

Hawea Basin Groundwater Review

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Overview

Background

The Otago Regional Council (ORC) is responsible for managing the region's groundwater and surface water resources. This investigation assesses how much groundwater in the Hawea Basin can be pumped or 'allocated' for irrigation or other large uses of water that require consents. This report also studies the impact that land use intensification could have on groundwater quality.

Why is allocation of groundwater necessary?

Groundwater can be more vulnerable to over-exploitation than surface water because it can take years or decades to replenish water that is pumped by boreholes. Also, groundwater can be closely linked to surface water resources, and the pumping of an aquifer can adversely affect streams and wetlands. The setting of an allocation limit for an aquifer helps to prevent surface and groundwater resources from being over-exploited.

What this study found

The main resources in the Hawea Basin are the Hawea Flat and High Terrace aquifers. Most of the water entering the Hawea Flat Aquifer from Lake Hawea is rapidly discharged into the Hawea River. This north-west corner of the Hawea Flat Aquifer accounts for most of the groundwater flow through the aquifer. The rest of the Hawea Basin relies on rainfall and stream flow to recharge groundwater.

The flow of groundwater in the Hawea Basin is largely controlled by geology and the distance to surface water, which act as water sources and sinks. A computer model of the Hawea Basin was used to make groundwater budgets for areas with similar physical characteristics. The results indicate that plenty of groundwater is available close to Lake Hawea, although there is very little demand in this area. Conversely, further away from the lake, the potential demand for water is greater than the amount that can be safely allocated. The main limitations on groundwater pumping are considered to be the potential for boreholes to become dry if Lake Hawea falls below its operational range, and the lowering of the water table around Butterfield and Campbell's Reserve wetlands.

The quality of groundwater is excellent throughout the Hawea Basin. The computer model was also used to study the impact that more intensive land use would have on groundwater quality. The results indicate that groundwater would be only slightly impacted if the whole of Hawea Flat was covered in dairy farms. The impact is greatly reduced if farmers move from border dike irrigation to more efficient spray irrigation. Groundwater samples indicate that septic tank effluent from domestic residences may be having a greater impact on water quality than leaching from farmland.

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

This investigation has focused on two main groundwater resources: the Hawea Flat and High Terrace aquifers. The boundary between these two aquifers is the base of the escarpment next to Newcastle Road. Four peripheral aquifers have also been identified: Te Awa, Maungawera Valley, Maungawera Flat and Sandy Point.

The two main aquifers have been further divided into domains for allocation purposes. The identification of these domains is a reflection of each aquifer's access to a surface water reservoir for groundwater recharge, and therefore is an indicator of groundwater availability.

There is an increasing demand for groundwater in the southern part of the Hawea Flat Aquifer. This area does not directly receive beneficial recharge from surface water bodies. As such, the drawdown associated with groundwater pumping is greater than in areas located closer to Lake Hawea and the river. The Hawea Flat settlement also contains a large number of domestic supply bores, and public concern is growing over the availability and quality of the groundwater resource.

This study has found that most of the water entering the Hawea Flat Aquifer from Lake Hawea is rapidly discharged into the Hawea River. The north-west corner of the Hawea Flat Aquifer accounts for most of the aquifer throughflow. The rest of the aquifer relies on rainfall and tributary stream flow for replenishing storage lost through groundwater abstractions.

The Hawea Flat Aquifer typically has a relatively high permeability. However, flow within the aquifer is primarily driven by the shape of the basement and its proximity to recharge sources and discharge boundaries. A basement high, consisting of glacial silt exists at the southern end of the Hawea Flat Aquifer, in the Loach Road area. This basement high acts as a kind of dam, and forces groundwater to flow westward towards the Hawea River. The result is that the dominant direction of groundwater flow is south-west towards the Hawea River.

Only a small volume of water flows over the top of the basement high to recharge the High Terrace Aquifer. The High Terrace Aquifer receives most of its recharge from rainfall. The western part of the aquifer receives the benefit of recharge from the Hawea River. Most of the water in this aquifer is discharged via springs into the Clutha River/Mata-Au.

In this study, a numerical model was developed for the Hawea Flat and High Terrace aquifers. The optimisation of model parameters to match observed water levels, fluxes, and groundwater ages from isotopic dating are such that a high degree of confidence can be placed in the model's predictions.

The numerical model enables flows through the Hawea Flat and High Terrace aquifers to be quantified. Default, consented and recommended allocation volumes are shown in the table below. Values have also been provided for the peripheral aquifers, based on mean annual rainfall recharge calculations.

Hawea Basin aquifers potential demand, default and recommended allocation volumes

Aquifer	Irrigable area (ha)	Potential demand (Mm ³ /y)	*Default allocation (Mm ³ /y)	Consented allocation (Mm ³ /y)	Recommended allocation (Mm ³ /y)	¥Currently allocated %
Hawea Flat D1	697	4.60	15.44	1.40	4.60	30.5
Hawea Flat D2	2,079	12.77	4.08	2.69	4.08	66.0
Total:	2,776	17.37	19.52	4.09	8.68	47.1
High Terrace D1	2,515	16.36	4.07	0.41	0.41	100
High Terrace D2	818	5.43	7.30	0	1.56	0
Total:	3,332	21.79	11.37	0.41	1.97	21.0
Te Awa	245	1.557	0.297	0.051	0.297	17.1
Maungawera Valley	610	3.67	0.65	0.46	0.651	71.2
Maungawera Flat	443	2.981	0.568	0.002	0.568	0.3
Sandy Point	808	5.288	0.863	0	0.863	0

*Based on 50% of mean annual recharge volume ¥Recommended allocation consented

There is insufficient groundwater available to meet the potential irrigation demand in the two main aquifers. The shortfall will need to be sourced from the existing irrigation races or new development of adjacent water bodies. The largest consented volumes are located in areas reliant on annual-rainfall recharge for replenishment of groundwater storage. In contrast, areas where groundwater is plentiful, because it is recharged from surface water bodies, are under-utilised.

Numerical modelling has also shown that many bores at Hawea Flat have not been drilled to sufficient depth. The security of supply for many bores becomes vulnerable if lake levels fall below the operational low. Some bores may experience a drop in performance if low lake levels coincide with high groundwater demand from existing consents.

Groundwater quality is excellent throughout most of the basin. The exception is at Hawea Flat settlement, where samples show elevated nitrate-nitrogen concentrations. This effect is probably caused by septic tank leaching, although further investigations are required.

Numerical modelling of land use intensification was also carried out for the Hawea Flat and High Terrace aquifers. The results indicate that land use intensification would not significantly degrade groundwater quality if the leaching limit of 30Kg/ha/y proposed for Plan Change 6A (Water Quality) is adopted. The highest predicted nitrate-nitrogen values lie beneath areas where the soil has a low water holding capacity. These soils are located in the discharge zones of the two aquifers. This means that nitrate is not given sufficient opportunity to accumulate to values approaching the drinking water standard.

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1 Introduction

The Hawea Basin is coming under increasing pressure from land use intensification, particularly for dairy farming and its support. The basin is not entirely agricultural, but has a substantial rural-residential and rural-lifestyle population. The Hawea Flat settlement contains a large number of domestic supply bores, and public concern is growing over the availability and quality of the groundwater resource.

This report is a technical review of the current status of groundwater availability and quality in the Hawea Basin. The report mainly focuses on areas of increasing development: Hawea Flat and the high terrace located south of Newcastle Road. Rainfall-recharge estimates are also made for peripheral aquifers in the basin: Maungawera Flat, Maungawera Valley, Te Awa and Sandy Point.

A report outlining preliminary investigations at Hawea was published nearly ten years ago by Otago Regional Council (ORC) (Heller, 2003). Since then, considerable new data has become available to enable a more comprehensive assessment of groundwater in Hawea Basin.

1.1 Objectives

The Hawea Basin study was initiated with the following objectives:

- To characterise the hydrogeology of the basin
- To characterise the groundwater hydrology of the basin and its relationship with surface-water bodies
- To characterise the relationship between hydrology and groundwater quality
- To develop a conceptual model for individual aquifers
- To develop an appropriate allocation regime that considers environmental thresholds
- To determine the impact of land-use intensification on groundwater quality.

1.2 Background

The Hawea Basin extends from Lake Hawea to Luggate and is bounded by two northerly trending mountain ranges. The area lies on the fringe of the dry continental climate of Central Otago. The southern part of the study area receives about 550mm of rainfall per year. The northern part of the study area receives the benefit of rainfall along the fringes of the main divide, with about 800mm of rain falling along the shores of Lake Hawea. The hillside catchments are even wetter, and contribute valuable stream recharge to the drier valley plain.

Land use in the Hawea Basin has historically been dryland sheep farming. The Hawea water race has provided irrigation water for Hawea Flat, which instigated a move towards feed crops and mixed sheep and beef farming. The more recent dairy boom has prompted a move towards providing dairy support, and an interest in dairy farming itself.

The Hawea Basin is also a desirable area in which to live a rural lifestyle, and the residential population has continued to grow, resulting in a large number of domestic supply bores at Hawea Flat and Windmill Corner. The Lake Hawea township has recently moved to a centralised water supply.

2 Geology

2.1 Basement rocks

The basement geology of Hawea consists primarily of Haast Schist, which provides the structural framework for the basin. The basin is formed between two northerly trending fault systems: the Cardrona and Grandview faults (Turnbull, 2000). These faults have formed a 'graben' structure, whereby the ground between them has been displaced downwards, providing a pathway for erosion of the schist to preferentially occur via rivers and glaciers.

2.2 Sediments

Erosion of the schist has provided the source rocks for the sediments that fill the valley floor of the basin. Most of the erosion has been caused by glaciers during the Quaternary Period, which have formed a classic u-shaped valley and remnant lake.

McKellar (1960) identified four main glacial advances in the Hawea Basin (Table 1). Common protocol is to map Quaternary deposits according to their oxygen isotope stages, whereby odd numbers represent glacial periods, and even numbers represent interglacial periods with associated outwash gravels.

Table 1. Recognised glacial advances in the Hawea Basin

Glacial advance	Age	Glacier terminus	Outwash Stage
Hawea	16-18,000	Lake Hawea Foreshore	Q2
Mount Iron	23,000	Lake Hawea Foreshore	Q2
Albert Town	35-50,000	Newcastle Road escarpment	Q4
Luggate	70,000	Luggate - Red Bridge	Q6

The terminus of each glacial advance is shown in red in Figure 1. The thickness and type of sediment overlying the basement varies relative to the position of Quaternary glacial advances. There are four main types of sedimentary deposit found within the basin: alluvium, glacial till, alluvial outwash and proglacial lake silt.

Alluvium

Alluvium is formed by the reworking action of rivers. Alluvial deposits tend to be good sources of water because of their high permeability. Alluvial terraces are found along the margins of the Hawea River and Clutha River/Mata-Au.

Substantial alluvial fan deposits have also formed along the margins of the basin, where valleys emerge into the valley floor. The most distinctive alluvial fans are at Grandview and Hospital creeks. Groundwater in these alluvial fans tends to be fed by flow loss from the associated valley streams. Geological and hydrological information suggests that groundwater in these alluvial fans is perched above the Hawea aquifer as they overlie either schist bedrock or older lower permeability Quaternary sediments.

Glacial till

The deposits that have formed around the margins of glaciers are known as ‘moraine’, and the sediments that constitute moraine are ‘till’. Glacial till is poorly sorted and tends to be heterogeneous. Till deposits typically consist of a random mixture of rock fragments or boulders within a finer matrix of clay, silt or sand.

Glacial outwash

The streams that leave a glacier terminus tend to form outwash plains. These outwash plains form distinctive terrace surfaces in the basin. They also form most of the aquifer hosting sediments. Soils formed on these sediments are dominated by Luggate Series shallow sandy loams, which have a moderate soil moisture capacity. Soils are discussed in more detail in Appendix C.

Terraces formed by the Hawea and Albert Town advances cover most of the present day Hawea Basin. The Luggate outwash surface has been almost entirely buried by subsequent glacial outwash surfaces, although some remnants can still be seen along the valley margins near Luggate. The Mount Iron outwash surface has been completely removed by the Hawea advance.

Proglacial lake sediments

The erosive action of glaciers tends to generate large volumes of silt and clay. Silt deposits form effective barriers to groundwater flow (aquicludes) in the Hawea Basin.

During a glacial retreat, it is common for a lake (‘a proglacial lake’) to form between the glacier terminus and its terminal moraine. A good present day example of a proglacial lake is Lake Tasman, at the terminus of the Tasman Glacier.

As a glacier retreats, the proglacial lake enlarges up-valley until the terminal moraine is breached, and the lake can drain. As a result, the lake sediments tend to be thicker beside the terminal moraine. Because a lake is a low energy environment, the sediments deposited tend to consist of very fine silts and clays.

The subsurface distribution of proglacial lake sediments is fairly well known from drillers’ logs. Much of the schist basement in the Hawea Basin is overlain by glacial silts. In fact, the Clutha River/Mata-Au has carved its channel into proglacial silt that formed behind previous terminal moraines. This silt forms the river banks between the Cardrona confluence and the end of the Luggate advance, upstream of Sandy Point. The only way, therefore, that the southern Hawea aquifer can discharge into the Clutha River/Mata-Au is via springs.

Figure 1 shows a geological map of the Hawea Basin to illustrate the influence of glaciation on geology. Alluvial deposits have been omitted from the map for simplicity. Alluvial outwash deposits have also been omitted, except for the Q4 outwash alluvium, which forms an important terrace surface.

Distinctive features in Figure 1 are the structural influence of the two major fault systems and the presence of till deposits marking the edge of successive glacial advances. Other interesting features are the presence of silt along the Clutha and Hawea rivers. It is surprising that this silt has survived more recent glaciation. The Q12 or Cluden Formation silt was deposited about 450,000 years ago. The Manuherikia Group silt is much older and contains lignite measures. This silt was deposited 11-16 million years ago, when a large lake covered most of Central Otago.

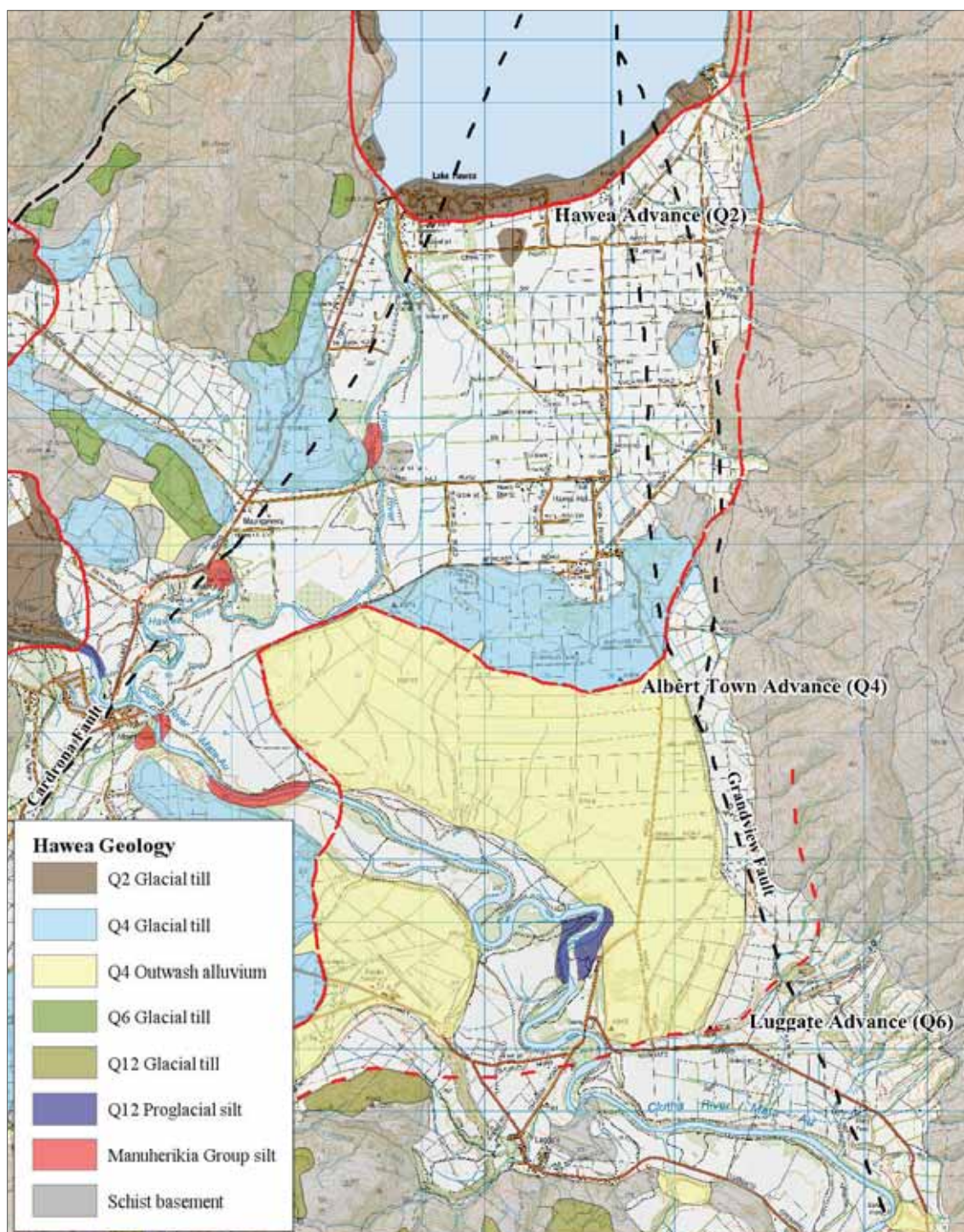


Figure 1. Simplified geological map of the Hawea Basin. The terminus for recent glacial advances is shown in red (after Turnbull, 2000).

2.3 Sediment thickness

The base of the aquifers at Hawea is marked by the appearance of silt or schist in drillers' bore logs. Because drillers normally drill until they have sufficient productive sediment to screen a bore, very few drill holes have penetrated the aquifer base. Sometimes the bore is known to have been drilled until the aquifer base is reached, but no silt or schist is recorded at the end of the borehole.

Drillers' logs indicate that the glacial outwash gravels associated with each glacial advance tend to thin southwards. At the shoreline of Lake Hawea, boreholes have been drilled and screened up to 50m depth, which puts the aquifer base below 310m elevation.

At the terminus of the Hawea glacial advance, along the eastern end of Newcastle Road, proglacial silts have been intercepted in drill holes at shallow depths (Figure 2). Bore depths tend to be 20m or less, and the water table is at about 15-20m depth. Two bore logs constrain the depth to silt in this area. G40/0133, at Loach Road, intercepts clay at 28.5m, and an abandoned exploratory bore, to the west, intercepts dry blue silt at 36m¹. This constrains the aquifer base elevation to 306m and 330m, respectively, for these two bores.

The area of shallow silt forms a basement highpoint, and creates an important hinge between the northern and southern parts of the Hawea basin hydrogeology. Beneath the Albert Town terminal moraine, to the south of Newcastle Road, the elevation of the basement becomes deeper again, at about 275m, and the thickness of the sediments is greater. There is expected to be another gentle shallowing of the basement to the south of the escarpment, which continues until the terminus of the Luggate advance is reached, downstream of Luggate (Red) Bridge.

