Alexandra Groundwater Basin
Allocation Study

Otago Regional Council
Private Bag 1954, 70 Stafford St, Dunedin 9054
Phone 03 474 0827 Fax 03 479 0015
Freephone 0800 474 082
www.orc.govt.nz

ISBN 978-0-478-37646-3

Published September 2012

Foreword

Otago's prosperity is largely based on water. The Clutha River / Mata Au drains much of the Otago region and has the largest annual discharge of any river in New Zealand. However, despite the large total water volumes present in the region's water bodies, many areas of Otago are short of water. In many cases, irrigation particularly in these drier areas is critical to the continued well being of the people and communities who rely on the primary production it supports.

The Regional Policy Statements for Water provide for the Otago people and communities having access to water for their present and reasonably foreseeable needs.

Groundwater can be the sole or major source of water to supply basic water needs to communities and stock watering. Currently groundwater only supplies a small proportion of irrigation needs, however there is increasing pressure for people to turn to groundwater because surface water supplies are heavily allocated. Over abstraction can result in loss of supply to other users and therefore careful management is required to keep abstraction rates sustainable.

Groundwater resources have varying rates of recharge and often form a complex dependency with adjacent water courses, wetlands and stream networks. The effects of inappropriate land and water use and development on groundwater quantity and quality are often long term, and in some cases permanent. It is therefore important that particular consideration be given to the protection of aquifers for the continuing benefit of present and future generations.

Through the Regional Plan: Water and our Annual Plans we ensure linkage with the community to deliver the efficient use and protection of our groundwater aquifers.

This report describes future allocation of water from the Alexandra Basin. It is based on local knowledge, scientific evidence and monitoring information. The best way forward is to use to advantage this valuable resource but to maintain control so that over abstraction does not occur. This is a complex topic and further monitoring and review of the aquifer will continue to ensure a sustainable allocation.

Table of Contents

Table of figures

Table of tables

Executive summary

The four aquifers in the Alexandra groundwater basin are located within glacial outwash, alluvial fans or flood plains. The Earnscleugh Terrace aquifer and the Dunstan Flats aquifer have a common origin, in that they result from a glacial outwash following the Albert Town glacial advance; however, they differ in that the Dunstan Flats aquifer is in closer hydraulic communication with the Clutha River that divides them. The Manuherikia claybound aquifer, overlooking the Dunstan Flats, is composed of high permeability, deep water-table Lindis outwash, and also low permeability alluvial fans that have formed on the slopes below Leaning Rock. The Manuherikia alluvium is more closely associated with the Manuherikia River, in both its formation as flood plain alluvium and its linkage between the river and groundwater system.

The aquifers are largely unconfined, although they vary greatly in terms of depth to water table, aquifer properties and hydraulic communication to the adjoining surface water system. The Lindis outwash terraces of the Manuherikia claybound aquifers tend to have high permeability and large depths to the water table. The Manuherikia alluvial aquifer has shallow saturated thickness and a shallow water table. All aquifers are replenished or recharged at the land surface by a combination of water infiltrating from excess rainfall, pasture irrigation losses, leakage from water races and by-wash soak holes. The Fraser River, as it crosses the permeable surface of Earnscleugh Flat, loses a substantial portion of its base flow to the underlying aquifer, with an average of 25 million cubic metres (Mm^3/y) of water entering the Earnscleugh aquifer by this vector every year. The net excess of the groundwater that recharges the Alexandra Basin aquifers percolates through the gravel deposits between the water table and base of the gravels until it discharges at one or more of the following surface water bodies:

- miscellaneous springs and seepage drains along the other edges of outwash terraces
- Clutha River
- lower Manuherikia River
- lower Fraser River.

Groundwater recharge modelling has been used to develop a more comprehensive understanding of the aquifer water balances and to assess the groundwater allocation status of each aquifer. The recharge and groundwater allocation settings are summarised below.

Summary of aquifers, numbers of takes, recharge and groundwater allocation issued in current consents

	No. of takes	Mean annual recharge (Mm^3/y)	50% of mean annual recharge (Mm^3/y)	Consented allocation (Mm^3/y)
Dunstan aquifer	34	3.68	1.84	1.45
Earnscleugh aquifer	4	25.5	12.75	0.514
Manuherikia claybound aquifer	11	1.36	0.68	0.610
Manuherikia alluvium aquifer	4	1.41	0.7	0.014
Alexandra Basin: Total	**53**		**15.97**	**2.59**

None of the aquifers in the Alexandra Basin are allocated at more than 50% of the mean annual recharge, although the Dunstan and Manuherikia claybound aquifers approach this point. In accordance with policy 6.4.10A(ii)(1) of the Regional Plan: Water (RPW), which stipulates that the default allocation limit must be 50% of the calculated mean annual recharge, all of the basin's aquifers can be considered "under allocated". It is considered that this allocation status and volume setting is appropriate for the groundwater management of the Alexandra Basin aquifers.

1 Introduction

1.1 Background

While the infrastructure and population contained within the Alexandra sedimentary basin is mainly centred on Alexandra, it also includes the township of Clyde and the communities of Earnscleugh, Springvale and Galloway. Geologically, the sedimentary basin has produced the conditions for enhanced groundwater resources from such sediments as sandy gravel. In 1995, the combination of water demand to support the basin's population and industries, and the available underground water resources, motivated Otago Regional Council (ORC) to investigate and monitor the area's aquifers. ORC commissioned field investigations then, and in 2001, used the field data to extend existing geo-hydrological analyses. In 2005, the council presented its initial strategy on the allocation of groundwater in the Alexandra basin.

As part of ORC's renewed approach to allocating groundwater and surface-water, ORC has resolved to prepare a groundwater allocation plan for the Alexandra Basin, which includes Dunstan Flats, Earnscleugh Flat, Manuherikia claybound and the lower Manuherikia alluvial aquifers. This investigation intends to examine the aquifer-recharge processes and dynamics in order to develop a physical basis for allocating groundwater in the Alexandra basin.

1.2 Study's objectives

The study's objectives are to provide:

- a basis for recommending groundwater allocation limits for the Alexandra basin
- an updated reference to the basin's groundwater hydrology.

2 Previous studies

The first investigations and data gathering for the groundwater data in the Alexandra basin were probably related to the Clutha Valley Development (CVD) undertaken by a mixture of governmental agencies, namely:

- Ministry of Works and Development (MWD)
- Clutha Valley Development (CVD) or Clutha Power Project (CPP)
- DSIR New Zealand Geological Survey (NZGS)
- Ministry of Agriculture and Fisheries (MAF)
- DSIR New Zealand Soil Bureau
- Otago Catchment Board (OCB).

During the investigation and commissioning phase of the Clyde Dam development, the focus was on the groundwater potential of the Earnscleugh Flat and Dunstan Flats (Jewel, 1978; Weissing, 1981; Proffitt, 1985). In particular, the Clyde Dam tailrace deepening project, which began in 1986, generated a great deal of investigation and monitoring (Proffitt, 1987). Data gathering was at its most intensive between 1992 and 1994 to coincide with the start of power station operations and tail-race deepening activities. Approximately 210 separate bores on either side of the Clutha River, downstream of the Clyde Dam, were monitored during this period (Thomson, 1992; Thomson, 1993; Saul & Watts, 1993). In 1998, a review of the groundwater level monitoring results allowed a revision of the number of monitoring bores (AquaFirma Ltd, 1998). In the early 2000's management for recording continuous groundwater levels of the Dunstan Aquifer at Muttontown was transferred to ORC.

The CVD-related activities included drilling hydrogeological investigation bores in a number of places on the Earnscleugh Flat and Dunstan Flats, some existing bores were deepened and alternatives to the current Alexandra water supply were investigated. The question of intensifying the irrigation of the Earnscleugh Flat generated engineering geology studies by NZGS, MWD and soil investigations by DSIR Soil Bureau (Jowett, 1983; Paterson, 1984; Beecroft *et al*., 1986; Joe *et al*., 1984).

In the mid-1990s, gold prospecting and alluvial mining plans on the Earnscleugh Flat advanced to the level of commissioning hydrogeological investigations (AquaFirma Ltd, 1995; AquaFirma Ltd, 1997). Resource consent applications were lodged with ORC in 1999 and granted in 2004 (L & M Mining, 1994). L & M Mining Ltd began mining on the southern Earnscleugh Flat in 2009.

Then, in 1995, Central Otago District Council (CODC) commissioned a number of groundwater investigations into the hydrogeology of the Alexandra zone of Dunstan Flats to manage the council's solid waste and water supply assets in the area (Pattle Delamore Partners, 1995).

In 1998, ORC commissioned a large field survey of the Alexandra basin (IRRICON, 1998). This survey was the first to include the Manuherikia claybound and Manuherikia alluvial aquifers. The survey found the following numbers of bores used for taking groundwater in each of the zones within the Alexandra Basin:

Earnscleugh Flat	85
Dunstan Flats	153
Manuherikia claybound	54
Manuherikia alluvium	46
Total:	**340**

The study included the location and bore-collar surveying of all bores described. Water levels were measured and samples of groundwater were taken for analysis. Currently, ORC database includes 595 records of wells in the Alexandra Basin, so the record count has risen significantly since 1998.

Since 1998, ORC has commissioned two aquifer water balances of the Dunstan Flats and Manuherikia claybound aquifers (MWH, 2003; MWH, 2004). In 2005, ORC undertook an investigation to estimate the groundwater allocation for the entire Alexandra basin (ORC, 2005). This last document was essentially a review of existing information, and it remains the most recent on the groundwater management of the area.

In 2007, ORC formed a partnership with gold explorer, Glass Earth Gold Ltd, to undertake a region-wide airborne geophysical survey. The survey included the Alexandra basin, but excluded the Alexandra and Clyde township areas, as flight rules prohibited flying lower than 500 feet (150 m).

In this study, we correlated saturated aquifer parameters with earth-resistivity values to characterise groundwater properties. Previously, it was thought that the resistivity signature of saturated clean, sandy gravel lay between 400 Ωm and 1000 Ωm. Resistivity maps or conductivity profiles confirmed this to be the pattern in the clean, sandy gravel aquifers across Earnscleugh Flat and the Dunstan Flats, and the location of the aquifers is in keeping with their known distribution across the basin.

2.1 Non-investigation monitoring

Several agencies have also conducted groundwater studies of the Alexandra basin. These are summarised below.

2.1.1 Contact Energy Ltd

As the owner of the Clyde Dam, Contact Energy assumed the databases and environmental monitoring responsibilities of the CVD, MWD and DSIR's Geology & Geophysics Division in the Upper Clutha. This related primarily to medium-term groundwater-level monitoring in purpose-built piezometers and private bores. The company correlated these levels with surface-water levels measured in a river-recorder network operated by NIWA. In 1985 and 1986, it conducted manual dipping of private bores to establish a baseline of groundwater levels across the Earnscleugh and Dunstan flats aquifers.

In April 1986, continuous monitoring began, using a piezometer P-46, near the confluence of the Waikerikeri Creek and the Clutha River. In 1992, the monitoring was rejuvenated in anticipation of the tailrace deepening project. About 210 piezometers or bores were included in the monitoring programme at any one time, including about a dozen piezometers, fitted with continuous level recorders.

After a review of the level-monitoring network in 1998 (AquaFirma Ltd, 1998), Contact Energy decided to scale down its activities relating to the Dunstan and Earnscleugh flats. All private bores manually monitored by Contact Energy had their last measurement at the end of April 1998. Several continuous recorder sites continued until 2005, when the company relinquished operation of bore P-46 (ORC well record G42/0695) to ORC.

2.1.2 L and M Mining Ltd

The alluvial mining proposal for the southern Earnscleugh Flat began groundwater studies in 1992. However, the proposal did not progress to groundwater level monitoring until 1997 in the preparations for applying for resource consents. The company monitored a total of 31 bores on up to 83 occasions between 1993 and 1997. There was a long hiatus until 2009, when the consents granted by Environment Court consent order (particularly, consent number 2000.410) were activated. The level-monitoring network included groundwater-level monitoring in an indeterminate number of bores and the groundwater-quality monitoring of four.

2.1.3 Central Otago District Council

The district council operates the Alexandra water-supply bore field alongside the Clutha River at Alexandra and the landfill behind it. Both facilities are subject to resource conditions requiring the monitoring of groundwater level and quantity.

2.1.4 Various consent holders

Over 65 resource consents to take groundwater are held for Alexandra basin groundwater resources, many of which contain monitoring conditions for the volume of take, groundwater level or groundwater quality. The data are sometimes available through the ORC compliance filing system.

2.1.5 ORC State of the Environment monitoring

In 1996, ORC instituted State of the Environment monitoring (SOE) in the Alexandra basin. In most cases, SOE monitoring has remained in operation to the present day. Four of the monitoring sites on the Dunstan and Earnscleugh flats are part of the National Groundwater Monitoring Programme (NGMP). Two SOE groundwater quality monitoring sites are maintained in each declared aquifer (Manuherikia alluvium, Manuherikia claybound, Dunstan Flats and Earnscleugh Flat); whereas two SOE groundwater level monitoring sites, which coincide with the frequency of water quality sampling, are maintained in each of Manuherikia alluvium and Manuherikia claybound aquifers.

3 Existing environment

3.1 Location

The Alexandra basin is located immediately upstream of the junction of the Clutha River and its major tributary, the Manuherikia River. The basin lies between the Cromwell, Ophir, and Roxburgh gorges. The township of Alexandra, which is also the seat of Central Otago district, lies at the junction of the Clutha and the Manuherikia rivers, immediately upstream of the Roxburgh Gorge. Figure 1 shows the location of the aquifers and the layout of the basin.

