivity, the aquifer would respond rapidly to balance any over-draught of groundwater extraction by bores with corresponding volumes of infiltration from the lake. This has been conclusively demonstrated in numerical groundwater modelling.

Current groundwater management of the Cromwell Terrace Aquifer is primarily by way of a cap on the annual volume of consents issued equivalent to 50% of mean annual recharge (MAR). The current allocation limit is marginally in excess of 1.2 million cubic metres per year (50% of the 2.4 Mm^3/y estimated as mean annual recharge from all sources). Currently, there is a legal consented annual volume of 1.7 Mm^3/y for the approximately 20 groundwater take consents issued for the aquifer. In the interim, exceedence of 50% of the mean annual recharge by the consented annual volume may result in the Cromwell Terrace quifer being considered fully to over-allocated. However, groundwater modelling results point to the dynamic response of the aquifer in compensating for increased groundwater extraction with increased infiltration of lake water. This effect indicates the advisability of tailoring the maximum allocation volume in RPW Schedule 4A, with an annual volume higher than 50% of mean annual recharge. This report suggests a tailored annual allocation volume of 4 Mm^3/y could be adopted for this purpose, especially if combined with additional controls on water table reduction.

The effect of further sedimentation of the Kawarau Arm of Lake Dunstan, as a result of deposition of turbid Kawarau River waters, has also been the subject of numerical groundwater modelling. It is considered that the most probable, eventual morphology of the Kawarau Arm would be a braided river bed and steeper river profile. The raising of the river at the upstream end of the Kawarau Arm was not considered to be offset by the loss of bed permeability, with the net effect being an increase in groundwater availability for the Cromwell Terrace Aquifer.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

The Cromwell Terrace Aquifer comprises a thick and distinct pocket of glacial outwash immediately upstream of the Kawarau-Clutha confluence on the Upper Clutha and Kawarau branches of Lake Dunstan. The aquifer, which is defined between hill and lake margins, occupies an area of 22.2 square kilometres (km^2) and contains the single township of Cromwell. The Cromwell Terrace Aquifer is locally significant as a water resource, and is used conjunctively with water pumped from Lake Dunstan. The aquifer has 65 bore records and 20 current groundwater take consents issued from within it. Bore records indicate the mean depth of the aquifer is 30 m, with a mean depth to water at 20 m. The Cromwell Terrace Aquifer is also notable for having significantly benefitted from the raising of Lake Dunstan behind the Clyde Dam, and the water table rising in response, by up to 14 m in some instances. The groundwater resource has not previously been investigated by the Otago Regional Council (ORC), nor have tailored groundwater management measures been applied to the Cromwell Terrace Aquifer to date.

1.1 Objectives

The following aims and objectives were referenced in the course of this study:

1. To characterise the hydrogeology and groundwater hydrology of the aquifer.
2. To analyse the modes of aquifer replenishment and groundwater flow within the aquifer with relevance to the sustainable rates of flow or abstraction.
3. To develop a technically appropriate groundwater allocation and management regime.

2 Background

2.1 Location and Geography

The location of the Cromwell Terrace Aquifer is shown in Figure 1, overleaf. Cromwell township is the second largest service centre in the Central Otago District, and was originally located on the inside bank of the confluence of the Upper Clutha and Kawarau rivers. Since the filling of Lake Dunstan in 1992 and inundation of the original core of the township, the commercial centre of Cromwell has been relocated to higher ground further inland and to the north.

Cromwell Terrace is defined in a geomorphic sense as an elevated glacial outwash surface (although it is actually three adjoining surfaces, as outlined in ‘Geology’) that rests in the fork of the river confluence. The Cromwell Terrace Aquifer has an approximate an area of 22 km^2. Behind it, Cromwell Terrace has the flanks of the Pisa Range and the older terraces around Quailburn and Lowburn. The terrace is not crossed by any surface water courses, although artificial water races and ponds have been built across its surface in places. The terrace has always been a significant crossroads in human communication and holds an important highway junction between State Highway (SH) 88 to Alexandra and SH6 to Queenstown, Wanaka and the West Coast.

2.2 Soils

The Cromwell Terrace has generally sandy or sandy loam soils, partly as a result of the aeolian sand deposition across the terrace surface (McKinlay, 1997). The following soil types are recognised on the terrace:

- Cromwell
- Molyneaux
- Ripponvale
- Waenga.

The depth of these soils is either shallow or moderately deep. The entire terrace is considered well drained. A gradation in Profile Available Water (PAW) capacities are found in Cromwell Terrace soils. Low PAW dominate over the Gibbston and Albert Town outwash gravels, while moderate PAW is found over Lowburn outwash, as a rule (see Table 1).

Table 1: List of soil hydrology classes, PAW capacities and area percentages

Soil Hydrology Class	PAW (mm)	Percentage Area of Cromwell Terrace
1	30.0	36%
2	80.0	24%
3	80.0	15%
4	150.0	4%
8	60.0	0.2%
10	30.0	1%
Anderson Park (irrigated)	80	1%
Urban soils	_	18%

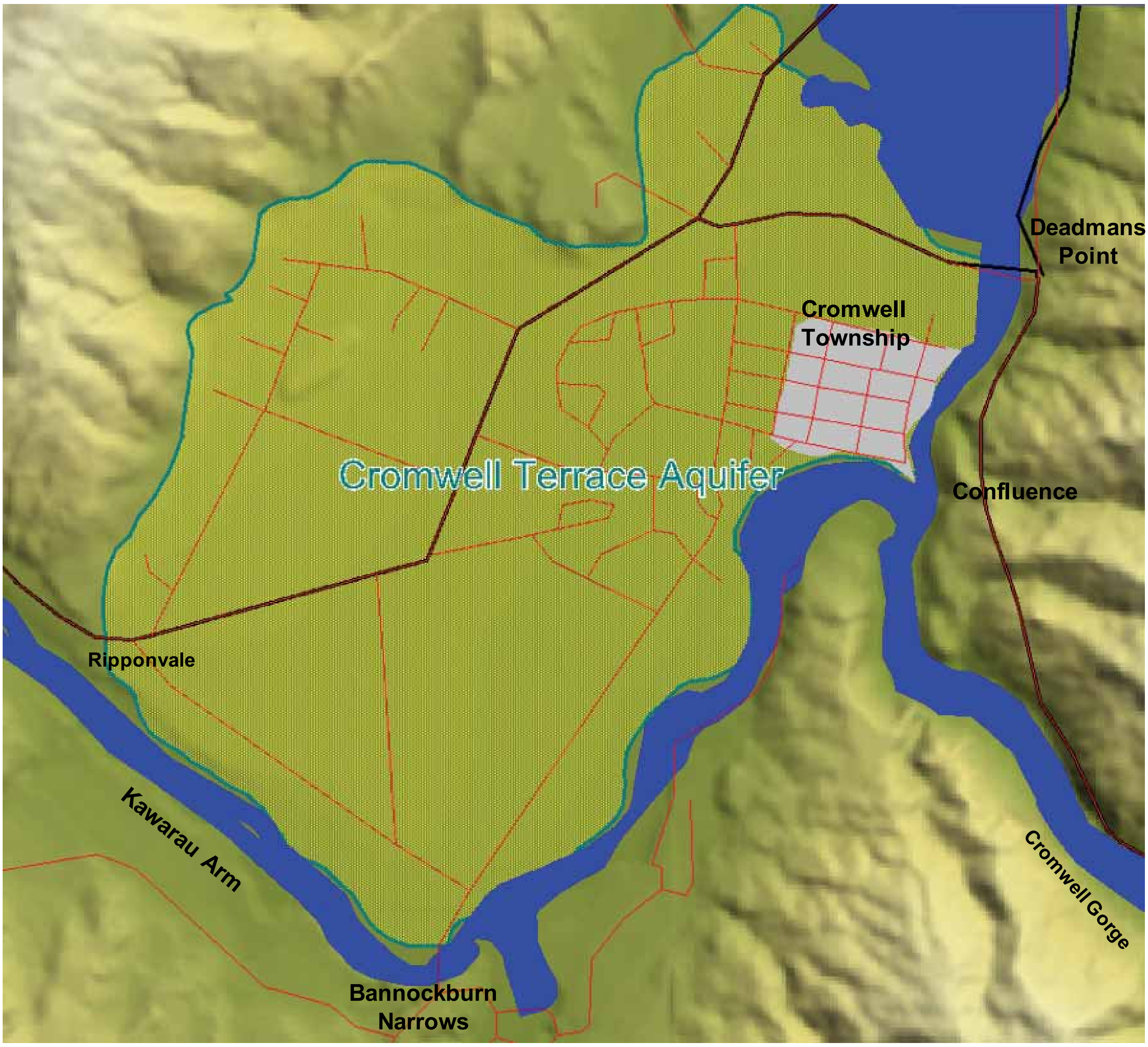

Figure 1: Location and layout of Cromwell Terrace Aquifer.

2.3 Geology

2.3.1 Basement Schist

The Central Otago district is underlain by schist and semi-schist of the Torlesse Supergroup. These schists are formerly deep-water marine sediments that have been metamorphosed to low- and medium-grade meta-sedimentary rocks. The rocks contain the fundamental minerals of quartz and feldspar, and are termed 'quartzo-feldspathic' as a result. The process of metamorphosis has segregated these minerals into distinct bands of crystalline quartz, feldspar and mica in a groundmass of non-crystalline (lithic) lithologies. Metamorphosis has also over-printed the original sedimentary bedding pattern with a metamorphic foliation pattern. This imparts a distinct grain to the schist rocks and has implications in providing pore spaces for groundwater in the schist.

The surrounding ranges, primarily the Pisa, Cairnmiur and the Dunstan, are exclusively composed of basement schist rocks, with the exception of in-faulted Tertiary sediments in valleys such as Bannockburn. These ranges define the margins of the sedimentary basin. Otago has a number of sedimentary basins resulting from the down-warping of the basement rocks. The Cromwell Basin is an intermediate feature of a series of adjoining basins trending south-west from Tarras to Bannockburn. The western margin of the Cromwell – Tarras Basin is defined by the Pisa – Grandview Fault. The fault displacement lifting the Pisa Range makes the Cromwell Basin quite uneven, from deep and steep-sided in the west, to shallow and gently sloping in the east. For the most part, the Cromwell Basin is filled with Tertiary terrestrial sediments.

2.3.2 Geophysical indications of basin geological structure

Estimates have been made of the depth and three-dimensional shape of the basin containing Tertiary and Quaternary sediments. The most comprehensive investigation was a geophysical survey of the Cromwell – Tarras Basin using gravity measurements (Broadbent & Bennie, 1981). The survey was supported by the compilation of earlier geophysical measurements and drill hole data from Thompson (1978). The Cromwell Terrace Aquifer was bracketed by several gravity transects. Analysis of the data and these transects reveals a distinct gravity contrast between the basement schist, saturated Tertiary – Quaternary sediments and unsaturated materials. The gravity transect cutting through the core of the Cromwell Terrace suggested that the basin depth is strongly asymmetric, with the deepest point being approximately 350 m below the terrace surface. The distinct shallowing of the east of the basin was more evident to the north, including the schist contact at 20 m depth near Deadmans Point. The more northerly transect also reveals the presence of unsaturated Quaternary sediments of older glacial outwash in the Quailburn area. Nonetheless, the action of the Pisa – Grandview Fault would appear, from contouring of the schist contact depth based on gravity data, to have preserved substantial thicknesses of mainly Tertiary terrestrial sediment beneath the terrace surface. Figure 2 shows a representative cross-section of the Pisa – Grandview Fault and associated sedimentary basin to the east.

The 2007 airborne geophysical survey covered the Cromwell area and distinguished some of the shallower features, particularly the paleo-channel next to the Kawarau Arm. (See Section

2.5.2 and the previous work of Mondriniak & Marsden, 1938). In general, the survey provided low resolution of outwash and basin structures.

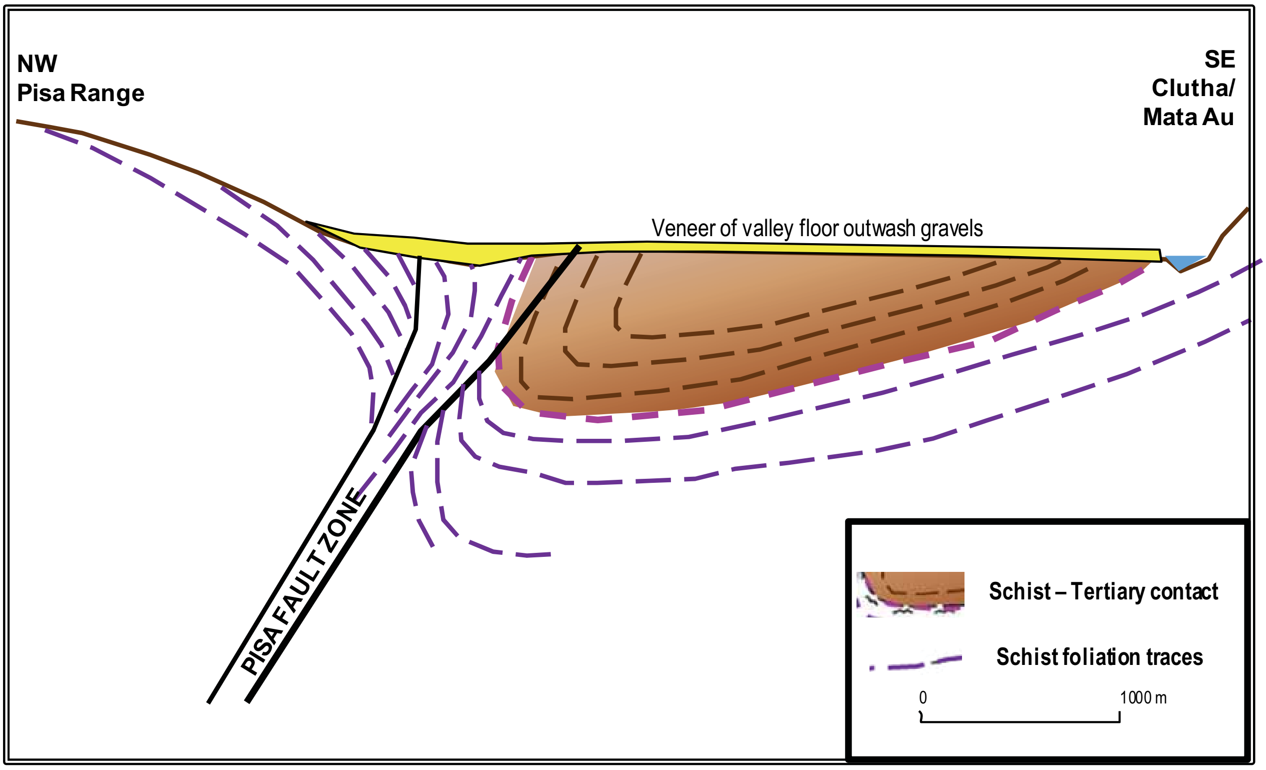

Figure 2: **Representative schematic cross-section of the Pisa – Grandview Fault, illustrating down-fault preservation of the Tertiary sediments beneath Cromwell Terrace.**

Source: Figure 4 of Beanland & Berryman (1989)

2.3.3 Tertiary Terrestrial Sediments

During the Miocene, Central Otago was a large river and lake environment. These rivers and lakes deposited sediment carried from the uplifting ranges to the north. A more recent mountain-building episode of the New Zealand landmass in the last two million years led to the bulk of these terrestrial sediments being eroded away as Otago ranges formed and were exposed to increasing erosive forces. However, remnants of the lake and river sediments were preserved and protected from erosion within the down-warped basins such as the Cromwell Basin.