¹ Pers. comm. Mike Simmons, McNeill drilling, Grid Ref. 1304500E 5047675N

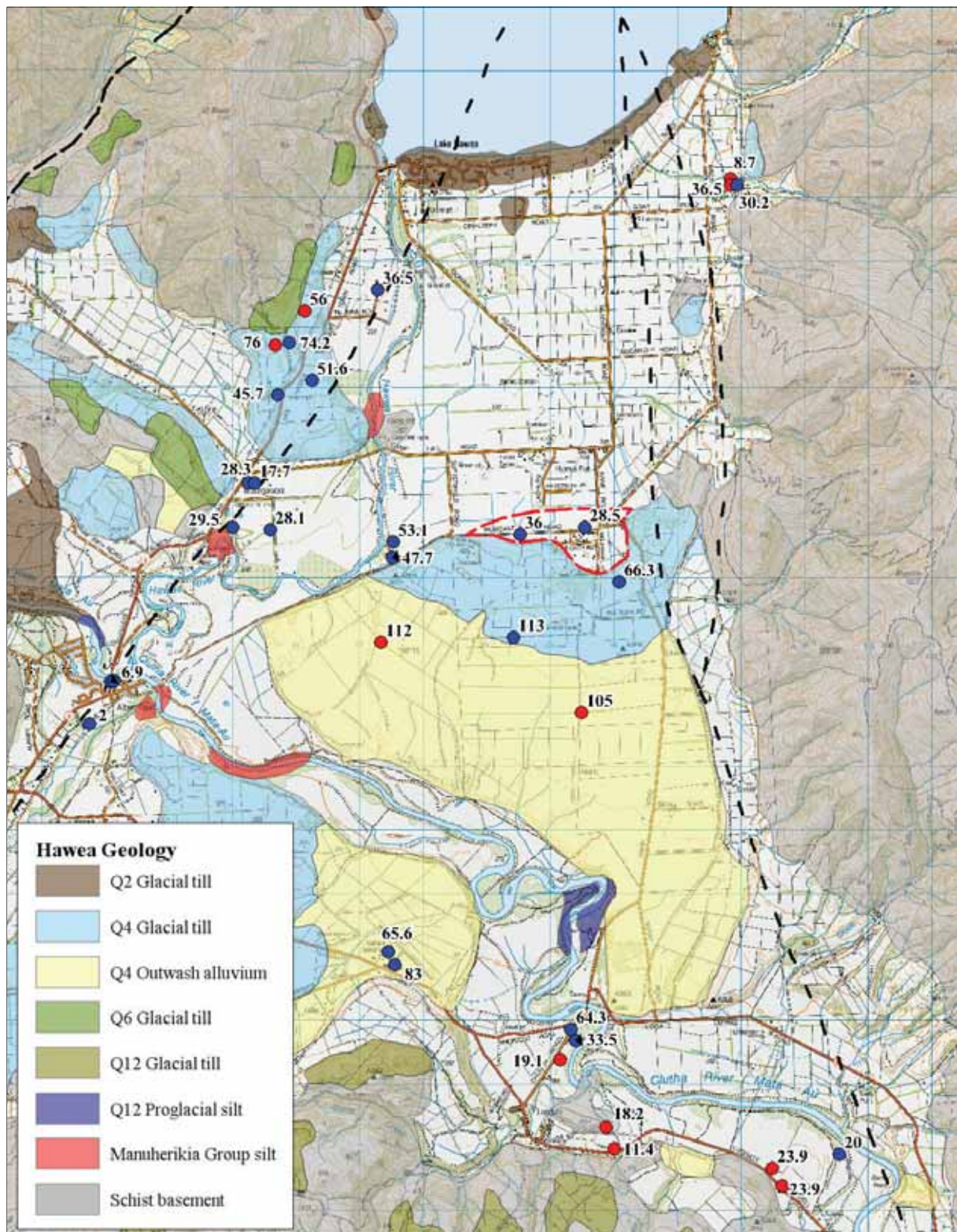


Figure 2. Simplified geological map showing drillhole intercepts of basement. Blue holes indicate silt intercepts; red holes indicate schist. The depth below ground level for each intercept is also shown in metres. The area of shallow proglacial silt at Hawea Flat is indicated in red.

3 Surface hydrology

3.1 Lake Hawea

The level of Lake Hawea follows a seasonal cycle and is regulated by Contact Energy to provide electricity supply when demand is highest. Lake levels are lowest during spring, typically in September. As flow discharge to Hawea River is controlled from then until the following winter when energy demand is at its highest, lake levels are highest during late autumn in preparation for winter. This regime is the opposite of a natural hydrological system where water levels are lowest in autumn and highest in spring.

Figure 3 shows the lake level record since measurements began in 1930. Before construction of the Hawea Dam, the median elevation of the lake surface was 327.6m. The lake level was also very stable, with an annual standard deviation of 0.5m. The level of the lake began to be artificially raised in late-1958, upon commissioning of the dam. Since stabilising at a higher level in 1960, the median lake level has been 343.7m, with a standard deviation of 3.4m. The piezometric survey for this report was undertaken when the lake level was 340.5m.

Since commissioning of the dam, the lowest level the lake has reached was 327.6m in 1977. Some domestic bores became dry at that time from the resulting drop in groundwater level. Since 1980, the operation level of the lake has typically been between 338 and 346m.

Since 2001, Contact Energy has been consented to maintain lake levels between 338 and 345.5m. Exceptions are allowed for flood management, or if the Electricity Commission deems that additional generation capacity is needed.

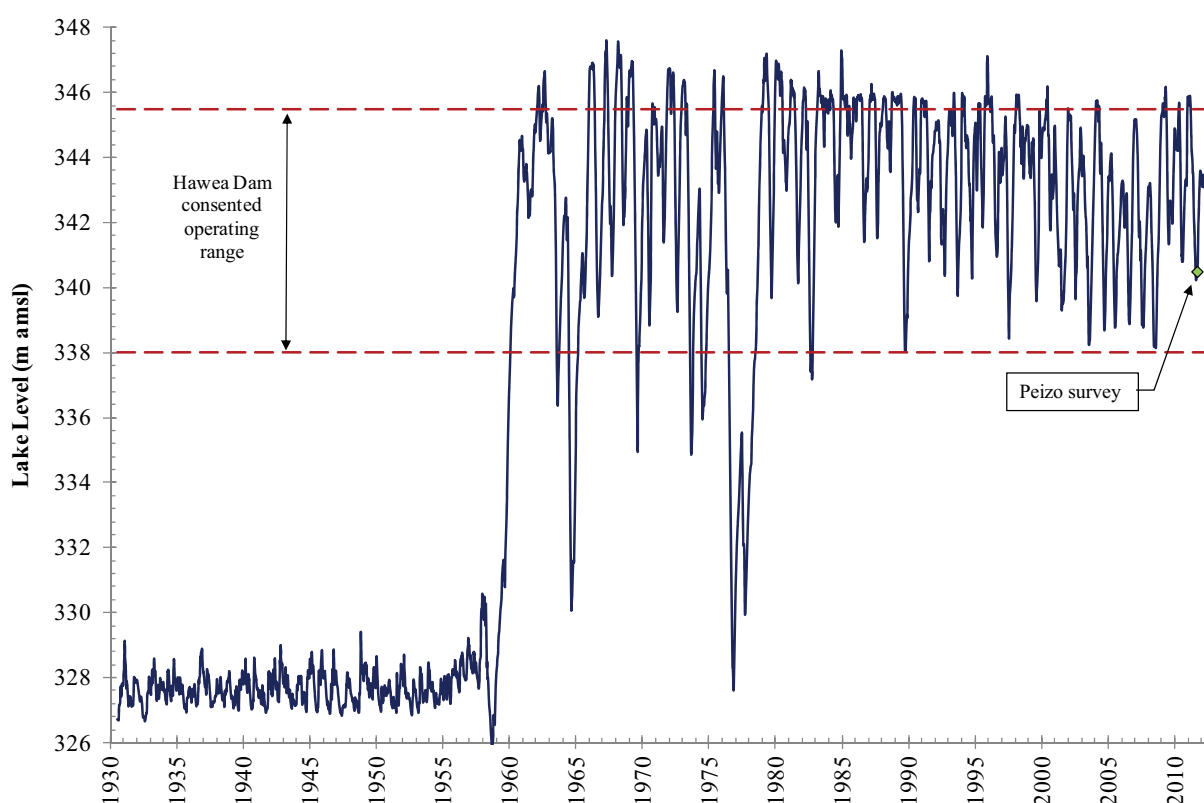


Figure 3. Lake Hawea level record since 1930

3.2 Rivers

There are two rated flow (river stage) recorders in the study area: Hawea River, at Camphill Bridge, and Clutha River/Mata-Au, downstream of the Cardrona confluence. The stage of the lake is also recorded at Hawea Dam, and Contact Energy has developed a crude flow rating curve for dam discharge.

The Hawea River, at the Camphill Road recorder, has had a mean annual low flow of 52.3 cumec since 1968. During spring, when lake levels are low, there is a flow gain of about 1.4 cumec between the dam and Camphill Road. At this time, flow in the river is held between 12 cumec and 14 cumec at Camphill Road.

The Clutha River/Mata-Au, downstream of Cardrona confluence, has a mean annual low flow of 247.7 cumec. Because the flow of the river is so large, it is difficult to gauge it manually, and any flow gains downstream to Luggate are not measurable.

3.3 Streams

A number of tributary streams provide an important groundwater recharge source in the Hawea Basin. Manual flow gaugings were carried out on some of these streams in summer 2011-2012. The measured flows were used to estimate their median flow as they cross from schist basement to valley floor sediments.

Table 2 shows the results of these gaugings, and compares them with the flow in the Lindis River, at Lindis Peak. Long-term median flow at Lindis Peak is 5 cumec, and, during the piezometric survey on 20 September 2011, it was 4.5 cumec.

Median flow for each tributary stream was derived by dividing its measured flow by the ratio of concurrent flow at Lindis Peak to the median. The resulting catchment yield can be used to verify that the estimated median flow for each catchment is reasonable. Table 2 shows a decrease in catchment yield from north to south, with Johns Creek and Grandview having a greater yield than Lindis Peak. This result agrees with the distribution of catchment yield suggested by the rainfall contours.

Table 2. Flow gauging data for tributary streams and their estimated median flows

Stream site	Easting	Northing	9-Dec-2011	11-Jan-2012	Median flow (l/s)	Catchment area (km ²)	Yield (l/s/ha)
Johns Creek	1310001	5055836	16.3	8.6	22	2.25	9.8
Grandview	1309786	5052801	64.9	41.5	98	10.23	9.6
Hospital Creek	1308890	5049178	17.3	6.5	25	3.37	7.4
Lagoon Ck north	1308238	5046706	28		36	5.11	7.0
Lagoon Creek	1308134	5046630		17.4	47	7.38	6.4
Lindis Peak	1323434	5040241	3,910	1,843	5,000	542	9.2

3.4 Springs

There are a series of springs on the true left bank of the Clutha River/Mata-Au, downstream of the Cardrona confluence. These springs are typically a diffuse zone of discharge over 7km of river length. The Clutha River/Mata-Au is entrenched within silt over this reach, which means that the Hawea aquifer will be perched, and hydraulically disconnected, from the river

in this area. Spring discharges can be seen along the river escarpment at the base of the underlying silt, and are typically 5m to 10m above the river surface.

The largest springs are found on the flats at the large bend in the river, upstream of the Fish and Game access way at 1305600 5042300². The springs on this terrace were also channelised by gold prospectors. Stream gauging on 27 September 2011 returned flow values of 10.4 l/s and 6.4 l/s for the upstream and downstream channels, respectively. There is no indication that there are any springs downstream of this location.

The total flow of the springs cannot be measured because all the other discharges are small and diffuse. As an estimate, the rate of aquifer loss is about 70 l/s per km, which is equivalent to a total spring discharge of 500 l/s from the High Terrace Aquifer to the Clutha River/Mata-Au.

3.5 Wetlands

Two wetlands have been identified within the Hawea Basin: Butterfield Wetland and Campbell's Reserve pond margins, both of which are recognised as 'Regionally Significant'.

Butterfield Wetland is an oxbow wetland that formed in an old channel of the Hawea River, downstream of Horseshoe Bend. This wetland is essentially a visible manifestation of the water table, and spring inflow can be seen at the northern end of the oxbow. The wetland is recharged by water that has left the Hawea River before Horseshoe Bend, at around 1299850 5046850. The water flows through the aquifer in a south-westward direction, before emerging as spring discharge to the wetland.

Campbell's Reserve is identified by Landcare as a 'marsh' (Ausseil, Newsome and Johnson, 2008). A marsh is a poorly drained wetland, formed within mineral soils and recharged by groundwater or surface water of slow to moderate flow. Marshes are also characterised by a large fluctuation in water table, and are often dry during summer months.

The Campbell's Reserve Wetland is considered to be a groundwater seep formed by the intersection of the water table with an old embayment in the river channel. The wetland probably receives additional recharge from runoff. The water table probably falls below the base of the wetland during summer.

3.6 Rainfall and recharge

Table 3 shows the rainfall and recharge data for the Hawea Basin. Appendix C outlines the method used to calculate recharge volumes. The results of the land surface recharge calculations indicate a mean natural recharge volume of 16.5Mm³/year. This volume increases under irrigation, since irrigation serves to retain soils closer to field capacity (FC) during drier periods. Therefore, irrigation allows rainfall events to infiltrate at times when rainfall recharge would not normally occur.

Median annual rainfall over Hawea Flat is 696 mm/year. The median annual depth of recharge is 182mm, which is 26% of rainfall. This percentage of recharge is high, compared to other parts of Otago, and is slightly greater than the Wakatipu Basin (Wilson and Lu, 2011), due to the relatively lower FC of Hawea soils.

² Grid coordinate in terms of New Zealand Transverse Mercator projection (NZTM)

The slightly drier High Terrace, south of Newcastle Road, has a median annual rainfall of 676mm/year. The median recharge rate is 170mm/year, which is 25% of rainfall.

There is considerable variation in both rainfall and recharge, with the minimum observed rainfall values being about half the maximum. Higher rainfall years, in particular, distort the annual means to values significantly higher than the median. Therefore, median values are considered to be a more accurate indication of long term rainfall and recharge in the basin.

Table 3. Rainfall and calculated recharge for each groundwater zone (mm/y)

		Hawea Flat	High Terrace	Te Awa	Maungawera Flat	Maungawera Valley	Sandy Point
Rainfall	Min	520	472	550	509	550	419
	Median	696	676	761	688	761	600
	Max	1043	991	1149	1013	1149	991
	Mean	738	677	798	721	798	620
Recharge	Min	51	69	46	83	24	32
	Median	182	170	204	208	183	125
	Max	425	396	459	458	433	395
	Mean	198	178	222	222	201	140
% Recharge	Median	26	25	27	30	24	21

3.7 Water use

The dominant source of water for irrigation comes from the Hawea Irrigation Company water race. This race has consent to take 1,850 l/s from Lake Hawea during 15 September to 30 April³, which is equivalent to 36Mm³/y. Unfortunately, ORC has no record of flow at the intake or outlet to determine actual water use.

The water race irrigates potentially 1,266 ha of land, which is about 45% of the irrigable land overlying the Hawea Flat Aquifer. The water race is fed via a siphon to a 36km canal network. Pumping is required to maintain inflow to the race when the lake falls below 140.5m.

The total volume of consented groundwater takes is considerably less than the volume of water provided by the water race. There are currently twenty groundwater take consents in the Hawea Flat Aquifer and two in the High Terrace Aquifer (Table 4), which constitutes about 20% of the potential provided by the water race consent.

Table 4. Groundwater consents in the Hawea Flat and High Terrace aquifers

Aquifer	Consents	m³/d	m³/month	m³/y
Hawea Flat Lake Domain	4	11,099	332,970	1,400,992
Hawea Flat Hillside Domain	16	17,385	521,538	2,689,042
Total:	20	28,484	854,508	4,090,034
High Terrace	2	1,201	36,030	413,883

Only two groundwater consents have water meter records: 2002.159 and 2003.076. The first has two complete years of record, which shows 67% use of the annual volume in 2008-2009 and 24% in 2009-2010. The second consent has four seasons of complete record: 2006 to 2010. Seasonal water use ranges from 16% to 31% of the annual volume.

³ Resource consent 99262

The available meter data is consistent with observations made elsewhere in Otago: about 30% of a consented volume is typically used through a season. To some degree, this consistency is due to the allocation methodology, which provides for confidence of supply 90% of the time (Aqualinc, 2006). The Aqualinc guidelines generate considerable allocation, which is only used in very dry years.

4 Aquifer hydrology

4.1 Aquifer definitions

Figure 4 shows the boundaries of distinct groundwater zones that have been identified in the Hawea Basin. Rainfall recharge volumes and allocation volumes have been calculated for each of these zones as part of this study.

The Hawea Basin consists of two main aquifers: the Hawea Flat Aquifer (3,331 ha) and the High Terrace Aquifer (4,495 ha). Additional groundwater zones have been identified on the west bank of the Hawea River, at Te Awa (267.5 ha), Maungawera Flat (511 ha) and Maungawera Valley (648 ha). The Sandy Point zone has also been delineated to extend the study area to the northern edge of the Lower Tarras allocation zone (Houlbrooke, 2010). This area has yet to be explored for groundwater potential.

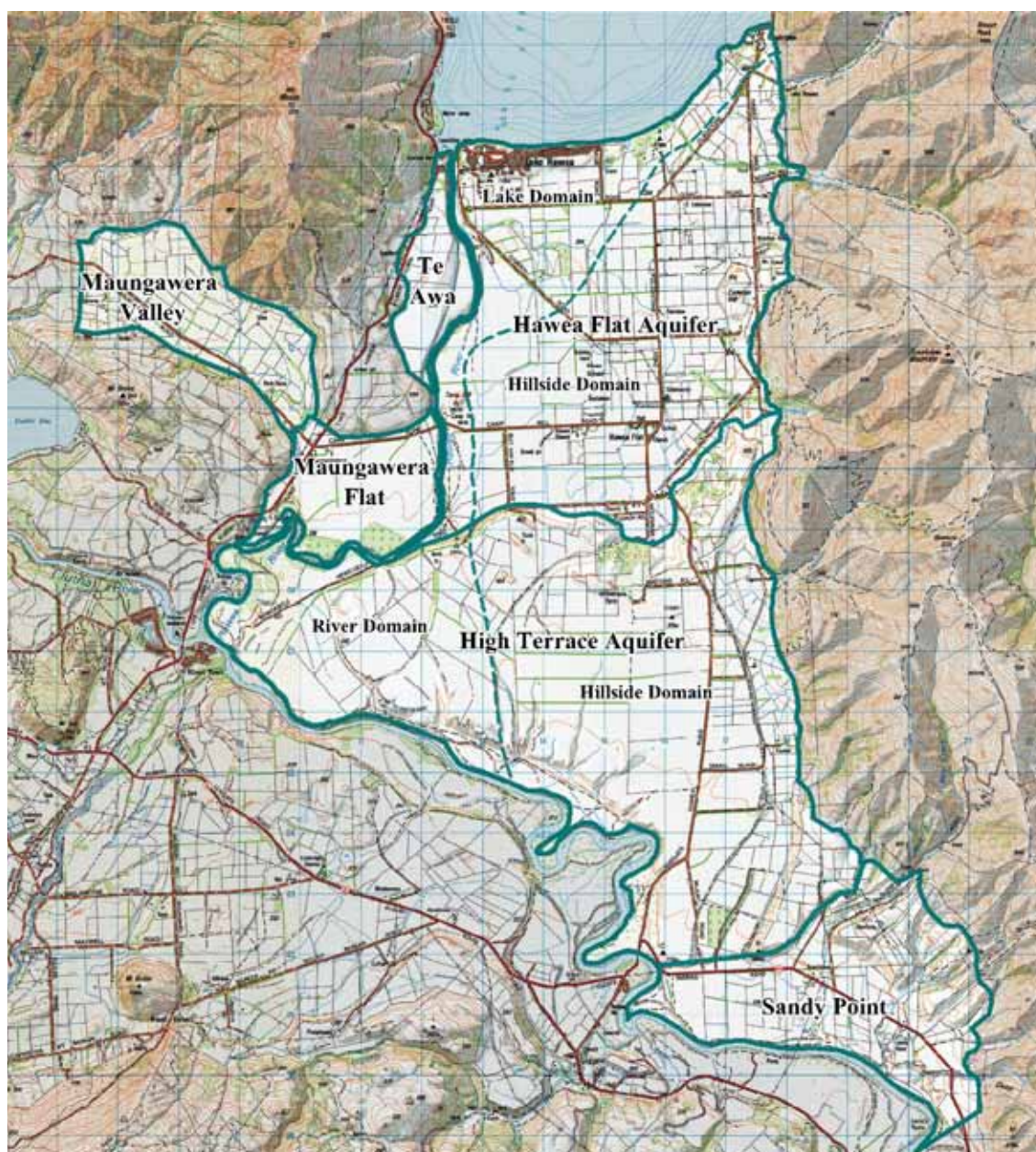


Figure 4. Map showing aquifer boundaries and sub-domains

4.1.1 Hawea Flat Aquifer

The Hawea Flat Aquifer extends from Lake Hawea to the escarpment south of Newcastle Road (Figure 4). The sediments that host the aquifer are Hawea advance glacial till and outwash alluvium.