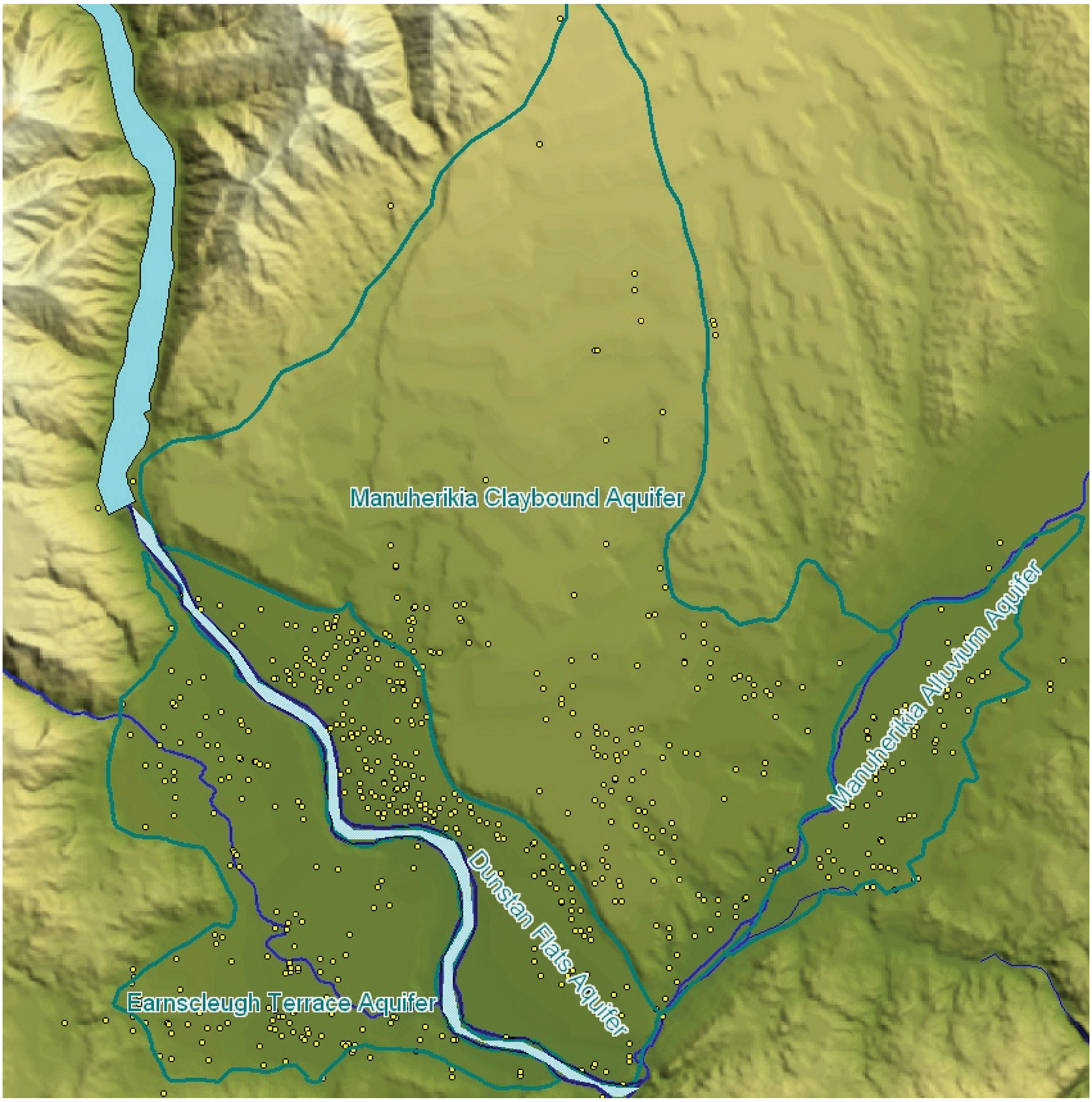


Figure 1 Location of Alexandra Basin aquifers. Density of bore records is shown by yellow dots

3.2 Geology

The geological structure that folds the basement schist defines the Alexandra Basin. This folding and associated faulting has preserved much of the Tertiary-aged sediments from the erosion that would otherwise have removed them. The softer sediments and topographic lows have also tended to capture the modern river systems. The river systems, particularly the Clutha River, deposited significant alluvial terraces and fans during the Quaternary period.

3.2.1 Basement schist

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

The surrounding ranges, primarily the Old Man, Obelisk, Cairnmuir, Dunstan, and Rough Ridge, are exclusively composed of basement schist rocks. These ranges define the margins of the sedimentary basin. Otago has several sedimentary basins, which are caused by the down-warping of the basement rocks. The Alexandra basin is the terminal feature of a large series of adjoining basins trending south-west from St Bathans and terminating at Earnscleugh.

3.2.2 Tertiary terrestrial sediments

During the Miocene geological period, Central Otago featured large, continental-scale rivers and lakes, which dropped substantial volumes of sediment carried from the uplifting ranges to the north. As Otago's current ranges formed in the Pleistocene and became exposed to increasing erosive forces, the bulk of these terrestrial sediments eroded away. However, remnants of the lake and river sediments were preserved and protected from erosion within the down-warped basins, such as the Alexandra basin.

These terrestrial sediments are grouped stratigraphically in the Manuherikia group, which contains a variety of sub-groups and formations. The main sub-divisions are:

- the Manuherikia formation, which consists of silts, clays, occasional sand and lignite, derived from lake deposition
- the Dunstan formation, consisting of silts, sands and occasional quartz pea-gravels, derived from river and lake delta deposits.

The Miocene terrestrial sediments are almost exclusively covered and obscured by Quaternary sediments in the Alexandra basin, so it is rare to find the Miocene sediment exposed at the surface. They are described from former gold mines or coal mines of previous centuries, and from drill hole logs.

3.2.3 Quaternary terrestrial sediments

The Quaternary geological period encompasses the Pleistocene ('Ice Age') period, of the last two million years, and the more recent Holocene period, of the last 6,000 years - during which there was stabilisation of the global climate and sea level. The headwaters of the upper Clutha and Wakatipu catchments were the site of significant valley glaciations during the four main glacial advances of the Pleistocene. While only peri-glacial effects were felt in the Alexandra basin during the glacial advances, the effect of glaciation on the upstream catchments was profound. During the inter-glacial periods between glacial advances, the rivers filled with glacial aggregates (outwash) that were carried downstream. Ultimately, the basin filled with succeeding generations of glacial sediment comprising boulders, cobbles, substantial quantities of gravel, sand, mica-rich silt and clay.

Four glacial advances leaving significant gravel outwash terraces have been recognised in the basin. From the youngest to the oldest, the upper Clutha glacial advances are:

- **Hawea advance**
- **Albert Town advance**
- **Lindis advance**
- **Lowburn advance.**

The timing of the deposition of the Manuherikia alluvium at Galloway is loosely correlated with the Hawea advance. The Albert Town advance left in its wake the main terrace surface that makes up the Earnscleugh and Dunstan flats. The Lindis advance left the higher Airport Terrace, between Dunstan Road and Springvale Road, in the Manuherikia claybound aquifer zone. Less significant is the Lowburn advance, which left scattered outwash remnants at Reservoir Terrace, above Clyde.

With differences in glacial advance and source aggregate deposited with each advance come differences in grain size, sorting and sedimentary features. These differences between the various glacial terrace deposits and their composition were significant in controlling groundwater properties. This aspect is explored further below.

Several alluvial fans also cross the basin as part of high gradient tributary streams. The most notable are:

- Waikerikeri fan, following the Waikerikeri Creek from the Dunstan Range to the Clutha River
- Omeo fan, following Omeo Creek onto Earnscleugh Flat.

By definition, alluvial fans are superficial and thin. The Waikerikeri fan has a range of ages, but the most recent alluvial veneer post-dates the Hawea advance.

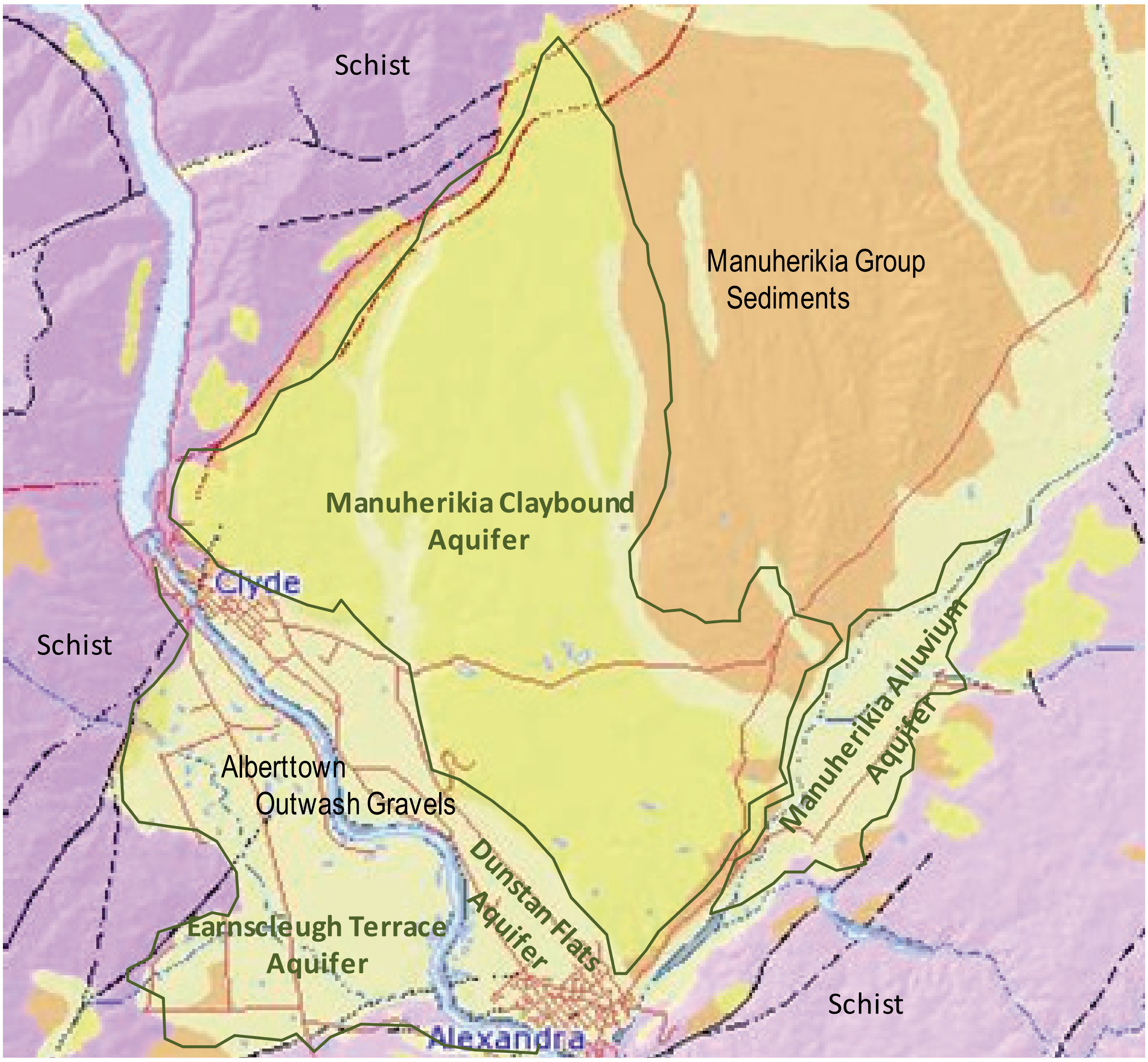


Figure 2 **Sketch geology of the Alexandra Basin**

3.3 Surface-water hydrology

The major perennial surface-water courses within the Alexandra basin include:

- Clutha River / Mata Au
- Manuherikia River
- Fraser River
- Waikerikeri Creek (intermittent in lower reaches).

The generalised pattern of rainfall and runoff in the Alexandra basin is for significant runoff to be generated outside of the basin, flow through as rivers and to leave the basin in the Clutha River. Surface water in the Clutha River enters the basin at the Clyde Dam from Lake Dunstan. The lake has a mean inflow of 510 cubic metres per second (m^3/s) or at an annualised rate of 16,090 Mm^3/y. The bulk of this upper Clutha and Kawarau surface water is derived from lakes Wakatipu, Wanaka and Hawea, which are originally glacial, as they are fed from high-net precipitation watersheds against the Main Divide. The Manuherikia River rises in a smaller and lower precipitation catchment. The mean flow of the Manuherikia River at Ophir is 13.7 m^3/s or an annualised rate of 432 Mm^3/y.

The Obelisk, Cairnmuir and Dunstan ranges surrounding the Alexandra Basin feed tributaries such as the Fraser River, Omeo Creek and Waikerikeri Creek. In general, there is a strong positive correlation between land elevation and rainfall/snowfall; typically, there is 350 millimetres per year (mm/y) of precipitation on the floor of the Basin, compared to more than 650 mm/y found on the flanks of the ranges. Thus, much of the tributary flow is generated in the flanks and flows onto the glacial outwash terrace surface as tributaries, where creeks can become intermittent due to the effects of irrigation abstraction, bed infiltration to the water table and riparian evaporation. Indeed, much of the basin floor is not drained by flowing creeks at all. Any excess water drains to the underlying water table instead, except in the case of flash flooding.

3.4 Groundwater hydrology

Much of the available groundwater in the basin is contained within unconfined, water-table aquifers, which are primarily recharged by irrigation losses. These groundwater systems discharge their excess into the Clutha, lower Manuherikia or into the last kilometre of the Fraser River. The aquifers are mainly high permeability sandy gravel systems, within glacial outwash of the Albert Town or Lindis advances. The base of these sandy gravel aquifers is generally defined by very low permeability silt and the mudstone beds of the Manuherikia group sediments.

3.4.1 Earnscleugh Flat

The Earnscleugh Flat consists primarily of Albert Town advance outwash, with boulder lags towards the base of the outwash, sandy gravels, with occasional cobbles, sand bodies and minor silt. These outwash gravels host a laterally extensive, continuous and unconfined aquifer, which is perched upon the underlying, low-permeability Manuherikia group sediment. Testing of the unconfined aquifer, conducted throughout the Earnscleugh Flat, has revealed transmissivity in the thousands of square metres per day (m^2/d) and permeability (as horizontal hydraulic conductivity) in the hundreds of metres per day (m/d).

The Earnscleugh Flat aquifer is notable in having substantial sources of natural and artificial recharge. The Fraser River leaves a schist-rock gorge at Fraser Domain, at the high end of Earnscleugh Flat. As it passes out onto the glacial outwash, the following gains and losses of river flow occur:

- inflow of water from the Pioneer Generation power station tailrace
- inflow of water from the Clyde Dam flow-augmentation pipeline
- the abstraction of river flow into several water race intakes
- the progressive infiltration of river water through the bed of the river to the underlying water table.

The moderate permeability of the river bed and the high permeability of the aquifer cause a significant loss of river flow to the aquifer. Below Fraser Domain, the river and the water table become detached, causing the infiltrating river water to pass through an increasing thickness of unsaturated gravels on its way to the water table. About 25 Mm^3/y of river water infiltrates through the bed of the Fraser River to the water table and recharges the aquifer. Downstream of the Earnscleugh Road crossing, the Fraser River increases bed gradient as it cuts down into the terrace surface and approaches the Clutha River's confluence. Therefore, the bed of the river once more touches the water table in the last kilometre upstream of the confluence. Within this zone, the polarity of water exchange with the aquifer is reversed and groundwater seeps into the Fraser River, augmenting its flow to approximately 16 Mm^3/y.

The Earnscleugh Flat aquifer is also recharged by infiltration of soil water across its land surface. Under natural hydrological conditions - low rainfall levels of excess rainfall even through soil profiles of low retention capacity - the amount of seasonal recharge would be low (less than 50 millimetres per annum (mm/y)). However, the surface of Earnscleugh Flat is crossed by an extensive network of leaky water races, and the irrigation practised is largely wild flood or border dyke. Consequently, a substantial portion of irrigation water applied contributes to land surface recharge to the aquifer.

As mentioned, the base of the Earnscleugh Flat aquifer is floored in Manuherikia group sediments. Drilling information indicates that these sediments consist of mudstone, siltstone and silty sandstone, all lithologies that one would expect to have low permeability. The resulting Quaternary-Tertiary contact is even higher than that of the entrenched Clutha River, east of Earnscleugh Flat, where the aquifer is 'perched' above the river. Springs and zones of seepage are visible in the river margin between the Earnscleugh terrace and the Clutha River, which supports the idea that the aquifer's water table does not make significant free connection with the Clutha. The lowest kilometre of the Fraser River is also a significant zone of discharge from the Earnscleugh Flat aquifer, as suggested by the arrangement of water-table contours in previous reports on the aquifer's hydrology.