The Miocene terrestrial sediments preserved in the base of the Cromwell Basin are stratigraphically grouped into the Manuherikia Group, which contains a variety of sub-groups and formations on the basis of the timing of deposition or the types of deposits. Within the Cromwell Basin, the principal sub-divisions are the:

- **Manuherikia Formation**, which comprising silts, clays, occasional sand and lignite, and is derived from lake deposition.
- **Dunstan Formation**, comprising silts, sands and occasional quartz pea-gravels,and is derived from river and lake delta deposits.

The Miocene terrestrial sediments are almost exclusively covered by Quaternary sediments in the Cromwell Basin, so it is rare to find the Tertiary sediment exposed at the surface. The Miocene sediments were mapped to outcrop on the edges of the Cromwell Terrace in the banks of the Kawarau River before the raising of Lake Dunstan (Turnbull, 1987). They are described from former gold mines or coal mines of previous centuries and from drill hole logs.

2.3.4 Quaternary Fluvio-Glacial Sediments

The Quaternary geological period encompasses the Pleistocene (‘Ice Ages’) of the last two million years and the more recent Holocene stabilisation of global climate and sea level of the last 6,000 years. The headwaters of the Wanaka, Hawea and Wakatipu catchments were sites of significant valley glaciations during the four main glacial advances of the Pleistocene. While mostly peri-glacial effects were felt during glacial advances of the late Pleistocene in the Cromwell area, the effect of upstream glaciations on the Clutha and Manuherikia rivers was profound. During the interglacial periods between glacial advances, the rivers filled with glacial aggregates and these were carried down river. In this way, the Cromwell outwash basin filled with succeeding generations of glacial sediment, comprising boulders, cobbles, substantial quantities of gravel, sand, mica-rich silt and clay. Four to five glacial advances leaving significant gravel outwash terraces have been recognised in the Cromwell area. From the youngest to the oldest, the Upper Clutha glacial advances are provided with the following names, with abbreviations of their mapped outwash formations given in brackets afterwards (Turnbull, 1987):

- **Hawea Advance** (hao)
- **Albert Town Advance** (ato or gio, Gibbston Outwash from the Kawarau Catchment)
- **Luggate Advance** (luo)
- **Lindis Advance** (ino)
- **Lowburn Advance** (owo)

These advances extended from the Wanaka – Hawea valley systems to various terminal positions in the upper Clutha Valley. Figure 3 illustrates the maximum ice margin extents of these advances and the distribution of Cromwell Terrace outwash gravels.

The Lowburn and Lindis glaciers advanced to within a few kilometres of Cromwell. Downstream of the glacier zones, the glacial outwash deposits range throughout the Clutha river system. A diverse mix of older deposits in the Lowburn/Quailburn area is found behind Cromwell. The glacial outwash surfaces of the Albert Town and Luggate glacial deposits are derived from the upper Clutha. The Kawarau catchment outwash forms the south of the Cromwell Terrace.

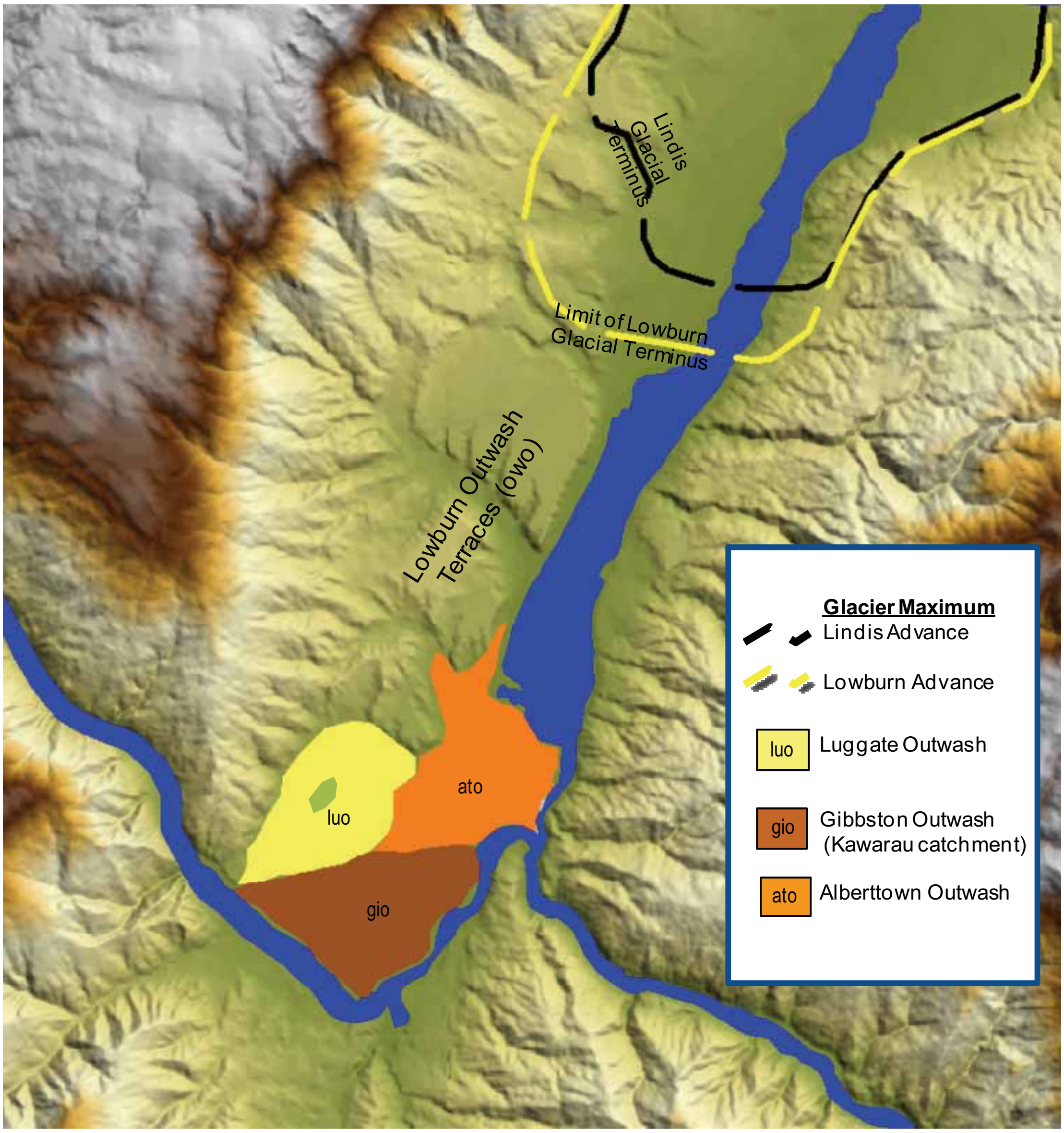

Figure 3: **Extents of Pleistocene ice margins during late Quaternary glacial advances and glacial-outwash gravel surfaces of the Cromwell Terrace.**

Sources: Figure 3 of Beanland & Berryman, (1989); Turnbull, (1987)

2.4 Water Use

Water is important in the land management and habitation of Cromwell Flat. A narrative summary of major water uses is given in 'Appendix 1 – Water Use on the Cromwell Terrace Aquifer', and a list of current groundwater take consents is contained in 'Appendix 2 – Consented Groundwater Extractions (Cromwell Terrace Aquifer)'.

2.5 Hydrology

The surface water hydrology of the area is dominated by the upper Clutha and Kawarau rivers flowing into the respective Clutha and Kawarau Arms of Lake Dunstan. Before the raising of the Clyde Dam and the filling of Lake Dunstan, these rivers were free-flowing as far downstream as Alexandra township. Lake Dunstan was filled between April 1992 and September 1993, in a series of hold-points. The long-term mean flow rate of Lake Dunstan, as measured at the Clyde Dam, is 510 cubic metres per second (m^3/s) or at an annualised rate of 16,090 million cubic metres per year (Mm^3/yr). The upper Clutha catchment contributes 285 m^3/s, on average, while the Kawarau catchment contribution averages 225 m^3/s. The bulk of Lake Dunstan's inflows are derived from the glacial lakes of Wakatipu, Wanaka and Hawea, which are partly glacier-fed from high net precipitation watersheds against the Main Divide.

A small tributary called the Low Burn rises on the flanks of the Pisa Range, north of Cromwell, and discharges into Lake Dunstan, on the northern edge of the Cromwell Terrace. Several minor creeks and streams rise on the same range overlooking the terrace, but are diverted into the Ripponvale Settlers Water Race, where the water is used for the local irrigation. Otherwise, there are no other natural surface water bodies associated with the Cromwell Terrace.

2.5.1 Kawarau, Clutha and Lake Dunstan

The major rivers have undergone a change in hydrology since the filling of Lake Dunstan. Previously, the Kawarau River flowed past the Cromwell Terrace as a series of rapids: a large set downstream of the Mining Centre and a shorter rapid at the Bannockburn Narrows, where the former Cromwell – Bannockburn Road bridge crossed. Similarly, the Clutha River/Mata Au broke into steep rapids downstream from Deadmans Point on its way to the Clutha - Kawarau confluence. An analysis of the river geomorphology would indicate that both rivers have cut into the outwash terraces as the sediment supply diminished after the most recent glacial period. The base level of the Cromwell Gorge has also declined under erosion and river degradation in the last 9,000 years.

Building of the Clyde Dam began in 1978, but the filling of the lake behind was delayed until substantial lake-shore stabilisation within the Cromwell Gorge was completed by 1992. The filling of Lake Dunstan began in April 1992 and progressed in four hold levels to allow monitoring of the effect of rising water levels on landslides. By May 1992, the lake water level was held at an elevation of 177 m above mean sea level (AMSL). This level would have brought the lake up to Bannockburn Bridge on the Kawarau Arm and mostly submerged the Cromwell rapids on the Clutha Arm. The second lift and hold of lake levels was to 185 m AMSL in September 1992. This was followed by a third lift to 190 m AMSL, which would have mostly inundated the full extent of the future lake. Final lake filling to a mean 194.2 m AMSL was completed by September 1993. Currently, the lake extends up the Kawarau Arm to the Goldfields Mining Centre in the Kawarau Gorge, and to Bendigo on the Clutha Arm.

The three arms of Lake Dunstan, Kawarau, Clutha and Cromwell Gorge could be more accurately described as low gradient rivers. Indeed, the Kawarau Arm, which is the narrowest and has the highest rate of sediment deposition, has a measurable gradient of 1 in 18,000 in lake water level from Ripponvale, compared to the dam wall at Clyde. Floods and high flows accentuate the lake level difference, which can reach in excess of 4 m, as they did during the 1999 flood. The long-term effect of sedimentation of the Kawarau Arm is projected to result in this part of the lake becoming a moderate gradient semi-braided riverbed, with willow vegetation stabilising the active channels.

2.5.2 Groundwater Hydrology

Due to the high permeability of the outwash gravels and overlying soils, there are no permanent water courses crossing the Cromwell Terrace surface, except for several ponds and water races specifically built to hold and conduct water to the sites of irrigation. Excess of rainfall, snow-melt or irrigation on the terrace does not ordinarily generate surface runoff; almost all percolates to the underlying water table. The Cromwell Terrace Aquifer is an unconfined aquifer with a free water table.

In its natural state before the filling of Lake Dunstan, the Cromwell Terrace Aquifer was much diminished, with a significantly lower water table and less extensive saturated zones than at present. A bore monitored in the core of the aquifer (F41/0171, on northern Sandpit Road) was monitored throughout the raising of Lake Dunstan from May 1992, before the lake filling, until June 1999 when monitoring ceased. Prior to the lake filling, the water table stood at approximately 183.9 m AMSL. After lake filling, the bore’s water level averaged 194.4 m AMSL, an increase of 10.4 m. Rough estimates of the net increase in groundwater resource stored in the Cromwell Terrace Aquifer suggest an additional 30 Mm^3 as a result of the filling of Lake Dunstan. Currently, the Cromwell Terrace outwash gravels have a saturated zone between the ambient water table and the underlying Tertiary sediments (Manuherikia Group). The elevation of the water table tends to conform to a surface less than a metre above the mean lake water level of 194.2 m AMSL.

There are few parts of the Cromwell Terrace Aquifer where the water table could be considered shallow. The depth to water table ranges between 2 m and 34 m, with most variability due to terrace topography. The mean depth to water table is 20 m. In the west of the Cromwell Terrace Aquifer, geophysical surveys and drilling have found the presence of deeper channels incised into the Manuherikia Group sediments (Mondriniak & Marsden, 1938). Modern drilling and bore log data have confirmed the presence of deepened alignments, which approximate the paleo-channels in the Cromwell Terrace Aquifer, as indicated by 1930’s geophysical investigations. The paleo-channels are likely to in-fill with higher permeability sandy cobble gravels, imparting a substantial influence on the velocity of groundwater flow towards the Kawarau Arm.

2.6 Water Quality

The water quality of the upper Clutha catchment is generally very good, and the Cromwell area is no exception. Lake Dunstan, at Cromwell, is classed as having a stable, very good water quality (ORC, 2012, *in press*). Similarly, the Kawarau River inputs to Lake Dunstan have high water quality, albeit with elevated suspended solids content and turbidity from the Shotover River contribution.

Groundwater quality has been monitored on a regular bi-annual basis since 2006 at two sites on the Cromwell Terrace: F41/0297, on Pearson Road, on the southern flank fringing the

Kawarau Arm, and F41/0300, at the corner of Sandflat Road and SH6, in the centre of the terrace. The groundwater quality can be characterised as low total dissolved solids, low nutrient content and oxygenated. Oxygenated chemical species, such as nitrate and sulphate, are present at concentrations that do not indicate reduction processes. Similarly, chemical species, such as dissolved iron and dissolved manganese, which indicate reduction in groundwater, are absent or very low in concentration.

The Cromwell Terrace Aquifer would appear to display indications, such as being unconfined and not having a reducing geochemistry, which would favour nitrate accumulation. Nitrate-nitrogen concentrations at bore F41/0297 on Pearson Road, near the Kawarau Arm, are low at a median 0.17 gN/m^3. At the more centrally located monitoring bore (F41/0300, on the corner of Sandflat Road and SH6), the median nitrate-nitrogen concentration is 3.7 gN/m^3. Dissolved chloride is a good indicator of trends in groundwater dilution or concentration. Figure 4 shows the dissolved chloride time series at bores F41/0300 and F41/0297.