The southern boundary of the Hawea Flat Aquifer marks the terminus of the Albert Town glacial advance. The Hawea River forms a groundwater discharge boundary to the west, and the eastern margin is marked by the contact with schist bedrock. The direction of groundwater flow is in a south-west direction across most of the aquifer.

The Hawea Flat Aquifer is separated into two domains, shown in Figure 4 and summarised in Table 5. These domains have been delineated through groundwater modelling. The separation into domains is important for recognising quite different recharge sources and flow paths within the aquifer. The impact of pumping on groundwater availability, or land use on groundwater quality, is quite different in the two domains.

Table 5. Groundwater domains within the Hawea Flat Aquifer

Hawea Flat Aquifer	Area (ha)	Area %	Main recharge source	Discharge area
Lake Domain	1,068	32	Lake Hawea	Hawea River
Hillside Domain	2,263	68	Rainfall and streams	Domain 1 and High Terrace Aquifer
Total	3,331	100		

The Lake Domain represents a groundwater recharge source that is dominated by Lake Hawea, and, to a lesser extent, the Hawea River. Pumping in this area draws more water into the aquifer from these two surface water reservoirs. The Hillside Domain represents groundwater that is recharged from rainfall and hillside streams. Pumping in the Hillside Domain does not have as ready access to surface water sources as the Lake Domain. The Hillside Domain is more reliant on long-term groundwater storage to attenuate pumping effects.

The core area of Domain 1 receives a large volume of gravity-driven recharge from Lake Hawea. This water is essentially making a shortcut from the lake through to the Hawea River, where most of the water from the aquifer is discharged.

The boundaries of the Lake Domain have been extended along the edge of Lake Hawea and the Hawea River to form a 500m buffer (Figure 4). Bores located within the 500m buffer are considered to be essentially surface water abstractions. Bores located beyond 500m are estimated to have a stream depletion effect of less than 5 l/s (85%) if pumping at 500 m³/d over a 180 day season⁴.

The surface water buffer encapsulated by the Lake Domain acknowledges the disparity between groundwater availability in the two Hawea Flat Aquifer domains. The 500m buffer is deemed more appropriate for managing stream depletion effects in the Hawea Basin than the default 100m rule specified in the Regional Plan: Water (RPW). If a river buffer were not included in the Lake Domain, an existing abstraction located beside the river would distort the allocation limit defined for the Hillside Domain.

⁴ Based on simulating stream depletion, using Hunt (2003). Aquifer properties were derived from G40/0307, resource consent RM11.352.

4.1.2 High Terrace Aquifer

The High Terrace Aquifer extends from the escarpment at Newcastle Road to the escarpment north of Tarras Road (Figure 4). This area encompasses the whole of the Albert Town (Q4) glacial outwash surface. The aquifer also includes Lagoon Valley and the alluvial terraces formed by Hawea outwash gravels to the east of the Hawea-Clutha River/Mata-Au confluence.

The High Terrace Aquifer is separated into two sub-domains, which show quite different recharge characteristics (Figure 4, Table 6). The Hillside Domain covers most of the aquifer and is primarily recharged by rainfall. The water table is located very deep, from 60 to 80m below the Albert Town outwash terrace surface. The direction of groundwater flow is primarily to the south-west, towards the Clutha River/Mata-Au.

The River Domain is mainly recharged from the Hawea River. The general direction of groundwater flow is from north to south. This domain essentially consists of water that is taking a shortcut from the Hawea River to the Clutha River/Mata-Au. Considerably more groundwater is available in the River Domain because of its proximity to river recharge.

The High Terrace Aquifer is perched above the Clutha River/Mata-Au, and discharge occurs as dispersed spring seepages along the edge of the river terrace. These seepages start just downstream of the Cardrona confluence, and can be followed along the true left bank of the Clutha to the tight Horseshoe bend, located north of Red Bridge (Figure 5).

Table 6. Groundwater domains within the High Terrace Aquifer

High Terrace Aquifer	Area (ha)	Area %	Recharge source	Discharge
Hillside Domain	3,278	73	Rainfall	Springs
River Domain	1,217	27	Hawea River	Springs
Total	4,495			

4.2 Aquifer properties

Sediments in the Hawea Basin are expected to be heterogeneous because of their glacial origins. Few aquifer tests have been carried out in the Hawea Basin to determine the range of hydraulic properties. Available test results are listed in Table 7. All the tests indicate that aquifer transmissivity is high. In fact, most of the tests have not been pumped at a sufficiently high rate to obtain an adequate drawdown response.

Table 7. Aquifer test results for Hawea Flat

Bore	Date	Pumping Rate (l/s)	Duration (mins)	Drawdown (m)	Transmissivity (m ² /d)	Storativity	Method	Comment
G40/0048	Sep-98	41	265	4.3	-		Cooper-Jacob	Poor test response
G40/0196	Feb-04	5-20	180	0.5	30,000		Eden-Hazel	Insufficient rate
G40/0266	Oct-08	25	270	1.1	-		-	Poor test response
G40/0279	May-07	16	1525	3.0	-		-	Poor test response
G40/0294	Aug-11	15-60	480	5.1	31,600		Eden-Hazel	River recharge
G40/0307	Jan-12	58.1	2880	0.2	6,000	0.01	Hunt	No screen
G40/0307	Jan-12	58.1	2880	0.3	2,000	0.001	Hunt	Piezo, 48m depth

The only aquifer test with a definitive result was performed on G40/0307, at the south-eastern corner of the Hawea Flat Aquifer (Resource Consent 11.352). This bore was pumped at 58.1l/s, with drawdown measured in two piezometers. The drawdown response showed a clear recharge effect from the Hawea River. This recharge effect was removed using the Hunt method (Hunt, 2003) to obtain an aquifer transmissivity and storativity for each piezometer. The results indicate a transmissivity range of around 2,000 to 5,000 m²/d.

Specific capacity data, as recorded on drillers' bore logs, is often used as a proxy for aquifer properties. However, the aquifer transmissivity at Hawea is so high that specific capacity is not a good indicator of permeability because the construction of the bore becomes the limiting factor on well yield rather than the permeability of the aquifer. Specific capacity values range from 14 to 3,527 m³/m/d, roughly equivalent to a transmissivity range of 30 to 1,500 m²/d. These values are lower than those obtained through proper aquifer tests, but they may be representative of values in lower permeability areas, where bore construction is not the limiting factor on well yield.

Another method of estimating aquifer properties is to observe the aquifer's response to lake fluctuations. Lake fluctuations form a pressure response in the aquifer and cause groundwater levels to rise and fall. An aquifer responds in a similar way to tidal fluctuations, but on an annual, rather than a daily, scale. The magnitude of the pressure wave is attenuated with distance from the lake, and the time it takes for the wave to affect groundwater levels increases with distance from the lake.

Two long-term monitoring bores at Hawea Flat show this attenuation in water level and time lag in response to lake fluctuations well (4.3.3). The record of these two bores has been used to estimate aquifer transmissivity and storativity from the Jacob (1950) tidal equation (Table 8).

Table 8. Application of the Jacob tidal equation to annual lake fluctuations

	Distance	Delay (days)	Transmissivity (m ² /d)	S
G40/0120	4,740	53	1,300	0.012
G40/0129	2,410	28	1,260	0.012

The Jacob tidal method has separate equations for groundwater level attenuation and time lag. Values for both transmissivity and storativity are required to solve these two equations. Seasonal water level measurements were correlated with lake level measurements to generate a continuous synthetic water level record for each bore. The 'Solver' function in Excel was used to find the best combination of transmissivity and storativity values by finding the least squares error between the synthetic water level records and equivalent values calculated by the Jacob equation.

The results of the tidal method give a bulk aquifer transmissivity of 1,300 m²/d and a storativity of 0.012. The transmissivity value seems reasonable for such a highly heterogeneous aquifer, and suggests that the aquifer test results may have been biased by preferential flow into the bore screen.

A storativity value of 0.01 was obtained using the tidal method. This value agrees with the shallow piezometer response to the aquifer test on G40/0307. Values for unconfined aquifers are typically 0.02 to 0.3. A storativity value of 0.01 is low and suggests some degree of confinement resulting from geological heterogeneity within the aquifer. Lenses of silt and

clay can create a degree of semi-confinement, and evidence in the bore logs suggests that heterogeneity is the cause for such a low storativity value.

4.3 Groundwater levels

4.3.1 Piezometric survey

A survey of the static water levels and bore collar heights at 56 sites was carried out on 21 September 2011. Bore collar heights were adjusted to elevations using the Land Information New Zealand Digital Elevation Model, based on a 10m grid. Data for the September 2011 survey are included in Appendix A. The level of Lake Hawea was 340.5m at the time.

The survey found that the depth to the water table was about 20m along Cemetery Road, and decreased to about 10m along Newcastle Road. The water table is found at greater depths near the Hawea River because the river is a discharge boundary for the Hawea Flat Aquifer.

Depth to the water table is much greater in the High Terrace Aquifer, from 75 to 100m beneath the Albert Town outwash terrace surface. The greater depth to the water table in this aquifer is a considerable hindrance to accessing groundwater in this area.

Figure 5 is a piezometric or water table map showing the contoured results of the survey. Water levels are plotted as elevation above mean sea level to track the direction of groundwater flow in relation to sources and sinks.

A piezometric map is read in similar way to a topographical map, with the contours representing lines of equal elevation. Groundwater flow is perpendicular to the contours, in a down-gradient direction. A narrow gap between contours indicates a steep gradient, whereas a wide space between contours indicates a very flat water table with little groundwater flow.

Recharge sources can readily be inferred on the piezometric map as being Lake Hawea, the lower Hawea River and tributary streams along the eastern ranges. Sinks or discharge points are the upper Hawea River and springs along the Clutha River/Mata-Au.

What is immediately apparent in Figure 5 is the rapid flow of water from Lake Hawea to the Hawea River. All recharge from the lake is discharged to the river upstream of Camp Hill. The rest of the aquifer either receives its recharge from tributary streams on the eastern range or from rainfall recharge. The steep hydraulic gradient along the eastern foothills suggests that groundwater in this area may be perched above the Hawea Flat Aquifer.

The Hawea Flat aquifer discharges the majority of its water into the Hawea River, which causes a prevailing easterly to south-easterly groundwater flow direction across the Hawea Basin.

The western part of the High Terrace Aquifer is being recharged from the Hawea River. This water travels southwards where it is discharged to the Clutha River/Mata-Au. The eastern part of the High Terrace Aquifer receives relatively little recharge. Groundwater flow is in a south-westerly direction towards the Clutha River/Mata-Au, where it is discharged as springs.

The shallow proglacial silt deposit in the Loach Road area has a marked effect on groundwater flow. Groundwater flow, to the north of the silt, is in a westerly direction. Across the silt deposit, the flow direction changes to the south. This suggests that the silt is

acting as a barrier to groundwater flow, causing the groundwater to be preferentially squeezed towards the Hawea River, rather than southwards.

The silt deposit acts as a kind of dam for the Hawea Flat Aquifer, maintaining the water table at a higher level than it would otherwise rest. The hydraulic gradient of the aquifer is very slight in the Hawea Flat area. This means that there is very little flow within the aquifer, resulting in a long residence time for groundwater.

4.3.2 *Aquifer saturated thickness*

Table 9 shows the saturated aquifer thickness at bores where the aquifer base depths are known. The saturated thickness is probably about 30-40m for most of the Hawea Flat Aquifer, although there is evidence of thinning towards the eastern ranges.

At the southern end of the aquifer, the saturated thickness is likely to be about 15m. The area is underlain by a shallow occurrence of proglacial silt, which forms a basement high at Loach Road. This silt was intercepted at 28.5m depth in bore G40/0133 and further west in an exploratory bore, where blue silt was found at 29.9m depth (Table 9). One bore has been completed in silt at 18.3m depth (G40/0132), which suggests a saturated thickness of 3.2m. However, a number of neighbouring bores have been drilled more deeply, suggesting that this bore could have intercepted gravels at a greater depth if drilling had persisted.

The High Terrace aquifer has a saturated thickness of about 36m along the northern escarpment. An exploratory bore drilled 1.5km to the south of Watkins Road (G40/0305) was dry, indicating that aquifer saturation thins rapidly to the south. Less saturation is also expected towards the Clutha River/Mata-Au because of aquifer discharge to springs.

Static water levels at Maungawera Flat show a saturated thickness of 5-10m. Similar values are found in bores located on the Q4 moraine hill, to the north, although the depth to the water table is over 40m in this area.

Table 9. Observations of aquifer saturated thickness, estimated values are italicised

Name	Aquifer	Aquifer base depth (m)	Water depth (m)	Saturated thickness (m)
Exploration	Hawea Flat	36.0	<i>17.3</i>	<i>18.7</i>
G40/0013		30.2	18.0	12.2
G40/0133		28.5	<i>12.8</i>	<i>15.8</i>
G40/0226		53.1	20.1	32.9
G40/0294		47.7	17.8	29.9
G40/0279	High Terrace	66.3	29.7	36.6
G40/0295		113	96.2	16.8
G40/0296		112	75.8	36.2
G40/0004	Maungawera Flat	28.3	22.2	6.1
G40/0182		29.5	23.8	5.7
G40/0274		28.1	22.7	5.4
G40/0198	Te Awa	36.5	21.8	14.7

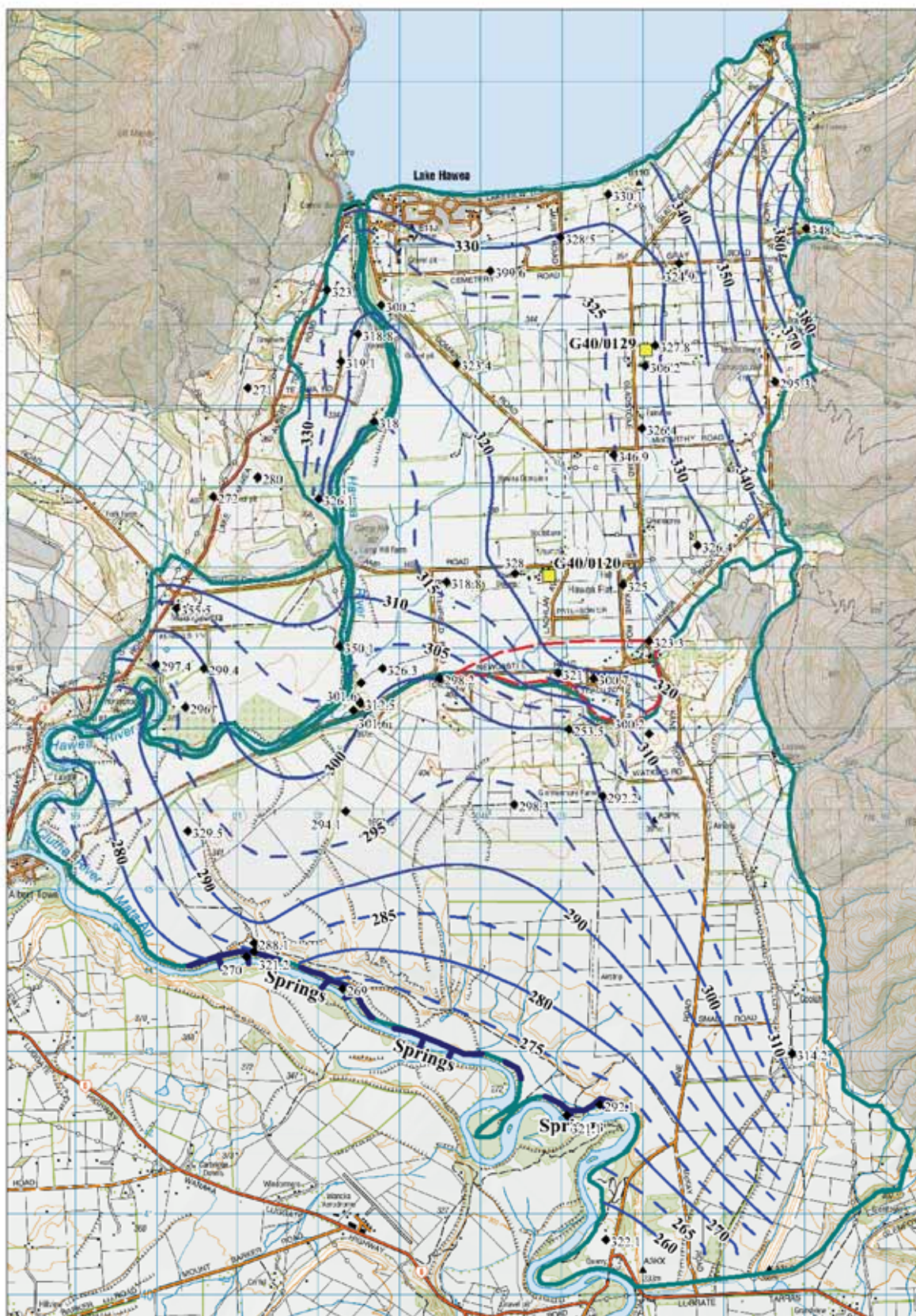


Figure 5. Piezometric survey of September 2011, showing measuring points with water level elevation. Long-term monitoring bores are shown in yellow. The zone of spring discharges and area of shallow silt are also shown.

4.3.3 Trends in groundwater level

Groundwater levels are monitored on a seasonal basis at G40/0120 and G40/0129, situated 4.7 and 2.4 km from the lake, respectively. Figure 5 shows the location of these two bores, both of which are in the Hawea Flat Aquifer. Figure 6 shows the results of seasonal water level monitoring at these bores. No long-term upward or downward trend in water levels is discernible.

Water levels in the two monitoring bores clearly respond to fluctuations in the level of Lake Hawea, due to the transference of pressure across the aquifer when the level of the lake rises and falls. There is a time lag between a rise in the lake and a corresponding rise in groundwater level at each site. This lag is a function of the aquifer properties and is about 30 days at G40/0129 and 55 days at G40/0120.

It is important to note that groundwater fluctuations in the two monitoring bores are a pressure response, and not the direct result of recharge from the lake. Lake inflow is discharged into the Hawea River within the Lake Domain of the Hawea Flat Aquifer, and this water does not reach either of the monitoring bores. Both bores receive their recharge from local rainfall and stream recharge.