3.4.2 Dunstan Flats

The Dunstan Flats are also an outwash feature of the Albert Town advance. The terrace surface can be correlated with the Earnscleugh terrace across the Clutha River, suggesting that they were once joined and/or formed under the same sequence of outwash deposition. The Dunstan Flats extend from Clyde to Alexandra townships, and are bounded by the Lindis outwash terrace to the northeast and the Clutha River to the southwest. Albert Town outwash gravels host a laterally extensive and largely continuous, unconfined aquifer. In contrast to the Earnscleugh Flat aquifer, the outwash gravels are underlain by older gravels from the early Quaternary period, possibility formed at the time of the Lowburn advance. Early Quaternary gravels are permeable, but less so than the overlying Albert Town outwash. The Early Quaternary Gravels Manuherikia group sediments at their base at a much lower elevation than the similar Quaternary-Tertiary contact on the Earnscleugh side of the Clutha River. A major difference between the Earnscleugh Flat and the Dunstan Flats aquifers is that the latter is not perched above the Clutha River by the Quaternary-Tertiary contact. Instead, its base tends to be below the river bed and to make a direct connection with the river. This proposition is supported by the observation of the response of the water table to flooding of the Clutha River. Because of the large and hydrologically diverse upstream catchment of the Clutha, flooding may occur in the river without the Alexandra basin having experienced the rainfall that caused the floods. Therefore, the observation that Dunstan Flats' bores near the river rise significantly in response to floods suggests a direct connection between the river and aquifer.

Several aquifer tests have been conducted on Albert Town outwash gravels (i.e. late Quaternary gravels) that have been used to derive estimates of transmissivity and permeability (transmissivity ranging between 1,250 to 7,000 m^2/d). However, only one test has been conducted on the early Quaternary gravels (transmissivity of 2.5 m^2/d).

The pattern of recharge of the Dunstan Flats aquifer is simpler than that of the Earnscleugh Flat aquifer. The aquifer has a moderately deep water table throughout and is recharged from the following sources:

- the infiltration of irrigation losses
- natural rainfall-induced infiltration of soil-water
- the losses of Waikerikeri Creek as the Waikerikeri alluvial fan enters Dunstan Flats from the north
- the subsurface inflow of groundwater from the adjoining Manuherikia claybound aquifer.

One of the larger recharge process is estimated as the infiltration of irrigation losses. The Manuherikia Irrigation Society imports substantial quantity of Manuherikia River water to the Dunstan Flats in water races almost to the banks of the Clutha River. The application of the water has been typically prone to infiltration losses, and the terminals of the water races sometimes include soak holes for the disposal of surplus water (by-wash). Averaged across the wider Dunstan Flats, the irrigation-induced recharge is estimated at approximately 300 mm/y. Natural, rainfall-only recharge over the low-retentive soils of the Dunstan Flats is probably limited to less than 50 mm/y under soil groups of low retention capacity.

The Dunstan Flats aquifer has one primary site of groundwater discharge: the Clutha River. Water table contour maps of the aquifer support this idea, as they show water-table contours arranged parallel to the course of the Clutha River, suggesting that the majority of groundwater passes through the aquifer to join the river directly.

3.4.3 Manuherikia claybound aquifer

The name of Manuherikia claybound aquifer was chosen in 1998 for inclusion in the Regional Plan: Water to make a distinction between the high permeability outwash of the Dunstan Flats and the lower permeability outwash of the Lindis advance. The term ‘claybound’ may have originated from observations and bore logs taken north of Springvale Road, causing a wide range of characteristics to be lumped into a single aquifer designation. However, the area that the aquifer covers also includes the Lindis outwash, Airport Terrace and less distinct landforms such as the Waikerikeri fans.

Groundwater exploration north of Springvale Road encountered pervasively silty, weathered gravels of significant thickness and a moderate depth to the water table. Aquifer testing associated with vineyard development there found values of hydraulic conductivity of approximately 1 m/d (bores G42/0626 and G42/0613), which are, at least one order of magnitude, lower than the Dunstan Flats aquifer. The lower permeability of this part of the Manuherikia claybound aquifer is believed to be the result of geochemical alteration (weathering) of the non-quartz components of the outwash, which, in turn, enriches the weathered material with silts and clays.

Water-bore development in the Letts Gully Road area of the aquifer has revealed a different pattern. Bore logs indicate the presence of less silt and clay within gravel deposits in this area. Significantly, the depth to water table is substantially greater than north of Springvale Road. In Letts Gully the depth to water ranges between 40 m and 65 m, depending on the site of measurement. The supposition is that the permeability of the Letts Gully outwash is substantially greater than the aquifer materials north of Springvale Road, which allows the water table to stabilise at significantly lower levels.

The only natural water body crossing the Manuherikia claybound aquifer is Waikerikeri Creek, although the Manuherikia River makes up its southeast boundary of the declared aquifer. Interestingly, no natural surface water bodies of a perennial nature were found in the Airport Terrace or Letts Gully parts of the aquifer. Possibly a combination of dry climate and infiltration of excess soil-water to the water table through permeable outwash prevents the coalescing of runoff into a water course.

3.4.4 Manuherikia alluvium

The Manuherikia alluvium or Manuherikia alluvial aquifer is defined by the flood plain of the Manuherikia River on its true left bank between the exit of the Ophir Gorge and Alexandra. This area, and the Quaternary alluvium within it, defines a shallow, unconfined aquifer in hydraulic connection with the Manuherikia River. Bore logs suggest a degree of consistency in the depth to the base of the alluvium of about 8 m. The water table is relatively shallow and slopes with the river. No historic aquifer tests are known to have been conducted on bores installed in the Manuherikia alluvium.

The inflows and outflows of the Manuherikia alluvium are understood to be closely tied to the presence of the Manuherikia River and the practice of low-efficiency irrigation on parts of its surface. The Galloway Irrigation Society takes up to 300 l/s of water from the Manuherikia River at the upper end of the alluvium and spreads it on subscribers' land to maintain pasture and tree-crop growth during the spring, summer and autumn months. Water is also diverted out of the Dip Creek tributary. The upper and lower Manorburn dams provide a water-harvesting system for the scheme, with the water also being used for irrigation on the alluvium in the irrigation season.

Some groundwater discharge occurs as spring flow on the western, downhill side of Fisher Lane, which coincides with the transition from the modern floodplain to the Hawea advance terrace surface. Anecdotally, these springs are more likely to flow strongly once irrigation starts in September.

3.5 Groundwater quality

3.5.1 History

Early attention on the groundwater quality of the wider Alexandra basin focused on the results of an early study commissioned by ORC (IRRICON, 1998). This survey collected 43 samples from the basin's bores to characterise the aquifers' hydro-chemistry.

The groundwater of the basin was remarkably consistent within and across aquifers: low in iron in all but 15% of samples, and low in nitrate. Water hardness is an aesthetic detraction of many samples taken from Alexandra basin bores. The major ion concentrations were summarised as follow in Table 1:

Table 1 Major ions in Alexandra basin groundwater

	Concentration range (g/m^3)
Calcium (Ca^+)	15 – 40
Magnesium (Mg^+)	3.5 – 6
Sodium (Na^+)	6 – 10
Chloride (Cl^-)	2.5 – 5
Sulphate / sulphate (SO_4^-)	5 – 10
Bicarbonate (HCO_3^-)	60 – 100

In general, the groundwater quality of the Alexandra Basin is good and suitable for most applications. Clyde township has some of the densest concentrations of septic discharges in Otago. Despite these vulnerabilities, only 8% of the samples across the basin returned positive faecal coliform results, which may be due to the thick unsaturated zones found everywhere within the Alexandra basin, with the exception of the Manuherikia alluvium.

Central Otago District Council maintains the Alexandra water-supply bore field on the north-eastern bank of the Clutha River. These shallow bores are within 20m of the river, but the water chemistry reflects a mixing of aquifer and river water. Consumers of the bore-field water have registered repeated complaints of 'limey' or 'hard' water. The district council has been pursuing investigations into shifting the bore field to a position with lower groundwater hardness for some years.

3.6 Patterns of groundwater use

3.6.1 Historical patterns of groundwater use

Traditionally, surface water brought to individual properties in water races was the primary source of water. The Fraser Irrigation Company, the Manuherikia Irrigation Society, and the Galloway Irrigation Society are the main suppliers of irrigation water today. Groundwater tended to be used largely for domestic potable water supply, and was considered to be unsuitable for irrigation because of the cost of pumping the water to the surface and of the larger diameter bores compared to the gravity-fed water race supplies.

3.6.2 Current water use

More recently, private interests have explored the option of developing groundwater supplies for small-scale irrigation and communal water supply. More efficient irrigation techniques with newly introduced crops, such as the drip irrigation of grapes, have reduced the need for irrigation and justified the use of bores from an economic perspective. Fifty-three resource consents to take groundwater in the basin have been issued and remain current. Only twenty include a requirement for metering the volume of water taken. At present, ORC holds incomplete information on the actual use rates of groundwater pumped from aquifers. However, with the steady improvement in the implementation of water metering on remaining groundwater-take consents, more complete data will emerge in the future.

ORC allocates (by resource consent) about 2.5 Mm^3/y of groundwater from the four aquifers in the basin. This represents:

- about 1.5 Mm^3/y for the Dunstan aquifer
- approximately 0.5 Mm^3/y each from the Earnscleugh and Manuherikia claybound aquifers
- a negligible amount from the Manuherikia alluvial aquifer.

Irrigation and communal domestic end-uses of the water make up the majority of the groundwater takes. Minor additional end-uses include frost-fighting and bottling of water.

Non-consumptive water-take consents have not been included in the calculation of aquifer allocation volume because they are unlikely to affect the aquifer water balance. Two examples of consent that do not need be counted in the allocations are the Alexandra bore field and the Earnscleugh Flat goldmine. CODC operates the Alexandra borefield for the Alexandra township water supply. This bore field consists of three 15 m deep bores installed within 20 m of the river's edge. The proximity of the bores to the river and the high transmissivity of the alluvium mean that the extraction of water at the bores is counter-balanced by the inflow of river water to the aquifer; therefore, the 2.5 million cubic metres of water allocated to the bore field is assigned to the river rather than to the Dunstan aquifer. The Earnscleugh Flat goldmine excavates the glacial outwash near the base of the deposit, thereby intercepting the water table. Large pumps are used to create a temporary drawdown cone surrounding the excavation, thus permitting the mine to operate a lowered water level. The excess water is pumped out and discharged to land on the terrace surface, thereby inducing recharge of the aquifer. Since the evaporative losses of this dewatering process are negligible, the operation is non-consumptive in terms of the aquifer's water balance.

4 Aquifer water balance

Knowing an aquifer's water balance - the accounting of its inflows and outflows - is important in understanding the hydrology of groundwater basins. The water balance of an aquifer is usually expressed arithmetically, as follows:

Soil profile recharge + Surface water recharge = Discharge +Well pumping ± storage

'Soil profile recharge' and 'surface water recharge' or 'discharge' are terms to describe complex hydrological processes between the soil profile or the water-course bed and the groundwater. In the case of the Alexandra Basin aquifers, rainfall recharge, irrigation excess soil drainage, downward infiltration through water-course bed and upward seepage into the water-course bed are all active components of the water balance. Historically, several water balances have been undertaken for the Alexandra basin aquifers, particularly from the Earnscleugh and Dunstan aquifers. AquaFirma (1998) carried out a water-balance test for the Earnscleugh and Dunstan aquifers; after which ORC commissioned two water balances of the Dunstan Flats and Manuherikia claybound aquifer (MWH, 2003; MWH, 2004). The investigations took into account the following water-balance terms:

Earnscleugh Flat

- rainfall recharge
- irrigation excess soil drainage related to the Fraser Irrigation Scheme
- downward infiltration of Fraser River water, between the Fraser Domain and the Earnscleugh Road crossing
- upward seepage of the Earnscleugh aquifer water into the lower Fraser River, immediately upstream of the Clutha River confluence
- pumping from the Earnscleugh aquifer
- seepage into springs cascading into the Clutha River where the aquifer is perched
- seepage directly into the Clutha River where the aquifer is in contact.

Dunstan Flats

- rainfall recharge
- irrigation excess soil drainage related to the Manuherikia irrigation scheme
- subsurface through-flow from the adjoining Manuherikia claybound aquifer
- downward infiltration of Waikerikeri Creek water into the Dunstan aquifer
- pumping from the Dunstan aquifer
- seepage directly into the Clutha River.

Manuherikia claybound aquifer

- rainfall recharge
- irrigation excess soil drainage, induced by the Manuherikia Irrigation Scheme
- irrigation race and holding dam downward infiltration, caused by the Manuherikia Irrigation Scheme
- pumping from the Manuherikia claybound aquifer
- subsurface outflow to the adjoining Dunstan aquifer
- seepage directly into the Manuherikia River.

Manuherikia alluvial aquifer

- rainfall recharge
- irrigation excess soil drainage caused by the Galloway Irrigation Scheme
- irrigation race and holding dam downward infiltration, caused by the Galloway Irrigation Scheme
- pumping from the Manuherikia alluvial aquifer.
- seepage directly into the Manuherikia River.

4.1 Recharge modelling

Land surface recharge equates to rainfall recharge and irrigation excess soil-drainage, which are both mediated by soil hydrology. These sources of recharge can be modelled using soil moisture water balances.

4.1.1 Approach: Soil-moisture balance model

The basic principle of the soil moisture balance model is a mass-balance approach that calculates the day-to-day soil-water content as the soil profile is subjected to inputs and outputs of water due to rainfall/irrigation, evapotranspiration and drainage. Soil properties attenuate the soil moisture balance by promoting water retention in heavy soils, infiltration in permeable soils or runoff in less permeable soils. Appendix 1 – Recharge Modelling sets out the technical description.

In brief, modelling entailed a daily water balance for which the input values were daily rainfall, Penman evapotranspiration and sometimes also irrigation depth. The Rushton (et al, 2006) equations are embedded in the spreadsheet encompassing the model. For every daily water balance period the soil-moisture was computed. The model has three possible losses of incoming water:

- evapotranspiration to the atmospheric water vapour store
- surface runoff, presumably directly into a water course
- drainage through the soil profile into the unsaturated zone and ultimately the aquifer.

Any remaining soil-moisture was passed onto the next daily period in the sequence. The model simulates the natural processes, whereby the soil-moisture store builds up and depletes because of changes the effects of climate or irrigation practices It is the last soil-moisture loss to the aquifer that comprises groundwater recharge. In the context of the basin, with its semi-arid terrace surfaces, surface runoff after rainfall is exceedingly rare. Evapotranspiration, followed by soil-drainage, controls the soil-moisture balance.

The Alexandra basin was classified as to the soil-water groupings drawn from existing soil maps of the area. Areas of soil-moisture parameter common to multiple soil classifications were grouped together. In this way, the mapped soil classifications were brought down to ten groups of common soil-water parameters. We assumed that the Alexandra basin had the same climate conditions throughout, which allowed each of the ten soil-water groups to be modelled once with the same climate data set.
Table 2 shows the soil classification groups and summarises their nature.