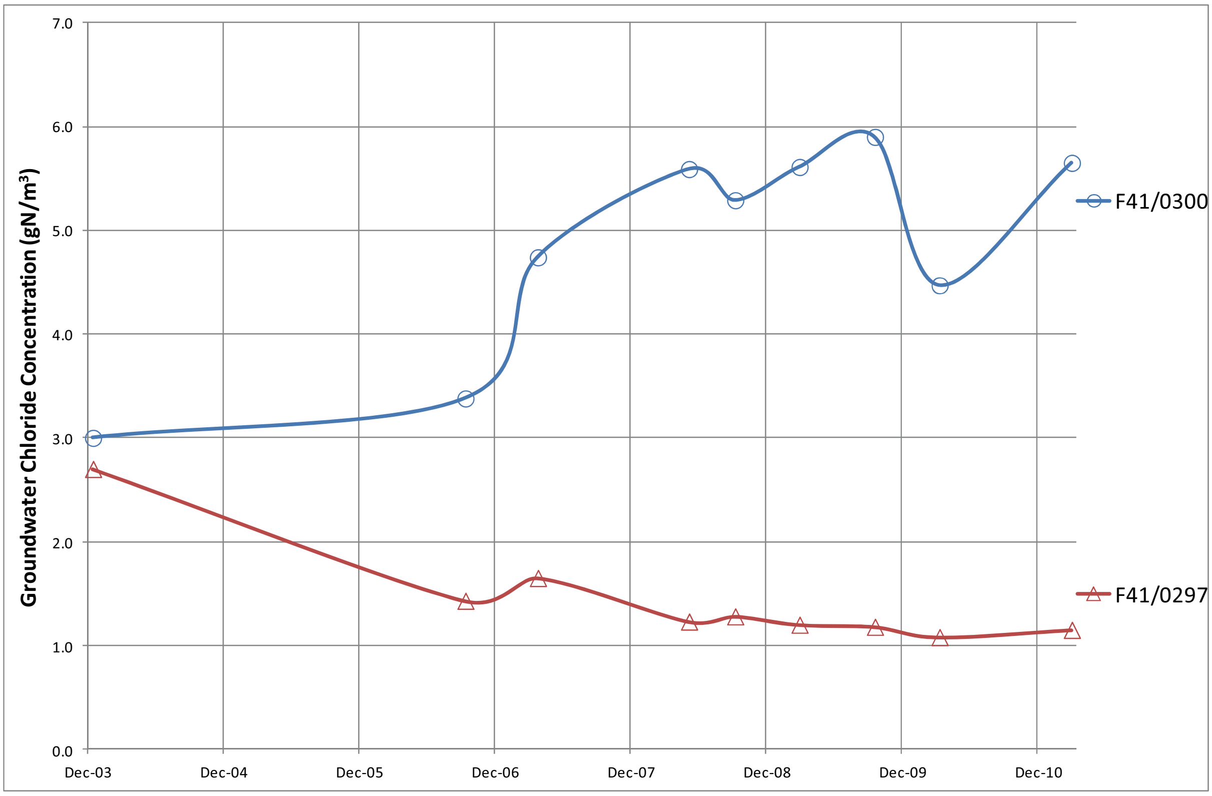

Figure 4: **Dissolved chloride concentration time series at two Cromwell Terrace monitoring bores.**

Figure 4 appears to indicate opposing trends in chloride concentration, which are perhaps indicative of the long-term effects of displacing native groundwater with lake water (see 5.2.5 Conceptual Dynamics). Recharge-affected groundwater has exerted a larger influence in observed concentrations, from 2003 to 2009 in bore F41/0300. The infiltration of lake water may also have an influence in diluting the chloride concentration on Pearson Road. Otherwise, the Cromwell Terrace aquifer has few water quality issues. There are no water quality issues that affect groundwater allocation management.

3 Groundwater Management

3.1 Historic Water Management

Initial settlement of the Cromwell District was strongly influenced by the area's river network, mineral and water resources. Following initial gold finds at Bannockburn and on the margins of the Cromwell Terrace, gold mining changed to hydraulic sluicing techniques supplied by higher elevation water races and dams. The Cromwell Mining Warden, eventually called the 'Wardens Court', issued prospecting, mining, land occupation and water licences for the Crown throughout the goldfield.

The Cromwell Wardens Court continued to issue new mining privileges to water and renewing existing privileges into the 1960s. The Water & Soil Conservation Act 1967 took over issuing new water rights in the late 1960s, and integrated the Mining Act 1908 provisions relating to mining privileges over water. An amendment in 1982 added the management of groundwater into the Water & Soil Conservation Act 1967. The Resource Management Act 1991 strengthened the management of groundwater and eventually gave rise to the RPW, which took full legal effect in 2004, and was substantially amended in 2012.

3.2 Current Water Management

The Cromwell Terrace is one of the driest areas of New Zealand. Median rainfall is about 450 millimetres per year (mm/y). Mean annual potential evapotranspiration is approximately 825 mm/y. As a result, the terrace is served by irrigation schemes, a community water supply and a variety of private water supplies, provided by Lake Dunstan and the Cromwell Terrace Aquifer. The bulk of the water is derived from Lake Dunstan in several pumped irrigation schemes. In addition, the Cromwell Terrace Aquifer supplies the water used in approximately 20 bore water supplies for low volume irrigation.

3.2.1 Current Surface Water Management

Water abstraction from Lake Dunstan for the handful of private irrigation schemes is authorised by surface water take consents, which are issued in terms of the transitional regional plan (prior to 1998) and the RPW. Lake Dunstan is not yet included in any allocation plan, so taking water from the lake is not subject to an allocation limit or minimum flow rationing. Permitted activity rules within the RPW allow for the taking of water from the lake without consent at rates up to 100 l/s and 1 million litres per day (or 11.5 l/s on a 24 hour basis). Recent amendments to the RPW have resulted in hydraulically connected groundwater takes within 100 m of the lake shore being allocated and managed as surface water. Similarly, the taking of groundwater that intercepts or depletes surface water is required to split the water allocation between groundwater allocation and surface water allocation.

3.2.2 Current Groundwater Management

The Cromwell Terrace Aquifer is defined within the RPW and mapped spatially in Map C3. However, there is no other specific mention of the aquifer within the plan. This is partly due to the lack of previous scientific investigations of the aquifer by ORC. Consequently, the

RPW policies and rules relevant to the management of the aquifer tend to be generic or default.

The most relevant default provisions of the RPW include:

- Permitted activity takes of groundwater up to 25 m^3/d.
- Controlled activity requirement to obtain consent for any drilling or bore construction within the aquifer.
- Restricted discretionary activity requirement to obtain consent for the taking of groundwater from the aquifer (for takes over 25 m^3/d).
- A default groundwater volume limit related to '50% of Mean Annual Recharge (MAR)', which has applied to the Cromwell Terrace Aquifer since 1 March 2012.
- MAR is determined by ORC on the basis of scientific derivation of all annual anticipated sources of recharge to the aquifer.
- Hydraulically connected groundwater is considered as allocated from surface water and subject to minimum flow restrictions if taken within 100 m of the water course concerned (primarily Lake Dunstan) since 1 March 2012.
- Hydraulically connected groundwater is considered as a dual allocation from surface water and groundwater if the Jenkins equation shows the effect on surface water is more than 5 l/s since 1 March 2012.

Possible future additions to the groundwater management of the Cromwell Terrace Aquifer could include the setting of a tailored maximum allocation volume (MAV), groundwater level restrictions or the imposition of groundwater protection zone(s). The process of adding to the groundwater management provisions is usually informed by scientific investigations such as this report.

4 Aquifer Water Balance

4.1 Rainfall Recharge Modelling

This investigation has the advantage of a recent ORC investigation into the rainfall recharge modelling of thirteen Otago aquifers (ORC, 2011). The result of the investigation for the Cromwell Terrace Aquifer is summarised in Table 2 below:

Table 2: Cromwell recharge modelling results (million m^3/year)

	Area (Ha)	Mean (Mm^3/y)	Standard Deviation	Max. (Mm^3/y)	Median (Mm^3/y)	Min. (Mm^3/y)
Cromwell	1,779	1.2	0.7	2.8	1.0	0.2

The modelling only considers recharge due to rainfall or snow-melt. Increases in soil-moisture, due to the application of irrigation water and the resulting elevated recharge, were not included in the rainfall-only recharge modelling. As a result, this investigation has undertaken focused modelling on the recharge under the approximate 800 ha of the Cromwell Terrace that is under irrigation.

It should also be noted that almost 400 ha of the Cromwell Terrace Aquifer was excluded from the modelling of rainfall recharge due to the extent of the Cromwell township's built-up area. The rationale for the exclusion is that built-up areas are generally impermeable surfaces and networked with stormwater sewers that tend to prevent appreciable recharge. However, the recharge from grassed areas within the township from the irrigation of reserves (Anderson Park, Cromwell Golf Club and Alpha Street reserves) is considered below.

4.2 Irrigation Recharge Modelling

4.2.1 Information on Applied Irrigation Volumes

The Cromwell Terrace rests within a climate zone and the rain shadow of the Pisa Range that includes low rainfall and high potential evapo-transpiration (PET). Introduced grasses, fruit trees and grape vines all require additional irrigation to be productive. The result is that most of the productive land on the terrace is viable only through connection to some type of irrigation system. Analysis of resource consents indicate that the following approximate areas of the Cromwell Terrace are under irrigation:

- Surface water source:	690 ha
- Groundwater source:	100 ha.

The irrigated land supplied by surface water almost exclusively obtains its water from Lake Dunstan, and mostly using direct intakes on the Kawarau Arm. The smaller areas under irrigation from individual groundwater supplies are primarily used in private orchards and vineyards. These bore water supplies tend to use more efficient methods such as spray and drip applicators. The land supplied by riparian water sources includes the few large capacity bores installed directly next to Lake Dunstan near Deadmans Point. The land irrigated from these bores includes the Cromwell Golf Club and the Alpha Street reserves in Cromwell township. Anderson Park is irrigated from a bore located in Cromwell.

While the various irrigation schemes are likely to have a variety of irrigation practices, and the terrace is covered in six main soil classes, grouped by soil-moisture properties, modelling of recharge induced by irrigation was considered important to the wider estimate of total recharge. To deal with irrigation recharge, simulated irrigation water was added to the existing soil-moisture models covering the aquifer, including the 800 ha under irrigation. Thus the aquifer water balance would account for rainfall recharge in non-irrigated areas and irrigation-induced recharge under the various irrigation schemes. The combined rainfall and irrigation recharge from both sources would account for all recharge through the terrace soils.

4.2.2 Estimated Applied Irrigation

The ‘Aqualinc tables’ (Aqualinc, 2006), which are based on irrigation design parameters, were used in developing an estimate of the total irrigation water applied at the aquifer surface. The tables are based on calculations of required irrigation volumes, application rates and return periods. These parameters are differentiated in accordance with the following factors:

- Crop (grass, stonefruit, vines).
- Climate region in Otago.
- Soil available water capacity (PAW).

Tailored to crop, climate and PAW capacity, the calculated maximum monthly or annual irrigation volume imposes a *de facto* cap. For the Upper Clutha, the seasonal irrigation guidelines are specified as follows in Table 3:

Table 3: Aqualinc Irrigation Guidelines as Seasonal Totals for the Upper Clutha Climate Region.

PAW Range (mm)	Pasture Guideline Limit (m^3/ha/y)	Stonefruit Guideline Limit (m^3/ha/y)	Viticulture Guideline Limit (m^3/ha/y)
45	6750	3280	1650
70 – 90	5950	3060	1410
105 – 155	5775	2750	1140
155 – 175	6000	2680	1080

Since almost all consented groundwater extractions are used in irrigation, these are also the values in the Aqualinc tables that specify the irrigation application volumes used in irrigation recharge modelling. Table 4 shows the best estimates of actual irrigation applied over the aquifer.

Table 4: Estimates of Applied Irrigation over the Cromwell Terrace Aquifer.

	Irrigation Applied (m^3/y)	Sub-totals	Total
Surface Water Source			
Stonefruit	2,145,234		
Viticulture	4,950	**2,150,184**	
Groundwater Source			
Pasture	220,150		
Stonefruit	79,676		
Viticulture	56,961	**356,787**	
Surface and Groundwater Total			**2,506,971**

To assess whether irrigation of pasture, orchards and vineyards is efficient in terms of water conservation, applications for water take are compared with indices of water use efficiency. In the Cromwell Terrace Aquifer, there are fifteen groundwater takes with the following end uses:

Table 5: Cromwell Terrace Aquifer Groundwater Take number, areas, allocations and estimated volume.

End Use	No. of Groundwater Takes	Area Irrigated (ha)	Calculated Allocation (m^3/y)*	Estimated Volume (m^3/y)¥
Pasture (within Cromwell)	2	37	217,267	220,150
Stonefruit	7	26	678,096	79,676
Viticulture	5	39	471,224	56,961
Water bottling	1	_	21,600	21,600
TOTAL	15	102	1,388,187	378,387

Note:

* Allocation volume was calculated from annual volume specified in consent or calculation scheme within RPW Method 15.8.3, where there was no annual volume specified.

¥ An estimate of actual groundwater use, based on application volume guidelines, was taken from the Aqualinc tables and area for irrigation specified in the resource consents.

4.3 Interactions with Lake Dunstan

The existence of lake – aquifer interactions is obvious, but the detailed nature of interaction between the Cromwell Terrace Aquifer and Lake Dunstan is more difficult to gauge. However, given the lake's presence as an effective infinite fixed head on the margins of the aquifer, the net interaction between the lake and aquifer is defined by whether the aquifer is in surplus or deficit.

4.3.1 Lake Filling

This study assumes that, during the filling of Lake Dunstan in 1993, the water table rose faster than could be compensated for from prevailing land surface recharge. The increase in water resource of more than 30 Mm^3 observed during lake filling is substantially more than the potential annual land surface recharge during a one year period. The most plausible inference is that lake water entered and filled the aquifer during the period of lake filling from September 1992 to September 1993.

4.3.2 Ambient Post-Filling Interaction

In the post-filling state since September 1993, the water table, outside of the Ripponvale area, has been observed to slope towards the lake, strongly implying recharge at land surface and groundwater flow outwards to the lake margin. Generally, land surface recharge to the Cromwell Terrace Aquifer significantly exceeds the actual removal of groundwater by bores. Hence, the aquifer has a surplus that flows outwards into Lake Dunstan. There is thought to be sufficient observed stability in the water table profile to preserve this polarity of interaction year-round. Any future disturbance of this pattern by decreases in recharge or increases in groundwater extraction could alter the polarity of the interaction with the lake. However, Lake Dunstan would substantially buffer against any large-scale drop in the water table height and augment the aquifer. In such a setting, the groundwater resource is unlikely to be adversely affected.

4.4 Groundwater Extraction

The pumping of groundwater is thought to be a relatively minor water balance component compared to rainfall and irrigation-induced land surface recharge. As mentioned above, there are approximately 20 groundwater takes requiring resource consent. Consented groundwater takes provide freshwater for orchards, vineyards, mown grass, grazed grass, and in one instance, bottled water for export. One groundwater extraction on the north-western edge of the terrace draws aquifer water to be piped into the Lowburn catchment outside of the aquifer boundary, which allows it to be included to the total of extraction from the aquifer but excluded from the modelling of irrigation-induced recharge.

4.4.1 Groundwater Extraction Monitoring

Each consented groundwater take has restrictions on the rate, and usually also the annual volume, of water that can be legally extracted from the assigned bore. In practice, these maximum rates and volume are rarely exceeded, and, in fact, usually significantly under-utilised, on an annual basis. This presents difficulties for quantifying *actual* groundwater extraction. All but three of the 18 aquifer groundwater takes, which are not otherwise riparian, are required to be fitted with totalising water meters. Figure 5 shows the variation in monthly mean groundwater extraction from bore G41/0246 for the period 2003 – 2010. The recording and forwarding of meter readings is not yet universal, so a consistent picture of actual groundwater extraction across the aquifer has not yet emerged.

The uncertainty as to the rates and volumes of irrigation applied within the various schemes is unfortunately not dispelled by monitoring of consented takes by meters. Only four meter records were available for review of the approximately 25 irrigation water take consents within the Cromwell area. Of these, only two contained more than six years of record that could be used to compare allocation volume and actual annual water take, as shown in Table 6.