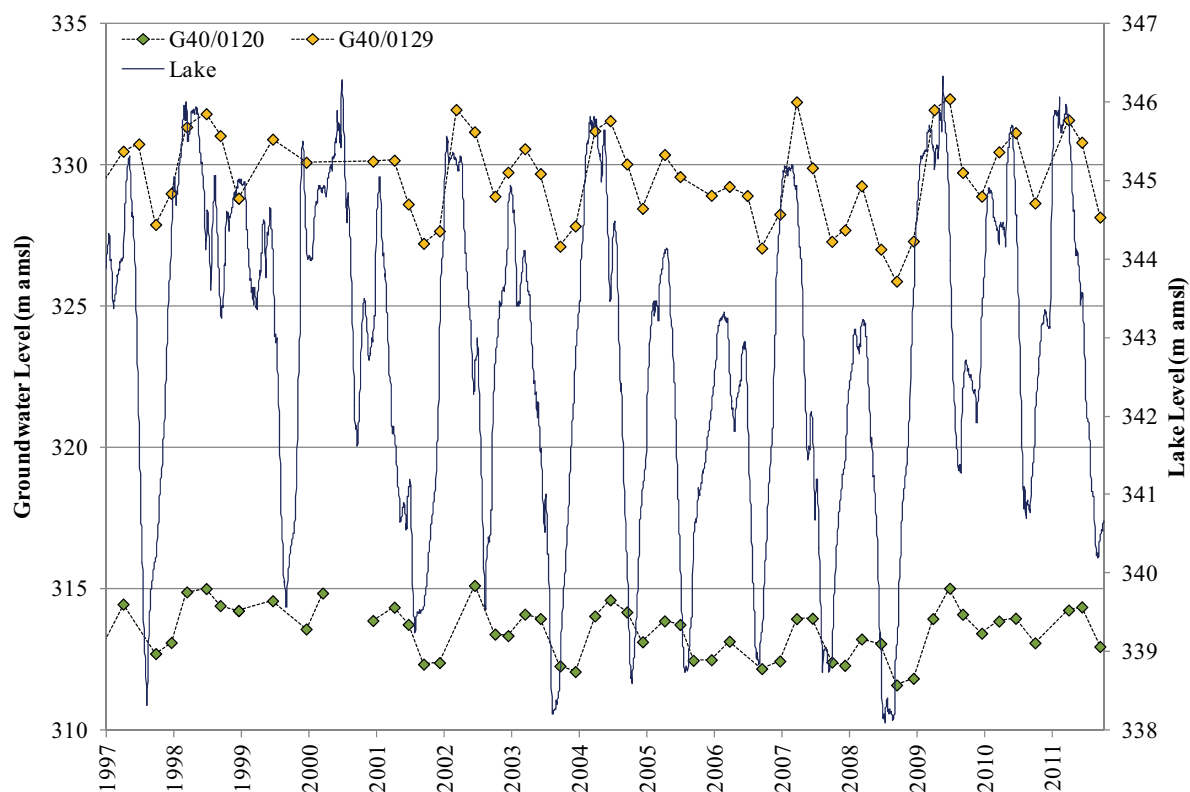


Figure 6. Water levels at the two long-term monitoring bores and Lake Hawea

5 Isotope data

Four sites within the Hawea Basin have been sampled for a suite of isotopes. Isotope tracers, particularly tritium, give an estimate of the mean residence time of the aquifer. The Hawea samples were analysed by Rob Van der Raaij, at Geological and Nuclear Sciences (GNS). The result for each site agrees with the age predicted by the numerical groundwater model, using the MODPATH particle tracking tool.

Unstable isotopes, such as tritium, change their atomic structure through time, via radioactive decay. The rate of this decay has been well documented for different isotopes, enabling the residence time for water containing an unstable isotope to be determined. Tritium is a radioactive form of hydrogen, and has one proton and two neutrons, unlike the common form of hydrogen, which has one proton and no neutrons. The decay of tritium to helium-3 has a half-life of 12.3 years.

Tritium is naturally produced in the atmosphere by cosmic rays. However, since 1945, the testing of nuclear weapons has released large amounts into the atmosphere. Concentrations peaked in 1965, due to the intensity of testing carried out in the early 1960s, but they are now close to background levels. Tritium is an ideal groundwater tracer because it is a component of the water molecule, and so its decay clock begins upon recharge into the aquifer.

Two National Groundwater Monitoring Program (NGMP) sites at Hawea were sampled twice for tritium dating. The results of repeat sampling concur with those obtained from initial samples. The groundwater mean residence times (MRT) are 49 years for G40/0129 and 51 for G40/0120.

The two NGMP bores are located along the eastern edge of the Hawea Flat aquifer in an area where the water table has a low hydraulic gradient. The MRT of both bores are similar, which suggests that groundwater at the bores is recharged by rainfall or tributary stream runoff rather than inflow from Lake Hawea. This assumption is supported by the piezometric survey, which shows that groundwater at the two bores is recharged from the hills to the east.

Two groundwater springs discharging into the Clutha/Mata-Au were also sampled and analysed for unstable isotope concentrations. The spring to the west is located due south of the Hawea River, at Camp Hill. Water leaves the river at the Newcastle Road bend and migrates through the aquifer to springs in this area. Its proximity to an abundant recharge source gives this bore the youngest MRT of 11 years.

The eastern-most spring discharges onto flats at the big bend north of Red Bridge. Tritium data suggested a possibility of two mean residence age ranges: 16-37 and 57-63 years. The presence of CFCs and SF₆ in this bore would suggest that the younger age is more likely. The concentrations of these gas tracers in the atmosphere were close to zero within the older time range: 1949 to 1955. However, gas tracers may become enriched within the unsaturated zone, which gives a younger age estimate for the sample. The mean residence time predicted by MODPATH is 27 years, which confirms that the younger age is more likely.

6 Water quality

6.1 Introduction

Groundwater quality at Hawea Flat is among the most pure in Otago. This is due to a combination of factors, including good quality recharge sources and low amounts of organic matter within the aquifer. These factors create a highly oxidised aquifer environment.

The only discernible impact of land-use on the Hawea Flat Aquifer is contamination from septic tanks in the Hawea Flat and Windmill Corner residential areas. Evidence of a slight impact from fertiliser application along the eastern margin of the Hawea Basin has also been found.

Trace elements, such as arsenic, boron, bromide, iron and manganese, tend to be found in very low concentrations at Hawea. Values for these analytes are normally below or close to the detection limit of the laboratory. While some of these trace elements are of important health significance, they were not included in this study as their observed concentrations were so low.

6.2 Sample sources

Appendix B contains the water quality data used in this study. Most of the sample sites are private bores. More confidence can be placed in sites sampled by ORC, as a standard sampling protocol is observed when taking the sample. ORC samples have been taken in two main sampling periods: 1996-1998 and 2012.

ORC also carries out long-term monitoring for the NGMP at two sites: G40/0120, at Camp Hill Road, and G40/0129, at Gladstone Road.

ORC samples include a full suite of major elements, allowing an ion balance to be carried out as a check on the quality of the sample. Ideally, a sampled cation/anion ratio should balance to within $\pm 5\%$. Significant errors suggest that the sample was not stable at the time of analysis, which is usually the result of poor sample collection or storage.

Unfortunately, sites sampled privately have been analysed according to a standard list of parameters of health significance. Many of these parameters are useful for surface water assessment, but are of little relevance to groundwater quality. Important analytes, such as sodium and potassium, which are good tracers of sewerage contamination, have been omitted from the standard list. As an ion balance could not be carried out, it was not possible to assess the overall quality of these samples. Analyses of samples taken privately should be treated with caution, particularly with regard to more mobile analytes such as alkalinity.

6.3 Major ion composition

The best way to classify groundwater and illustrate its evolution is on a Piper diagram, which plots the percentage constituent of the major ions onto two trilinear diagrams: one each for cations and one for anions. The samples are then projected from these trilinear diagrams onto a diamond-shaped field for classification.

Figure 7 shows major ion compositions for sites sampled by ORC. Hawea groundwater composition plots on the left-hand side of the diamond-shaped field on the Piper diagram.

This water is calcium-bicarbonate type, which is characteristic of immature, freshly recharged groundwater.

Chloride concentrations are very low because of the distance to the coast. The sea is ultimately the main origin of water for precipitation and the main natural source of chloride. Chloride can be a useful indicator of trends in groundwater quality because it increases with land-use intensification and sometimes with groundwater abstraction. The long-term monitoring record for the two NGMP sites shows that chloride concentrations are stable.

The anion trilinear diagram shows a slight variation in groundwater composition, with no evidence of chemical evolution. Samples along the eastern side of the valley are enriched in sulphate, having concentrations greater than 7 mg/l. Fertiliser is a common source of sulphate; however, nutrient concentrations at these sites are low. These bores are located close to schist bedrock and are likely to be receiving additional sulphur, localised through the oxidation of pyrite. Localised areas of higher sulphate have also identified in the Wanaka and Wakatipu basins (Rosen *et al.*, 1997).

The cation trilinear diagram shows a subtle trend of ion exchange between calcium and sodium, which is a common groundwater trend, caused by cation exchange between sodium held in clay minerals and dissolved calcium. The result is a relative increase in dissolved sodium as groundwater residence time increases.

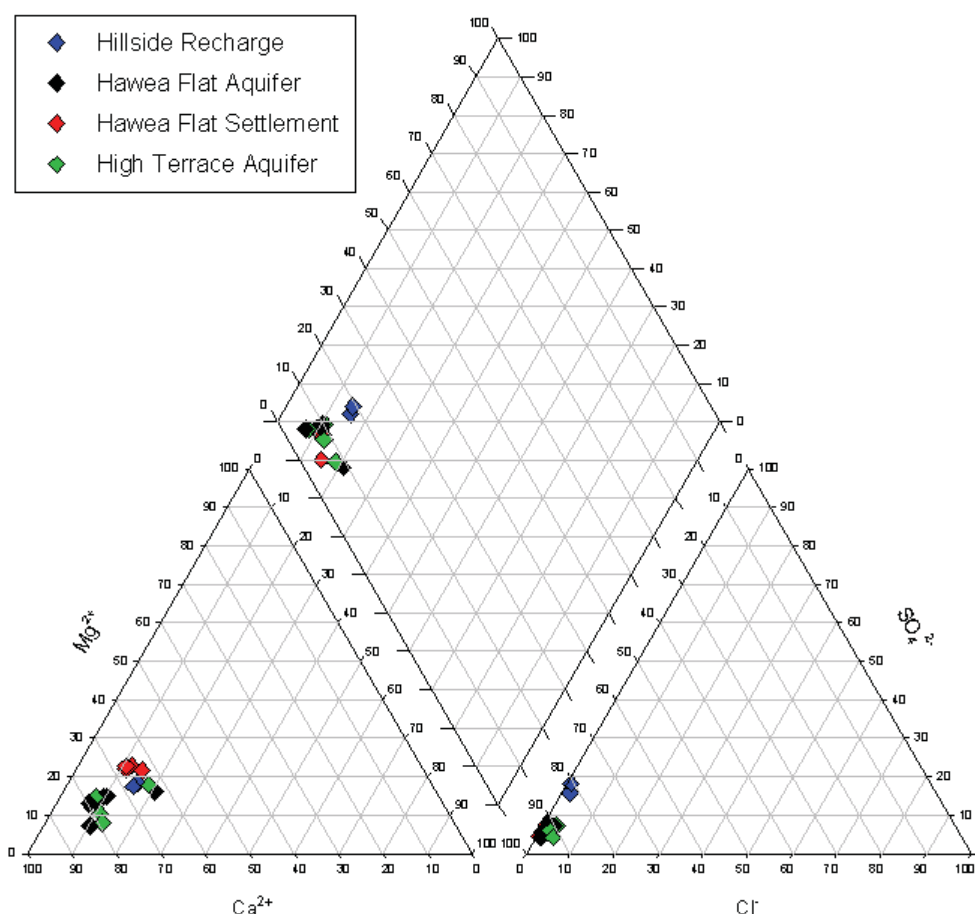


Figure 7. Piper diagram of major element chemistry

The Piper diagram also shows three subtle water sources of increasing magnesium composition. Most samples lie on a calcium-sodium cation exchange trend, with a starting composition of about 15% magnesium. River-sourced water has a relatively low proportion

of magnesium, below 10%. The Hawea Flat settlement has a relatively high proportion, over 20%, which causes a departure from the cation exchange trend, followed by the rest of the aquifer. These samples are also high in nitrate, which means that groundwater in this area is probably contaminated by septic tank effluent.

Calcium and bicarbonate constitute around 80% of the ion balance. Samples from the Wanaka and Wakatipu basins show a 1:1 equivalent ratio for Ca^{2+} and HCO_3^- , which is the result of calcite dissolution (Rosen *et al.*, 1997). Figure 8 shows that most of the samples at Hawea also follow the calcite dissolution trend. However, there are some samples that are relatively depleted in calcium, probably due to an ion exchange between calcium and sodium as the groundwater interacts with clay minerals.

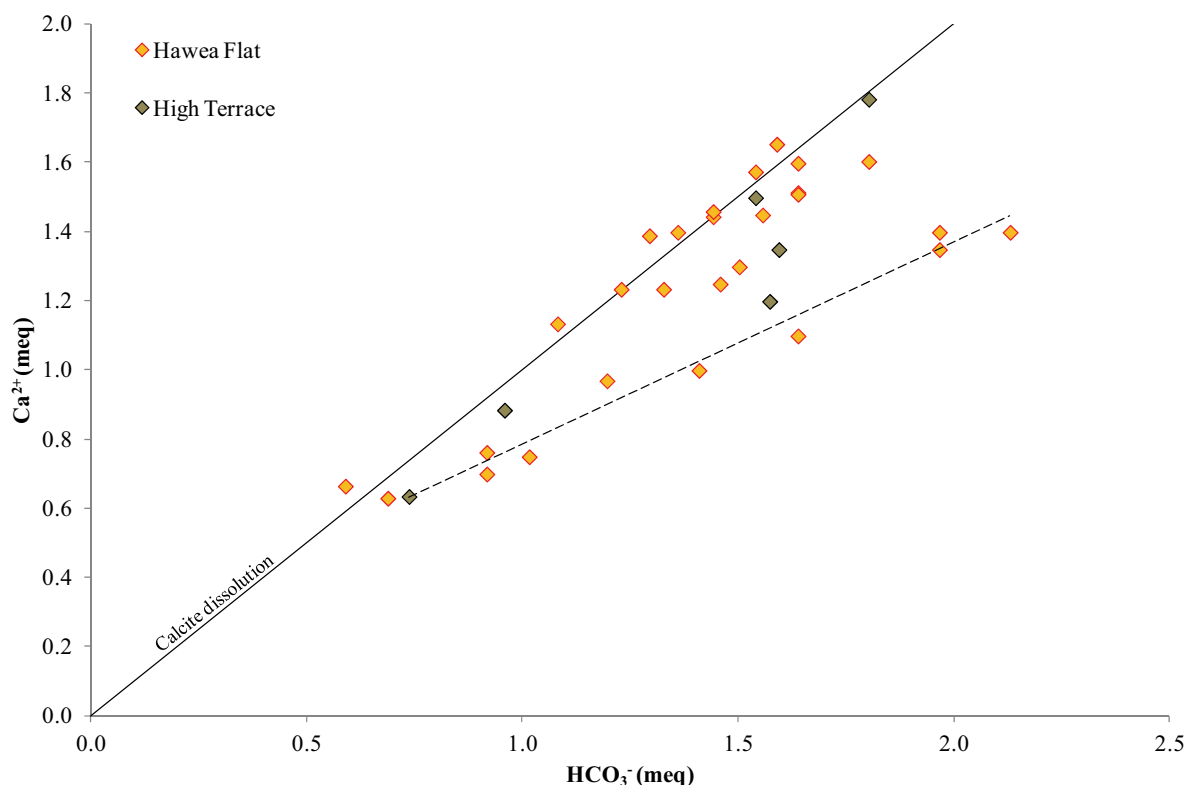


Figure 8. Molar equivalent concentrations of Ca^{2+} and HCO_3^-

6.4 Electrical conductivity and pH

The concentration of total dissolved solids is indicated by the electrical conductivity (EC) of water. Measured EC values in the Hawea Basin range from 7 to 25 mS/m. These values are relatively low, which reflects the overall pristine quality of the groundwater. Figure 9 shows that EC is greater in areas where rainfall recharge is dominant: the south-eastern Hawea Flat Aquifer and the eastern High Terrace Aquifer. There is also a localised cluster of EC values above 20 mS/m in the Hawea Flat community area, which probably comes from septic tank contamination.

A sample from G40/0293 at Lagoon Valley also has an elevated EC value. This bore is probably the most evolved and reduced of all the samples, having elevated chloride, iron and manganese. This indicates that the bore is located in an area that receives relatively little recharge. By comparison, a low EC value is seen on the lower terrace beside Red Bridge, which suggests a local, young water source for this bore. This result suggests that there may be interaction between the aquifer and the Clutha River/Mata-Au in this area.

Values of pH show a wide range, from 6.9 to 8.5, with a median of 7.6. There does not appear to be any clear pattern to the distribution of pH, which is probably being controlled by the localised variation of mineralogy within the host sediments.

One conclusion that can be drawn from the pH data is that a few of the samples represent very young groundwater. Rainfall typically has a pH value of less than 6. Accordingly, freshly recharged, oxidised water tends to have a similarly low pH value. Values of pH greater than 7, in the absence of organic matter, indicate a considerable degree of interaction with the host sediments. The pH values observed at Hawea suggest a residence time of years, rather than weeks or months.

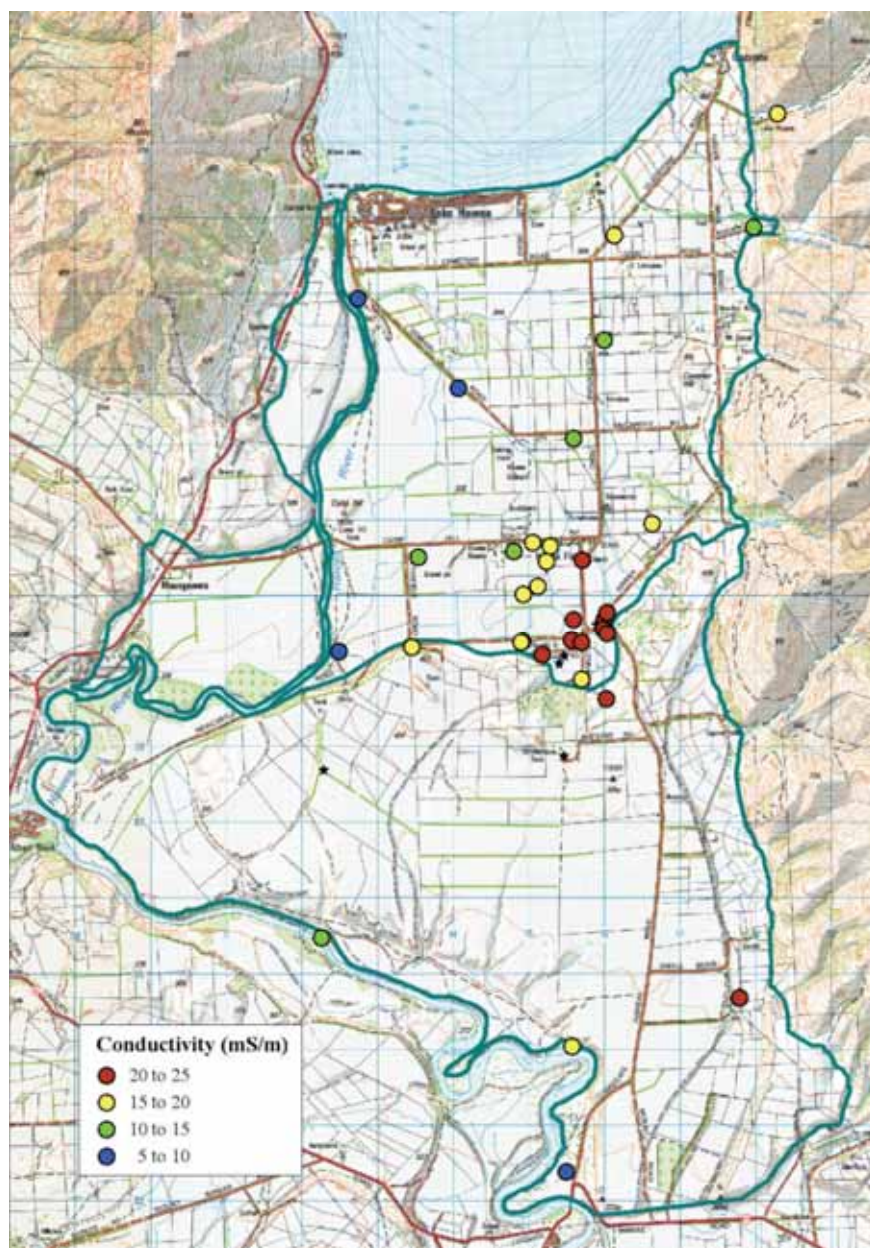


Figure 9. Map of electrical conductivity of groundwater samples

6.5 Nutrients

Water quality parameters suggesting land-use impacts on groundwater quality are nitrate-nitrogen and the bacteria *Escherichia coli* (*E.coli*). Of the samples taken, only one returned a positive result for *E.coli*: bore G40/0250, located down-gradient from Hospital Creek. The

reason for low *E.coli* counts is the large depth to the water table in the Hawea Basin. The unsaturated zone is typically 20m or greater for most of the area, which acts as an effective filter for micro-organisms.

6.5.1 Nitrate

Nitrate-nitrogen concentrations in New Zealand are rarely above 1 mg/l in natural groundwater water (Close *et al.*, 2001). Figure 10 shows the distribution of Nitrate-N concentrations across the Hawea Basin.