Table 2 List of soil groups and attributed soil-moisture parameters

Soil group	FC	WP	PAW	PRAW	Drainage class	SCS
1	40	10	30	21	W	40
2	110	30	80	64	W	40
3	110	30	80	48	W	50
4	200	50	150	90	W	60
5	200	50	150	90	I	65
6	240	60	180	90	P	75
7	100	40	60	36	W	65
8	100	40	60	36	W	75
9	120	40	80	65	I	75
10	40	10	30	21	W	80
FC = Field capacity WP = Wilting point PAW = Profile available water PRAW = Profile readily available water Drainage classes: W = Well drained (FracStor = 0.4) I = Imperfectly drained (FracStor = 0.5) P = Poorly drained (FracStor = 0.7) SCS = Soil Conservation Service runoff potential number All depths in millimetres						

The above soil groups and corresponding parameters have variable distributions across the surface of the Alexandra Basin, as Table 3 lists.

Table 3 Soil groups and extent over the Alexandra Basin aquifers

	Dunstan aquifer	Earnscleugh aquifer	Manuherikia claybound aquifer	Manuherikia alluvial aquifer
Soil group	**Extent of soil group (ha)**			
1	687	516	1,711	353
2	278	110	4	*Absent*
3	206	228	817	57
4	*Absent*	181	31	40
5	82	511	490	156
6	*Absent*	345	587	127
7	*Absent*	109	717	24
8	*Absent*	56	1,659	180
9	*Absent*	19	95	*Absent*
10	257	89	762	*Absent*
Aquifer total	1,510	2,164	6,873	937

4.1.2 Results

The results of modelling natural rainfall-induced recharge over the four aquifers are shown in Table 4:

Table 4 Results of land surface recharge modelling, with natural rainfall inputs only

Soil group	Recharge rate (mm/y)	Dunstan aquifer (m^3/y)	Earnscleugh aquifer (m^3/y)	Manuherikia claybound aquifer (m^3/y)	Manuherikia alluvial aquifer (m^3/y)	Basin total (m^3/y)
1	49.06	336,862	253,409	839,409	172,957	1,602,637
2	5.87	16,333	6,440	229	*Absent*	23,002
3	8.43	17,358	19,232	68,819	4,824	110,232
4	0.00	*Absent*	0	0	0	0
5	0.00	0	0	0	0	0
6	0.00	*Absent*	0	0	0	0
7	18.51	*Absent*	20,254	132,667	4,351	157,273
8	16.94	*Absent*	9,405	280,991	30,490	320,887
9	4.50	*Absent*	854	4,264	*Absent*	5,117
10	42.22	108,695	37,756	321,782	*Absent*	468,233
Mean*	23.4					
Total		479,247	347,351	1,648,161	212,623	***2,687,382***
*Note: * Mean recharge rate is weight averaged for total basin area*						

Table 4 shows the aquifer-specific totals for the modelled recharge rate and land-surface areas. The recharge rates under each soil group range from nil to 49 mm/y. Significantly, three of the most retentive soil groups passed no recharge over the 25-year modelling period (September 1985 to September 2010). These three soil groups have a field capacity greater than 200 mm, which results in them holding soil-moisture the longest before shedding excess moisture as recharge. Retentive soils tend to hold soil-moisture and pass it to evapotranspiration, so soil drainage is much reduced beneath these soils. Low field capacity soil groups, such as group 1 and 10, are more prone to soil drainage as the soil profile fails to hold moisture during wet conditions. Almost 50 mm/y on average or 12% of annual rainfall passes through the profile of the low field capacity soils to join groundwater.

The Dunstan Flats aquifer tends to be dominated by lower field capacity soils. The Earnscleugh Flat aquifer has generally more retentive soils, so the Earnscleugh aquifer receives less recharge volume through the soil, despite being more extensive. The Manuherikia claybound aquifer extends over 6,873 ha and is the largest Alexandra aquifer by several orders; however, the aquifer also contains more retentive soil groups than the Dunstan Flats. Accordingly, the Manuherikia claybound aquifer has the largest recharge volume, but not by the margin that is suggested by its size. Considering rainfall only, the mean land surface recharge volume of all four aquifers combined is 2.69 Mm^3/y.

4.2 Surface-water recharge

4.2.1 Fraser River

In the last forty years, the Fraser River has had three long-term hydrological recorder sites and a further seven temporary gauging sites. Multiple gaugings of the river flow between 1982 and 1998 were directed towards quantifying the losses and gains for the river with the underlying aquifer. Complications in isolating the water interactions between the river and aquifer include irrigation off-takes and irrigation by-washes.

Two sets of multi-site, consecutive flow gaugings were carried out until 1998. The first was conducted by the Ministry of Works & Development (Jowett, 1983) in 1982 and 1983, and included six flow-gauging sites. Mintago Investments Ltd (AquaFirma, 1997) conducted the second, which included five rated river cross-sections. In both instances, the main objective was to measure the loss and gain with the underlying aquifer. The 1997-98 flow measurements were supported by a better understanding of the separation of the river bed and water table, and explicit measurements of the irrigation flows.

Table 5 Measured and calculated losses and gains in the Fraser River

	1982-83 Flow gaugings	1997-98 Flow gaugings
Mean loss (l/s)	780	770
Mean gain (l/s)	510	515
No. of measurement instances	3	3
Loss volume* (Mm^3/y)	24.6	24.3
Gain volume* (Mm^3/y)	16.1	16.2
*Note: * Volume is calculated as if the mean flow loss or gain were annualised (l/s × 86.4 × 365)*		

The correspondence between the two episodes of flow measurements may be coincidental and belie the overall variability in the recorded flows. However, in the absence of better data, the calculated volumes are thought to represent the annual exchange with the underlying Earnscleugh aquifer. From the losses and gains in Table 5, it can be inferred that up to 8.5 Mm^3/y of river recharge remains in the Earnscleugh aquifer to discharge at sites other than the lower Fraser River. This surplus groundwater leaves the aquifer at the Clutha River margins in the form of spring flow and seepage into the river bed.

4.2.2 Waikerikeri Creek

The headwaters of Waikerikeri Creek are located on Leaning Rock, which is situated on the slopes of Dunstan Mountains. They have a median specific runoff of 6.025 $l/s/km^2$, as estimated from an adjoining gauged catchment in the headwaters of Chatto Creek. The median flow of 95 l/s was calculated according to the 15.8 km^2 catchment area of the Waikerikeri Creek headwaters. Waikerikeri Valley is the intermediate catchment of the creek. Downstream of the Springvale Road crossing, the creek crosses the Dunstan Flats on its way to the Clutha River.

A multiple-site, same-day survey of Waikerikeri Creek was carried out by ORC hydrologists in early April 2011. The survey found that the headwater flow was almost entirely taken at a double water-race intake at the head of Waikerikeri Valley. The small remainder of creek flow downstream of the intake was lost into the creek alluvium. However, downstream at the Springvale Road crossing, flow was gauged to have recovered to 26 l/s. Whether the recovery in flow was due to return of seepage from the creek alluvium or by-wash discharges to the creek from the Manuherikia Irrigation Scheme is unknown. Flow in the creek was observed to diminish gradually with distance as it crossed the Dunstan Flats. The flow of the creek immediately upstream of the Clutha River at the State Highway 1 crossing was measured as 16 l/s. The difference in flows was considered to be within the accuracy of gauging and suggests that the decline in flow rate as the creek crossed the aquifer was approximately 10 l/s, which further implies that creek losses of about 0.3 Mm^3/y accrue to the Dunstan aquifer.

4.2.3 Manuherikia Irrigation Scheme – Main Race

The Main Race is supplied from the Manuherikia River and rests 15m higher than the Borough Race throughout its course. The Main Race thus commands the Springvale Road area, including storage reservoirs supplying the MN and FF lateral races. Up to 400 l/s can be fed via a drop structure onto the Dunstan Flats. This race water is used from Clyde township to the northern edge of Alexandra township. Approximately 1,400 l/s of race water is estimated to be imported from the Manuherikia River within the Main Race. Only 75% of the imported race water can actually be delivered to irrigators, with approximately 300 l/s estimated to be lost to water-race bed infiltration. Thus, about 9 Mm^3/y of groundwater recharge may be provided to the affected areas of the Manuherikia claybound and Dunstan aquifers as losses from water races.

The Manuherikia Irrigation Scheme has a design delivery to subscribing properties allowing an application of irrigation water of between 900 mm and 1,200 mm in any year Although there may be supply restrictions on the Manuherikia River intake, the interruptions or curtailments in most years are minor.

4.2.4 Earnscleugh Irrigation Scheme - races

The Earnscleugh Irrigation Scheme derives water from the upper Fraser River, drawn from the Pioneer Generation power station tailrace, and from the water of Lake Dunstan, delivered to Fraser Domain by a diversion pipeline from the Clyde Dam. The Earnscleugh Irrigation Company Ltd holds consents to take up to 4,400 l/s either from the Fraser River or Lake Dunstan, providing it maintains a residual flow of 1,000 l/s in the Fraser River downstream of all intakes. The intakes are generally in the Fraser Domain area. A limited amount of Omeo Creek water is also taken for use in the Blackman Road area.

Losses from the Earnscleugh Irrigation Scheme race network were estimated at 22% in the 1930s (Wood, 1934). To what extent this level of loss is continuing is not known, even though the scheme has been modernised, and the water delivered is considered to have a higher notional value than in the 1930s. This study has adjusted the potential distribution system loss to 5% of the scheme's capacity, accordingly. Taking the water that could be delivered to the distribution system after the augmentation of the Fraser River with 1,000 l/s, the scheme capacity would lie in the realm of 3,400 l/s. Of this amount, 5% losses to the ground would assume the order of 170 l/s. However, as the scheme is inactive over the winter months, an estimated loss rate of 110 l/s would be more realistic. Annualised, the volume of loss due to the distribution system races and storages might assume 3.4 Mm^3/y.

4.2.5 Minor water races

The Borough Race, fed from Chatto Creek, crosses the Manuherikia claybound aquifer down-hill from Springvale Road. The race has a capacity of approximately 400 l/s and commands the Long Gully, Letts Gully and Rock View areas north of Alexandra township. The only published measurement of race losses in this area dates from the 1930s, and indicated a loss of about 14% (Wood, 1934). Were such losses to occur today, the rate of loss from the Borough Race would be about 55 l/s, or 1.7 Mm^3/y.

4.2.6 The Galloway, Dip Creek and Manorburn schemes

The Galloway Irrigation Society operates a multiple-source irrigation scheme from the following water bodies:

- Manuherikia River (up to 310 l/s after by-wash back to the river)
- Dip Creek (up to 225 l/s)
- Lower Manorburn Dam (up to 85 l/s).

Water from the scheme is used on the Galloway Flats, which encompasses the Manuherikia alluvium, and has a subscriber area of 504 ha. About 1000 mm/y of water is delivered over the area, suggesting that an application volume of 5 Mm^3/y is used each season. About 310 l/s can be taken from the Manuherikia River using the current pumping equipment. The Dip Creek catchment is semi-arid and moderately small, so there is little likelihood that it contributes much to the scheme. Late summer storage of water for irrigation is provided by the lower Manorburn Dam against the possibility of Manuherikia River flow being insufficient to meet demand.

Losses of irrigation race water have been observed as 'spring flow' along the base of the Q2a terrace, in the Fisher Lane area of Galloway. This spring flow tends to increase after the beginning of the irrigation season. A very approximate estimate of irrigation losses from the distribution system at 15% of seasonal capacity is made herein, and would equate to about 40 l/s or 0.83 Mm^3/y.

4.3 Irrigation recharge – land surface

In the previous sections on groundwater recharge, the following sources of natural and artificial sources of recharge were considered:

- natural rainfall recharge distributed across the land surface
- surface-water recharge from significant rivers and creeks
- irrigation scheme distribution system losses to the ground that also provide artificial recharge of underlying aquifers.

In the course of examining these sources of recharge, it became clear that the surface hydrology of the Alexandra basin has been highly altered by irrigation schemes. Similarly, the soil hydrology of the irrigated land surface is artificially augmented by the application of irrigation water, primarily the wild-flood or border-dyke irrigation methods.

Using the recharge resulting from existing inefficient irrigation methods such as wild-flood or border-dyke and by-washes to the aquifer is problematic if the resulting water balance volumes are to be used in supporting the allocation of groundwater. One solution is to substitute the existing inefficient irrigation with application rates that are considered efficient in the calculation of the water balance. In Otago, the definition of efficient pasture irrigation for the purpose of processing resource consents is set out in AquaLinc tables (AquaLinc, 2006). These tables commissioned to define the optimal irrigation practices necessary to maintain pasture production while conserving water resources, and are used to compare proposals for taking water resources from either surface water or groundwater within consent applications. Since new consents to take water currently observe these tables and are likely to continue to in the future and progressively replace older consents, any modelling of irrigation-induced groundwater recharge should take them into account.

4.3.1 Approach

Modelling similar to that of recharge modelling was carried out herein. The modelling incorporated both rainfall and irrigation inputs to soil moisture for those areas with fixed irrigation. The AquaLinc tables for pasture irrigation and the Manuherikia Valley climate area were selected for the four profile available water (PAW) classes of seasonal irrigation application limits. These values are summarised in Table 6 below.

Table 6 Summary of AquaLinc values for pasture used in irrigation – recharge modelling

Area	PAW (mm)	Monthly irrigation limit (m^3/ha)	Seasonal irrigation limit (m^3/ha/y)
Manuherikia Valley	45	1800	8850
Manuherikia Valley	70	1750	8050
Manuherikia Valley	105	1575	7875
Manuherikia Valley	120	1800	7800

The seasonal limit was divided by the 240 days occurring between 1 September and 30 April in any season, and the daily irrigation rate was applied as an irrigation depth equivalent alongside daily rainfall. There was an obvious mismatch between the four PAW classes contained in Table 6 and the six distinct PAW classes defined in Table 2 for soil-moisture modelling. To merge the PAW classes, the two least retentive and the two most retentive soils were combined in terms of assigning seasonal irrigation volume limitation. In all other respects, the modelling followed the same pattern as outlined in Section 4.1.1 and Appendix 1. Most of the irrigation in the basin is applied with fixed networks of water races and graded paddocks. Table 7 lists the schemes, the aquifer over which the irrigation is applied and the area under irrigation.

Table 7 Irrigation scheme and irrigated areas

Scheme	Aquifer	Irrigated area (ha)
Manuherikia (MN and FF races)	Manuherikia claybound	256
Manuherikia (AG, CDE and LM races)	Dunstan	232
Earnscleugh / Fraser	Earnscleugh	394
Galloway	Manuherikia alluvium	504

4.3.2 Results

The application of irrigation invariably caused substantial increases in groundwater recharge. Table 8 lists the results of modelling irrigation-induced recharge alongside rainfall only.

Table 8 Summary: Comparison of rainfall-only and irrigation-induced recharge

Soil group	PAW (mm)	Seasonal irrigation limit*	Rainfall only recharge	Irrigation applied	Irrigation-induced recharge	Increase due to irrigation
		(m^3/ha/y)	(mm/y)	(mm/y)	(mm/y)	(mm/y)
1	30	8850	49.06	885	390	341
2	80	7875	5.87	788	285	280
3	80	7875	8.43	788	287	279
4	150	7800	0.00	780	269	269
5	150	7800	0.00	780	268	268
6	180	7800	0.00	780	262	262
7	60	8850	18.51	885	376	358
8	60	8850	16.94	885	371	354
9	80	8050	4.50	805	294	290
10	30	8850	42.22	885	376	335

Note: A recharge rate of 0 means nil recharge throughout the modelled period of 25.1 years.
** From Table 6 and AquaLinc tables.*

The effect on the model of the irrigation at depths between 780 mm and 885 mm is to induce recharge of between 33% and 46% of the irrigation water applied. The soil is held at higher levels of saturation than would otherwise be feasible with rainfall alone. Consequently, the soil is more frequently at a moisture level that allows soil drainage. Rainfall or irrigation may trigger soil drainage, but irrigation applications are responsible for substantially increasing the frequency and volume of soil drainage. In fact, the retentive soils (groups 4 to 6) that passed nil recharge with rainfall only scenario allow recharge under 780 mm of irrigation.