Table 6: Metered Groundwater Extraction Statistics

Consent No.	Consent Allocation (m^3/y)	Mean Actual Take 2004-09 (m^3/y)	Percentage of Consented Allocation
2002.045	400,000	61,280	15% (12% - 17%)
2003.657	10,382	4,220	41% (19% - 88%)

These records reinforce the perception of low *actual* water use compared to consented allocation (for example, bore G41/0246 (resource consent 2002.045), which is authorised to extract up to 400,000 m^3/y of groundwater). Meter records indicate the actual annual extraction is between 47,006 and 66,702 m^3/y, with a mean from 2005 to 2010 of 61,283 m^3/y. Thus, actual extraction, on average, represents only 15% of the volume allocated to the bore in consent 2002.045 (see Table 6 and Figure 5).

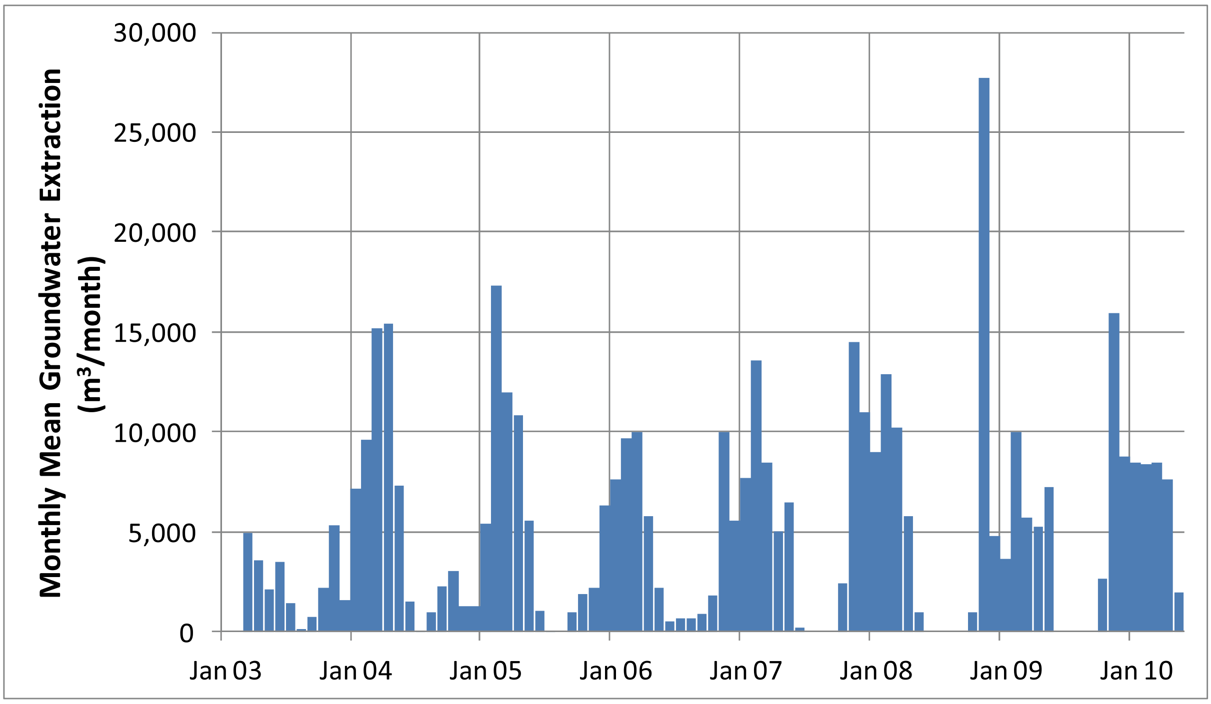

Figure 5: **Mean monthly groundwater extraction at bore G41/0246 authorised under consent 2002.045 to irrigate up to 22 ha of grapes in the north of the Cromwell Terrace Aquifer.**

It has been found that the allocation overhang is quite common through other groundwater basins in Otago. An estimate of the percentage of actual groundwater use compared to allocated volume is often placed at about 30%. It is worth noting that the estimated annual groundwater extraction volume of 0.4 Mm^3/y, based on the Aqualinc tables, is only 24% of the legal consented groundwater allocation volume of 1.7 Mm^3/y for all groundwater consents in the Cromwell Terrace Aquifer.

4.4.2 Summary

All of the significant water balance terms for the Cromwell Terrace Aquifer can be defined and quantified. These are outlined in the sections above. The summary water balance for the aquifer in total is given graphically in Figure 6, and listed in Table 7.

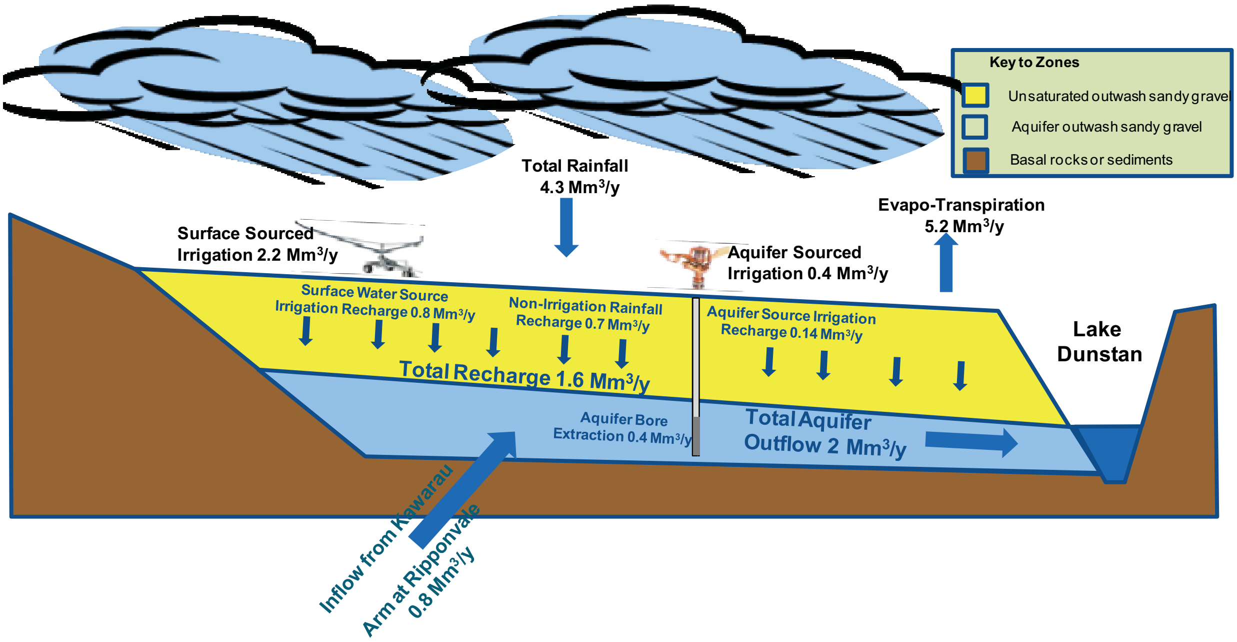

Figure 6: **Schematic profile of Cromwell Terrace Aquifer, quantifying the water balance as annual totals in million cubic metres per year (Mm^3/y).**

Table 7: Cromwell Terrace Aquifer Water Balance

	Aquifer Inflows (Mm^3/y)	**Aquifer Outflows (Mm^3/y)**
Bore Extraction ('actual')		0.4
Net Rainfall Recharge	0.7	
Net Irrigation Recharge*	0.9	
Infiltration from Lake Dunstan¥	0.8	
Seepage into Lake Dunstan		2.0
Totals	2.4	2.4

* Irrigation includes bore water and water pumped from Lake Dunstan.

¥ Infiltration volume was determined using groundwater modelling. The volume increases as groundwater extraction from the aquifer by bores increases.

The water table rests at a marginally higher elevation than the adjoining lake base level, and the surplus flows out to Lake Dunstan. A hypothetical situation exists where groundwater extraction exceeded recharge would reverse the polarity of exchange with Lake Dunstan. The water balance includes a quantity for lake infiltration that had not been determined by the methods described above. Instead, the lake infiltration quantity of 0.8 Mm^3/y was derived from transient numerical modelling, as described in 'Numerical Modelling' further on in this report.

5 Groundwater Modelling

5.1 Purpose of Modelling

The usual purpose of using a groundwater flow model is to develop a predictive tool for estimating the response of an aquifer to stresses. The use of modelling for the Cromwell Terrace Aquifer is no different. The aquifer water balance characterises the current concept of the aquifer being recharged by net soil moisture from rainfall, surface water sourced irrigation and groundwater sourced irrigation. What happens in the aquifer if the recharge were to decline or if the actual groundwater extraction were to increase? A calibrated groundwater model can be used to simulate these effects and examine the impact in terms of groundwater levels and flows of groundwater. Predictive modelling of aquifer response is usually framed in terms of a range of scenarios. This process is further outlined in the following sections.

5.2 Conceptual Model

A conceptual model is important to the wider modelling process, since it develops and refines a concept of the current state of the aquifer in terms of the following qualities:

- The **geometry** of the aquifer being modelled, such as the extent, thickness and geological structure.
- Aquifer properties and hydrological **parameters** that quantify those properties (e.g. permeability and hydraulic conductivity).
- The hydrological **boundaries** of the aquifer, such as hard boundaries (e.g. no flow boundaries) or soft boundaries, involving groundwater exchanges with other water bodies.
- The aquifer **water balance**.
- Temporal changes in the hydrology of the aquifer, particularly **fluctuations in recharge** and resulting **groundwater level variability**.

5.2.1 Geometric Framework

The Cromwell Terrace Aquifer is a single outwash sheet resting on basal schist or Tertiary sediments. Figure 7 illustrates the general geometric framework of the aquifer. Departures from the general pattern include:

- A Tertiary sediment outcrop in the north-west of the aquifer that projects through the outwash gravels to form a low hill.
- Two paleo-channels crossing the south of the aquifer that are the probable abandoned courses of the Kawarau River.
- Schist outcrops on the edge of the aquifer at Bannockburn Narrows and the Cromwell effluent ponds.
- Thinning of the outwash gravels, due to ‘highs’ in the Tertiary sediments mapped in the banks of the Kawarau Arm, upstream of the Bannockburn Bridge.
- Thickening of the outwash gravels in the Deadmans Point area.

Figure 7: Conceptual outline map of the Cromwell Terrace Aquifer, showing extent in yellow, paleo-channel alignments in gray and approximate post-filling lake levels.

5.2.2 Conceptual Parameters

Aquifer parameters available from past aquifer tests indicate a significant variability from one point to another. The result from an aquifer on the Anderson Park irrigation bore was a transmissivity of 30,000 square metres per day (m^2/d), while the aquifer test of NZ Nut bore, near the Bannockburn Bridge, derived only 700 m^2/d. Interpreted step drawdown tests indicate a similar degree of variability: from a transmissivity of 14,425 m^2/d at bore G41/0246 in the 'grape belt', north of Cromwell, to 695 m^2/d at the Central Otago District Council (CODC) borefield on the Clutha Arm. The difference in parameters may be due to different saturated thicknesses, but there must also be significant variation in hydraulic conductivity between these sites. The hydraulic conductivity of the saturated alluvium within the north and south paleo-channels is considered to be higher than outside the channels.

Other contrasts in aquifer parameters are expected between the Albert Town Outwash and Luggate Outwash. Recorded aquifer tests in the Cromwell Terrace Aquifer have been performed in the Albert Town Outwash or Gibbston Outwash gravel deposits.

5.2.3 Conceptual Boundaries

Lake Dunstan is the main aquifer boundary of note. As noted in the section on 'Interactions with Lake Dunstan', the lake boundary can be either a discharge or a recharge boundary. However, in normal conditions, the boundary is a discharge boundary, with the potential to be locally reversed to recharge, either due to loss of recharge or escalation in groundwater extraction.

Geological contacts with the schist and Tertiary sediments are straightforward no-flow boundaries that assume impermeability. A short segment at the northern margin of the Cromwell Terrace Aquifer, between the Clutha Arm and the basement margin, is assigned as 'no-flow boundary status', on the basis that it coincides with a flow divide.

5.2.4 Conceptual Dynamics

The Cromwell Terrace Aquifer has several long-term level records, the first beginning in 1992. These level records indicate a regular pattern of declining water table in winters and rising level in spring - summer. It is believed that summertime irrigation and resulting recharge are the drivers for the observed water level dynamic.

Figure 8 illustrates the best record of groundwater level fluctuation in the aquifer taken from a bore near the mid-point of Cromwell Terrace. Shading indicating the onset of the irrigation season coincides with the rise of the water table in Figure 8. The rising water levels plateau in late summer in the months of February or March and begin a decline at this time to the respective annual minimum in late winter. The water level rise and fall pattern is broadly consistent with the pattern of soil moisture deficit extracted from the soil-moisture model run most relevant to the soil class and irrigation practice.

A few approximate estimates of aquifer dynamics can also be made using annual water table variability data, recharge modelling and the water table rise observed in lake filling.

The first approximation uses the mean annual water table level fluctuation and the specific yield (or drainable porosity) of the aquifer to calculate an estimate of the mean annual rate of recharge across the entire aquifer. The mean annual water table level fluctuation can be derived from Figure 8 below.

Mean Annual water table variability (ΔH) $= 0.4$ m
Aquifer specific yield (S_y) $= 0.2$

Calculated annual net recharge rate $= \Delta H \times S_y$
$= 0.4 \text{ m} \times 0.2$
$= 0.08$ m/y (or 80 mm/y)

The second approximation uses the mean annual recharge determined in recharge modelling and the estimated area of the aquifer surface considered to be active in recharge processes.

Estimated mean annual recharge (Q)	= 1.6 Mm^3/y
Estimated aquifer area (A)	= 20 million m^2
Calculated annual mean recharge rate	= Q / A = 1.6 / 20 = 0.08 m/y (or 80 mm/y)

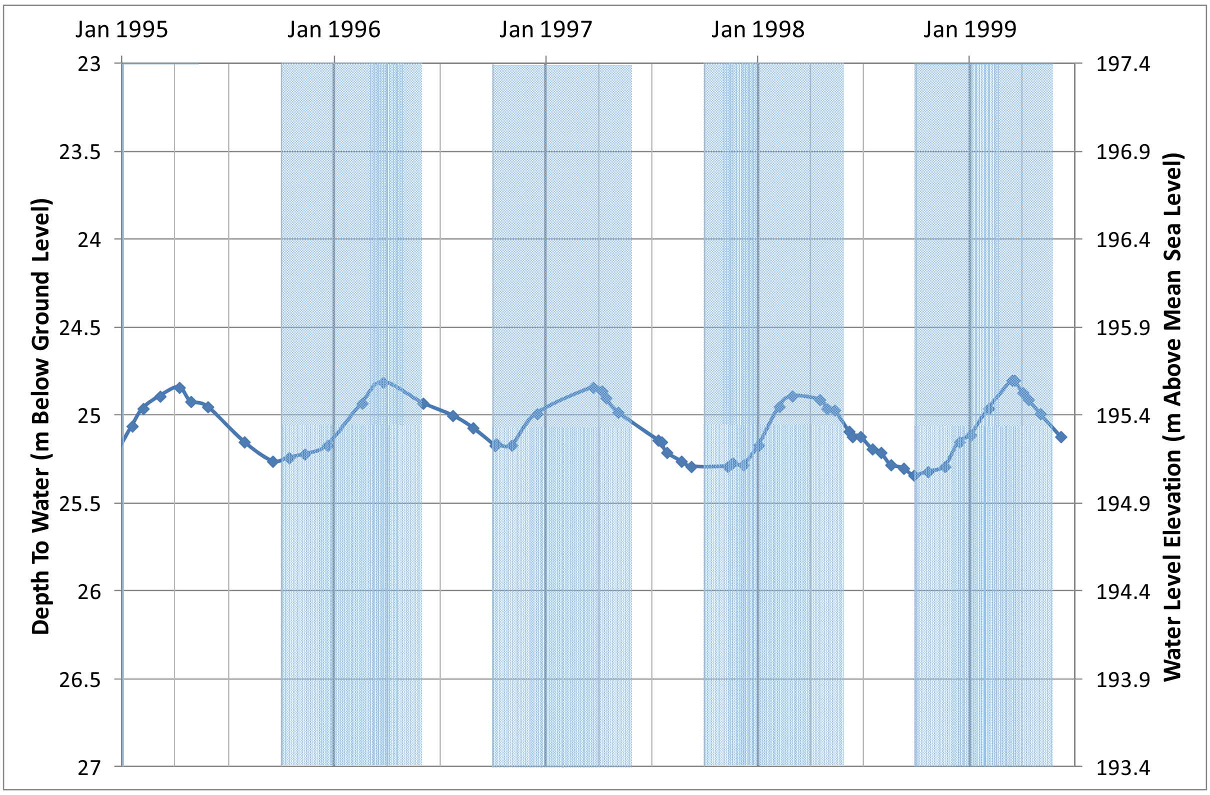

Figure 8: **Groundwater level record of bore F41/0171 located near the middle of the Cromwell Terrace Aquifer, showing level fluctuations recorded through time from January 1995 to June 1999. Blue shading indicates representative irrigation season for the area.**

The third approximation uses the observed rise in the mean annual water table height and the specific yield (or drainable porosity) of the aquifer to calculate an estimate of the increase in the aquifer's water resource after the filling of Lake Dunstan. The three-dimensional factors inherent in the presence of basement projections into the aquifer dictated that an adjusted area was used.