Figure 10. Map of nitrate-N concentrations in groundwater samples

Most of the area shows few signs of land-use impact, with concentrations being below 1 mg/l. However, there are two exceptions: the south-eastern corner of the Hawea Flat Aquifer and along the eastern edge of the High Terrace Aquifer. No samples exceeded the drinking water standard of 11.3 mg/l Nitrate-N.

Nitrate-N values of 1 to 2 mg/l probably indicate the impact of farming activities on water quality, particularly fertiliser use, which explains the elevated nitrate-N concentrations along

the eastern margin of the High Terrace Aquifer. Nitrate concentrations may be elevated here because the unsaturated zone is thinner along Lagoon Valley. In areas where the unsaturated zone is thin, there is less potential for denitrification by bacterial consumption.

Nitrate-N values higher than 2-3 mg/l probably indicate contamination from septic tank effluent rather than agricultural leaching, which could explain the peak concentration of high nitrate values clustered around the Hawea Flat settlement. However, as the samples with higher nitrate concentrations were collected by drillers upon the completion of the borehole, they were not collected to the same standard of sampling protocol as the ORC samples. Drillers' samples probably had a higher suspended solid content too, so the elevated nitrate level can be attributed to the binding of nitrogen to clay particles. While the actual nitrate-N concentration may not be reliable, the presence of elevated nitrate does indicate some deterioration of water quality in the aquifer from land use.

Figure 11 illustrates how nitrate-N concentrations peak at the Hawea Flat and Windmill Corner residential areas. Values are at natural levels for most of the Hawea Plain until Camp Hill Road is reached at a distance of 4,700m from the lake. Nitrate concentrations reach a peak at Newcastle Road, where the density of housing is greatest. The general direction of groundwater flow across this area is to the west and south-west. Therefore, concentrations are lower again in the High Terrace Aquifer, which is not subject to a nitrate-enriching source.

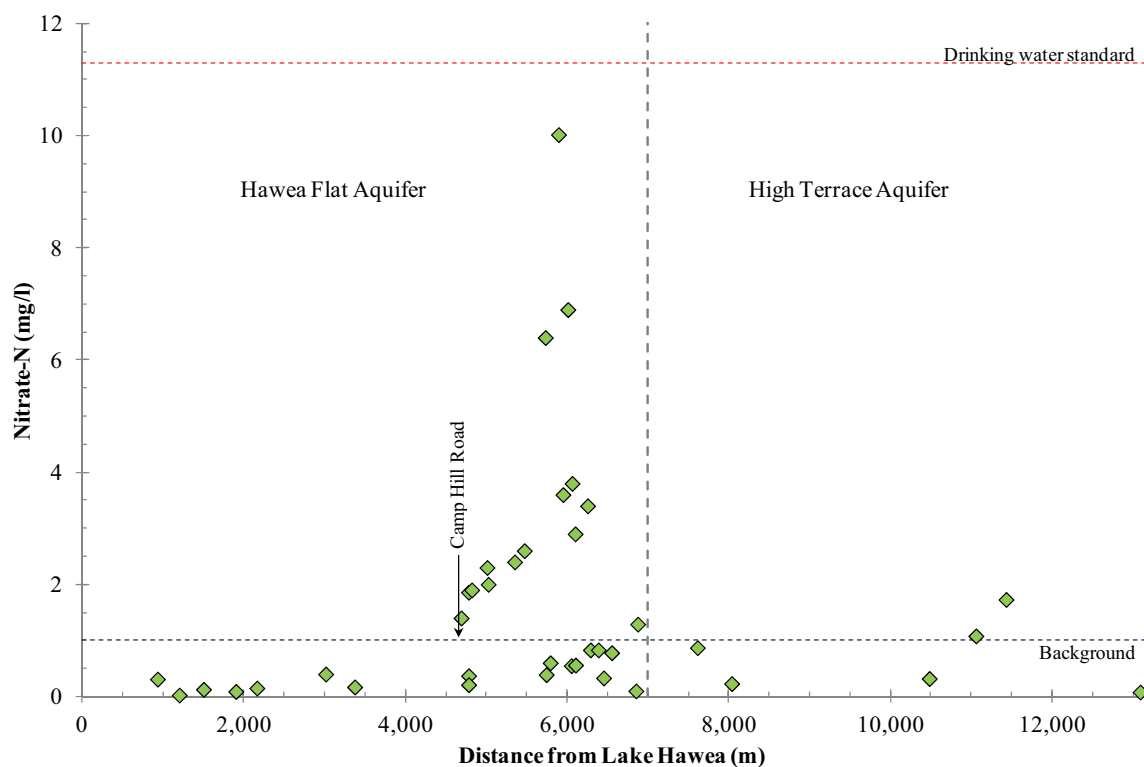


Figure 11. Nitrate-N concentrations with distance from Lake Hawea

The two NGMP bores have quarterly records of nitrate-N from 1997, which can be used to indicate the presence of trends in nitrate (Figure 12). These records show no clear trend of increasing or decreasing concentrations through time. G40/0129, which is closest to Lake Hawea, shows a more regular fluctuation. However, it is difficult to determine what is influencing this fluctuation as the changes are not seasonal.

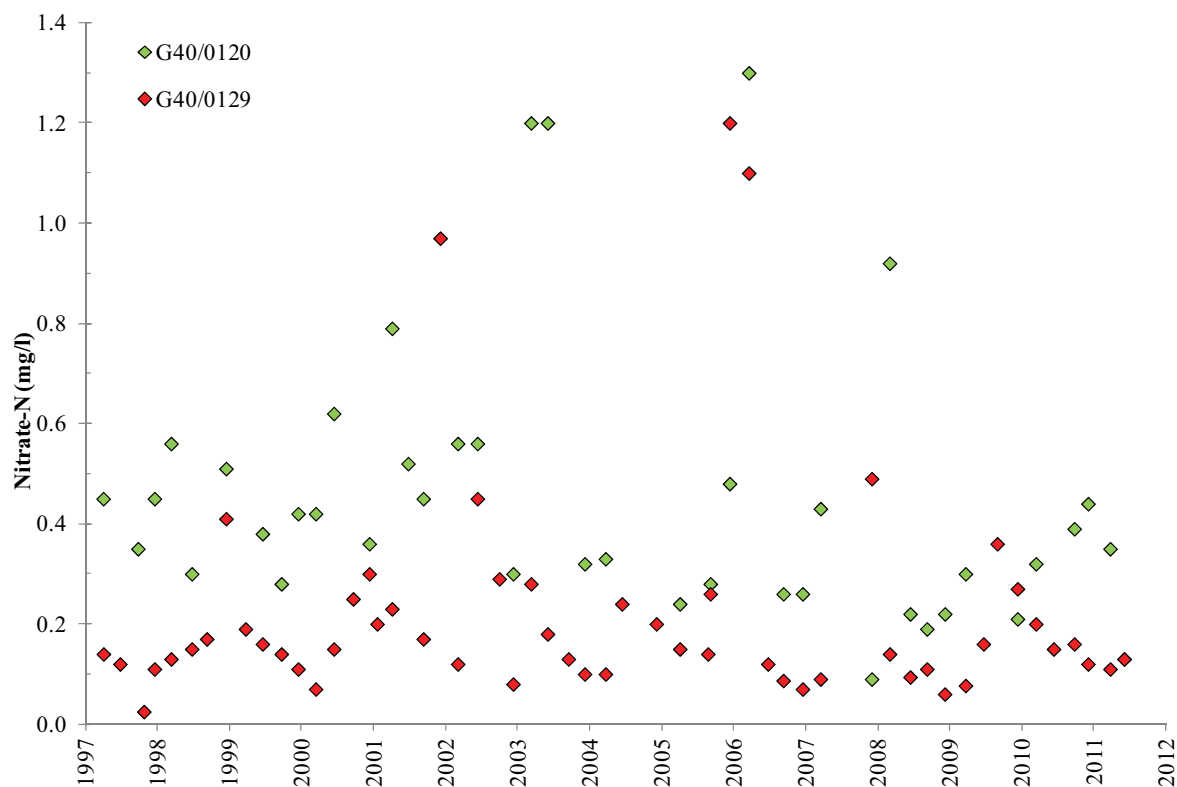


Figure 12. Nitrate-N trends at G40/0120 and G40/0129

6.5.2 Phosphorous

Phosphorous in groundwater is normally reported as dissolved reactive phosphorous (DRP). Values of DRP in the Hawea Basin are typically at, or close to, the detection limit of 0.004 mg/l. Phosphorous is usually low in groundwater because it readily bonds to clay particles in the soil horizon. Slightly higher values are seen in the middle of Hawea Flat, which may be the result of historical fertiliser application, or the dissolution of the mineral, apatite.

7 Conceptual groundwater model

7.1 Introduction

A conceptual model sets a framework for how a groundwater system works, and is integral to establishing a numerical flow model of an aquifer. The development of a conceptual model involves piecing together all available information to provide a consistent story. A conceptual model is not static, therefore, but improves over time, as more information becomes available.

This section proposes a summary conceptual model for the Hawea Flat and High Terrace aquifers based on the information available at the time. The two aquifers have been formed by different glacial outwash episodes, and, as they also have different recharge and flow characteristics, they will be considered separately.

7.2 Hawea Flat Aquifer

The Hawea Flat aquifer is essentially a hydrological extension of the lake. The lake forms a base level for the aquifer, with land surface recharge and tributary stream inflow superimposed on top. If the lake is high, the hydraulic gradient in the aquifer is high. Conversely, if the lake is low, the hydraulic gradient in the aquifer is low.

Movement in lake levels exerts pressure on the aquifer, and groundwater levels respond accordingly. Changes in water level at the south end of the aquifer are caused by a pressure response, and do not directly represent recharge from the lake.

The aquifer mainly discharges into the Hawea River. A limited volume of discharge also occurs southwards to the High Terrace Aquifer.

All of the recharge sourced from Lake Hawea discharges into the Hawea River, upstream of Camp Hill. Groundwater levels in the southerly part of the Hawea Flat Aquifer (Hillside Domain) do not directly receive the benefit of recharge from the lake because this water is lost to the river.

The Hillside Domain receives most of its recharge from rainfall infiltration and inflow from tributary streams. However, the lake forms such an important hydrological boundary that it imparts an up-gradient pressure response across the entire aquifer as lake levels rise and fall. This means that water can flow into the southern part of the aquifer under gravity if water levels in the vicinity of Hawea Flat settlement drop considerably.

The proglacial lake sediments formed at the terminus of the Albert Town glacial advance have a strong influence on groundwater flow. This is apparent from the shape of the piezometric surface, and the long residence times returned from tritium isotope sampling. The proglacial silts form a barrier to groundwater flow, much like a subsurface dam. This barrier forces groundwater westwards towards the Hawea River rather than southwards towards the High Terrace Aquifer.

While the aquifer transmissivity appears to be quite high, the proximity to aquifer boundaries is considered to be the main control on aquifer flow. These boundaries may be flow boundaries, such as the lake, the river, or impermeable boundaries formed by the shape of the basement.

Drawdown caused by pumping is expected to be exacerbated in the southern part of the Hawea Flat Aquifer due to a combination of greater distance from surface water recharge sources, together with proximity to impermeable boundaries, such as schist and proglacial silt deposits.

7.3 High Terrace Aquifer

The High Terrace Aquifer lies beneath the distinct elevated terrace formed by the Albert Town glacial advance. This aquifer thins to the south, where a basement high marks the terminus of the Luggate glacial advance.

Recharge in the Lake Domain is mainly sourced from rainfall, with only 20% of recharge derived from the up-gradient Hawea Flat Aquifer. The high proportion of rainfall recharge results in younger MRT than samples from the Hawea Flat Aquifer. The direction of groundwater flow is south-west, away from the direction of supplemental recharge provided by tributary streams along the eastern range.

The Hillside Domain is mainly recharged from the Hawea River, and groundwater flow is in a southerly direction towards the lower elevation Clutha River/Mata-Au.

The High Terrace Aquifer discharges most of its water into the Clutha River/Mata-Au, via springs upstream of Red Bridge near Luggate. Some interaction between the aquifer and the river may occur in the area opposite the Cardrona confluence and near Red Bridge.

Because the aquifer is mostly perched above the Clutha River/Mata-Au, drawdown from pumping is not attenuated by recharge from the river. Water discharge through pumping must be sourced from storage within the aquifer, or be drawn in from the up-gradient Hawea Flat Aquifer. The exception is west of Butterfield Road, where water leaving the Hawea River may be induced down-gradient by pumping.

8 Numerical modelling

8.1 Introduction

A conceptual model and available geological and hydrological information have been combined to create a numerical model of the Hawea Basin. The numerical model that has been developed is a simplification of the natural environment and, as such, is a tool to be used on a regional or aquifer-scale. A summary of the attributes of the model is provided in Appendix D.

The creation of a numerical model includes the following steps:

1. *Development.* All of the conceptual and geological information is used to create the model's structure.
2. *Optimisation.* Model properties, such as hydraulic conductivity, are altered from initial values, so that the model calculates values that are similar to actual observations. Observational data consist of groundwater levels and fluxes (river gains and losses).
3. *Verification.* The model results are compared with an independent data set, in this case, isotope results.

An accurately optimised numerical model is a powerful tool for groundwater management. In this report, the model has been used for three purposes:

- To quantify the fluxes within different aquifer domains in order to better understand the system
- To assess cumulative effects of groundwater pumping, and to set appropriate groundwater allocation limits
- To assess the potential impact of nutrient leaching on groundwater quality.

8.2 Approach

This section outlines the philosophical approach used to develop and optimise the numerical model. The Hawea Basin model is a steady-state model, which represents long-term average values for the aquifers. The finite-difference MODFLOW code (McDonald and Harbaugh, 1984) was used for the model.

A steady-state model was selected for two reasons. Firstly, seasonal groundwater level fluctuations throughout the basin appear to be very small compared to the saturated thickness of the aquifer. Secondly, there is insufficient data to optimise a transient model accurately. Knowledge of seasonal river and tributary stream fluxes is particularly poor at this stage, so there is insufficient data to have confidence in a transient model.

The domain for the Hawea model is considerably larger than the Hawea Flat and High Terrace aquifers. The size of the model allows a stable flow field to be generated around the key area of interest.

The timing of the steady-state model has been set at early September 2011 to coincide with the piezometric survey. This is the time of year when water levels are at their lowest, and the aquifer is most vulnerable to drawdown from groundwater pumping. Furthermore, there was

no significant irrigation at the time of the survey, which eliminates groundwater pumping as a variable for model optimisation. There are few records available for water use, so this eliminates a model parameter of great uncertainty.

The PEST utility was used for optimisation of model hydraulic properties (Doherty and Hunt, 2010). Model optimisation involved one major numerical hurdle. The three main components of the steady-state model are strongly correlated (recharge, hydraulic conductivity and river conductance). To use PEST to estimate parameter values confidently, it was necessary to make the following assumptions:

- Rainfall recharge has been fixed at median annual values, as calculated by the Rushton model (Appendix C).
- River fluxes have been estimated to provide prior information.
- River fluxes are assumed to be controlled more by bed conductance than aquifer properties.

For model optimisation, firstly, PEST was run to solve for river bed conductance. Greater weights were applied at hydraulic conductivity pilot points along the river margins, and flux targets were used to provide realistic river gains and losses at different reaches. River bed conductance was then given tighter constraints so that hydraulic conductivity could be solved.

Initial model runs used zones of piecewise constancy for hydraulic conductivity. Minimum values for each zone were estimated from specific capacity data. Pilot points were used and given values at boreholes where specific capacity has been recorded. Constraints were set at $\pm 50\%$ of the estimated value. Areas where no specific capacity data is available were assigned initial values from the relevant hydraulic conductivity zone, with constraints set at $\pm 100\%$.

8.3 Model verification

Tritium isotopes values were compared with particle travel times in MODPATH as a verification of aquifer properties. Reverse particle tracking was used to trace particles from their sampled locations to their recharge sources. A porosity of 0.3 was used for the entire model.

Table 10 lists the results, which indicate a good overall match between predicted and sampled MRT. Site G40/0129 does show considerable error, and a lesser error is also apparent at G40/0120. However, adjacent model cells give similar values to those obtained from the tritium samples, suggesting that the error is caused by local aberrations in the model structure.

Table 10. Comparison of sampled and modelled mean residence times

Site Name	Easting	Northing	MRT	Modpath MRT	Water source	Travel distance (m)
G40/0120	1304825	5048894	51	42	Rainfall	730
G40/0129	1306024	5051697	49	28	Grandview Creek	2,780
Spring2	1302283	5043774	11	11	Hawea River	3,620
Spring1	1305609	5042348	26	25	Rainfall	3,750

8.4 Model fluxes

The mass balance for the numerical model was optimised to less than 1% error⁵. Mass balances have been exported from the numerical model so that the fluxes of each aquifer domain can be quantified.

Table 11 shows the results for the Hawea Flat Aquifer, and Table 12 shows the results for the High Terrace Aquifer. The results give a clear indication of the availability of groundwater in different parts of Hawea Basin.

Table 11. Mass balance for Hawea Flat Aquifer and its two domains

Hawea Flat Aquifer	Fluxes (m³/d)	Fluxes (l/s)	%
Lake inflow	78,350	907	73
Rainfall	17,950	208	17
Stream Inflow	10,930	127	10
Total aquifer recharge	107,230	1,241	100
Hawea River baseflow	94,056	1,089	88
High Terrace Aquifer	13,174	152	12
Total aquifer discharge	107,230	1,241	100
Lake Domain	Fluxes (m³/d)	Fluxes (l/s)	Estimated flux (l/s)
Lake inflow	78,350	907	
Domain 2 inflow	18,603	215	
Rainfall	6,479	75	
Lake Domain recharge	103,432	1,197	
Hawea River baseflow	94,056	1,089	1,200
High Terrace Aquifer	9,376	109	
Lake Domain discharge	103,432	1,197	
Hillside Domain	Fluxes (m³/d)	Fluxes (l/s)	Estimated flux (l/s)
Rainfall	11,471	133	
Stream Inflow	10,930	127	127
River Domain recharge	22,401	259	
Domain 1 outflow	18,603	215	
High Terrace Aquifer	3,797	44	
River Domain discharge	22,401	259	

The disparity in water availability between the two Hawea Flat domains is clear from Table 11. The overwhelming source of lake water gives the Lake Domain a recharge flux about five times the magnitude of the Hillside Domain.

Only 12% of the water that enters the Hawea Flat aquifer is discharged south to the High Terrace Aquifer. Consequently, the latter shows considerably lower flux volumes than those of the Hawea Flat Aquifer. The most dynamic part of the High Terrace aquifer is the River Domain, which receives the benefit of recharge from the Hawea River.

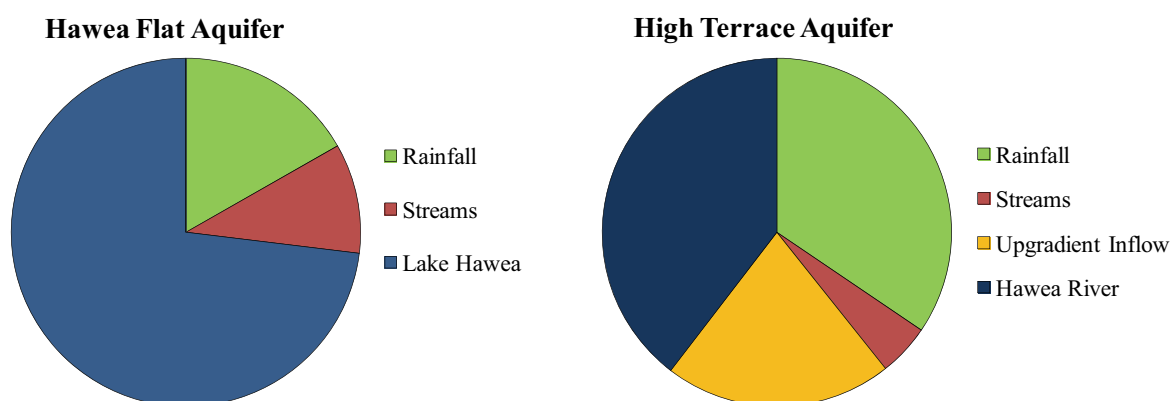
Recharge provided by the up-gradient Hawea Flat Aquifer is less than the volume gained by rainfall recharge, which explains why MRT in the High Terrace aquifer is considerably younger than the Hawea Flat Aquifer.