4.4 Combined basin recharge patterns

Putting all of the above information together some distinct patterns in the intensity and distribution of recharge emerge. These can be summarised as follows:

- rainfall-only recharge is a relatively minor part of the estimated aquifer and basin water balance
- the contribution of the Fraser River losses to the underlying Earnscleugh aquifer dominates the aquifer water balance on that side of the Clutha River
- Waikerikeri Creek contributes a small amount to the water balances of the Manuherikia claybound and Dunstan aquifers, although the precise nature and rates of interchange are obscured by irrigation off-takes and by-washes
- water-race losses from the Manuherikia, Earnscleugh and Galloway irrigation schemes are thought to be significant in all basin aquifers
- all aquifers in the basin are inferred to have some degree of net outflow to either the Clutha or lower Manuherikia rivers
- efficient irrigation rate scenarios were used in recharge modelling, although current irrigation practices are known to result in higher rates of loss to the aquifers
- the rates of water-race loss to the underlying aquifer and throughflow between the Manuherikia claybound and Dunstan aquifers are the least certain aspects of the water balance
- the rates of Land surface recharge and surface-water losses to underlying aquifers are the better known aspects of the water balance than the discharge back to surface water.

4.4.1 Dunstan aquifer recharge and water balance

The Dunstan aquifer has one of the more complex patterns of recharge and interchange. Rainfall recharge, irrigation recharge, surface-water recharge, water-race losses and inflow from the adjoining aquifer all contribute. At 0.43 Mm^3/y (see Table 9), the aquifer also has the highest level of estimated actual groundwater pumping from bores within the basin. The rest of the outflows are into the Clutha River.

Figure 3 illustrates the sources and percentages of inflows and outflows to/from the Dunstan aquifer. Percentage components of inflow and outflow have been separated through division into inner and outer rings within the donut chart.

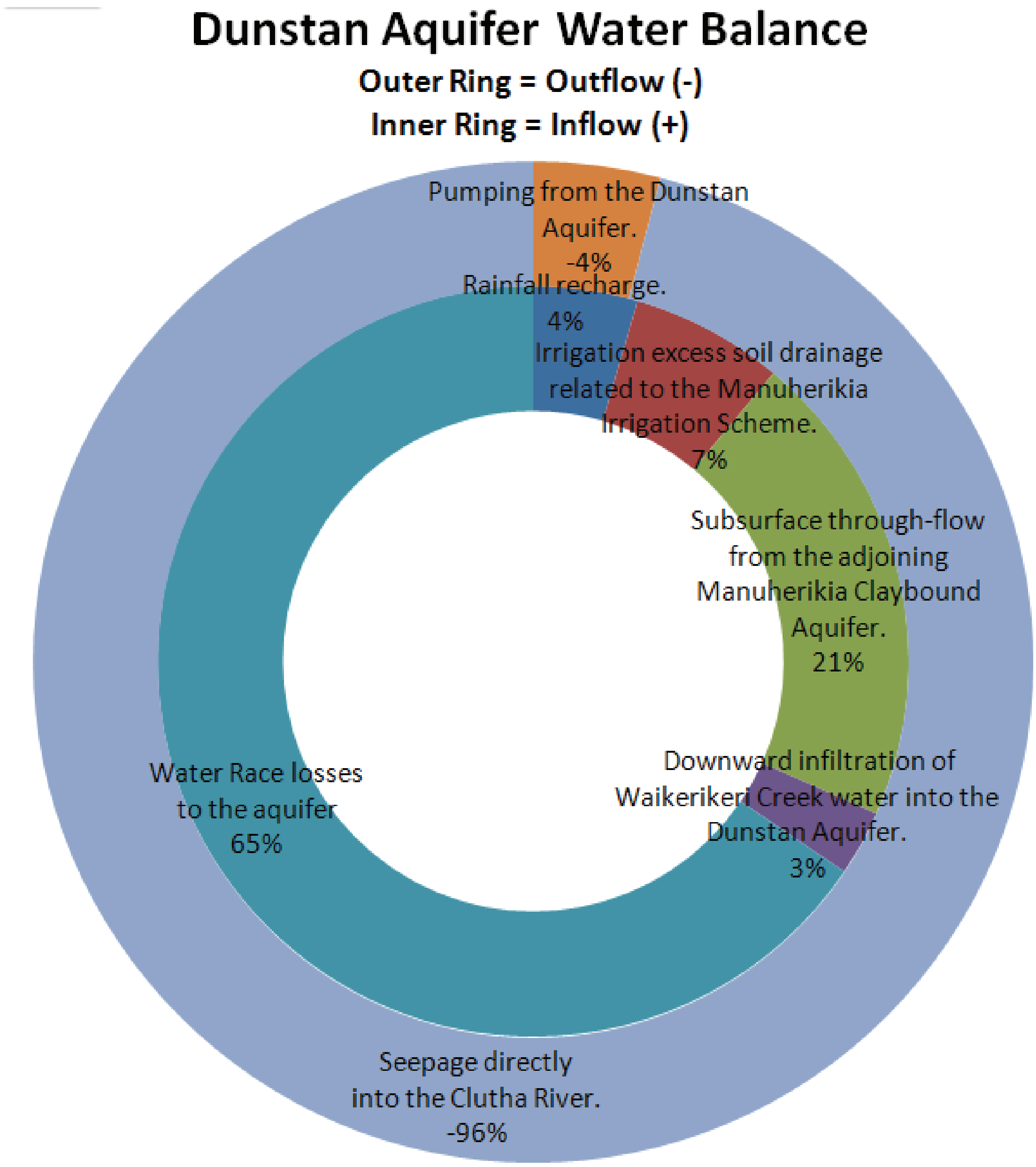


Figure 3 **Graphical representation of estimated Dunstan aquifer water balance**

The absolute values of recharge from various sources and balancing outflows are shown in Table 9, which lists mean annual recharge as 3.7 Mm^3/y contributed by rainfall, efficient irrigation, throughflow from the Manuherikia claybound aquifer and surface-water infiltration (excluding water races).

Table 9 Accounting of inflow and outflow to/from the Dunstan aquifer

	Mean annual inflow (Mm^3/y)	Mean annual outflow (Mm^3/y)
Rainfall recharge	0.48	
Irrigation excess soil drainage related to the Manuherikia Irrigation Scheme	0.70	
Subsurface through-flow from the adjoining Manuherikia claybound aquifer	2.20	
Downward infiltration of Waikerikeri Creek water into the Dunstan aquifer	0.30	
Water race losses to the aquifer	7.00	
Pumping from the Dunstan aquifer *		0.43
Seepage directly into the Clutha River		10.20
Totals	10.7	10.6
*Note: * Actual pumping estimated as 30% of groundwater take consent allocation for the aquifer*		

4.4.2 Earnscleugh aquifer recharge and water balance

The water balance of the Earnscleugh aquifer is dominated by the infiltration of Fraser River water. Measured losses from the Fraser River to the underlying aquifer make up a mean of 24.6 Mm^3/y. Up to 16.2 Mm^3/y of groundwater returns to the lower Fraser River, and the remainder flows to the Clutha River either by direct seepage or discharge at springs along the river banks on the edge of the Earnscleugh terrace. The Earnscleugh aquifer is mostly perched on a mudstone base above the level of the Clutha River, which distinguishes it from the Dunstan aquifer.

Figure 4 shows the proportions of inflows and outflows to/from the Earnscleugh aquifer. The figure reinforces the impression as to the dominance of Fraser River interchanges with the aquifer, since losses to the aquifer comprise 85% and returns to the lower river amount to 56% of the aquifer water balance. Compared to these interchanges, rainfall and irrigation-related recharge is minor. Bore pumping from the aquifer is thought to account for 0.15 Mm^3/y or about 1% of the overall water balance, which is also minor to negligible.

Table 10 lists the absolute values of the Earnscleugh aquifer water balance. The total water balance for the aquifer is almost three times that of the Dunstan aquifer, which can be attributed to the large amount of surface-water infiltration from the Fraser River compared to that of the Waikerikeri Creek.

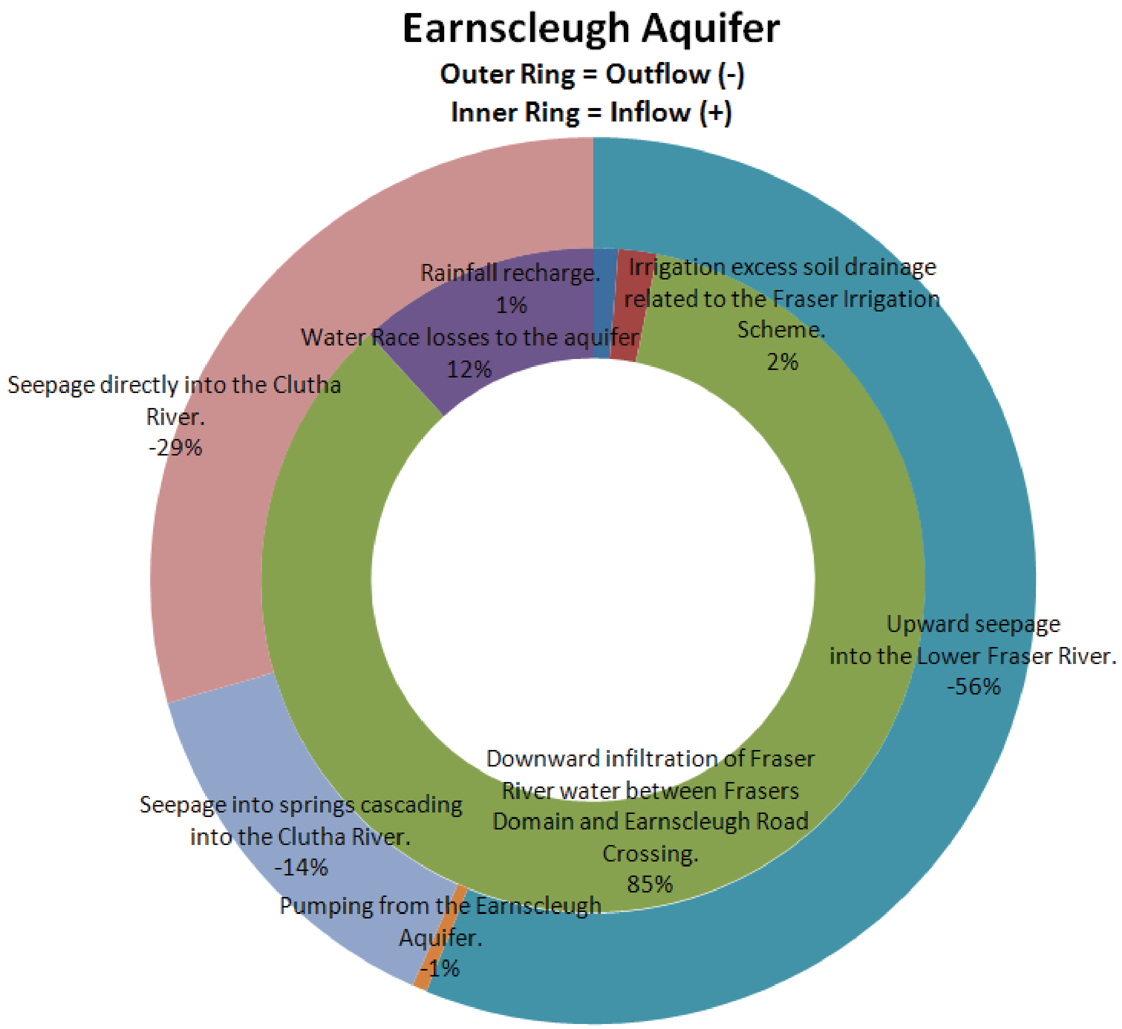


Figure 4 **Graphical representation of estimated Earnscleugh aquifer water balance**

Table 10 **Accounting of inflow and outflow to/from the Earnscleugh aquifer**

	Mean annual inflow (Mm^3/y)	**Mean annual outflow (Mm^3/y)**
Rainfall recharge	0.35	
Irrigation excess soil drainage related to the Fraser Irrigation Scheme	0.55	
Downward infiltration of Fraser River water between Frasers Domain and Earnscleugh Road crossing	24.60	
Water Race losses to the aquifer	3.40	
Upward seepage into the lower Fraser River		16.20
Pumping from the Earnscleugh aquifer*		0.15
Seepage into springs cascading into the Clutha River		4.00
Seepage directly into the Clutha River		8.5
Totals	28.9	-28.9

*Note: * Actual pumping estimated as 30% of groundwater take consent allocation for the aquifer*

4.4.3 Manuherikia claybound aquifer recharge and water balance

The Manuherikia claybound aquifer consists of a large elevated, semi-arid area of fossil alluvial fans. The chief water bodies crossing the aquifer surface are the Waikerikeri Creek, Main Race and Borough Race. Rainfall recharge is relatively minor due to the predominance of retentive soils. However, under irrigation the claybound aquifer soils admit significant recharge, as estimated in land surface recharge modelling.

The Manuherikia claybound aquifer is estimated to transfer 2.2 Mm^3/y of its groundwater to the Dunstan aquifer by subsurface throughflow across the boundary between them. Otherwise, the aquifer has little in the way of visible discharge. Figure 5 illustrates the proportions of inflows and outflows estimated for water balance purposes. Land Surface Recharge as rainfall-only recharge and efficient irrigation-related recharge, make up 34% of the estimated recharge, which is higher than for the Dunstan or Earnscleugh aquifers.