Water table rise due to lake filling (ΔH)	= 10.5 m
Aquifer specific yield (S_y)	= 0.2
Estimated area, adjusted for margins (A_a)	= 15 million m^2
Calculated increase in saturated storage (Q)	= $\Delta H \times S_y \times A_a$ = 10.5 m x 0.2 x 15,000,000 m^2 = 31.5 Mm^3

This increase in saturated storage occurred entirely within the period of September 1992 to September 1993, essentially one year. As the land surface recharge during the same period was in the order of 1.6 Mm^3, approximately 30 Mm^3 is inferred to have been contributed by the inflow of Lake Dunstan water.

5.2.5 Summary

To summarise the conceptual model of the Cromwell Terrace quifer, we could specify the following:

- The aquifer comprises glacial outwash deposited between Lake Dunstan and the basement margin, and underlying basement schist or Tertiary sediments.
- The outwash sandy gravel deposits hosting the aquifer have high permeability.
- The aquifer is unconfined and hydraulically bound to Lake Dunstan at the Kawarau and Clutha arms of the lake.
- The aquifer's water balance is dominated by the infiltration of excess irrigation to the extent that up to 1.6 Mm^3/y enters the aquifer at the surface (and to a lesser extent, rainfall).
- The aquifer discharges the net excess of 2 Mm^3/y as groundwater seepage into Lake Dunstan.
- The above observation of discharge to the lake tends to be confirmed by the observed water table contour pattern.
- Observed water table fluctuations indicate increases in aquifer storage, after the onset of irrigation, and declines, after the peak in irrigation activity.
- A consistent annual water table fluctuation range and derivation from the mean annual volume of land surface recharge allow the estimation of the mean annual rate of land surface recharge across the wider area as approximately 80 mm/y.
- Localised rates of recharge based on soil-moisture balance modelling are thought to range from 10 mm/y to 240 mm/y, depending on geographic variations in the soil available water capacity or irrigation practices.
- The 10.5 m rise in aquifer water level as a consequence of lake filling is estimated to have resulted in an inflation of the aquifer groundwater resource of approximately 30 Mm^3/y largely as a result of the inflow of Lake Dunstan water.
- It could be inferred that the one-off inflow of dilute lake water would have a significant and long-term influence on groundwater quality.

5.3 Numerical Modelling

5.3.1 Framework

The Cromwell Terrace Aquifer was modelled using the MODFLOW modelling code, which is implemented within the Groundwater Vistas pre-processing/post-processing software package. The numerical model was progressively developed from the quantitative parts of the conceptual model as follows:

- The basal surface of the single layer model was obtained from the geological interpretation and the elevation of points of known basal contact.
- The land surface was obtained from the current Digital Elevation Model from Land Information New Zealand (LINZ).
- The mean water level elevation was obtained from depth to water measurement through time, at a number of suitable bores with a known ground surface.
- The pre-filling topography was used to delineate the Lake Dunstan bathymetry relevant to the numerical model.

The model framework was based on a 50 × 50 cell network, with each cell having a side dimension of 160 m. Consequently, the model domain was 8 × 8 km, with the Cromwell Terrace Aquifer's 22 km^2 area being represented by approximately 860 active cells. The rest of the domain was blanked out with no flow boundaries that are not part of the active model domain. Once this geometric framework had been developed, the assignment of hydrological boundary effects and parameters could be undertaken.

5.3.2 Hydrologic Boundaries

The dominating hydrological boundary is Lake Dunstan. Soon after its raising, the lake established a stable water level elevation averaging 194.2 m AMSL. Following the deposition of flood debris and sediment, particularly in the aftermath of the 1999 flood event, the Kawarau Arm of the lake formed a shallower channel and emergent sandbanks that have slightly raised the hydraulic profile relative to the lower lake (URS, 2002). The long-term mean height difference between the Ripponvale and Dam stage monitoring sites is approximately 0.3 m (ref. ORC hydrological database), and has become more accentuated since 1997 to the extent that the difference is currently 0.5 m. Conversely, there has been very little sedimentation in the Clutha Arm of Lake Dunstan, so there is very little, if any, measurable height difference in the lake surface (on the Clutha side of the confluence) between the dam and Clutha Arm.

The lake boundary was simulated using a MODFLOW River (RIV) boundary type. This allowed steady state and transient water levels to be specified in the river boundary, and the specification of riverbed conductances. Significantly, the water lake levels specified in the river boundaries used measured contemporaneous levels at the dam for the Clutha Arm and Ripponvale. This created a post-filling groundwater gradient from Ripponvale, where the lake level difference averages 0.5 m higher than the Clutha Arm. Figures 9 and 10 show the model arrangement as numerical setup and conceptual model, respectively.

Figure 9: Numerical model boundaries: river (RIV) in green, head no flow (HNF) in black.

Figure 10: Conceptual framework model of the Cromwell Terrace Aquifer, used above.

Basement boundaries to allow for the steep permeability contrasts between the Quaternary outwash and either schist rocks or Tertiary sediments were simulated in MODFLOW, using no flow (HNF) boundary type cells.

5.3.3 Aquifer Parameters

Parameter optimisation was used to fill out the large gaps in knowledge as to aquifer parameters. The process of parameter optimisation is further explained in the section describing calibration (‘Appendix 3 – Numerical Model Calibration’).

5.3.4 Model Recharge

MODFLOW has the facility to vary the recharge rate applied to the upper aquifer surface. The modelling software allows the delineation of numerous recharge zones with unique recharge data. Accordingly, the recharge information and classifications were aggregated until the range of recharge conditions could be represented in the transient model as four irrigated recharge zones and four non-irrigated zones. The timing of rainfall and irrigation was explicitly included in the input variables for the recharge modelling and formatted for inclusion in the groundwater model. The recharge model is detailed in ‘Section 4: Aquifer Water Balance’.

5.3.5 Model Calibration Process

The modelling project possessed measured water levels in five locations, including 130 time series measurements made at bore F40/0171 from 7/05/1992 to 6/06/1999. The remainder of a smaller number of level measurements were made at SOE monitoring bores F41/0247, F41/0297, F41/0300 and G41/0246 during the period 18/09/2006 to 23/06/2011. Ultimately, the transient calibration process used the richer time series from bore F40/0171, which also encompassed the lake-filling period mentioned previously. Automated parameter optimisation was used to assist the calibration process. The parameter-optimisation package (PEST) was slaved to the MODFLOW model within the Groundwater Vistas package to facilitate seamless operation of optimisation. After each optimisation model run, the fit of modelled heads was compared with that of observed groundwater levels. Optimisation runs were undertaken until diminishing levels of improvement in the model calibration indices were considered to have been reached.

5.3.6 Resulting Model

After calibrating the model, it was examined for information on the aquifer’s hydrology and dynamics. The water table contour map revealed a relatively low gradient surface resting under the direct influence of the mean lake level. Due to the slightly higher lake level in the sediment-choked Kawarau Arm, water table contours sloped from Ripponvale towards the Kawarau – Clutha confluence. Throughout the transient period after lake filling, the Kawarau Arm oscillates between losing and gaining water with the adjoining aquifer. The paleo-channels with higher transmissivity may also channelise groundwater flow direction to the north-east. ‘Appendix 3 – Numerical Model Calibration’ details the calibration process and results.

5.3.7 Transient Model Scenarios

The main objective of scenario modelling is to identify potential limitations on the ability to sustainably extract groundwater from the aquifer. One area of groundwater resource limitation is transgressed when continued extraction imparts adverse effects. The other area is where an external condition directly limits the ability to extract groundwater.

The two main scenario groups involve the following manipulations:

- Scenarios of differing groundwater extraction rate to assess the point at which sustainability becomes compromised.
- Scenarios varying the Kawarau Arm surface water – groundwater interface parameters in order to anticipate the effect of possible future changes to the nature of Lake Dunstan.

Accordingly, the list of model scenarios encompasses the following:

Table 8: Modelled Scenarios

Scenario	Short Title	Explanation
0	Base scenario	The calibrated-based situation with little appreciable groundwater extraction.
1	30% allocation	Extraction of groundwater close to the inferred actual rate of 33% of allocation (0.4 Mm^3/y).
2	100% allocation	Modelled extraction at full rate and volume allocation (approximately 1.3[1] Mm^3/y).
3	200% allocation	Modelled extraction at twice fully allocated annual volume at 2.6 Mm^3/y.
4	300% allocation	Modelled extraction at three times fully allocated annual volume at 3.9 Mm^3/y.
5	Aggraded Kawarau Arm	Further aggradation of the Kawarau Arm lake bed so that the arm becomes a graded river and assumes an equivalent hydraulic gradient.
6	Clogged lake interface	Further sedimentation of the Kawarau Arm such that the interface between lake and aquifer becomes appreciably clogged, reducing bed conductance.

It was inferred that the simulation of actual extraction based on 30% of allocation (scenario 2) would display little or no difference in modelled aquifer behaviour. Simulation of once, twice or three times the current groundwater resource allocation (i.e. scenarios 2 – 4) would be likely to induce significant changes compared to the base scenario. It was also inferred that increasing the groundwater extraction at bores beyond the mean annual land surface recharge rate (i.e. scenarios 2 – 4) would alter the groundwater flow pattern, especially the inflow and outflow of water at the lake margins, but would not induce significant water table decline due to the high transmissivity of the aquifer.

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[1] Full allocation was assumed to be 1.3 Mm^3/y, while full legal allocation was later found to be 1.7 Mm^3/y. For the purposes of numerical modeling, the lower value was used.

5.3.8 Extraction Scenario Results

Figure 11 shows the difference in water table height in the Cromwell Terrace Aquifer compared to the modelled height without groundwater extraction.

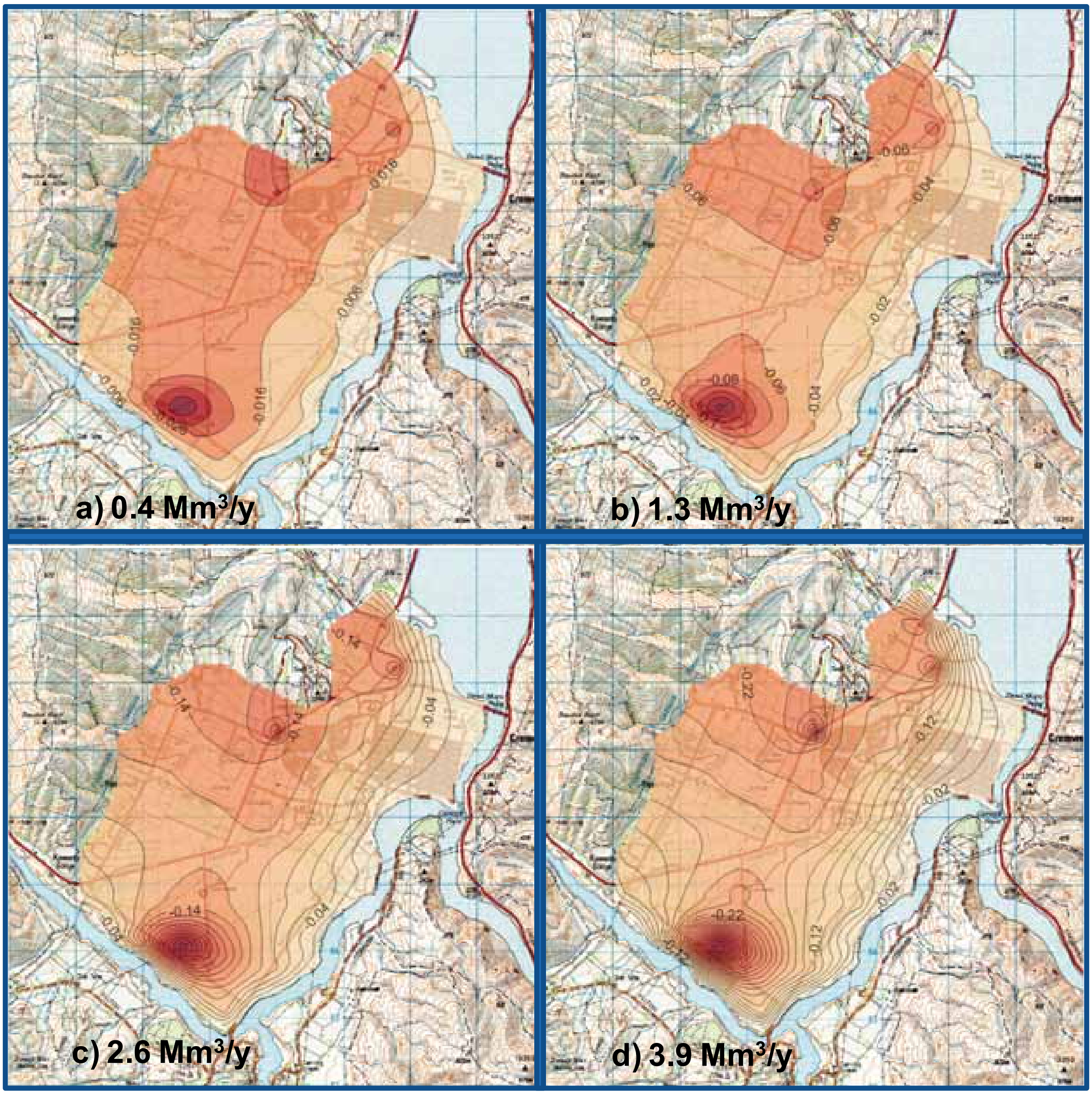

Figure 11: Colour flood contour maps of the distribution of water table decline resulting from groundwater extraction in accordance with allocation scenarios:

a) scenario 1 33% of current allocation
b) scenario 2 100% of current allocation
c) scenario 3 200% of current allocation
d) scenario 4 300% of current allocation.