⁵ This error value relates to the difference between inflow and outflow within the MODFLOW mass balance package. A low percentage indicates good numerical resolution.

Table 12. Mass balance for High Terrace Aquifer and its two domains

High Terrace Aquifer	Fluxes (m³/d)	Fluxes (l/s)	%
Rainfall	21,549	249	35
Hawea Flat Aquifer inflow	13,174	152	21
Stream inflow	3,000	35	5
Hawea River inflow	24,733	286	40
Total aquifer recharge	62,455	723	100
Clutha River/Mata-Au	62,455	723	100
Total aquifer discharge	62,455	723	100
Hillside Domain	Fluxes (m³/d)	Fluxes (l/s)	Estimated flux (l/s)
Rainfall	14,107	163	
Hawea Flat inflow	5,233	61	
Stream inflow	3,000	35	35
Domain 2 inflow	4,088	47	
Hillside Domain recharge	26,427	306	
Clutha River/Mata-Au Springs	26,428	306	
Hillside Domain discharge	26,428	306	
River Domain	Fluxes (m³/d)	Fluxes (l/s)	Estimated flux (l/s)
Hawea River Inflow	24,733	286	
Rainfall	7,441	86	
Hawea Flat Inflow	7,941	92	
River Domain recharge	40,115	464	
Clutha River/Mata-Au and Springs	36,028	417	
Domain 1 Outflow	4,088	47	
River Domain discharge	40,115	464	

Figure 13 shows the proportion of recharge sources for the two aquifers. At Hawea Flat, almost three quarters of recharge comes from the lake. Most of this water rapidly leaves the aquifer via the Hawea River, north of Camp Hill Road.

**Figure 13. Graphical comparison of recharge sources for Hawea Flat and High Terrace aquifers**

8.5 Low lake level scenario

Contact Energy is currently consented to maintain lake levels between 338 and 345.5m. Levels outside this operational range are allowed for flood management, or if the Electricity Commission deems that additional generation capacity is required. The numerical model was used to estimate the impact on groundwater levels of lowering the lake below its operation limits.

Figure 14 shows predicted water levels with distance from the lake under different scenarios. The results show that the groundwater levels used to optimise the numerical model are only

slightly higher than those expected during low operational lake levels. The change in elevation is about a metre on average across the aquifer.

Changing the lake level within the model to its historical low of 327.6m has a large impact on groundwater levels across the whole aquifer. Water levels within 500m of the lake are expected to be at least 6m lower than the current operational minimum. At Camp Hill Road, water levels are predicted to be 1.5 to 2m lower.

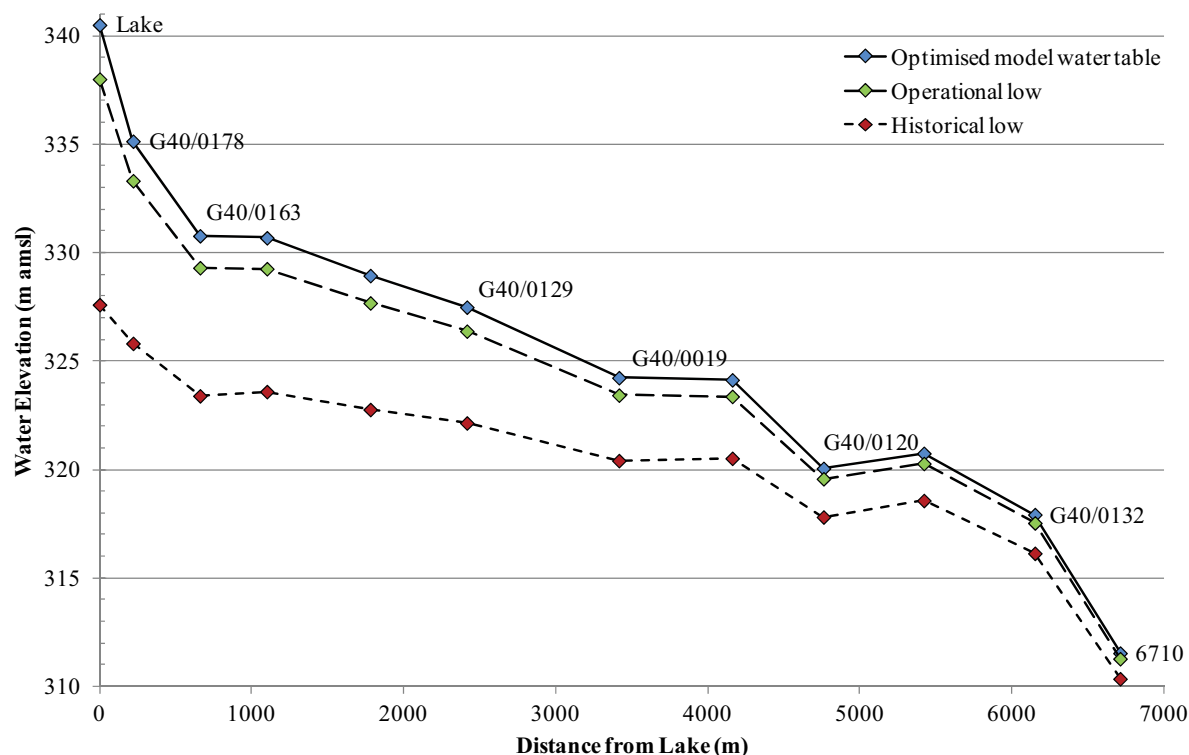


Figure 14. Predictions of groundwater levels at lower lake elevations

The area most affected by a change in lake levels is the south end of the Hawea Flat Aquifer, where the saturated thickness is the least. Landholders in this area cannot drill deeper bores if groundwater levels drop. The saturated thickness of the aquifer is least in the Loach Road area, and is considered to have been about 15m during the September 2011 piezometric survey.

Changing the lake level to its lowest operational limit, 338m, reduced the saturated thickness at Loach Road by 0.4m. Changing the level to 327.6m, the lowest level recorded since commissioning of the dam, reduced the saturated thickness by 1.8m, which may have a detrimental impact on the performance of some irrigation bores in the vicinity if low lake levels coincide with high irrigation demand. However, there should be no problem accessing groundwater for domestic supply if bores have been drilled to the base of the aquifer.

9 Groundwater allocation

9.1 Introduction

The numerical model is a powerful tool for predicting the cumulative effect of existing water permits across the entire Hawea Basin. The model can also be used to estimate an appropriate allocation limit for different aquifer domains, given a set of environmental thresholds.

A default mechanism for groundwater allocation is specified in the RPW, policy 6.4.10A(a)(ii)(1). This policy specifies an allocation limit that is 50% of the calculated mean annual recharge. Allocation values have been calculated for each aquifer and domain under the following conditions:

1. *Current consented allocation.* The cumulative impact of consented water permits
2. *Default allocation.* The default allocation of 50% of mean annual recharge for the Hawea Flat and High Terrace Aquifers has been derived from the mass balance of the steady-state numerical model. The peripheral Hawea Basin aquifers have been attributed a default allocation based on 50% of mean annual rainfall recharge.
3. *Potential demand over irrigable area.* Potential water demand can be calculated using the Aqualinc tables for pasture requirements in the Upper Clutha (Aqualinc, 2006). Irrigable areas have been calculated for each soil class, and reduced by 5% to accommodate roads and other minor land uses that would not be irrigated.

This section proposes a recommended allocation limit for each aquifer and domain. In some cases, the recommended limit is less than the default allocation because of additional environmental considerations. Key environmental thresholds for the Hawea Basin are considered to be:

- maintaining sufficient saturated thickness in the aquifer for existing domestic and irrigation supply wells
- avoiding drawdown in Butterfield and Campbell's Reserve wetlands.

9.2 Allocation assessments

Table 13 and Table 14 compare the monthly and annual volumes of consented allocation, default allocation and potential demand for the Hawea Flat and High Terrace aquifers, respectively. Table 15 shows an assessment for the peripheral Hawea Basin aquifers. These tables indicate that there is a large disparity between the default allocation and potential demand. There is insufficient groundwater available to meet the potential demand in all areas, except for the Lake Domain at Hawea Flat.

The disparity between the recommended allocation and potential demand suggests that it may be difficult for some landholders to access water in the future. At Hawea Flat, the Hawea water race could readily supply any shortage. However, availability of water depends on farmers adopting efficient irrigation methods and having access to the race. Properties further from the water race, such as those overlying the High Terrace Aquifer, would need to obtain water from the Hawea River or Clutha River/Mata-Au.

9.2.1 Hawea Flat Aquifer

The calculated default allocation for the Hawea Flat Aquifer is 19.52 Mm³/y (Table 13). Only 3.3 Mm³/y of this volume is derived from rainfall infiltration, which indicates that retention of groundwater storage within the aquifer is heavily dependent on lake level. Lowering the lake level reduces recharge to the Lake Domain, which accelerates loss of groundwater storage via drainage to the Hawea River and lowers groundwater levels across the whole aquifer.

Table 13. Hawea Flat Aquifer irrigable area, potential demand, default and recommended allocation

Hawea Flat Aquifer domains	Potential demand ⁶	Default allocation	Consented allocation	Recommended limit	% currently allocated
Lake D. irrigable area (ha)	697				
Monthly limit (Mm ³)	1.10	2.57	0.33		
Seasonal limit (Mm ³)	4.60	15.44	1.40	4.60	30.5
Hillside D. irrigable area (ha)	2,079				
Monthly limit (Mm ³)	3.19	0.68	0.62		
Seasonal limit (Mm ³)	12.77	4.08	2.69	4.08	66.0
Annual total	17.37	19.52	4.09	8.68	47.1

In the Lake Domain, the calculated default allocation far exceeds the potential demand. Aquifer drawdown in this area is attenuated by recharge from surface water resources. The more often the aquifer is pumped, the more water is drawn in to replace the loss of groundwater storage.

However, large abstraction volumes from the Lake Domain impact on the regional hydraulic gradient, creating a level water table across Hawea Flat and exaggerating drawdown in the Hillside Domain. Therefore, some limitation must be placed on the Lake Domain allocation. The allocation limit for the Lake Domain is recommended to be capped at 4.6 Mm³/y, which is the volume of potential demand. There is currently very little demand in this area, despite its abundance of water, in contrast with the Hillside Domain, which has considerably less available water, but almost twice the consented allocation.

The Hillside Domain has specific areas that are sensitive to cumulative aquifer drawdown, which may constrain the allocation to less than the default limit to ensure a suitable saturated aquifer thickness. To test this assumption, a worst-case pumping scenario was set up in the numerical model, where the default allocation of 4.08 Mm³/y was pumped at steady state. The level of the lake was set to its lowest operational level of 338m to simulate a period of water stress. Two environmental thresholds were set in the model where the available drawdown is known:

- *Hillside Domain, G40/0013, at Grandview Creek.* This eastern margin of Hawea Flat has a shallower depth to basement because of uplift along the Grandview Fault system. This area is possibly perched above the main aquifer.
- *Hillside Domain, G40/0133 at Loach Road, Hawea Flat.* This area represents the thinnest part of the aquifer, with a saturated aquifer thickness of about 15m.

As well as these environmental thresholds, sufficient water should be allowed to flow through to recharge the High Terrace Aquifer. In particular, pumping drawdown at Campbell Reserve Wetland, a regionally significant wetland, needs to be minimised. This wetland lies at the

⁶ Note that Aqualinc uses plant available water (PAW), which in common ORC use is 'profile readily available water' or PRAW.

discharge end of Hawea Flat-High Terrace system, and is vulnerable to the cumulative impact of pumping.

The results indicate that the aquifer will cope with the default allocation of 4.08 Mm³/y without excessive environmental impact. Drawdown is predicted to be 1.4m, at Grandview Creek, and 8.6m, at Loach Road, which leaves a saturated aquifer thickness of around 9.5m and 6.5m, respectively. This amount of saturated thickness would ensure access to groundwater for all parts of the aquifer. However, domestic bores in the vicinity of Hawea Flat settlement may experience a loss of performance or even go dry if they are less than 20m deep. This situation is also expected to occur if the existing water permits were used fully during a period of low lake levels.

The numerical model indicates that the cumulative impact of pumping from the Hillside Domain at the default allocation rate induces a drawdown of 0.45m at the wetland. Most of this drawdown comes from existing Hillside Domain water permits located south of Camp Hill Road.

The critical environmental threshold for the Hillside Domain is retention of water for Campbell's Reserve Wetland. While extra groundwater abstraction from the Hawea Flat Aquifer would only have a slight impact on the wetland, the Hawea Irrigation Scheme is available as an alternative water source to groundwater. With this in mind, it is recommended that the water race be a preferred source for irrigation water, particularly for takes to the south of Camp Hill Road.

9.2.2 High Terrace Aquifer

The default allocation for the High Terrace Aquifer is 11.4 Mm³/y (Table 14). Only 4 Mm³/y of this volume is sourced from rainfall infiltration. The potential irrigation demand over the aquifer is nearly double the default groundwater allocation. However, the consented allocation is currently very small, presumably because of the large depth to the water table, which would deter drilling for irrigation water.

Table 14. High Terrace Aquifer irrigable area, potential demand, default and recommended allocation

High Terrace Aquifer domain	Potential demand	Default allocation	Consented allocation	Recommended limit	% Currently allocated
Hillside D. irrigable area (ha)	2,515				
Monthly limit (Mm ³)	3.93	0.68	0.04		
Seasonal limit (Mm ³)	16.36	4.07	0.41	0.41	100
River D. irrigable area (ha)	818				
Monthly limit (Mm ³)	1.27	1.22	0		
Seasonal limit (Mm ³)	5.43	7.30	0	1.56	0.0
Annual total	21.79	11.37	0.41	1.97	21.0

The High Terrace aquifer has three environmental considerations that limit its allocation to a volume less than its calculated default volume:

- aquifer saturation (Hillside Domain)
- Campbell Reserve Wetland (Hillside Domain)
- Butterfield Wetland (River Domain)

Simulations in the numerical model indicate that it is difficult to abstract more water from the Hillside Domain without significantly reducing the saturated thickness of the aquifer as it has low transmissivity in this area, and recharge water is not readily available to replenish lost groundwater storage.

Abstractions from the Hillside Domain also have a significant direct impact on water levels at Campbell's Reserve Wetland. Therefore, it is recommended that the allocation limit for Domain 1 be capped at its current consented volume.

The River Domain still has plenty of potential for abstraction, although there are currently no groundwater consents in this area. The key environmental thresholds are Butterfield Wetland, and the Campbell's Reserve Wetland. The numerical model predicts that it is very difficult to abstract groundwater from River Domain without having a significant impact on either wetland. To avoid drawdown at the wetlands, an abstraction bore would need to be positioned beside the Hawea River to maximise the river recharge response to pumping and attenuate drawdown in the wetlands.

To maintain wetland water levels, an allocation limit of 1.56 Mm³/y is recommended for the River Domain. This volume is equivalent to a long-term instantaneous take of 100 l/s. While this rate appears small compared to the potential demand, the River Domain also has the benefit of easy access to the Hawea River and Clutha River/Mata-Au for sources of irrigation water.

9.2.3 *Peripheral aquifers*

Aquifers located around the periphery of the Hawea Basin have not been numerically modelled. In these areas, a suitable allocation is considered to be the lesser of the potential demand or the default allocation.

Default allocation volumes have been calculated using mean annual rainfall-recharge values (Table 15). These volumes are considered to be a provisional allocation volume until more detailed work is carried out on these aquifers in the future. Additional groundwater is still available in all these aquifers.

Table 15. Irrigable area, potential demand, default and recommended allocation for peripheral aquifers

Aquifer		Potential demand	Default allocation	Consented allocation	Recommended limit	% currently allocated
Te Awa	Irrigable area (ha)	245				
	Monthly limit (Mm ³)	0.387	0.147	0.010	0.147	
	Seasonal limit (Mm ³)	1.557	0.297	0.051	0.297	17.1
Maungawera Valley	Irrigable area (ha)	610				
	Monthly limit (Mm ³)	0.94	0.322	0.039	0.322	
	Seasonal limit (Mm ³)	3.67	0.651	0.463	0.651	71.2
Maungawera Flat	Irrigable area (ha)	443				
	Monthly limit (Mm ³)	0.697	0.281	0.000	0.281	
	Seasonal limit (Mm ³)	2.981	0.568	0.002	0.568	0.3
Sandy Point	Irrigable area (ha)	808				
	Monthly limit (Mm ³)	1.259	0.427	0	0.427	
	Seasonal limit (Mm ³)	5.288	0.863	0	0.863	0

10 Groundwater quality predictions

10.1 Introduction

Hawea Flat and High Terrace aquifers are currently attracting interest from the dairy sector. Soils in this area are characterised by low profile available water (PAW), which renders the groundwater vulnerable to leachate contamination. The Hawea Flat aquifer also has a sizeable population reliant on domestic bores for their drinking water supply.

The numerical flow model was used to assess the impact of land-use intensification on groundwater quality. In particular, the accumulation of nitrate-nitrogen was estimated under advective flow conditions. The contaminant transport model, MT3DMS (Zheng and Wang, 1999), was used to simulate nitrate accrual in groundwater.

10.2 Model methodology

The impact of land use on nitrate concentrations was determined by applying a nitrate-nitrogen concentration to irrigated land surface recharge values. Estimates of nitrate leaching under different land uses may be found in a set of lookup tables commissioned by Environment Canterbury (Lilburne *et al.*, 2010). This publication compiled leaching estimates by many of the country's leading soil scientists and agronomists. A relevant selection of values used for the Hawea study is provided in Table 16.

Table 16. Nitrate-N leaching mass in Kg/ha/year for selected land uses (after Lilburne *et al.*, 2010)

Stock type	Soil group:	Extra light	Very light	Light	Medium to heavy
	PAW:	<50	50-80	80-110	>110
3 cows/ha winter on	Spray irrigation	50	41	31	19
	Border dike		86	76	76
50% beef, 50% sheep	Dryland	18	16	14	9
	Spray Irrigation	46	37	29	17
	Border dike	122	79	70	70
100% sheep	Dryland	10	9	8	5
	Spray irrigation	25	20	16	9
	Border dike	66	43	38	38

Land surface recharge was calculated for the Hawea Basin for different land uses and soil types. Figure 15 is a map of the Hawea Basin's PAW. The map has been colour-coded to match the soils groups listed in Table 16. The lightest soils are located on steep land or on terrace areas close to the Hawea River.

Land use was mapped for the Hawea Basin so that appropriate recharge rates and leachate concentrations could be assigned to each MODFLOW cell. The concentration for each recharge zone in the model was calculated by dividing the nitrate-N mass for each soil type, as specified in Lilburne *et al.*, (2010), by its land surface recharge. This gives a concentration of nitrate-N in mg/l for local conditions.

Nitrate-N transport simulations accounted for additional recharge from the water race. An estimate of 30% annual leakage was made, contributing around 185 l/s to the Hawea Flat Aquifer under steady-state conditions.