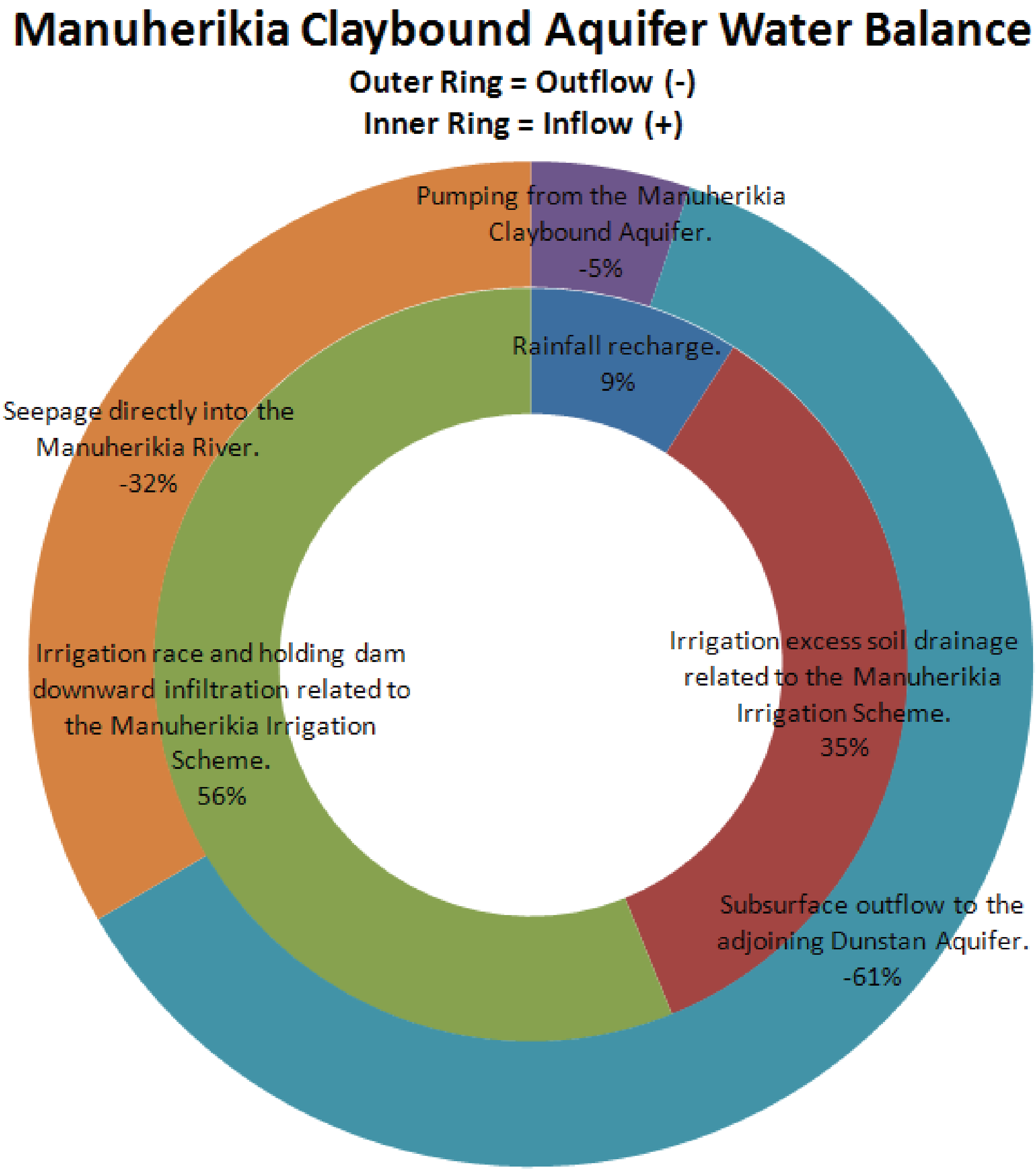


Figure 5 Graphical representation of estimated Manuherikia claybound aquifer water balance

The absolute values for the Manuherikia claybound aquifer are shown in Table 11 below.

Table 11 Accounting of inflow and outflow to/from the Manuherikia claybound aquifer

	Mean Annual Inflow (Mm^3/y)	**Mean Annual Outflow (Mm^3/y)**
Rainfall recharge	0.32	
Irrigation excess soil drainage related to the Manuherikia irrigation scheme	1.24	
Irrigation race and holding dam downward infiltration related to the Manuherikia irrigation scheme	2.00	
Pumping from the Manuherikia claybound aquifer *		0.18
Subsurface outflow to the adjoining Dunstan aquifer		2.20
Seepage directly into the Manuherikia River		1.2
Totals	3.6	3.6
*Note: * Actual pumping estimated as 30% of groundwater take consent allocation for the aquifer*		

The Manuherikia claybound aquifer land has been going through significant changes in water use in recent years. There has been significant life-style property development in the Letts Gully Road area and substantial conversion of unimproved pasture north of Springvale Road into vineyard plantings or homesteads. Associated with vineyard development, three large, lined storage dams have been built to store Manuherikia main-race water. The stored water is drip irrigated onto plantings, which has increased the irrigated command area of the Main Race, but has applied the water in a hyper-efficient manner that is unlikely to result in additional groundwater recharge.

4.4.4 Manuherikia alluvial aquifer recharge and water balance

The Manuherikia alluvial aquifer is a small thin groundwater system, with minor storage capacity. Groundwater pumping is small to negligible, but the resource is nonetheless important for the maintenance of private domestic or stock-water supplies. The main source of LSR comes from the infiltration of soil-moisture excess related to the application of irrigation across the Galloway Flats.

Figure 6 shows the proportions of the various recharges and discharges in the Manuherikia alluvial aquifer. Without flow measurement of the discharge at springs and seepage channels within the Manuherikia alluvial aquifer, the split between the direct discharge and indirect seepage in Figure 6 is approximate. However, it can be confidently assumed that the discharging water provides for baseflow in the Manuherikia River.

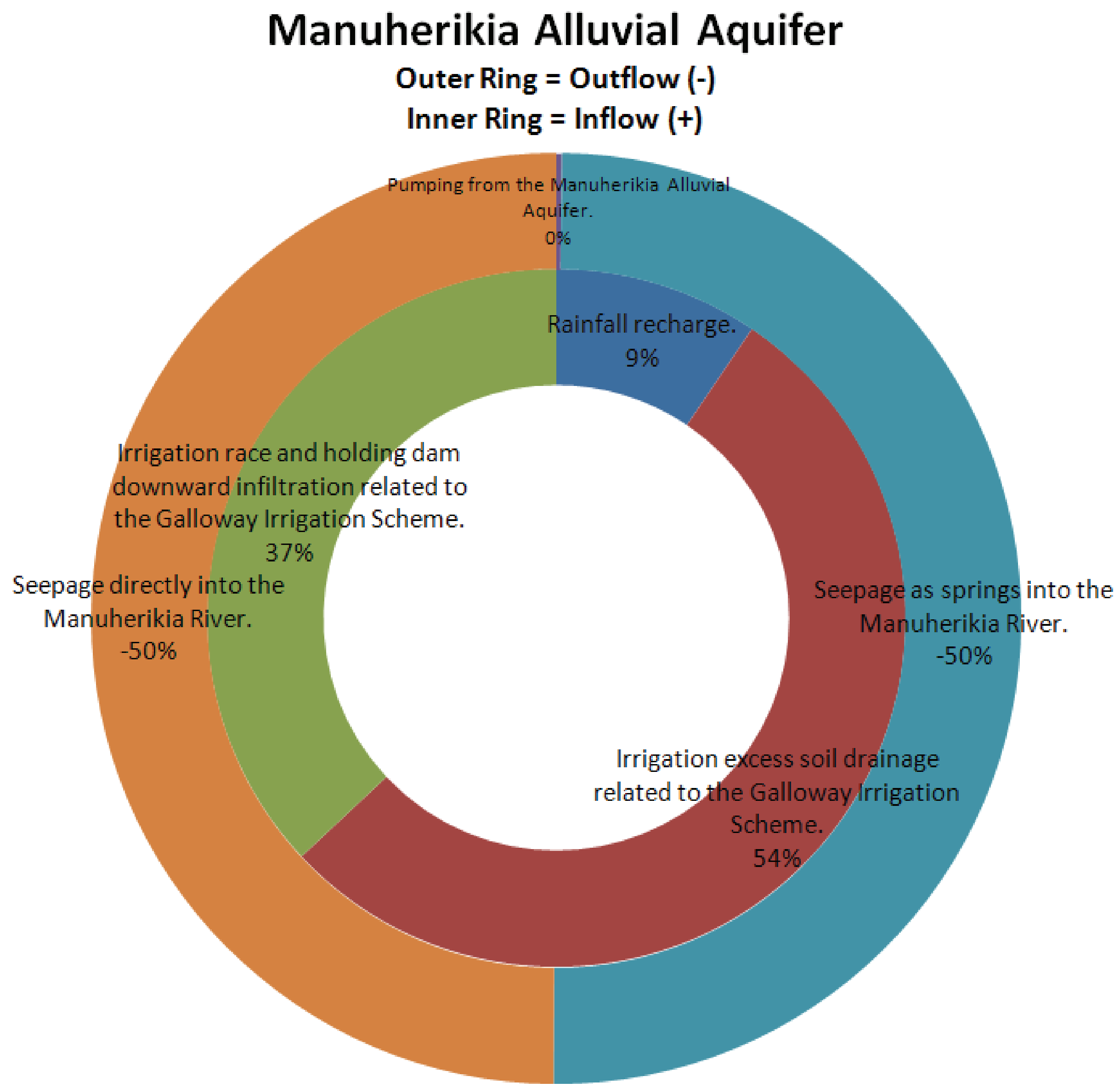


Figure 6 Graphical representation of estimated Manuherikia alluvial aquifer water balance

The absolute values for the Manuherikia alluvial aquifer are shown in Table 12 below. The table shows that the aquifer has a small water-balance volume and close associations with the Manuherikia River (e.g. most of the irrigation water is pumped from the river on the western margin of the aquifer). Future use of the aquifer is likely to be dominated by domestic and stock-water requirements, which are low in volume compared to that needed for irrigation.

Table 12 Accounting of inflow and outflow to/from the Manuherikia alluvial aquifer

	Mean annual inflow (Mm^3/y)	Mean annual outflow (Mm^3/y)
Rainfall recharge	0.21	
Irrigation excess soil drainage related to the Galloway Irrigation Scheme	1.20	
Irrigation race and holding dam downward infiltration related to the Galloway Irrigation Scheme	0.83	
Pumping from the Manuherikia alluvial aquifer*		0.00
Seepage as springs into the Manuherikia River		1.10
Seepage directly into the Manuherikia River		1.10
Totals	2.2	2.2
*Note: * Actual pumping estimated as 30% of groundwater take consent allocation for the aquifer*		

4.4.5 Whole basin water balance

The Alexandra Basin has three significant rivers entering it, as well as the seepage discharge of the associated aquifers into the rivers. As an exercise in completeness, this section outlines an estimated water balance for the entire basin. The 'water-balance approach' combines the incoming surface water from the Clutha, Fraser, and Manuherikia rivers (and the Waikerikeri Creek) with the net outflows from aquifers. The rationale for using this approach is that the rivers enter and leave the basin, while the groundwater systems collect and discharge the surplus of the basin sediments themselves.

The downstream side of the basin draws to an outlet at the Roxburgh Gorge of the Clutha River. The basin's surface water and groundwater coalesces at the Clutha-Manuherikia confluence before entering the basement rock gorge. Table 13 lists the passage of net-water flows through the basin.

Table 13 Whole basin flow routing

	West (Mm^3/y)	Central (Mm^3/y)	East (Mm^3/y)
Waikerikeri Creek headwaters		3	
Clutha River @ Clyde Dam	16,090		
Manuherikia River @ Ophir			435
Fraser River @ Liang Road	50		
Manuherikia claybound aquifer outflow			1.2
Dunstan aquifer outflow		10.2	
Earnscleugh aquifer outflow	28.7		
Manuherikia alluvial aquifer outflow			2.2
Clutha River @ Alexandra – d/s Manuherikia confluence (as the sum of surface flows and aquifer outflows)		16,620	
Clutha River @ Roxburgh hydro (as measured)		16,811	

It is useful to note that the annual flow at Alexandra is the simple sum of all estimated upstream flow contributions, while the flow at the Roxburgh Dam is measured. While the measured flow at the Roxburgh Dam exceeds the estimated flow at Alexandra, the intervening semi-arid catchment along the Roxburgh Gorge could plausibly provide the 190 Mm^3/y difference.

The whole basin water balance is useful in that it places the groundwater flows in the context of the surface-water flows. Of note is the large contribution of the Earnscleugh aquifer (at 28.7 Mm^3/y) the whole basin water balance, compared to that of the other aquifers. In effect, the Earnscleugh aquifer is something of a bypass for Fraser River water through the sandy, cobbly gravels of the Earnscleugh terrace, since 85% of the aquifer outflow originates as river-bed infiltration to the water table. The Dunstan aquifer outflow is inflated by the throughflow from the adjoining Manuherikia aquifer and significant infiltration from water races and by-washes to ground. By comparison with the groundwater contributions to the Clutha River, the aquifers' contribution to the Manuherikia is modest. All the aquifer contributions amount to no more than a quarter of a per cent (0.25%) of the basin's water resource available from the rivers and aquifers.

5 Water resource management

5.1 Historic water management

Water management in Central Otago was originally provided by the issuing of mining privileges to water-race owners for the taking and conveying of surface water used for gold sluicing. The Alexandra basin was an early goldfield, so mining privileges were issued from the Alexandra and Cromwell Warden's Court. Once mining in the area started to wane, the Warden's Court continued to be used for the management of water rights granted to the area's pastoralists and orchardists until the Water and Soil Conservation Act 1967. Thereafter, the mining privileges were 'grandfathered' over in the same act as 'mining privileges' to water. With the introduction of the Resource Management Act in 1991, mining privileges became 'deemed permits', with a twilight period of 30 years, expiring on 1 October 2021.

Water races originally installed for the delivery of water for sluicing were progressively re-tasked to flood irrigation. From the 1930s, the Public Works Department extended water races and built headworks, including holding dams, for the specific needs of irrigators. These assets were progressively privatised and devolved into irrigation companies. These works were originally authorised under purchased mining privileges, Orders in Council and Crown water rights. These authorisations have progressively been regularised under the RMA to renewable water permits. The Clyde Power Project was authorised under an empowering act and ultimately re-authorised under a suite of resource consents after the expiry of the Clyde Dam Empowering Act (1982) in 2001. The first groundwater-take consents were issued under the Water and Soil Conservation Act provisions as 'underground water rights' especially after the WSC Amendment Act in 1981. Bores permits or consents became a requirement of the Otago Catchment Board after 1988.

5.2 Current water management

The RPW, first proposed in 1998, and operative by 2004, recognises the four aquifer areas of the Alexandra Basin: the Earnscleugh, Dunstan, Manuherikia claybound and Manuherikia alluvial aquifers. The Dunstan aquifer has also been accorded groundwater protection zone status under the RPW. In the early 2000s, ORC assumed responsibility for the long-term Dunstan aquifer monitoring bore from Contact Energy Ltd. However, the basin does not contain a water-take restriction zone or other regulatory constraint on groundwater management.

5.2.1 Surface-water allocation

While residual-flow conditions are imposed on the Fraser River abstractions, the Manuherikia River is the only river in the basin with a minimum flow regime. A minimum flow of 850 l/s is set for the Manuherikia River at the Ophir Gorge recorder site. The Manuherikia River should be considered fully allocated. Other tributaries, such as Waikerikeri Creek, Dip Creek, Manorburn, Omeo Creek, and Conroy Creek, should also be considered fully allocated. The Clutha River has an unrestricted allocation and is not subject to minimum-flow curtailment of takes from its waters.

5.2.2 Groundwater allocation

About 53 groundwater-take consents are active within the basin. Table 14 lists the number of takes and total annual allocation totals for each of the basin's aquifers.

Table 14 Alexandra Basin groundwater allocation, by aquifer

	No. of takes	**Consented allocation (Mm^3/y)**
Dunstan aquifer	34	1.45
Earnscleugh aquifer	4	0.514
Manuherikia claybound aquifer	11	0.610
Manuherikia alluvium aquifer	4	0.014
Alexandra Basin: Total	53	2.59

Of course, as well as consented or authorised takes, the permitted activity rules of the RPW allow the hundreds of domestic, stock-water or general light-purpose takes of groundwater from the aquifers to continue without specific authorisation. Residents are authorised to take up to 25 m^3/d for general domestic, stock water and other purposes without resource consent. Using the IRRICON (1998) count of bores within the Alexandra basin of 340, the groundwater 'allocated' to permitted activities could be considered to amount to an additional 8,500 m^3/y. Adding the permitted activity 'allocation' would merely shift the total basin allocation from 8.59 Mm^3/y to 8.6 Mm^3/y.