The magnitude of modelled water table decline increased in proportion to the succession from scenario 1 to scenario 4, as shown geographically in Figure 11 above. Due to the very small modelled decline in scenario 1 (i.e. 0.4 Mm^3/y extraction), the contours are at 0.01 m (1 cm) intervals. All other plots (b – d) in Figure 11 were in 0.02 m (2 cm) intervals. The water table heights as time series for each scenario tracked the others, as shown in Figure 12 below.

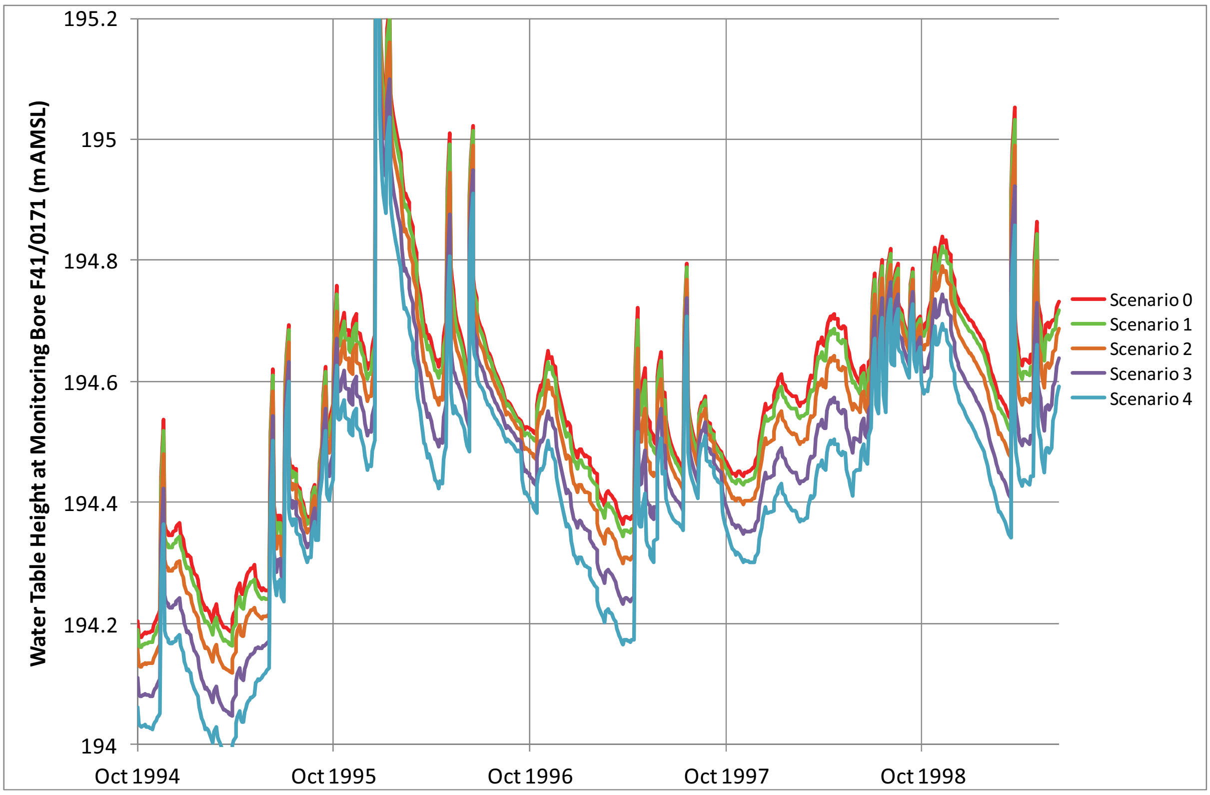

Figure 12: **Comparative hydrographs of water table height modelled for monitoring bore F41/0171.**

Figure 12 showed that the modelled water table decline was greatest for the largest modelled groundwater extractions, but even this decline would be manageable for continuing use of the aquifer. Table 9 lists the mean water table declines from the base scenario for the period October 1994 to May 1999.

Table 9: **Mean Water Table Decline modelled for monitoring bore F41/0171.**

	Extraction (Mm^3/y)	Mean Water Table Decline (m)
Scenario 1	0.4	0.016
Scenario 2	1.3	0.050
Scenario 3	2.6	0.102
Scenario 4	3.9	0.153

Given that the recorded annual water table variability at monitoring bore F41/0171 was 0.4 m (40 cm) for the same period, as considered in Figure 12 and Table 9, the higher order declines modelled for scenario 3 and scenario 4 would not be likely to impart significant effects on the ability to extract groundwater from the aquifer. The greatest modelled drawdown was at bore F41/0350 under the authorisation of consent number 2007.411, with a decline of 0.5 m (50 cm) for scenario 4 when total extraction was at 3.9 Mm^3/y.

Numerical modelling revealed that a reach of the Kawarau Arm between Ripponvale and the Bannockburn Narrows loses water into the adjacent aquifer at a rate of 0.8 Mm^3/y when the groundwater extraction rate was simulated as 0.4 Mm^3/y. The quantity of loss was found to be variable and increased in response to higher bore extraction rates.

5.3.9 Kawarau Arm Sedimentation Scenario Results

Aquifer modelling scenarios for the Kawarau Arm concern the gradation of the lake bed in the Kawarau Arm of Lake Dunstan (scenario 5) and the loss of high permeability interface between the lake and the aquifer in the area of the Kawarau Arm. Both scenarios examine the possible consequences of ongoing sedimentation of the Kawarau Arm since lake filling.

The long-term effect of sedimentation of the Kawarau Arm was projected to result in this part of the lake becoming a low-gradient semi-braided riverbed, with willow vegetation stabilising the active channels (URS, 2002). The modern analogue for such a low-gradient semi-braided riverbed was cited as the Kawarau River between the Shotover River and Arrow River confluences (URS, *ibid*). Braided rivers typically have a small channel cross-section and high gradients. The Kawarau River, between the Shotover and Arrow rivers, has a gradient of 0.077% or 1 in 1300. Were the same gradient to be applied to the Kawarau Arm, upstream of the Clutha – Kawarau confluence at Cromwell, the riverbed would lie 6.5 m higher at Ripponvale. The hypothetical braided-river profile was applied within the groundwater model as an alteration to the river (RIV) boundary to reflect the bed gradient of the upper Kawarau River.

The possibility of the Kawarau Arm of Lake Dunstan becoming clogged with impeded permeability of exchange with the aquifer has been raised by URS (2002). In essence, the scenario envisaged the deposition of fine material, mainly silts, micas and muds with low inherent permeability, along the interface between the lake arm. The loss in permeability (or conductance) would alter the flow rates of exchange between Lake Dunstan and the aquifer. For the purposes of the groundwater modelling of this scenario, the hydraulic conductivity of the lake bed was substantially reduced from 1,893 metres per day (m/d) to 0.25 m/d.

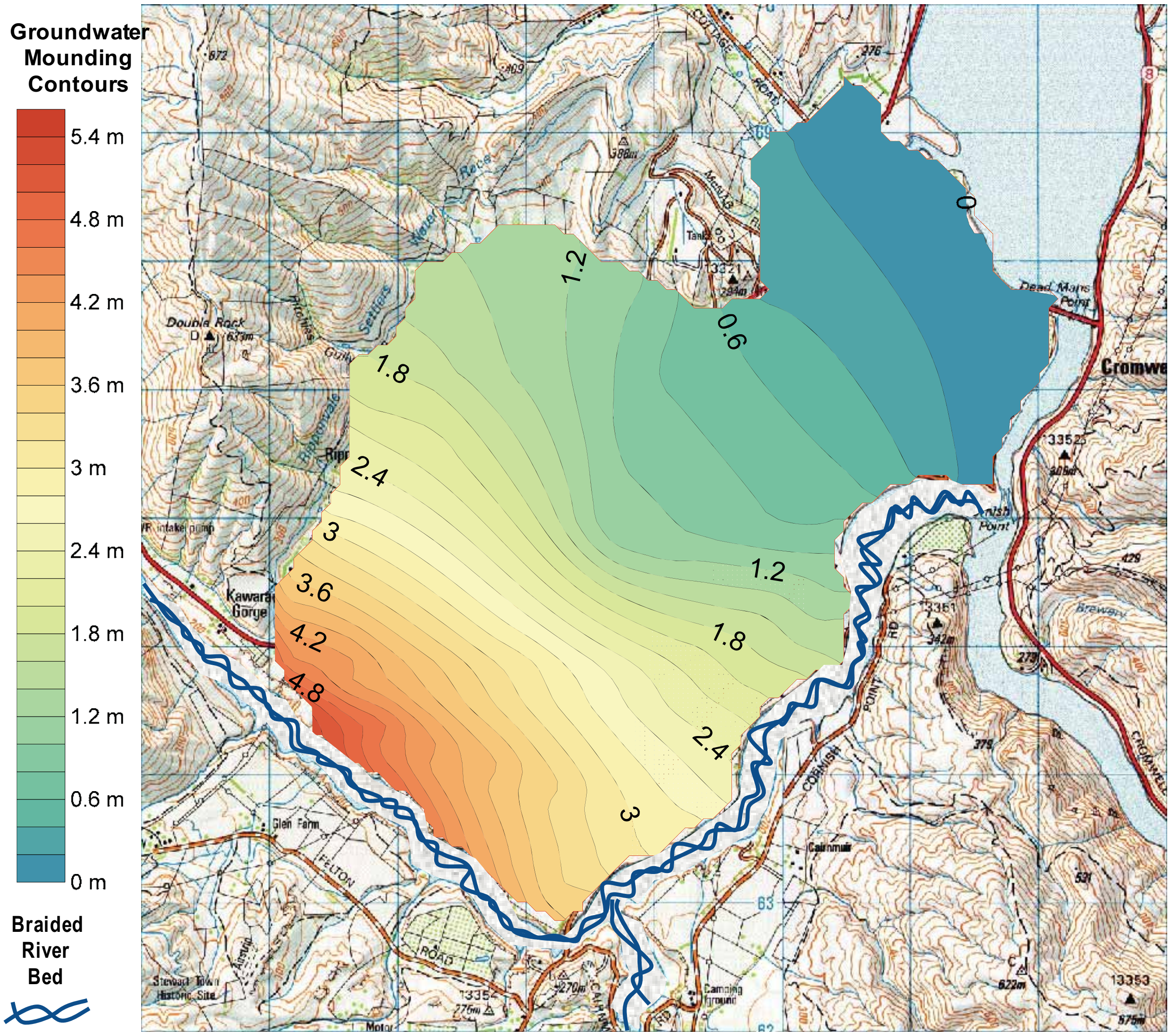

Figure 13: **Contour map of the elevation in water table height resulting from the aggrading of the Kawarau Arm of Lake Dunstan.**

Raising the hydraulic gradient of the Kawarau Arm in scenario 5 was modelled using a steady state model variant of the calibrated scenario 0 transient model. Figure 13 (above) shows the effect in terms of mounding contours across Cromwell Flat to the Clutha Arm. The surface water stage at Ripponvale was raised by 6.5 m in scenario 5, which induced up to 5.4 m of rise in the adjoining water table. Figure 13 shows the tapering off in the water table raising effects in the direction of Cromwell township as a result of the build up in hydraulic gradient. Rather than being an adverse effect on the Cromwell Terrace Aquifer resource, the groundwater resource capacity would be substantially increased. A conservative estimate of the increase in groundwater resource as a result of the new hydraulic gradient indicated in scenario 5 was 20 Mm^3, as set out in the equation below:

Calculated increase in saturated storage $= \Delta\text{Vol.} \times S_y$ (see Section 5.2.4)

$= 100{,}000{,}000 \text{ m}^3 \times 0.2$

$= 20 \text{ Mm}^3$

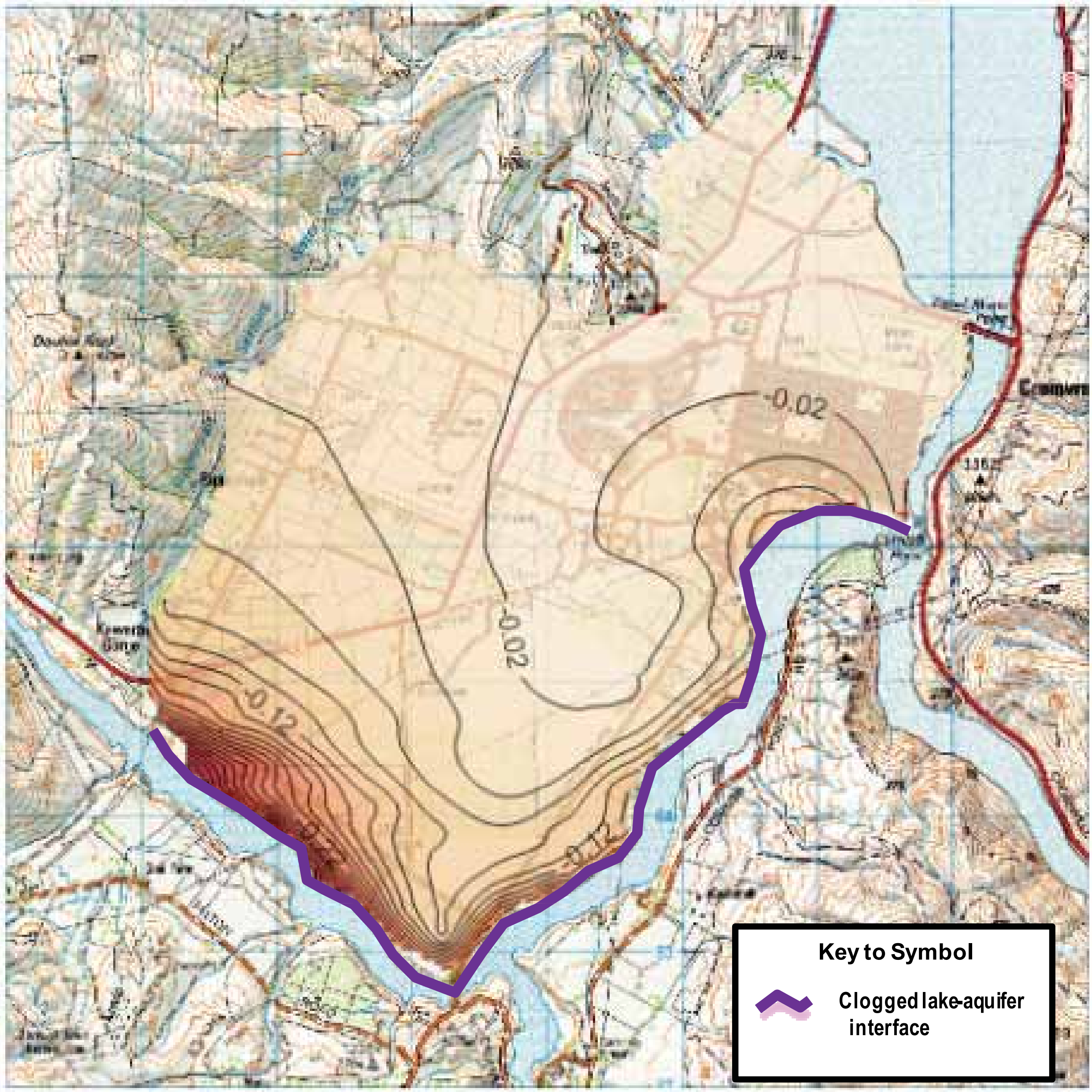

Figure 14: Water table height decline contours in relation to the modelled clogging.