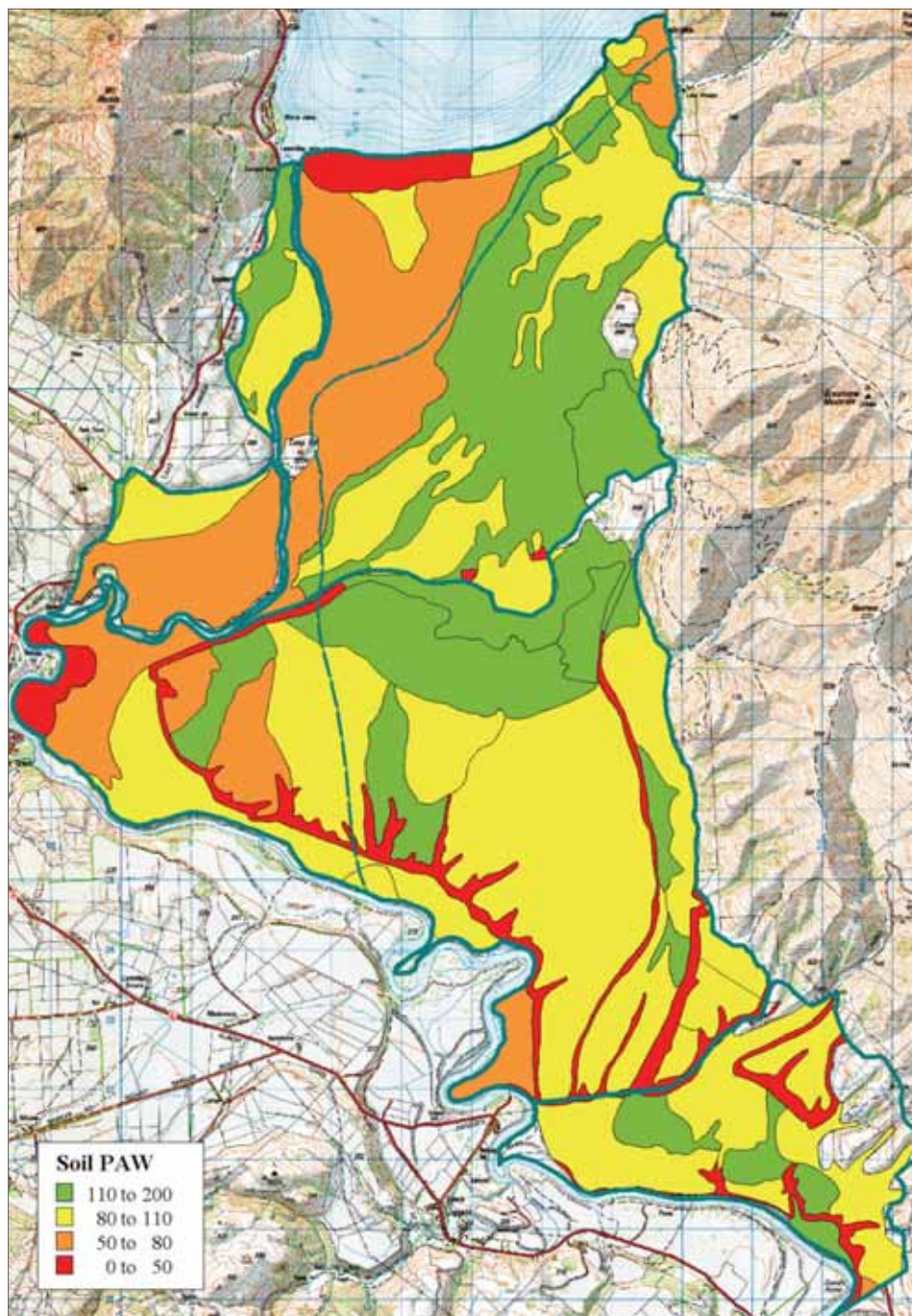


Figure 15. Map of soil profile available water (PAW)

10.3 Model assumptions

The modelling of land surface nitrate-N accrual in groundwater is an extremely complex procedure. Several assumptions have been made to simplify the calculations:

1. Soils have been grouped according to their hydraulic characteristics (see Wilson and Lu, 2011). In some cases, a further coarse-scale grouping has been carried out. Soils with similar PAW were grouped to simplify the number recharge zones required for input to MODFLOW.
2. Leaching values calculated by Lilburne *et al.*, (2010) are assumed to be transferable to Otago's soil and climate conditions.
3. Predictions assume 100% dairy farming with a leaching cap of 30 KgN/ha/y.

4. The steady-state flow model is assumed to characterise nitrate-N accrual over long time intervals (50 years).
5. Nitrate-N is assumed to behave conservatively with no sorption or desorption.
6. No de-nitrification is assumed to occur in the vadose zone or in the aquifer. While evidence exists that de-nitrification does occur (e.g. at Hawea), it is difficult to predict at this stage.
7. The scenario modelled assumes widespread dairy farming at three cows/ha (winter on), or four cows/ha (winter off).

These assumptions give a worst-case scenario (100% dairy farming) for nitrate-N accrual at Hawea. The leaching rate limit of 30 Kg N/ha is taken from Proposed Plan Change 6A (Water Quality), which was the limit at the time of writing.

A leaching rate of 30 KgN/ha/yr is a significant improvement on current leaching rates. A major implication of the plan change is that border-dike irrigation would no longer be tenable, as it flushes nutrients through the soil profile, leaving little opportunity for denitrification by bacteria or pasture uptake.

Border dike irrigation on Hawea soils is currently expected to leach between 60 KgN/ha/yr (on heavy soils) and 120 KgN/ha/yr (on light soils for mixed beef and sheep farming). Values of less than 30 KgN/ha/yr can readily be achieved under dairy farming on the same soils if spray irrigation is used, stocking density is maintained at three cows per hectare, and cows are wintered off-site.

For areas under spray irrigation, the leaching limit only imparts a significant restriction on leaching over extra light soils. These soils have a PAW of 50 mm or less and are found on the western edge of Hawea Flat, and along the Clutha River/Mata-Au terraces, south of Sandy Point (Figure 15).

10.4 Model predictions

The model tends to over-estimate nitrate-N concentrations under existing land-use conditions. Sampled nitrate-N values are all at natural or background concentrations. The most likely reason for such low observed nitrate-N concentrations is denitrification in the unsaturated zone, which is typically tens of metres thick.

The observed weak correspondence between water quality and land-use impacts makes the nitrate-N observations unsuitable as an optimisation or verification parameter in MT3DMS. However, the greatest unknown in contaminant transport modelling is the porosity value. A porosity value of 0.3 has been constrained by tritium sampling results, which gives confidence in the results of the MT3DMS modelling.

Figure 16 shows the nitrate-N distribution for the 100% dairy farming scenario. The results indicate that groundwater nitrate concentrations resulting from more intensive farming activities will be retained at 3 mg/l nitrate-N or less for most of Hawea Basin, which is well below the Ministry of Health drinking water standard of 11.3 mg/l.

Localised hotspots are seen to the west of Hawea Flat settlement, at the bottom of Lagoon Valley, and along the high terraces next to the Clutha River/Mata-Au. The soils in these areas are either light or very light. Since groundwater flow is mainly in a south-westerly direction, no communities are located down-gradient of these hotspots.

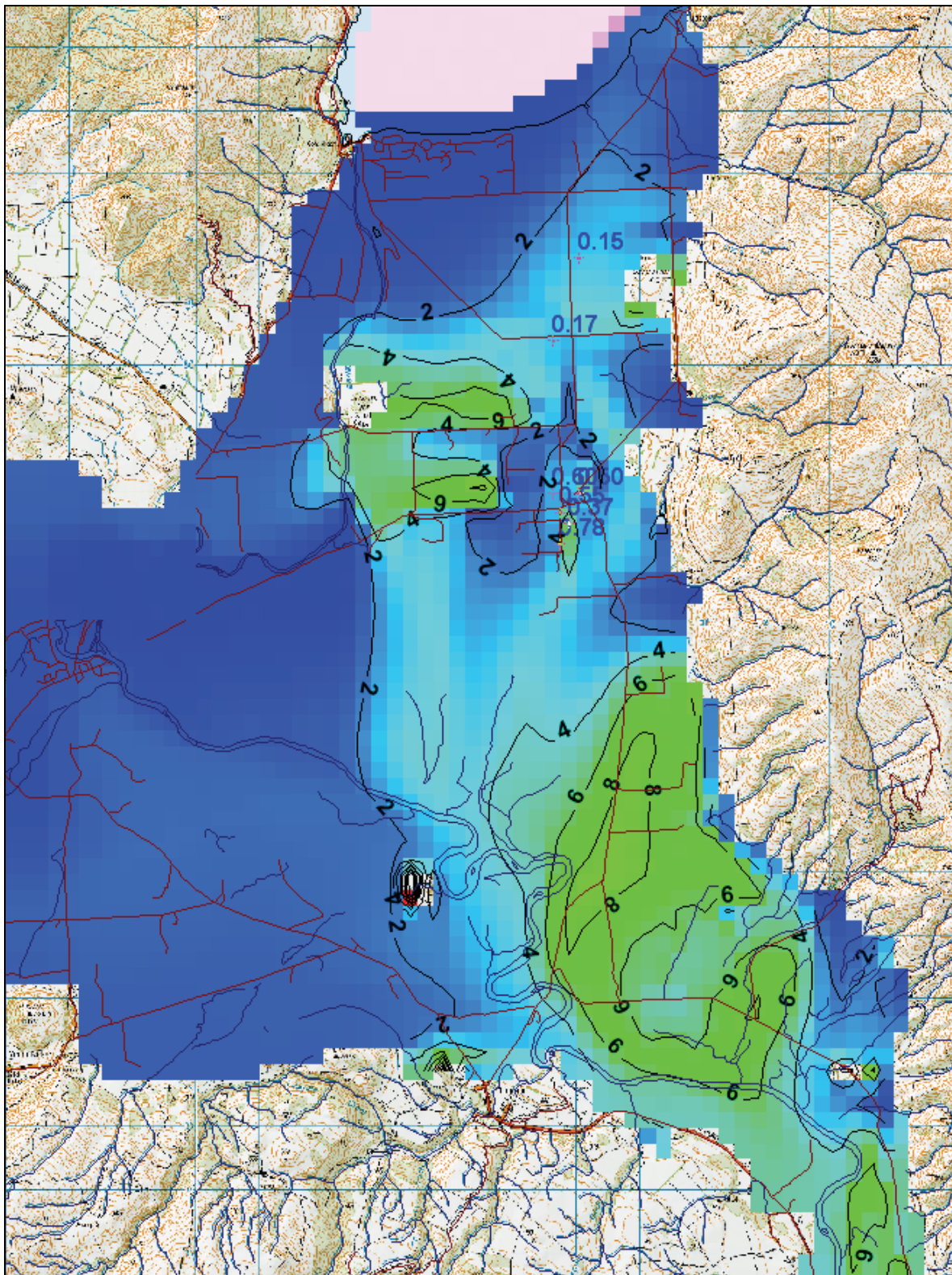


Figure 16. Predicted nitrate-N concentrations in the Hawea Basin

11 Conclusions

11.1 Groundwater allocation

A total allocation limit of 8.68 Mm³/y is recommended for both domains of the Hawea Flat Aquifer. Of this volume, no more than 4.08 Mm³/y should be permitted from the Hillside Domain. In the High Terrace Aquifer, a total allocation limit of 1.97 Mm³/y is recommended. No further groundwater permits should be permitted from the Hillside Domain. Table 15 provides recommended allocation volumes for the peripheral aquifers.

11.2 Water sources

Future water use in the Hawea Basin needs strategic planning. In the Hawea Flat Aquifer, there is currently a large disparity between the location of water permits and water availability. Ideally, the Lake Domain should be a preferred groundwater source for irrigation water.

A disparity also exists between potential demand and recommended groundwater allocation. To address this predicament, it is suggested that the irrigation race or other surface water bodies be a preferred source of irrigation water supply if they are accessible. This recommendation applies to the Hawea Flat and High Terrace aquifers, which have a limited groundwater resource compared to the adjacent surface water resources.

11.3 Groundwater-take restriction zone

A groundwater-take restriction zone is recommended for the Hawea Flat and High Terrace aquifers to ensure security of groundwater supply when Lake Hawea falls below its operational level of 338m. Schedule 4B of the RPW (ORC, 2012) lists existing groundwater-take restriction zones.

The water-take restriction should apply to a water level threshold on the proposed ORC monitoring bore at Loach Road to enable the enforcement of pumping restrictions when water levels are equivalent to a lake level of 338m.

11.4 Bore depths

The numerical modelling scenarios indicate that many bores have not been drilled to a sufficient depth to ensure the availability of water during low lake levels and high demand from existing water permits. Under a high water stress scenario, water should be available in the aquifer, so the problem is one of poor resource access by individual bore owners. Bores in the Hawea Flat area should be drilled to a minimum of 24m depth, preferably deeper where the base of the outwash gravels allows.

11.5 Water supply protection

The immediate threat to the Hawea Flat community water source is septic tank effluent. The operative water plan allows for a Groundwater Protection Zone (Zone A) to protect water supplies from contaminants (Rule 12.6), providing an option for halting further deterioration of water the Hawea Flat community area.

A Groundwater Protection Zone will not protect water supplies from farming activities, but it would place restrictions on future septic tanks. The disadvantage of this option is that any

discharge of sewage becomes a discretionary activity, which means that an ORC resource consent would be required for new septic tanks, or changes to existing septic tanks. A higher standard of septic tank is also likely to be required.

The proposed Plan Change 6A (Water Quality) is expected to protect the Hawea Flat water supply from farming activities. At the time of writing, the relevant section of the plan change (Rule 12.C.1.3) states that ‘The discharge of nitrogen from land to groundwater, is a permitted activity providing calculated nitrogen leaching by the Council using OVERSEER does not exceed 30 kilograms nitrogen per hectare per year’.

11.6 Groundwater monitoring

A new state of the environment (SOE) monitoring bore is proposed for the Loach Road area, at the Hawea Flat settlement. The bore should be drilled to a sufficient depth to determine the base of the aquifer. A water level recorder will be installed in the bore, and the bore will also be sampled on a quarterly basis for water quality.

11.7 Future investigations

Future investigations in the Hawea Basin should focus on:

- characterising Hawea River gains and losses
- collecting aquifer-hydraulic property data
- characterising tributary stream flows throughout the year.

Acknowledgements

ORC would like to thank the McNeill Group drilling unit, for providing additional bore information, and the people of Hawea Basin, who have allowed groundwater sampling and monitoring to be carried out on their properties.

Glossary

Alluvium

Sediments that have been deposited by a river

Aquifer

A saturated geological unit, or group of units, with sufficient storage and permeability to yield economic volumes of water

Basement rock

Solid rock, such as schist or greywacke, that underlies younger unconsolidated rocks

Confined aquifer

An aquifer in which water is stored under elastic pressure. Confined aquifers are generally (but not always) encountered at a depth below the ground surface where low permeability mud, silt or clay have overlain permeable sediments such as gravels.

Cumec

A measure of flow rate, which is cubic metres per second (m^3/s). (One cumec is 1000 l/s.)

Drawdown

The lowering of water levels in response to pumping

Flux

Flow through a unit of aquifer or the rate of exchange with a hydraulically connected surface water body

Formation

A distinctive unit of rock that can be mapped

Heterogeneous

Having properties that vary throughout space

Hydraulic conductivity

The rate at which water can pass through a permeable medium in m/day

Hydraulic gradient

The slope of the water table or piezometric surface

Hydrogeology

The study of aquifers and groundwater

Leaky aquifer

Aquifers that are partially confined. When a leaky aquifer is pumped, some or all of the water eventually is drawn from shallower (or deeper) low permeability strata

Permeability

The ability of a rock or sediment to transmit water. Highly permeable gravel will allow water to flow quite freely.

Piezometer

A small diameter observation well used to monitor water levels (often abbreviated to ‘piezo’)

Porosity

A measure of the void or pore space within a rock. For example, sand typically consists of 30% pore space, which is a porosity of 0.3.

Quaternary

The most recent geological Period (2.6 million years ago to the present day)

Schist

A type of metamorphic rock in which the individual mineral grains have been elongated or flattened. The fabric of a schist rock is usually planar, or foliated. Schist is the distinctive basement rock found throughout most of Otago.

Screen

A filter installed at the end of bore casing to keep sediment from entering a borehole

Specific capacity

Describes well productivity, which is determined by pumping a well at a constant rate for a specified duration, usually 30 minutes to two hours. The specific capacity of the pumped well is the rate of discharge divided by the drawdown.

Storativity

A measure of the storage characteristic of an aquifer. In confined aquifers, ‘storativity’ refers to elastic storage (contraction and expansion of water and aquifer matrix). In unconfined aquifers, it is a measure of the water released from the pores between grains as a result of flow under gravity (specific yield).

Structure

Structural geology is the study of the faults, folds, fabrics and bedding of rocks. ‘Structure’ refers to a particular structural feature, or related series of features within a rock or region.

Terrace

A flat topographic feature formed by erosion or deposition of sediments by a river

Transmissivity

A measure of the permeability of an aquifer (i.e. the ease with which water can move through an aquifer). ‘Transmissivity’ is equivalent to hydraulic conductivity multiplied by the aquifer thickness and is reported as m²/day.

Unconfined aquifer

Typically shallow aquifers, recharged directly from rainfall infiltration onto the ground surface, or from water flowing from surface water bodies. Streams, lakes and wetlands are usually the surface expression of an unconfined aquifer.

Water table

The water surface of an unconfined aquifer in which the pressure is atmospheric

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Appendix A Bore survey data

Site	Easting	Northing	Water depth	Collar level	Collar elevation	Water depth	Water level elevation
Allison	1305974	5050720	14.3	0.2	340.5	14.2	326.4
Church	1305382	5047624	11.6	-0.1	332.9	11.8	321.1
Clutha River	1298879	5044812					271.4
ECNZ 14	1304104	5052675	21.0	0.3	347.0	20.7	326.3
ECNZ 17	1306434	5052765	36.0	0.3	365.1	35.7	329.5
G40/0004	1300222	5048491	-22.2	0.0	300.2	0.0	300.2
G40/0009	1305531	5040689	20.7	-0.7	274.9	21.4	253.5
G40/0013	1308006	5053196	21.1	0.1	420.6	21.0	399.6
G40/0019	1305625	5050396	11.0	-0.5	336.3	11.5	324.9
G40/0039	1307626	5051298	47.2	0.0	355.5	0.0	355.5
G40/0041	1302760	5052245	15.4	0.4	337.1	15.0	322.1
G40/0047	1300686	5049882	40.3	0.0	348.0	0.0	348.0
G40/0053	1301235	5050113	39.9	0.0	346.9	0.0	346.9
G40/0054	1305494	5046168	93.4	0.0	300.2	0.0	300.2
G40/0108	1301187	5044342	5.9	1.0	297.1	4.9	292.2
G40/0109	1301190	5044235	7.0	0.9	294.2	6.1	288.1
G40/0120	1304407	5048925	8.3	-0.5	330.0	8.9	321.2
G40/0129	1306012	5051491	18.5	-0.6	347.1	19.1	328.0
G40/0138	1302237	5048025	12.9	0.0	319.0	12.9	306.2
G40/0156	1301111	5051218	51.5	0.0	350.1	0.0	350.1
G40/0159	1303476	5047622	41.6	0.0	339.9	41.6	298.2
G40/0162	1302470	5051892	19.7	0.2	338.4	19.5	318.8
G40/0163	1304968	5053086	19.8	-0.6	349.0	20.5	328.5
G40/0169	1307835	5042979	31.3	0.3	345.2	31.0	314.2
G40/0178	1305558	5053628	33.5	-0.7	364.4	34.2	330.1
G40/0182	1299976	5047795	23.8	0.0	297.4	0.0	297.4
G40/0198	1302258	5051551	22.1	0.3	340.9	21.8	319.1
G40/0203	1301985	5049851	-4.3	0.0	326.1	0.0	326.1
G40/0226	1302511	5047565	19.5	-0.6	321.6	20.1	301.6
G40/0227	1306137	5051748	22.1	0.3	349.5	21.8	327.8
G40/0230	1303683	5051521	14.4	0.2	337.5	14.1	323.4
G40/0249	1306068	5048090	13.0	-0.6	336.9	13.6	323.3
G40/0250	1306664	5049266	32.3	-0.6	359.3	32.9	326.4
G40/0253	1300337	5047269	21.5	0.0	296.0	0.0	296.0
G40/0257	1305738	5048782	10.9	-0.6	336.4	11.5	325.0
G40/0261	1303566	5048822	9.6	0.4	327.9	9.2	318.8
G40/0264	1304944	5047696	11.0	-0.6	332.5	11.6	321.0
G40/0274	1300564	5047750	22.1	-0.6	322.1	22.7	299.4
G40/0276	1302086	5052433	36.0	0.8	358.2	35.2	323.0
G40/0277	1302670	5050812	1.5	-0.8	320.2	2.3	318.0
G40/0279	1306061	5046939	42.4	-0.7	355.6	43.1	312.5
G40/0294	1302497	5047325	18.0	0.3	318.5	17.7	300.7
G40/0295	1304395	5046063	96.5	0.3	390.3	96.2	294.1
G40/0296	1302315	5045981	76.1	0.4	374.1	75.8	298.3
G40/0298	1302775	5047748	23.1	0.2	324.5	22.9	301.6
G40/0306	1300367	5045734	21.7	0.0	313.8	21.7	292.1
G40/0307	1302410	5047237	16.8	0.2	317.0	16.6	300.4
Hawea River	1302353	5049033					310.8
Lake Hawea	1302426	5053642					340.5
Spring C	1305458	5042345					270.0
Spring E	1305598	5042339					269.0
Spring Mid	1302283	5043774					272.0
Spring US	1301092	5044175					280.0
Spring W	1305044	5042220					271.0
Sutherland	1305073	5047002	55.9	0.2	351.0	55.7	295.3
Wetland	1303558	5043425					273.7