5.3 Future groundwater allocation

The future allocation for the basin's groundwater resource was considered at length in 'Groundwater Allocation of the Alexandra Basin' (ORC, 2005). The report concluded by presenting options or models of possible allocation:

- Option 1: to continue with the current approach
- Option 2: to follow a modified 'Lincoln' approach
- Option 3: to maintain minimum groundwater levels
- Option 4: to set thresholds for trends
- Option 5: to use hotspot elimination tools
- Option 6: to adopt a safe yield or sustainable yield limits.

Unfortunately, the committee process did not result in ORC adopting any of these options and the selection of either an allocation regime or a groundwater management limit was not pursued any further at the time. To be fair to the responsible committees, the RPW did not provide a set of rules that would allow for applying allocation limits. The groundwater policy relevant to allocation specified the "avoidance of exceeding the renewable yield" of the aquifer without extending that policy direction into an associated rule. The policy was also unclear as to how to define or measure "exceeding the renewable yield" of an aquifer.

Recent changes to the Regional Plan: Water provide for a default limit on the volume of groundwater that can be allocated from an aquifer, or the setting of a tailored allocation cap. Policy 6.4.10A created a framework whereby the allocation limits would be set in one of the three possible scenarios:

- the default allocation limit in the absence of any other provision would be 50% of mean annual recharge
- where explicitly set out in a plan schedule, the limit would be specified in millions of cubic metres per annum. ORC would set the limit via plan change after considering the technical information and community wishes in consultation
- where the volume contained in existing resource consents exceeded the first two limits, the allocation limit would be the volume contained in the sum of all valid resource consents. In effect, this scenario covers an aquifer or groundwater system 'over-allocated' before Plan Change 1C, by protecting the rights of existing groundwater users with consents, but prohibiting further allocation above that contained within consents.

Under Policy 6.4.10A, the basin's aquifers have a default allocation limit as 50% of mean annual recharge. The policy has associated rules that prohibit the acceptance of an application that would cause the maximum allocation limit set in one of the three scenarios to be breached.

6 Groundwater management regime

A default groundwater allocation regime has resulted from recent plan changes to the RPW. The default regime for all basin aquifers can be summarised as follows:

- maximum allocation volume – 50% of mean annual recharge
- no water-take restriction zone, no restriction water levels
- 100m riparian margins of the following aquifers with the following rivers:
    - Earnscleugh aquifer with the lower Fraser River and Clutha River
    - Dunstan aquifer with the Clutha River
    - Manuherikia claybound aquifer with the Manuherikia River
    - Manuherikia alluvial aquifer with the Manuherikia River.
- Split surface water - groundwater allocation with adjacent rivers, especially the Manuherikia alluvial aquifer with the Manuherikia River.

Beyond the default groundwater management regime for the basin, a possible future regime would include the following:

- a tailored maximum allocation volume for one or all aquifers
- a tailored set of restriction level(s) to manage aquifer water levels within a yet-to-be-defined water-take restriction zone.

Customising the maximum allocation volume as a substitute for the default (50% of mean annual recharge) allows wider technical considerations to be included in the assessment. For example, the potential for adverse water level conditions developing in the Letts Gully Road area of the Manuherikia claybound aquifer might be sufficient to select a maximum allocation volume lower than that mandated under the default 50% of mean annual recharge.

Should any aquifer’s consented allocation volume exceed the mean annual recharge then the RPW policy provision 6.4.10A(a)(ii)(2) results in the maximum allocation volume being set at ‘the sum of consented maximum annual take’ for that aquifer at 10 April 2010. However, this maximum allocation volume cannot be exceeded by granting new consents. New consents can only be granted in cases of attrition (for example, when consent holders surrender or do not replace consents, or consents lapse), and the maximum allocation volume declines until it reaches the default 50% of mean annual recharge.

Restriction levels are also a tool for groundwater management available within the original and amended RPW. Restriction levels tend to be most effective when:

- an aquifer has a critical and readily identified water-level elevation that should be maintained to avoid adverse conditions
- when groundwater levels are significantly affected by groundwater pumping rather than climatic or surface-water conditions.

These conditions are not observed in Alexandra Basin aquifers, to date.

6.1 Default groundwater management of Alexandra basin aquifers

6.1.1 Dunstan aquifer

The Dunstan aquifer's essential characteristics relevant to groundwater management are as follows:

- It is the most intensively utilised aquifer in the Alexandra basin, with water requirements being served by the aquifer for household-water supply, stock water, irrigation (pasture, grapes, olives, orchards and gardens), communal residential water supplies and playing grounds watering (playing fields, racing clubs and golf courses).
- It is potentially influenced by the Clutha River. High river levels temporarily boost the water table along riparian strips of the aquifer and sustained low river levels can lower the water table over the whole aquifer.
- It benefits from through flow from the adjoining and higher elevation Manuherikia claybound aquifer.
- Its rainfall recharge is relatively minor and irrigation losses dominate LSR inputs to the aquifer.
- The surface-water recharge from Waikerikeri Creek is relatively minor.

When considering what constitutes mean annual recharge, it is important to consider the sources of recharge that have a degree of permanence for the life of the groundwater management regime. Since the way irrigation-water supplies are delivered could readily be restructured by requirements to improve the water efficiency of the scheme, the sources of recharge that rely on a leaky water-race system with terminal by-washes should not be included in the recharge total. There is currently an economic and regulatory drive towards improving irrigation-water efficiency, which includes the efficiency of the delivery system. This means that not only is it more efficient to apply 780 mm of irrigation water per season (as per AquaLinc tables, 2006) than the 900 mm to 1200 mm applied under the current water race-based schemes, but the delivery system should also have lower losses so that less water needs to be taken and infrastructure costs are better contained. It seems inevitable that the Dunstan Flats irrigation systems will in the future be supplied by pipelines and apply water by spray or dripper applicators at no more than about 4 mm/d on average. Accordingly, only rainfall recharge, irrigation losses from 'efficient' depths of application and the infiltration of Waikerikeri Creek are included in the summation of mean annual recharge.

Table 15 Comparison of mean annual recharge and groundwater allocated in consents within the Dunstan aquifer

	Mean annual recharge (Mm^3/y)	Groundwater allocation in consents (Mm^3/y)
Rainfall recharge	0.48	
Irrigation excess soil drainage related to the Manuherikia Irrigation Scheme	0.70	
Downward infiltration of Waikerikeri Creek water into the Dunstan aquifer	0.30	
Subsurface through-flow from the adjoining Manuherikia claybound aquifer	2.2	
Total: Mean annual recharge	3.68	
Current groundwater allocation in consents		1.45
50% of mean annual recharge	1.84	
Apparent remaining allocation	0.4	

Table 15 suggests that the Dunstan aquifer is not yet over-allocated and that a further 0.4 Mm^3/y of allocation could be granted in consents to take groundwater from it.

6.1.2 Earnscleugh aquifer

The Earnscleugh aquifer's essential characteristics relevant to groundwater management are as follows:

- It is one of the more lightly used aquifers in the basin, with most water requirements being served by the irrigation scheme.
- It is not potentially influenced by the Clutha River. Through most of the aquifer's contact with the riparian margin, the water table is perched.
- Its rainfall recharge is relatively minor, and irrigation losses dominate LSR inputs to the aquifer.
- Its surface-water recharge from the Fraser River is the outstanding major source of total recharge.

Again, the possibility of improving the water efficiency of the irrigation system in terms of application rates, irrigation method and delivery infrastructure leads to the current losses of water from the irrigation delivery system being excluded from the calculation of recharge. Table 16 lists the source and volumes of recharge contributing to mean annual recharge in the Earnscleugh aquifer.

Table 16 Comparison of mean annual recharge and groundwater allocated in consents within the Earnscleugh aquifer

	Mean annual recharge (Mm^3/y)	Groundwater allocation in consents (Mm^3/y)
Rainfall recharge	0.35	
Irrigation excess soil drainage related to the Fraser Irrigation Scheme	0.55	
Downward infiltration of Fraser River water between Frasers Domain and Earnscleugh Road crossing	24.60	
Total mean annual recharge	25.49	
Current groundwater allocation in consents		0.514
50% of mean annual recharge	12.75	
Apparent remaining allocation	12.24	

Table 16 suggests that the Earnscleugh aquifer is not yet over-allocated and a further 12.24 Mm^3/y of allocation could be granted in consents to take groundwater from it.

6.1.3 Manuherikia claybound aquifer

The Manuherikia claybound aquifer's essential characteristics relevant to groundwater management are as follows:

- It provides household water supply, stock water, irrigation (pasture, grapes, olives, orchards and gardens) and communal-residential water supplies, although access to such bore water supplies is patchy due to varying silt contents which constrain bore yield.
- It loses water by through flow with the adjoining Dunstan aquifer.
- Its rainfall recharge is relatively minor, and irrigation losses dominate LSR inputs to the aquifer.
- Its surface-water recharge is minor to non-detectable.

Once more, losses from the water-race system to the underlying aquifer are excluded from the calculation of mean annual recharge to establish default allocation status.

Table 17 Comparison of mean annual recharge and groundwater allocated in consents within the Manuherikia claybound aquifer

	Mean annual recharge (Mm^3/y)	**Groundwater allocation in consents (Mm^3/y)**
Rainfall recharge	0.32	
Irrigation excess soil drainage related to the Manuherikia Irrigation Scheme	1.24	
Total: Mean annual recharge	1.56	
Current groundwater allocation in consents		0.61
50% of mean annual recharge	0.78	
Apparent remaining allocation	0.17	

Table 17 illustrates the probability that groundwater allocated in consents is approaching the maximum allocation volume. It is particularly important that the aquifer groundwater users do not exceed this maximum allocation volume because recharge in the aquifer provides an important service in providing up to 2.2 Mm^3/y to the Dunstan aquifer by throughflow across the aquifer boundary. Since future water efficiency measures could serve to reduce water-race losses, the ability of the aquifer to serve outflows to the Dunstan aquifer and the lower Manuherikia River could be similarly compromised.

6.1.4 Manuherikia alluvial aquifer

The Manuherikia alluvial aquifer's essential characteristics relevant to groundwater management are as follows:

- Its use profile is dominated by domestic, stock-water and communal-domestic (private water supply) end uses.
- No irrigators use the aquifer.
- The aquifer is thin, open-ended, with high permeability and porosity, indicating a small storage capacity.
- Rainfall recharge is relatively minor and irrigation losses dominate LSR inputs to the aquifer.
- Significant groundwater pumping from the aquifer, especially in proximity to the river margin, could deplete the flow of the Manuherikia River.

Table 18 lists the calculated mean annual recharge for the aquifer and compares the recharge volume with the current groundwater allocation in groundwater take consents.

Table 18 Comparison of mean annual recharge and groundwater allocated in consents within the Manuherikia alluvial aquifer

	Mean annual recharge (Mm^3/y)	Groundwater allocation in consents (Mm^3/y)
Rainfall recharge	0.21	
Irrigation excess soil drainage related to the Galloway/Manorburn Irrigation Scheme	1.20	
Total: Mean annual recharge	1.41	
Current groundwater allocation in consents		0.01
50% of mean annual recharge	0.71	
Apparent remaining allocation	0.7	

As groundwater takes requiring consent are negligible, the available allocation virtually equals the maximum allocation volume total. Future groundwater pumping from the Manuherikia alluvial aquifer may also be limited by the surface-water depletion effect on the Manuherikia River. As the Manuherikia River has an active minimum-flow regime and is considered over-allocated, surface-water depletion rules are likely to be the chief limitation on the ability to grant consents to take groundwater, especially for bores in the west of the aquifer, closer to the river.

7 Conclusions

The following conclusions can be drawn from this allocation study of the Alexandra Basin aquifers:

Hydrogeology

- The aquifers of the Alexandra Basin are hosted within a variety of glacial outwash, alluvial fans and flood plain deposits.
- The Earnscleugh and Dunstan aquifers are sister aquifers, on opposite banks of the Clutha River, and are composed of Albert Town outwash.
- The base of the Earnscleugh aquifer differs from the Dunstan aquifer in that the Earnscleugh terrace outwash gravels are perched on low permeability Manuherikia group sediments that are generally higher than Clutha river level.
- The base of the Dunstan aquifer is lower than Clutha river level and there is an intervening early Quaternary gravel deposit between the Albert Town outwash and Manuherikia group sediments.
- The Manuherikia claybound aquifer comprises two distinct groups of formations: the Lindis outwash that makes up the 'Airport Terrace' and the Letts Gully Road area, south of Springvale Road, and the older Waikerikeri alluvial fans to the north.
- The Manuherikia alluvial aquifer is primarily penultimate alluvial terrace and flood plain of the Manuherikia River.

Groundwater hydrology

- All aquifers in the Alexandra basin are primarily unconfined, water-table aquifers, although localised semi-confined zones can be found within the highly stratified Manuherikia claybound aquifer.
- The aquifers have a geo-hydrological base against either:
    a. Manuherikia group silts and mudstone, or
    b. early Quaternary Gravels, which are stratified and claybound, or
    c. Otago schist basement rocks.

- The Earnscleugh, Dunstan, and Lindis outwash parts of the Manuherikia claybound aquifers generally have high permeability and large depths to the water table.
- The Manuherikia alluvial aquifer has both shallow saturated thickness and a shallow water table.
- All aquifers discharge into the adjoining Clutha, lower Fraser or lower Manuherikia rivers.
- The upstream section of the Fraser River as it crosses the permeable surface of Earnscleugh Flat loses a substantial portion of its base flow to the underlying aquifer, with an average 25 million cubic metres of water entering the Earnscleugh aquifer by this vector every year.
- All aquifers are replenished or recharged at the land surface by a combination of water infiltrating from excess rainfall, pasture irrigation losses, leakage from water races and by-wash to soak holes.

- The net excess of the groundwater that recharges the basin's aquifers percolates through the gravel deposits between the water table and base of the gravels until it discharges at one or more of the following surface water bodies:
    a. miscellaneous springs and seepage drains along the other edges of outwash terraces
    b. Clutha River
    c. lower Manuherikia River
    d. lower Fraser River.

Groundwater management and allocation

- Modelling of natural rainfall recharge and efficient irrigation onto the currently irrigated extent of land was undertaken to develop estimates of mean annual recharge that would be unlikely to become alienated from the respective aquifers.

The default groundwater allocation regime in Otago that applies to the Alexandra basin aquifers is specified in policy 6.4.10A(ii)(1) of the RPW, which stipulates that the allocation limit is 50% of the calculated mean annual recharge, unless the aquifer has already been allocated to a greater volume.

- Table 19 lists the mean annual recharge, 50% of this value and this compares with the volume issued in consents to take groundwater.