The effect of clogging modelled in scenario 6 and illustrated in Figure 14 (above) is to depress the watertable height in immediate proximity to the lake – aquifer interface. This effect is most intense within 300 m of the lake – aquifer interface, particularly in the Ripponvale reach of the lake. The largest decline in water table height decline as a result of clogging, with the potential to affect existing bores, would be 0.2 m (20 cm). The modelling of this effect in scenario 6 used the scenario 2 ‘full allocation’ groundwater extraction volume of 1.3 Mm^3/y. Higher volumes of extraction would exert greater levels of water table decline as the clogged boundary would behave less like a recharge boundary and more like a barrier boundary. Nonetheless, clogging would otherwise not have much effect on current groundwater flow patterns, nor would it significantly reduce groundwater resource availability.

6 Implications for Management and Conclusions

6.1 Future Groundwater Management Settings

Conceptual and numerical modelling of the Cromwell Terrace Aquifer has identified few constraints on groundwater resource availability. Groundwater extraction constraints usually arise from adverse effects triggered by over exploitation, such as seawater intrusion, extensive drawdown or depletion of flow-sensitive water bodies (creeks, rivers or wetlands). In the case of the Cromwell Terrace Aquifer, water quality or salinity is a negligible consideration. Most of the aquifer has high transmissivity and thus is relatively invulnerable to drawdown, and the only adjoining water body is Lake Dunstan, which has a substantial replenishment rate of 16,000 Mm^3/y. At even three times the current consented allocation for the aquifer, modelling has indicated the generalised water table decline induced by extraction would not exceed half of the seasonal variation in level.

Nonetheless, fixing the maximum annual allocation volume is the preferred means of managing the aquifer from a groundwater resource management perspective. The RPW provides for a default allocation regime as follows:

- Consent allocation volume limit is quantified as '50% of MAR'.
- MAR is determined by ORC on the basis of scientific derivation of all annual anticipated sources of recharge to the aquifer.

The estimated MAR for the Cromwell Terrace Aquifer has been calculated as follows:

Table 10: Aquifer Water Balance and derived MAR

	MAR (Mm^3/y)	**Aquifer Discharge (Mm^3/y)**
Bore Extraction ('actual')		0.4
Net Rainfall Recharge	0.7	
Net Irrigation Recharge*	0.9	
Infiltration from Lake Dunstan¥	0.8	
Seepage into Lake Dunstan		2.0
Totals	2.4	2.4

* Irrigation includes bore water and water pumped from Lake Dunstan.

¥ Infiltration volume determined using groundwater modelling. Volume increases as groundwater extraction from the aquifer by bores increases.

Future consent allocation volume limits can be tailored by one of two groundwater management techniques:

- Setting a tailored Maximum Allocation Volume (MAV) within Schedule 4A of the RPW.
- Declaring a Water Take Restriction Zone (WTRZ) within Schedule 4B of the RPW.
- The WTRZ would be managed from day-to-day by a centrally located monitoring bore to be installed by ORC.

Such tailored approaches are required to follow a plan change process, including public consultation and hearings. Nonetheless, the Cromwell Terrace Aquifer should have a tailored groundwater management regime since the default allocation settings would not optimally manage the groundwater resource.

The current legal groundwater MAV issued in valid consents is 1.7 Mm^3/y. Given the scientific determination that the long-term 50% of MAR is 1.2 Mm^3/y, the aquifer can be considered ‘over-allocated’ in terms of the RPW policy 6.4.10A(a)(ii)(1). As the legal MAV on 10 April 2010 was just over 1.7 Mm^3/y, RPW Policy 6.4.10A(a)(ii)(2) applies, which results in the granting of any further new or replacement groundwater takes consents being a prohibited activity (rule 12.0.1.4). Since groundwater modelling has shown that bore extraction more than twice the legal MAV would have little effect on groundwater availability and other environmental effects would be less than minor, it is suggested that ORC place the Cromwell Terrace Aquifer within Schedule 4A by writing a plan change with an MAV of 4 Mm^3/y. To prevent the adverse effect of generalised water table decline, it is further suggested that the tailored allocation measure be combined with the setting of a WTRZ and restriction groundwater levels, in accordance with Schedule 4B. While the specifications of the monitoring bore and restriction levels are preliminary, it is suggested that the abatement of groundwater extraction adheres to the following outline.

Table 11: Outline of suggested inclusion in RPW Schedule 4B for the Cromwell Terrace Aquifer.

	Aquifer Minimum below Maximum Height (m)	Preliminary Projected Elevations (m AMSL)
		Max. 194.65
25% restriction	0.75	193.9
50% restriction	1.0	193.65
100% restriction	1.25	193.4

6.2 Kawarau Arm Sedimentation and Groundwater Resources

Concerns had been raised that the ongoing sedimentation of the Kawarau Arm of Lake Dunstan would diminish the available groundwater resource in the southern part of the Cromwell Terrace Aquifer (URS, 2002). Numerical modelling has been used to indicate the following potential effects of such sedimentation:

- The aggradation of the Kawarau Arm bed from a hydraulic slope of 1 in 18,000 to 1 in 1,300 causes a significant raising of the water table height across the aquifer and an increase in groundwater storage of approximately 20 Mm^3/y.
- ‘Clogging’ of the Kawarau Arm lake bed to even very low values of permeability has little real effect on the available groundwater resource.

Taken together, the model scenario results tend to indicate generally positive effects of further sedimentation on the groundwater resource.

6.3 Groundwater Monitoring

State of the Environment (SOE) monitoring with quarterly measurement of level and bi-annual sampling for water quality analysis has provided less useful information to this investigation than the higher frequency level measurement record for bore F41/0171 archived by Contact Energy Ltd and obtained only recently. The lesson that might be drawn from this is that continuous or high-frequency level monitoring would be a better long-term monitoring approach than infrequent visits to privately owned bores.

Privately owned bores have also been shown to have the following drawbacks:

- Self-induced pumping interference on groundwater level monitoring.
- Insecurity of access to private bores and occasional loss of record resulting from lost access.
- Inconsistent purging requirements for the SOE water quality bores, resulting in uncertainty as to sampling error.

Optimisation of the SOE monitoring approach would use a single, centrally located monitoring bore, with continuous monitoring instrumentation, and securing ORC or private bores with guaranteed security of access and minimal interferences.

6.4 Conclusions

The following conclusions could be drawn from the results of this investigation in relation to the groundwater quantity management of the Cromwell Terrace Aquifer.

1. The Cromwell Terrace Aquifer is a set of sandy, gravel, glacial, outwash terraces with high permeability and a high degree of hydraulic communication with the encompassing lake.
2. The filling of Lake Dunstan in 1993 demonstrated a degree of hydraulic connection and added substantially to the available water resource of the Cromwell Terrace Aquifer.
3. Water budgeting and numerical modelling indicates a long-term MAR value of 2.4 million cubic metres of groundwater.
4. The hydraulic communication with Lake Dunstan allows a relatively elastic approach to setting a maximum groundwater extraction volume, due to the tendency for lake-water infiltration to balance the removal of groundwater with bores.
5. Further expected sedimentation of the Kawarau Arm of Lake Dunstan is unlikely to have an adverse effect on groundwater availability and is highly likely to have a positive impact.
6. It is suggested that tailoring with a MAV of 4 million cubic metres per annum, and with a WTRZ and provisional restriction levels in accordance with Table 11 would enhance groundwater management of the aquifer.
7. It is also suggested that a continuous monitoring bore and dedicated SOE sampling bores be established for the groundwater management of the Cromwell Terrace Aquifer in place of the current system of infrequent level measurement and using private bores.

Appendix 1 – Water Use on the Cromwell Terrace Aquifer

Surface water

1. Ripponvale Irrigation Scheme

The main irrigation scheme of the Cromwell Terrace is the Ripponvale Irrigation Scheme. The scheme comprises a pumping station drawing lake water from the Kawarau Arm, and a radiating network of water races originating at Ripponvale. The estimated irrigated area of shareholding properties is approximately 394 ha. Specific information on the actual use rates or volumes of the scheme could not be located. Power accounts over a period of time were obtained and, based on the rate of the pump, the quantity of water that has been used in the past has been estimated. In a dry year, 4.6 Mm^3/yr was used; while in a wet year, 3.2 Mm^3/yr was used.

The resource consent authorising the taking of water allows the instantaneous pumping of 0.45 m^3/s (455 l/s). The annual authorisation limit of the abstraction from Lake Dunstan is currently 4.1 Mm^3/yr, based on an application rate of 6,203 $m^3/ha/y$ and additional frost fighting. The irrigation water is applied to terrace land, primarily in the northwest of the Cromwell Terrace. As the irrigation application rate is up to 600 mm/yr, and the glacial outwash soils are permeable, irrigation results in significant drainage of soil moisture to the water table. Accordingly, the Ripponvale Irrigation Scheme represents a substantial source of recharge for the underlying aquifer.

2. NZ Nut/Muller Private Irrigation Scheme

A 25 ha nut orchard between Pearson Road and the Kawarau Arm draws its irrigation from Lake Dunstan. The total allocation of water is derived from a mining privilege (94319) and water permit (2004.284), which, when combined, would allow the instantaneous abstraction of 155 l/s. The annual allocation may equate to a total of 627,200 m^3/y. The issue of the water permit considered expansion of the irrigated area of the orchard to 80 ha. The expansion is not considered to have been implemented to date.

3. D. J. Jones Private Irrigation Scheme

The D. J. Jones Irrigation Scheme provides water for a 55 ha orchard south of SH6, at Ripponvale. The orchard of 37 ha is developed in fruit trees and irrigated by spray, with the balance in undeveloped pasture irrigated by border-dyke. The owners propose to develop this pasture area into orchard in the future as funds allow and to install spray irrigation.

Water is drawn directly from Lake Dunstan by pump and piped to two storage areas on the property, a distance of 0.75 km from the lake. From the dams, irrigation water is applied both by gravity and pump during summer. During the irrigation season, consent 2000.184 authorises the taking of 72,000 cubic metres per month, at a maximum rate of about 70 l/s. The irrigation application rate within the orchard is between 650 mm and 750 mm per season, so there is a reasonable expectation of significant soil-moisture losses to the underlying outwash aquifer in the same fashion to the neighbouring Ripponvale Irrigation Scheme.

Groundwater

1. Central Otago District Council - Cromwell

Cromwell township is serviced and reticulated by a piped water supply, stormwater network and foul sewer system. The source of the township's water is a series of bores installed on the edge of the Cromwell Terrace Aquifer within 30 m of the Cromwell Arm, near Deadmans Point. Water is collected at a chamber and treatment plant at Nepulsutra Street, and pumped to reticulation reservoirs. Cromwell's community water supply is extended to peripheral settlements at Bannockburn and Pisa Moorings. A limited rural water supply into the rural parts of the Cromwell Terrace extends from the periphery of the town system.

The Ministry of Education and CODC jointly operate a large bore at Anderson Park to irrigate playing fields and recreation areas. CODC is currently also converting the Alpha Street bore to supply untreated bore water to several council reserves arranged along Alpha Street, thus taking more load off the CODC water treatment facility.

2. Other Groundwater Extractions

The Cromwell Terrace Aquifer provides for about 20 private groundwater extractions holding resource consents, as detailed in Appendix 2. A further 40 water bores are registered within the aquifer area and are believed to operate under permitted activity rules. Domestic water, stock water and light watering of plantings are obtained from bores across the terrace. Bore water substitutes for a piped water supply network, allowing ready water supply for rural residential settlements of the terrace.

Appendix 2 – Consented Groundwater Extractions (Cromwell Terrace Aquifer)

Consent_No.	Owner	Date expires	Well No.	Instant. l/s	Daily m^3/d	Weekly m^3/wk	Monthly m^3/mth	m^3/a	Water Use
2000.161	Van der Velden Family Trust	26-May-25	F41/0253	25			14,400	138,800	Irr[2], frost
2000.337	Cromwell Saleyards Co Ltd	1/09/2035	F41/0262	2	86.4			15,811	Irr
2003.601	Benmarroc Estates Ltd	1/09/2028	F41/0312	20	864	6048	25920	64,800	Irr,frostfighting
2000.433	T/A Benmarroc Estate Ltd	1-Nov-35	F41/0245	20	824			125,248	Irr
2003.788	AJ and S Stuart Family Trust	14/10/2028	F41/0268	4.5	200			36,600	Irr
2001.102	AJ and S Stuart Family Trust	1-Apr-36		4.5				36,600	Irr
2002.218	Scott Mount Michael Trustees	27-May-27	G41/0256	7	22	154		5,120	Irr, frost fighting
2002.045	Bews G Bews J	1/03/2037	G41/0246	14.2	612			400,000	Irr, frost fighting
2006.326	Scott Base Vineyard Limited	27/05/2027	G41/0256	7	77		2100	9,100	Irr, frost fighting
2002.397	Pearson Road Society Inc	31/07/2022	F41/0361	7.8				93,628	CommDom, Irr
2002.57	JDC van Baarlen, & Others	30/09/2017	F41/0138	6.75	194.4	1360.8	6026.4	60,450	Irr
2003.657	Finlayson A A Finlayson S N	15/11/2028	F41/0316	1.5	54	378	1144	10,382	Irr
2007.411	Muller O Muller V E	31/10/2041	F41/0350	30	1400		43120	344,960	Irr
2007.626	Zyzykoff Olives Limited	1/02/2033	F41/0308	1.7	100		3083	15,400	Irr
2008.482	Briar Ridge Managemt Co Ltd	1/12/2033	G41/0354	6	502.4		15122	181,467	CommDom, Irr
2010.249	Central Otago District Council	16/08/2045	G41/0376	35	1500		46500	90,000	Irr
98037	Alpine Gold (C Otago) Ltd	20/03/2018	F41/0214	1.6	240			43,800	Bottled water
2004.641	Wallis Woods Family Trust	17-Aug-29	F41/0318	4				38,528	CommDom, Irr
	Allocated as Surface Water[3]								
RM11.057.01	Cromwell Golf Club Inc	23/03/2041	N/Reg.	32.22	1166		33075	127,267	Irr
2001.914	Mark Thomas Mitchell	31/10/2021	G41/0224	15	540	2160		43,200	Irr
98586	Central Otago District Council	1/02/2023	G41/0177	210	18000			6,570,000	PWS
								1,710,694[4]	

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[2] Irr = irrigation. CommDom = communal domestic. PWS = Public Water Supply. Water uses may be specified as dual, e.g. irrigation and frost fighting.

[3] Groundwater bores, located within 100 m, laterally, from a hydraulically connected surface water body, are allocated as if surface water.

[4] Total of 'groundwater' extraction only; bores classed as surface water for allocation are not included.

Appendix 3 – Numerical Model Calibration

Précis

A single transient calibration data set, spanning the period 1992 to 1999, was used for transient calibration. Automated parameter optimisation was used to assist the calibration process. PEST was slaved to the MODFLOW model within the Groundwater Vistas package to facilitate seamless operation of optimisation. After each optimisation model run, the fit of modelled heads was compared with that of observed groundwater levels. Optimisation runs were undertaken until diminishing levels of improvement in the model calibration indices were considered to have been reached.

Transient Calibration

Due to the relative lack of spatially distributed calibration data, and in view of the denser calibration available from the bore F41/0171, transient calibration was the primary approach used in calibrating the Cromwell model. Figure 15 illustrates the transient data set.