Appendix B Bore chemistry data

Summary for all sites:														
	Depth (m)	pH	Conductivity (mS/m)	NO ₃ -N (mg/l)	NH ₄ -N (mg/l)	DRP (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	HCO ₃ (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	Fe (mg/l)
Samples	29	32	31	32	16	16	30	30	15	15	30	32	30	31
Min	16.0	6.9	7.3	0.03	0.005	0.001	12.6	0.68	0.41	1.6	36	0.4	2.6	0.010
Median	21.3	7.6	17.0	0.83	0.005	0.008	27.0	4.24	0.74	3.0	89	0.8	7.5	0.050
Max	111.2	8.5	25.0	10.02	0.020	0.025	35.7	7.67	1.06	7.3	130	6.0	13.8	1.970

Bore	Source	E	N	Depth (m)	pH	Conductivity (mS/m)	NO ₃ -N (mg/l)	NH ₄ -N (mg/l)	DRP (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	HCO ₃ (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	Fe (mg/l)
G40/0009	ORC	1305531	5040689	33.0	7.5	8.3	0.08	0.016	0.016	12.7	1.02	0.69	1.7	45	1.0	2.9	0.010
G40/0013	ORC	1308006	5053196	27.2	7.4	14.2	0.09	0.005	0.002	19.4	3.30	0.71	4.8	73	1.1	11.0	0.010
G40/0019	ORC	1305625	5050396	16.5	7.9	10.9	0.17	0.005	0.022	15.0	1.80	0.52	1.9	62	0.4	3.8	0.050
G40/0029	ORC	1308324	5054701	22.1	7.1	18.9	0.03	0.005	0.001	14.0	2.20	0.64	3.2	56	0.4	10.0	0.050
G40/0033	ORC	1306027	5047994	21.3	7.0	22.7	0.60	0.005	0.001	28.0	6.00	1.00	5.3	130	1.0	8.7	0.050
G40/0037	ORC	1305727	5047694		7.8	20.9	0.55	0.005	0.017	27.0	5.40	0.83	4.7	120	0.7	7.7	0.050
G40/0041	QLDC	1302760	5052244	21.4	7.0	8.2	0.13		0.001						0.8		
G40/0117	ORC	1305626	5047994	20.0	7.4	23.7	0.39	0.005	0.001	28.0	5.80	0.81	4.8	120	0.8	8.0	0.050
G40/0120	NGMP	1304825	5048894	16.0	7.5	14.5	0.37	0.010	0.019	25.0	2.60	0.77	2.6	89	0.6	4.3	0.020
G40/0129	NGMP	1306024	5051697	26.4	7.7	11.0	0.15	0.010	0.017	15.3	1.90	0.41	2.0	56	0.5	3.8	0.020
G40/0139	ORC	1305727	5047194	40.8	8.4	16.6	0.78	0.005	0.001	20.0	3.10	1.00	6.9	86	0.5	6.1	0.050
G40/0159	ORC	1303476	5047622	58.6	7.8	17.0	0.33	0.010	0.002	27.0	3.10	0.89	2.7	97	1.0	3.8	0.010
G40/0196	ORC	1306159	5053084	54.0	8.0	15.9	0.31	0.005	0.013	26.0	2.60	0.74	2.3	92	0.8	3.3	0.010
G40/0226	ORC	1302511	5047565	45.0	7.9	8.2	0.10	0.005	0.006	12.6	0.68	0.48	1.6	42	0.8	2.6	0.010
Spring1	ORC	1305609	5042348		7.6	17.4	1.73	0.005	0.008	24.0	4.10	1.06	7.3	96	2.4	3.5	0.010
Spring2	ORC	1302283	5043774		7.8	10.3	0.32	0.005	0.017	17.7	1.09	0.53	3.0	59	0.9	3.0	0.010
Samples	13			13	16	16	16	15	16	15	15	15	15	15	16	15	15
Min	16.0			16.0	7.0	8.2	0.03	0.005	0.001	12.6	0.68	0.41	1.6	42	0.4	2.6	0.010
Median	26.4			26.4	7.7	15.2	0.32	0.005	0.007	20.0	2.60	0.74	3.0	86	0.8	3.8	0.020
Max	58.6			58.6	8.4	23.7	1.73	0.016	0.022	28.0	6.00	1.06	7.3	130	2.4	11.0	0.050

Bore	Source	E	N	Depth (m)	pH	Conductivity (mS/m)	NO ₃ -N (mg/l)	NH ₄ -N (mg/l)	DRP (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	HCO ₃ (mg/l)	Cl (mg/l)	SO ₄ (mg/l)	Fe (mg/l)
G40/0054	Pvt	1305494	5046168	111.2	7.2		0.87								4.0		0.070
G40/0101	Pvt	1304926	5047694	19.4	6.9	18.8	0.56		0.025	22.0	4.55			100	0.5	3.7	0.025
G40/0174	Pvt	1305076	5049010	20.8	7.8	17.0	1.86			27.8	3.63			79	0.9	6.9	0.070
G40/0179	Pvt	1305205	5047530	46.7	7.5	23.0	3.40			30.2	5.69			100	1.4	9.0	0.500
G40/0195	Pvt	1305427	5047394	21.3	7.1		0.83								2.0		0.040
G40/0200	Pvt	1305935	5047911	19.5	7.3		10.02								1.0		0.740
G40/0210	Pvt	1305500	5047493	21.3	7.1		0.83								2.0		0.040
G40/0214	Pvt	1306015	5047864	26.8	7.9	24.0	3.60			32.1	5.73			110	1.0	9.1	0.050
G40/0220	Pvt	1305153	5048434	19.3	7.5	17.0	2.40			28.0	4.24			83	0.8	7.5	0.040
G40/0231	Pvt	1304960	5048326	18.8	7.9	18.0	2.60			31.5	4.40			94	0.7	7.1	0.040
G40/0235	Pvt	1305268	5048758	19.2	7.6	17.0	2.00			29.2	4.33			88	0.7	7.5	0.060
G40/0237	Pvt	1305315	5048961	19.8	7.7	16.0	1.90			24.7	3.51			81	0.7	8.5	0.130
G40/0242	Pvt	1306066	5047808	18.0	7.5	23.0	6.90			30.3	7.10			100	2.6	13.8	0.040
G40/0249	Pvt	1306068	5048090	18.3	7.6	24.0	6.40			32.0	6.61			100	1.5	9.8	0.110
G40/0250	Pvt	1306659	5049266	47.7	7.6	17.0	1.40			24.7	4.36			75	0.8	11.0	0.130
G40/0257	Pvt	1305738	5048782	21.3	7.7	20.0	2.30			28.9	4.94			88	0.8	8.7	0.220
G40/0261	Pvt	1303566	5048822	18.0	7.9	14.0	0.21			22.7	2.37			66	0.5	3.8	1.140
G40/0264	Pvt	1304945	5047697	20.3	7.6	21.0	2.90			33.1	4.94			97	0.8	7.9	0.230
G40/0279	Pvt	1306061	5046939	66.1	7.5	25.0	1.29			35.7	7.67			110	1.5	10.0	1.970
G40/0280	Pvt	1305594	5047722	16.5	7.6	21.0	3.80			29.0	5.70			95	1.0	8.9	0.051
G40/0293	Pvt	1307827	5042993	68.6	7.5	21.0	1.08			30.0	5.50			94	2.3	5.7	1.770
G40/0296	Pvt	1302315	5045981	101.0	8.4		0.23	0.020							6.0		0.200
G40/0299	Pvt	1304095	5051060	28.2	8.5	7.3	0.40			13.3	0.74			36	0.5	3.7	0.011
				Samples	16	15	16	1	0	15	15	0	0	15	16	15	16
				Min	16.5	7.3	0.21			13.3	0.74			36	0.5	3.7	0.011
				Median	20.8	7.6	1.90			29.1	4.75			94	1.0	8.2	0.070
				Max	111.2	8.5	10.02			35.7	7.67			110	6.0	13.8	1.970

Appendix C Land surface recharge modelling

Rainfall recharge has been calculated using the soil moisture balance model of *Rushton et al.* (2006). The approach is the same as that used for other groundwater basins in Otago (Wilson and Lu, 2012), and the reader is referred to this report for an overview of the methodology.

Climate data

Table B.1 lists the climate sites used for rainfall recharge modelling. The period of recharge modelling is constrained by the beginning of the potential evapotranspiration (PET) record, and the end of the Luggate rainfall record. This provides a continuous climate record from 1 January 1972 to 28 February 2006.

Table B.1. Hawea climate site records.

	Zone	Site	Start	End	Duration (years)
Rainfall	1-Te Awa	Lake Hawea (5218)	Apr-55	Aug-09	54.4
	2-Lakeside	Lake Hawea (5218)	Apr-55	Aug-09	54.4
	3-Maungawera Flat	Hawea Flat (5219)	Jul-21	Sep-11	90.2
	4-Hawea Flat	Hawea Flat (5219)	Jul-21	Sep-11	90.2
	5-High Terrace N	Hawea Flat (5219)	Jul-21	Sep-11	90.2
	6-High Terrace S	Luggate (5225)	Jun-13	Feb-06	92.7
	7-Sandy Point	Luggate (5225)	Jun-13	Feb-06	92.7
	8- Maungawera Valley	Lake Hawea (5218)	Apr-55	Aug-09	54.4
PET		Queenstown	Oct-91	Sep-11	20.0
		Lauder	Sep-85	Sep-11	26.1
		Alexandra	Jan-72	Jan-83	11.0
		Clyde	Jan-83	Jun-96	13.4
Modelling period			Jan-72	Feb-06	34.2

Potential evapotranspiration data was mostly sourced from the Queenstown Aero AWS site. As this record starts in 1991, the record was extended to 1972 by developing a relationship with a composite Central Otago record. This composite record consists of data from the Lauder, Alexandra and Clyde sites. The method used to derive the PET relationship is outlined in Wilson and Lu (2011), and gives the following correlation:

$$\text{Queenstown PET} = 1.0544 \times \text{Composite PET} (r^2 0.98)$$

As PET follows a seasonal cycle, and is therefore fairly predictable, the use of the number of PET sites does not contribute a significant error to PET estimates.

Rainfall data were sourced from three sites: Hawea, Hawea Flat and Luggate. The study area was divided into three broad zones to reflect the variable influence of rainfall at these sites. These zones were further divided along hydrogeological boundaries to give recharge over different aquifer domains, giving a total of eight zones for rainfall recharge modelling (Table B.1). The spatial coverage of the zones is mapped in Figure B.1.

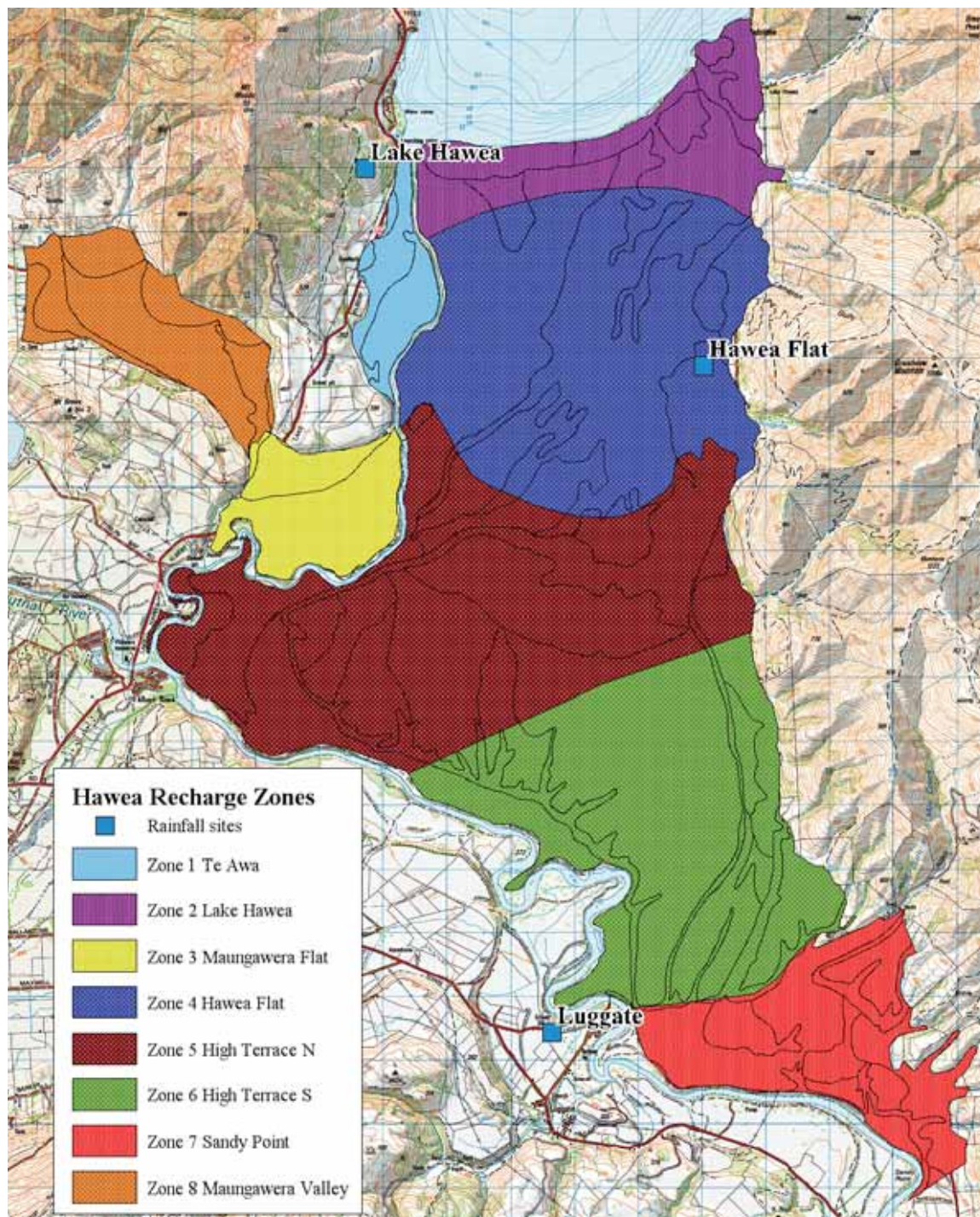


Figure B.1. Rainfall sites and land surface recharge zones

Soil data

A soil's storage potential, or water holding capacity, is the main factor determining drainage to the aquifer. The hydraulic properties of each soil type must be assigned or estimated for input to the soil moisture balance model. Landcare Research provided values of profile available water (PAW) and profile readily available water (PRAW). An SCS number was also provided by Landcare for estimating runoff during high intensity rainfall events. Values of Fracstor, or near surface soil storage, were estimated for each of the soil textures.

Table B.2 lists the main soils found in the study area and the hydraulic properties assigned to them. Soils at Hawea are all well drained sand or silt loams. The Luggate Series soil is the most dominant, and covers over 80% of the study area. The field capacity (FC) and PAW for this soil are moderate to low, which means that the soil moisture content is more responsive to rainfall events, and that recharge to groundwater can occur throughout the whole year. Soils with a high FC and PAW require more rainfall to become fully saturated. As a result, these soils typically only allow groundwater recharge to occur during winter months.

Table B.2. Soil types and hydraulic characteristics

Dominant Series	Description	Area (ha)	% Area	FC	PAW	PRAW	Fracstor	SCS
Koinga	Shallow sandy loam	620	8	40	30	21	0.2	45
Luggate	Stony sandy loam	621	8	81	50	30	0.1	45.2
Luggate	Stony fine sandy loam	1,243	17	110	60	36	0.3	50
Luggate	Shallow sandy loam	3,167	43	114	80	48	0.35	48.7
Luggate	Shallow silt loam	1,038	14	146	90	54	0.3	48.5
Maungawera	Shallow silt loam	472	6	158	100	56	0.3	49.8
Wanaka/Shotover	Mod deep sandy loam	1,014	14	217	120	69.5	0.3	56.5
Gladbrook	Mod deep sandy loam	88	1	235	140	84	0.25	55
Gladbrook	Mod deep silt loam	1,662	22	128	160	96	0.3	60
Gladbrook	Deep silt loam	238	3	139	200	90	0.4	63.1

Median recharge values

Zone	Dominant soil type	Area (ha)	Mean PAW	RCH (mm/y)
1 Te Awa	Mod deep sandy loam	258	135	203
2 Lake Hawea	Shallow silt loam	643	99	235
3 Maungawera Flat	Fine sandy loam	467	70	208
4 Hawea Flat	Silt loam	2,255	112	171
5 High Terrace north	Shallow silt loam	2,656	96	186
6 High Terrace south	Shallow sandy loam	2,078	77	137
7 Sandy Point	Shallow silt loam	979	88	125
8 Maungawera Valley	Deep silt loam	644	159	183

Appendix D Numerical model: Summary

Model Domain

The Hawea model focuses on Hawea Flat and the High Terrace aquifers, located to the south of Newcastle Road. The large bend in the river at Albert Town requires a model domain that extends across much of the Cardrona gravel aquifer. This large area has been included in the model to create a suitable flow field surrounding the focus area.

Dimensions: 17 km x 28 km

Total area: 47,600 ha; Hawea Flat Aquifer 4,263 ha; High Terrace Aquifer 6,090 ha

Minimum layer thickness: 15m

Cell dimensions: 250m x 250m, increasing to 660m x 660, at margins

Total active cells: 2,827; Hawea Flat Aquifer 682; High Terrace Aquifer 970

Boundary conditions

Lake Hawea was set as a boundary condition, with a water level of 340.5m, which was the level at the time of the September piezometric survey. The lake level was increased to a long-term median of 341.9m for contaminant transport simulations.

Bed conductance values are low for the mid Clutha (below Hawea confluence) and lower Clutha (below Red Bridge) reaches. The river has entrenched into silt in these areas, and most discharge is via springs along the gravel escarpments.

River Reach	Bed conductivity (m/d)	Bed conductance (m ² /d)
Upper Hawea	38	9,580
Lower Hawea	24	6,200
Upper Clutha	18	2,825
Mid Clutha	0.3	85
Lower Clutha	2.3	405

Hydraulic properties

Hawea Flat consists of glacial-till and outwash gravels, which are expected to be heterogeneous. A detail piezometric survey carried out on 20 September 2011 allowed for pilot points to be confidently used to create a conductivity field.

Hawea Flat Aquifer	K (m/d)	Sat thickness (m)	Transmissivity (m ² /d)
Min	0.6	22	21
Q1	12	35	443
Med	43	38	1,575
Q3	102	41	3,832
Max	302	55	13,335
Mean	73	37	2,778
Std Dev	79	5	3,091

High Terrace Aquifer	K (m/d)	Sat thickness (m)	Transmissivity (m ² /d)
Min	0.1	6	2
Q1	5	28	162
Med	22	38	843
Q3	46	44	1,850
Max	300	75	12,693
Mean	31	37	1,311
Std Dev	35	13	1,594

Parameter optimisation

Hawea Flat was optimised for September conditions, with low lake levels, which provides the best conditions for optimisation, with no estimation needed for pumping, irrigation or water race losses.

Optimised water levels

The largest residual errors are found in areas where the hydraulic gradient is steepest and are largely an artefact of the model-cell dimensions.