Table 19 List of aquifers, numbers of takes, recharge and groundwater allocation issued in current consents

	No. of takes	Mean annual recharge	50% Mean annual recharge	Consented allocation
		(Mm^3/y)	(Mm^3/y)	(Mm^3/y)
Dunstan aquifer	34	3.68	1.84	1.450
Earnscleugh aquifer	4	25.5	12.75	0.514
Manuherikia claybound aquifer	11	1.36	0.68	0.610
Manuherikia alluvium aquifer	4	1.41	0.70	0.014
Alexandra Basin Total	**53**		**15.97**	**2.59**

- None of the Alexandra basin aquifers are allocated to more than 50% of mean annual recharge and are therefore under-allocated, although the unallocated volume is available in the Dunstan and Manuherikia claybound aquifers is small.
- Substantial unallocated groundwater volume is indicated for the Earnscleugh aquifer, largely due to the modest volume allocated in current consents and the substantial recharge provided by the Fraser River infiltration.

Appendix 1 – Recharge modelling

Methodology

Method chosen

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

1. calculating runoff, using the USDA SCS runoff method

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

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

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

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

Required parameters

As well as rainfall and PET, the soil-moisture balance model requires four different input parameters to calculate daily soil moisture deficit. These parameters are described below.

SCS curve number

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

Profile available water (PAW)

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

Profile readily available water (PRAW)

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

Fracstor

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

Field capacity (FC)

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

Wilting point (WP)

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

Methods of defining additional parameters

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

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

1. Match the soil series with the same series, or with a similar soil series, within the database.
2. Determine the average FC and WP as percentages for these series to 1 m depth.
3. Multiply the percentage FC and WP values by the estimated rooting depth of the soils, for soils with rooting depth less than 1 m (moderately deep soils were estimated to have an average rooting depth of 0.7m, shallow soils 0.45m, stony soils 0.35m and very stony soils 0.2m).
4. The above figure provides an estimate of FC and WP in millimetres for the profile.
5. PAW is determined by subtracting WP from FC.
6. The PAW range indicates the likely variability of PAW across the map unit, taking into account the likely variation in the depth of fines over gravels.
7. PRAW is determined by multiplying PAW by a ratio of PRAW/PAW found from the database for similar soils. In the case of shallow and stony soils, the ratio is modified according to expert opinion. As soils become shallower, the percentage of PRAW/PAW becomes larger.

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

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

Recharge model inputs

Rainfall

There is relative uniformity of rainfall patterns across the low elevation parts of the Alexandra Basin. GrowOtago's contouring of median rainfall indicates that annual rainfall totals tend to fall within the range of 350 to 400 mm/y. After an analysis of the various rainfall-recording sites across the study area, a short-list of historical and operational sites was compiled:

- Alexandra I59234
- Alexandra CWS I5923B
- Clyde EWS I59239
- Cromwell EWS I59013
- Lauder EWS I59065.

Ultimately, the Clyde EWS (I59239) climate station was chosen on the basis of length of record and location within the Alexandra Basin.

Potential evapotranspiration (PET)

As a rule, measurements of evapotranspiration are undertaken at climate stations and are thus sparsely distributed throughout Otago. The closest climate stations are located at Clyde (I59239), Alexandra (I59234/ I5923B) and Lauder (I59065). Analysis of the evaporation records for these four climate sites within Central Otago indicated that there was a strong correlation between the Clyde and Lauder climate-site-evaporation records ($R^2 = 0.88$). The Lauder evaporation data also extends from October 1985 to the present and is, therefore, a more complete record. Accordingly, the Lauder evaporation (Penman evapo-transpiration) record was chosen for use in soil-water balance modelling.

Soil properties

Soil-moisture balance modelling requires knowledge of the spatial distribution of principal soil types, as well as knowledge of their ability to retain water. For this study, Landcare Research was commissioned to provide an evaluation of the soils within the project area, based on the New Zealand Soils Database.

The table below provides a summary of properties assigned to the 10 dominant soil classes in the study area.

Table 20: **Soil properties used in the Rushton soil-moisture balance model**.

Soil property zone	Field capacity	Wilting point	PAW	PRAW	Drainage class	SCS curve number	Mean recharge rate (mm/y)
1	40	10	30	21	W	40	49.1
2	110	30	80	64	W	40	5.9
3	110	30	80	48	W	50	8.4
4	200	50	150	90	W	60	0.0
5	200	50	150	90	I	65	0.0
6	240	60	180	90	P	75	0.0
7	100	40	60	36	W	65	18.5
8	100	40	60	36	W	75	16.9
9	120	40	80	65	I	75	4.5
10	40	10	30	21	W	80	42.2

This table also shows the percentage of annual rainfall that becomes groundwater recharge, as calculated by the Rushton spreadsheet model. The proportions of mean annual recharge represent the annual average for the 25-year model period (Sept 1985-Oct 2010).

Recharge model outputs

Calculated recharge inputs for the 25-year model period (Sept 1985-Oct 2010) for the predominant soils zones 1 and 2, which cover the basin's surface, are shown in the time-series plots below. These plots illustrate the influence of soil properties on daily modelled recharge. Soil zone 9 has the area's highest field capacity and PRAW, and consequently has the lowest modelled recharge rates, due to the retention of soil moisture that it will use later in transpiration and evaporation rather than shed in recharge and runoff. By contrast, soil zone 1 allows a significantly higher quantum of recharge through the soil due to the area's lowest field capacity and PRAW.

References

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., Shirmohammadi, A., 1992: Infiltration and soil water movement. In: Maidment, D.R. (ed.), 1992. Handbook of Hydrology. McGraw-Hill, New York.

Rickard, D.S. & Cossens, G.G. 1968: Irrigation investigations in Otago, New Zealand. IV. Physical properties of soils of the Arrow Basin and Upper Clutha Valley. *New Zealand Journal of Agricultural Research, 11*, pp 701-732.

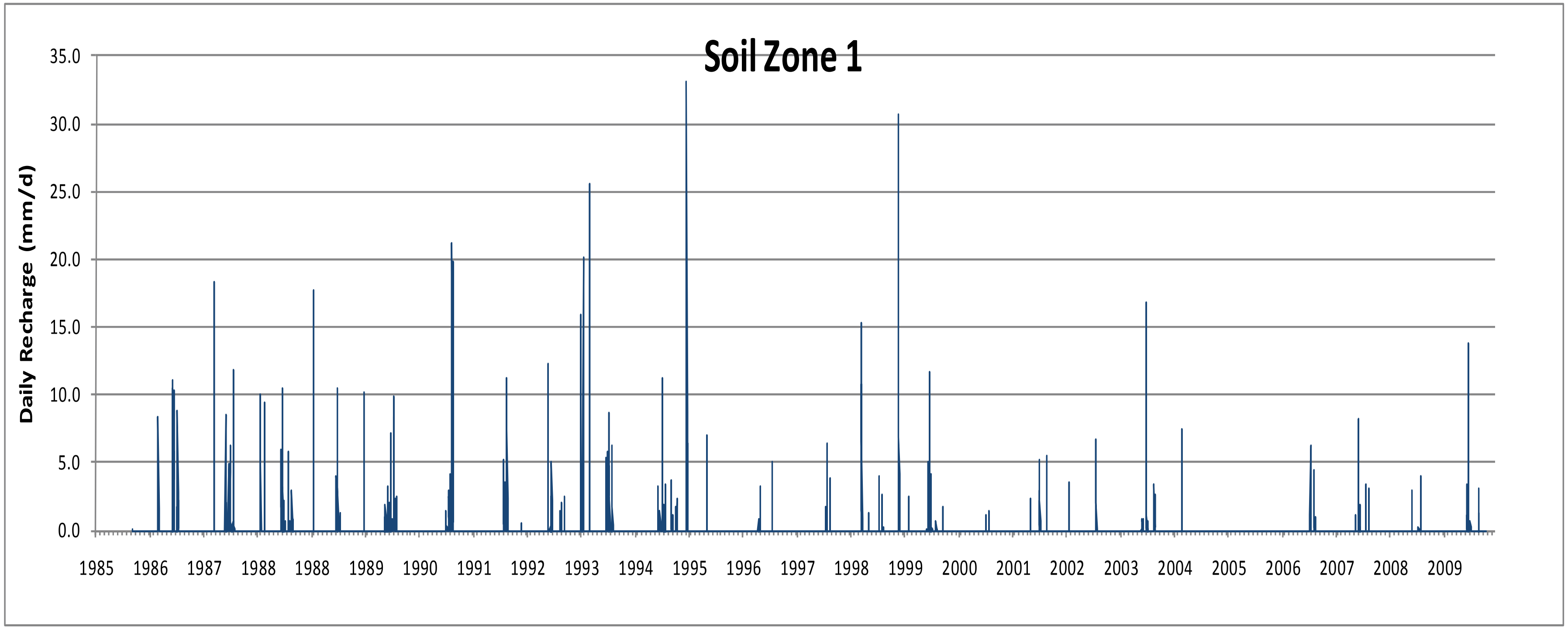
Rushton, K.R., Eilers, V.H.M., Carter, R.C., 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology 318, 379-399.

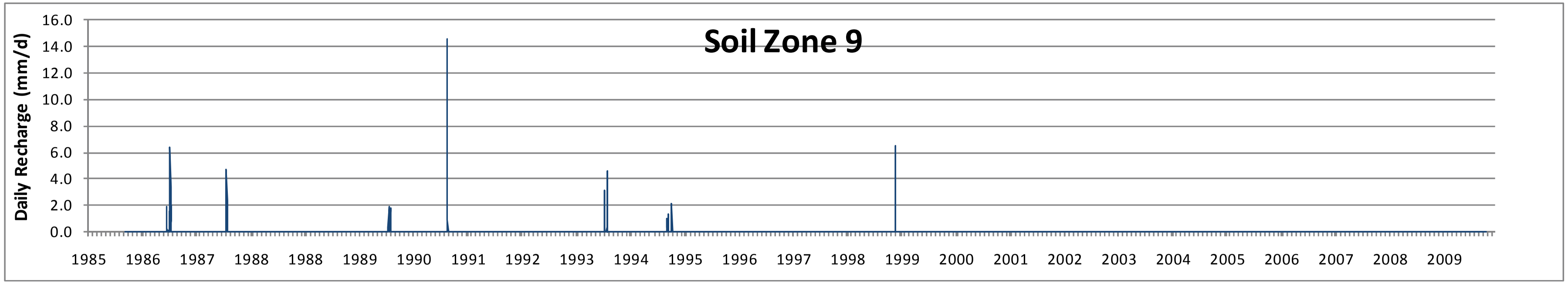
Scotter D, Heng L. 2003: Estimating reference crop evapotranspiration in New Zealand. Journal of Hydrology (NZ) 42: 1–10

Soil Conservation Service (USDA). 1967. National Engineering Handbook, Section 4, Hydrology.

Williams, J.R., 1991: Runoff and water erosion. In: Hanks, J., Ritchie, J. (eds.), Modelling plant and soil systems. Agronomy Monographs No 31, Crop and Science Society of America, Madison, Wisconsin.

Wilson, A.D.; Beecroft, F.G.; Smith, S.M. 1979: Soils of the Waitaki Plains and Oamaru-Ngapara Downlands, North Otago. Unpublished NZ Soil Survey Report. Map scale 1:20 000.


Soil Zone 1
Daily Recharge (mm/d)
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
1985 1986 1987 1988 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009


Soil Zone 9
Daily Recharge (mm/d)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1985 1986 1987 1988 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

Appendix 2 – References

AquaFirma Ltd. 1995: Groundwater pre-feasibility study. Prepared by AquaFirma Ltd for Earnscleugh Alluvial Gold Project – Mintago Investments Ltd on August 1995, Clyde.

AquaFirma Ltd. 1997: Hydrological feasibility assessment: Aquifer testing and inflow modelling. Prepared by AquaFirma Ltd for Earnscleugh Alluvial Gold Project – Mintago Investments Ltd on September 1997, Clyde.

AquaFirma Ltd. 1998: Dunstan / Earnscleugh Flats Groundwater Assessment of Tailrace Deepening Effects. Hydrogeological investigations report. Prepared by AquaFirma Ltd for Contact Energy Ltd – Hydro. March 1998, Clyde.

Aqualinc Research Ltd. 2006: Water Requirements for Irrigation Throughout the Otago Region. Prepared for Otago Regional Council. AquaLinc Report No L05128/2. October 2006.

Beecroft, F G; Griffiths, E; and Balks, M R. 1986: Suitability of land for irrigation within the Earnscleugh Irrigation Scheme, Central Otago, New Zealand. NZ Soil Bureau Report DN 20, DSIR, Wellington.

IRRICON. 1998: Groundwater of the Alexandra Basin: Preliminary Survey. Prepared by IRRICON Consultants for the Otago Regional Council, Dunedin.

Jewel, D G. 1978: Groundwater monitoring in the Clyde Area. CVD Investigation Report No. 79. Ministry of Works & Development, Cromwell.

Joe, E N; and Watt, J P C. 1984: Soil Water Characterisation Studies of 11 Soils in Central and Coastal Otago, New Zealand. NZ Soil Bureau SWAMP data sheets [1983(1-11)]. DSIR, Wellington.

Jowett, I. 1983: Fraser River Hydrology and Fish Habitat. Ministry of Works & Development, Power Division, Hydrology Section, Wellington.

L & M Mining Ltd. 1994: Application by L & M Mining Ltd to the Central Otago District Council and Otago Regional Council for the establishment and operation of an alluvial gold mine at Earnscleugh Flat, Alexandra. Prepared by Boffa Miskell Ltd for L & M Mining Ltd, Christchurch.

McCraw, J D. 1964: Soils of the Alexandra District. Soil Bureau Bulletin 24. DSIR, Wellington.

MWH. 2003: Dunstan Flats Aquifer Water Balance. Report prepared for the Otago Regional Council, Dunedin.

MWH. 2004: Water Balance – Lower Manuherikia / Alexandra Groundwater Zone. Report prepared for the Otago Regional Council, Dunedin.

ORC. 2005: Groundwater Allocation of the Alexandra Basin. Otago Regional Council, October 2005, Dunedin.

Paterson, B R. 1984: Engineering geological investigations for the feasibility study of the Earnscleugh Scheme. DSIR, Geological Survey, Lower Hutt.

Pattle Delamore Partners. 1995: Report on Alexandra Well Field. Prepared for Duffill Watts & King Ltd, report No. A28001.

Profitt, G T. 1985: Effect of tailrace deepening of groundwater levels: A review of investigations. CVD Investigation Report No. 408, Ministry of Works & Development, Cromwell.

Profitt, G T. 1987: Clyde Power Project: A study of the possible effects of tailrace deepening on water wells. CVD Investigation Report No. 534, Ministry of Works & Development, Cromwell.

Saul, G; and Watts, C. 1993: Clyde Power Project. Dunstan & Earnscleugh Flats: Assessment of tailrace deepening effects on groundwater. WORKS Consultancy Services report SP1993/13, Wellington.

Thomson, R. 1992: Clyde Tailrace Deepening: Preliminary geological evaluation marginal to the river. Unpublished letter (12 February 1992), DSIR, Geology & Geophysics, Cromwell.

Thomson, R. 1993: Clyde Tailrace Deepening: Location of Tertiary sediments within the Clutha River channel. Unpublished letter (4 March 1993), Institute of Geological & Nuclear Sciences, Cromwell.

Weissing, P R. 1981: Clyde Power Station Tailrace Deepening Proposal. Ministry of Works & Development, Power Design Internal Report.

Wood, J. 1934. Irrigation in Central Otago, New Zealand. Society of Civil Engineers; Proceedings 1933 – 1934, Vol. XX, pp 106 – 125.