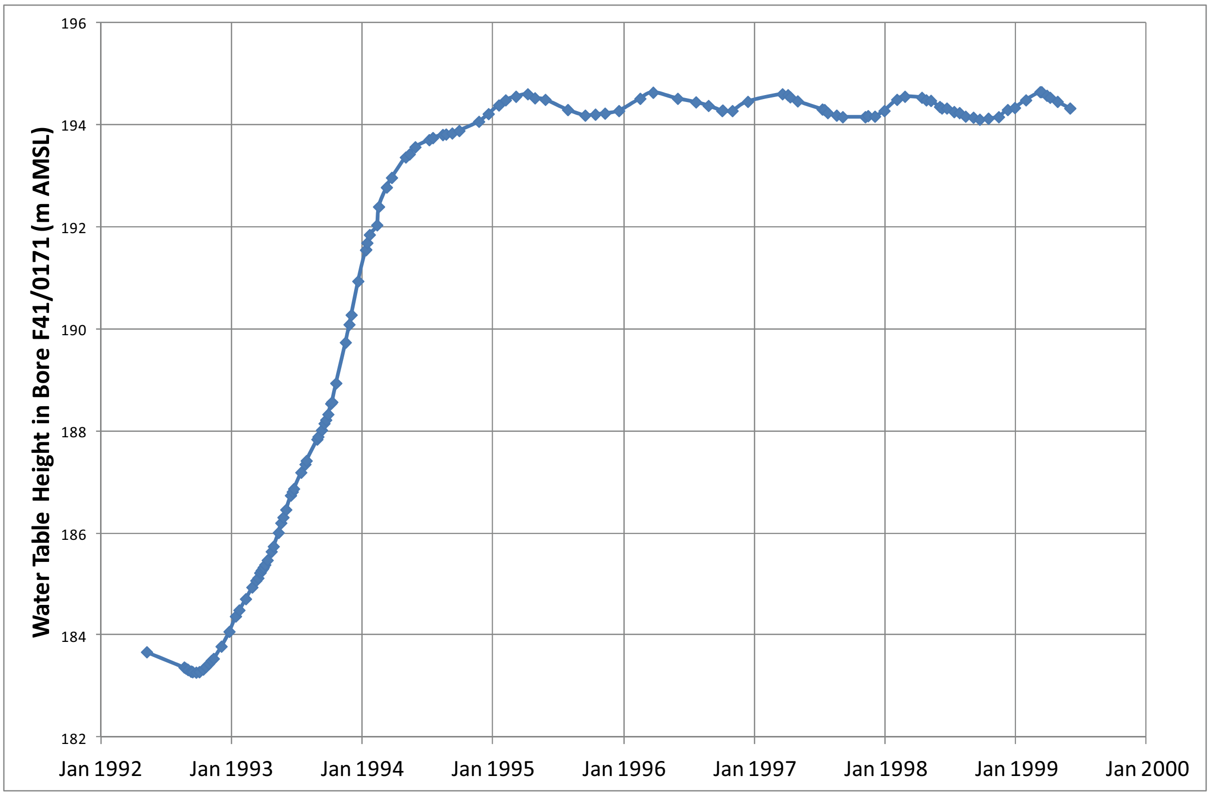


Figure 15: **Transient calibration data from bore F41/0171 encompassing the lake-filling period.**

The advantage of this data set is that it:

a) Encompasses lake-filling, which is the highest magnitude change in aquifer state in recent history.
b) Includes seasonal fluctuations following stabilisation of the water table.
c) Is sampled with sufficient frequency to highlight both of these features.
d) Is recorded in a non-pumping bore, which avoids self-induced pumping interference.

This monitoring bore was set as the principal calibration target in the numerical model.

Fixed and Variable Parameters

In the calibration process, the following model parameters were varied (i.e. the parameters were manipulated in the process of calibrating modelled observations to measured observations):

a) Hydraulic conductivity.
b) Lake bed (RIV) conductance.
c) Aquifer storage coefficients.

The following parameters were held fixed:

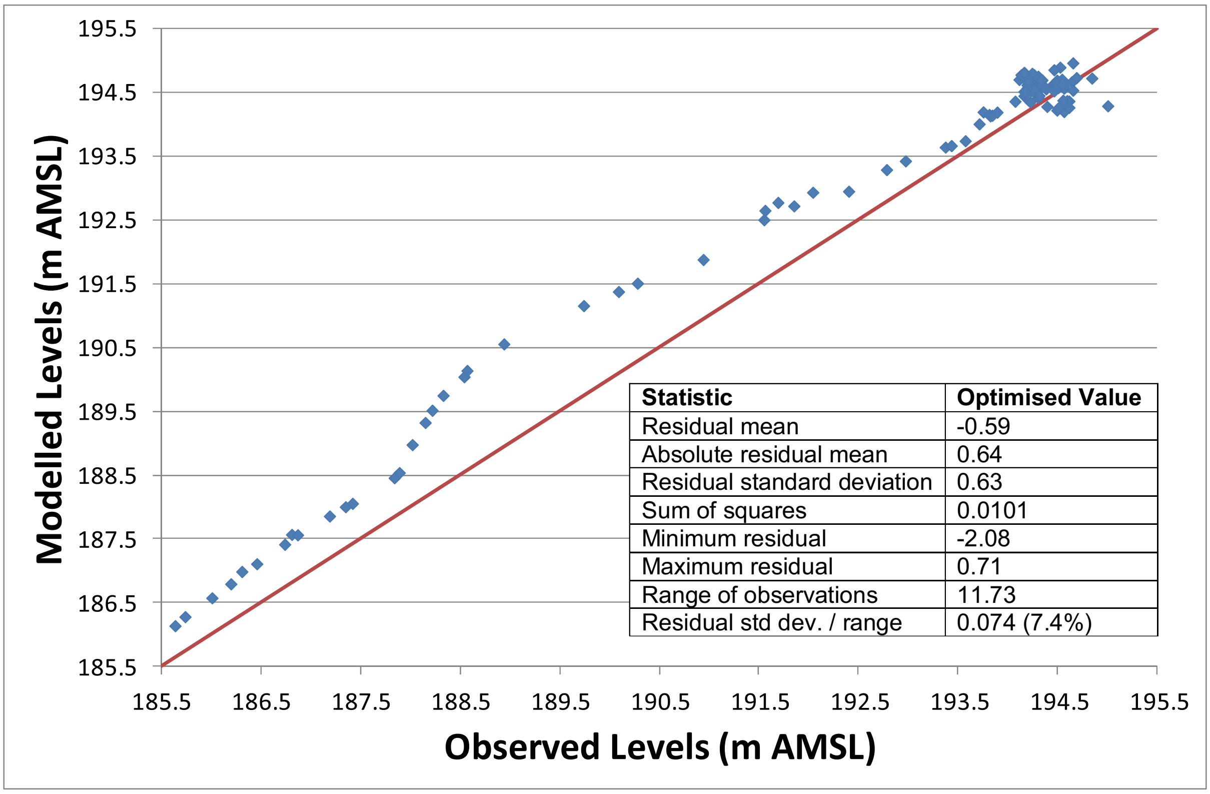
a) Aquifer geometry (tops, bottoms, position of no flow boundaries).
b) Zonation of hydraulic conductivity throughout the aquifer.
c) Position of boundaries.
d) Lake (RIV) boundary transient heads.
e) Aquifer recharge (set in recharge modelling).

Parameter Optimisation

In addition to trial-and-error calibration, automated parameter estimation was used to refine the calibration solution. The modelling package, Groundwater Vistas, integrates a parameter optimisation package (PEST). Automated running of PEST and MODFLOW within Groundwater Vistas eventually provided the best match between modelled and measured observations. The final calibration run provided the ability to compare statistically observed versus modelled water table heights.

Figure 16 shows the range of observed versus modelled groundwater levels for the entire transient modelling period. The red mid-line indicates the point of perfect match. The cross plot indicates that modelled levels are slightly higher than observed levels for the lake-filling phase of the model simulation. This pattern is clearer in Figure 17, where the offset is shown in a time series.

The statistic given in the table of Figure 17 is that of residual standard deviation divided by the range of observations (residual std. dev. / range) and has the value of 7.4%. In general, a value of 5% is considered very good.



Statistic	Optimised Value
Residual mean	-0.59
Absolute residual mean	0.64
Residual standard deviation	0.63
Sum of squares	0.0101
Minimum residual	-2.08
Maximum residual	0.71
Range of observations	11.73
Residual std dev. / range	0.074 (7.4%)

Figure 16: Cross plot of observed versus modelled groundwater levels at bore F41/0171.

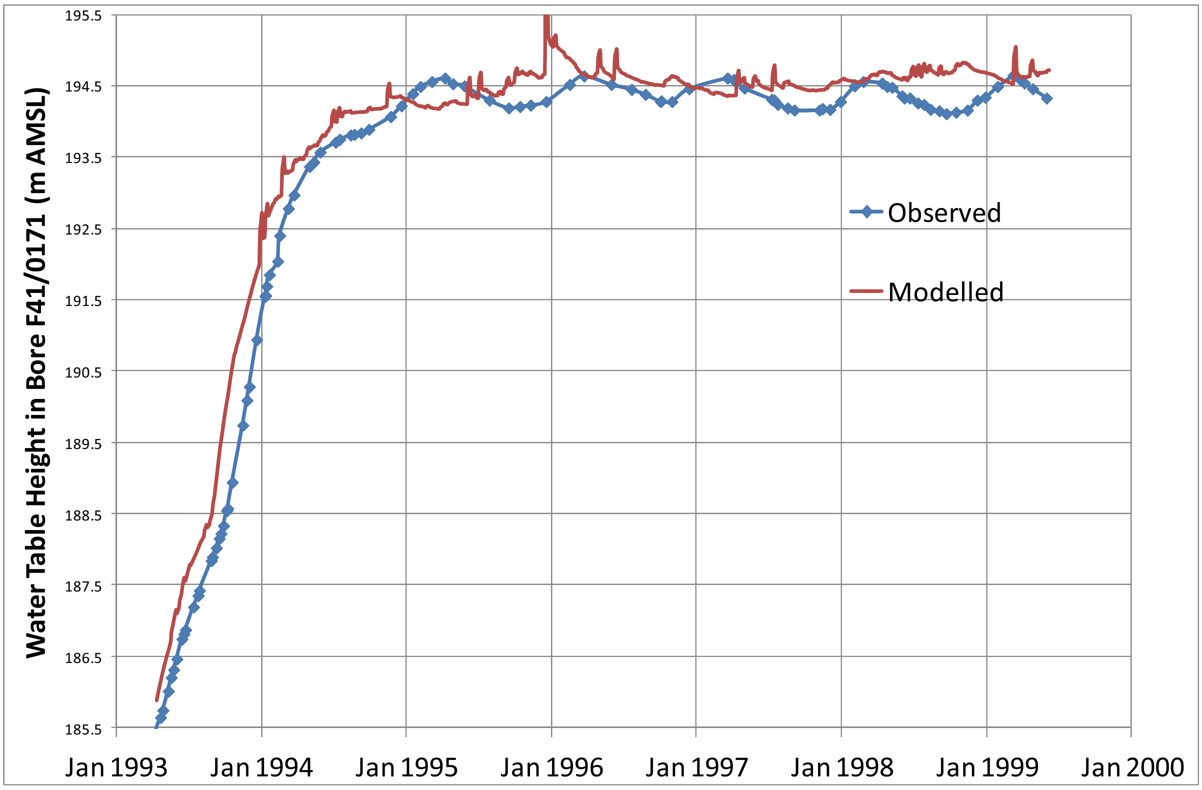


Figure 17: Comparison of observed and modelled water table heights at bore F41/0171, achieved through parameter optimisation and calibration.

Parameters Derived

During parameter optimisation, the hydraulic conductivity zones were altered to achieve the optimal model solution. The distribution and magnitude of the model's hydraulic conductivity parameters is shown in Figure 18 below. The values for the formations, implemented in the model as 'zones', are summarised in Table 12.

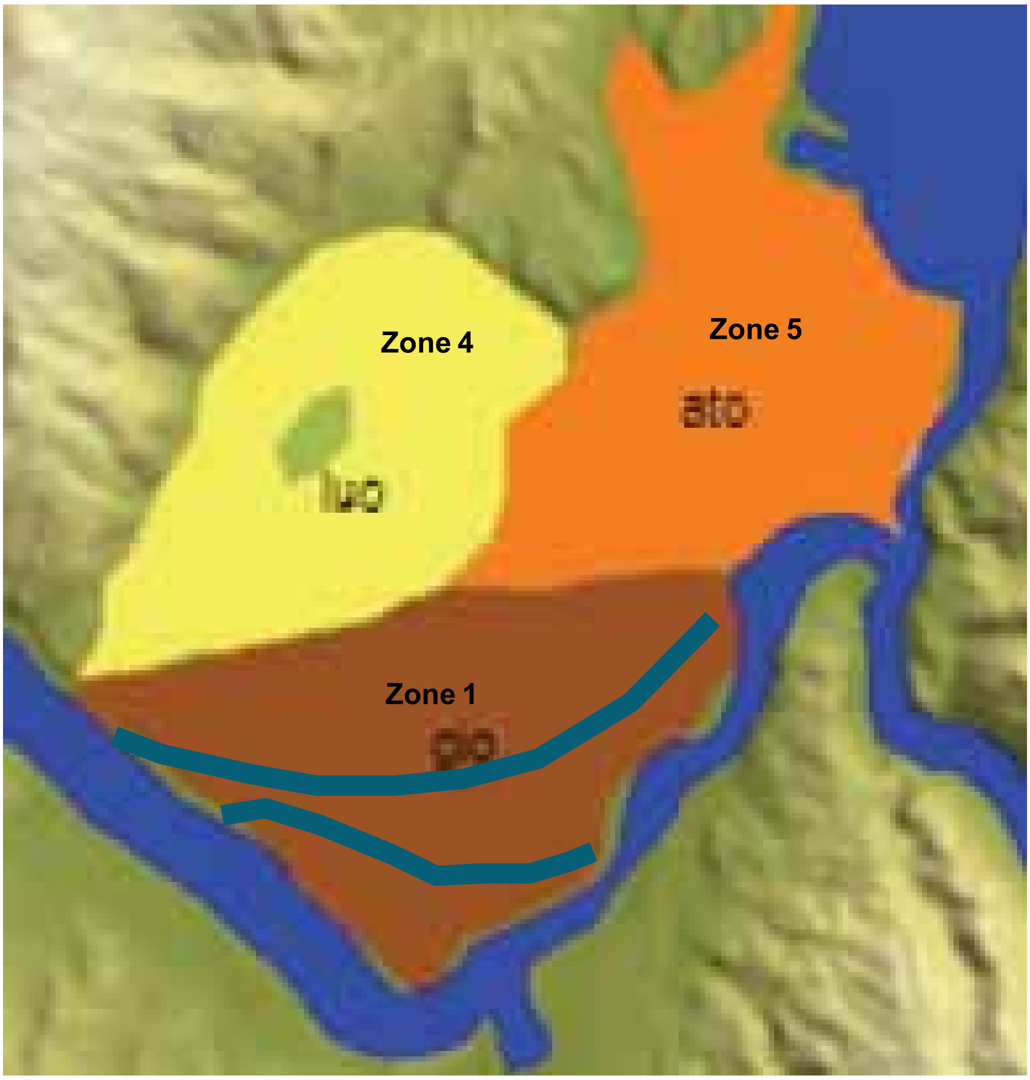


Figure 18: Distribution of hydraulic conductivity parameter zones.

Table 12: List of derived Hydraulic Conductivity parameters.

Zone #	Hydraulic Conductivity (m/d)	Description
1	92	Gibbston Outwash (gio)
2 (not shown)	2	Underlying schist regolith and Manuherikia Group sediment (bottom layer)
3	840	Kawarau paleo-channels (1 cell width strips through the model)
4	107	Luggate Outwash (luo)
5	1000	Albert Town Outwash (ato)

Appendix 4 – References

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