Rainfall recharge assessment for Otago groundwater basins

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Foreword

Groundwater in Otago is frequently 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 we ensure linkage with the community to deliver the efficient use and protection of our groundwater aquifers.

This report provides an assessment of the amount of rainfall recharge to some of the regions main aquifers. The information has been calculated using the best available information and will assist the understanding of the status of this valuable resource.

Executive summary

Groundwater recharge due to rainfall is one of the primary sources of replenishment for Otago aquifers. This report estimates rainfall recharge for 13 groundwater basins in Otago. The rainfall recharge totals will assist in informing groundwater allocation assessment within the Council's Regional Plan: Water with respect to Maximum Allocation Volumes.

A soil moisture balance model was used to calculate a daily soil water budget. Input data for this model included rainfall and potential evapotranspiration data, which was mostly sourced from the National Institute of Water and Atmospheric Research (NIWA) database. The hydraulic properties of soils and their spatial distribution were supplied as a GIS layer by Landcare Research. The input data and modelled recharge values have been archived in ORC's Hilltop database.

The model results are summarised in the following table. Mean annual recharge volumes range from 1.2 to 64.6 million m^3/year. To compare values between regions it is more informative to study recharge depths, expressed as mm/year, or as a percentage of median annual rainfall rather than volumes.

Groundwater basin	Mean recharge (Mm^3/year)	Median annual (mm/yr) Rainfall	PET (mm/d)	Recharge	Percentage recharge
Clydevale-Wairuna	64.6	781	2.1	152	20
Cromwell	1.2	408	2.2	53	12
Ida Valley	18.8	499	2.2	61	12
Inch Clutha	10.4	726	1.9	76	10
Kuriwao	24.2	836	1.9	205	25
Lower Waitaki	18.5	521	2.0	75	17
Maniototo	31.6	483	2.2	29	5
Manuherikia	45.1	531	2.2	64	13
Pomahaka	52.1	944	2.1	212	22
Roxburgh	1.8	599	2.2	88	17
Strath Taieri	8.3	486	2.3	25	5
Tokomairiro	10.3	771	2.1	137	19
Wakatipu	12.5	746	2.6	184	23

Mean annual recharge volumes were found to range from 5 to 25% of median annual rainfall. Higher recharge percentages were found in South Otago and Wakatipu. The Wakatipu basin also showed the least annual recharge variability in the region.

The lowest recharge percentages were found in the Strath Taieri and Maniototo basins, where recharge was most vulnerable to dry conditions. In these two areas, along with the Lower Waitaki, recharge showed the most annual variation from the mean.

Mean recharge values were found to be 5 to 30% higher than the median, indicating that mean values were strongly biased towards wetter years. Wakatipu was the exception, with its mean recharge values being biased towards drier years. This is because the Wakatipu basin is more prone to extreme dry events than extreme wet events.

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1. Introduction

This report estimates rainfall recharge for all the major groundwater basins in Otago that remained to be comprehensively studied. Some aquifers have not been included as they are currently under investigation. These areas are the Alexandra Basin, Hawea Flat and the Papakaio aquifers.

The purpose of this report is to provide baseline recharge data for the Regional Plan: Water, in accordance with the amendment proposed in plan change 1C. The amended plan states that, in the absence of a specific direction in Schedule 4A [Policy 6.4.10A (a) (i) (1)], the default groundwater allocation volume is to be 50% of the calculated mean annual recharge[1] [Policy 6.4.10A (a) (ii) (1)].

Groundwater recharge can come from a variety of sources. Rainfall recharge and river recharge typically contribute the greatest volumes to total aquifer recharge. The proportion of each recharge source largely depends on the geological setting of the aquifer. For example, riparian aquifers, such as the Lindis alluvial ribbon, are highly reliant on river flows, and groundwater drawdown is buffered by the presence of the river. By contrast, the North Otago volcanics are more reliant on rainfall recharge.

Rainfall recharge can be further enhanced by irrigation, which helps to maintain soil moisture close to field capacity during drier periods. It should therefore be borne in mind that rainfall recharge is only one component of the groundwater budget. In some groundwater basins, additional recharge sources can constitute a large proportion of total recharge budget and may need to be considered.

The data used in this study have been archived in ORC's Hilltop database. For each groundwater basin, this includes a daily record of:

- recharge volume (m^3)
- recharge depth (mm)
- rainfall (mm)
- potential evapotranspiration (mm)
- soil moisture deficit (mm).

This archive will provide a useful resource for future investigations into related areas of study, such as potential for nutrient leaching and sensitivity of recharge to irrigation.

[1] The 50% figure was subject to appeal by the Director-General of Conservation under proposed plan change 1C. To satisfy the Director-General's concerns, changes are being made to the limits of discretion for restricted discretionary activities.

2. Methodology

This section provides an overview of the input data used for the recharge assessment and presents the soil moisture balance model used to carry out the calculations. The methodology for estimating recharge in each groundwater basin involves the following steps:

- Collate daily rainfall and potential evapotranspiration (PET) rates for each basin (mm/d).
- Calculate the daily soil moisture balance for each soil group in the basin (mm/d).
- Multiply any soil drainage by the total area covered by each soil in the basin (m^3/d).
- Add the drainage from each soil to give the daily total recharge value (m^3/d).

Mean annual recharge volumes (m^3/yr) are calculated from the daily recharge record for full calendar years. Recharge has also been expressed as a depth (mm) to relate it to rainfall and to allow meaningful comparisons between basins.

2.1 Rainfall and evapotranspiration data

There are two main considerations for selecting rainfall and evapotranspiration data:

- The length and consistency of record
- The suitability or area of influence of each site. This largely depends on geographic variability and local rainfall gradients (orographic effects).

In carrying out this recharge study, we assumed that the climate observed in the past will continue into the future. This was necessary because only historical rainfall and PET records were available. The first question we needed to address was: How long should a record should be to adequately characterise long-term climate trends?

Otago's climate is largely determined by southern ocean weather patterns. In particular, the difference in air pressure between Australia and South America has a strong influence. This pressure relationship across the Pacific is known as the 'southern oscillation'. Such large pressure differences result in El Niño or La Niña weather patterns.

Calculations of the difference in air pressure between Darwin and Tahiti, are known by climate scientists as the Southern Oscillation Index or SOI (Figure 1). Sustained positive SOI values indicate La Niña conditions, while periods of sustained negative values indicate El Niño events.

El Niño conditions are characterised by prevailing westerly weather patterns during summer, which cause more rain to fall in the west and drier conditions to occur in eastern areas. During winter, southerly weather patterns prevail. La Niña conditions are characterised by more north-easterly winds, which cause wetter conditions in easterly areas and drier weather in southern and western areas.

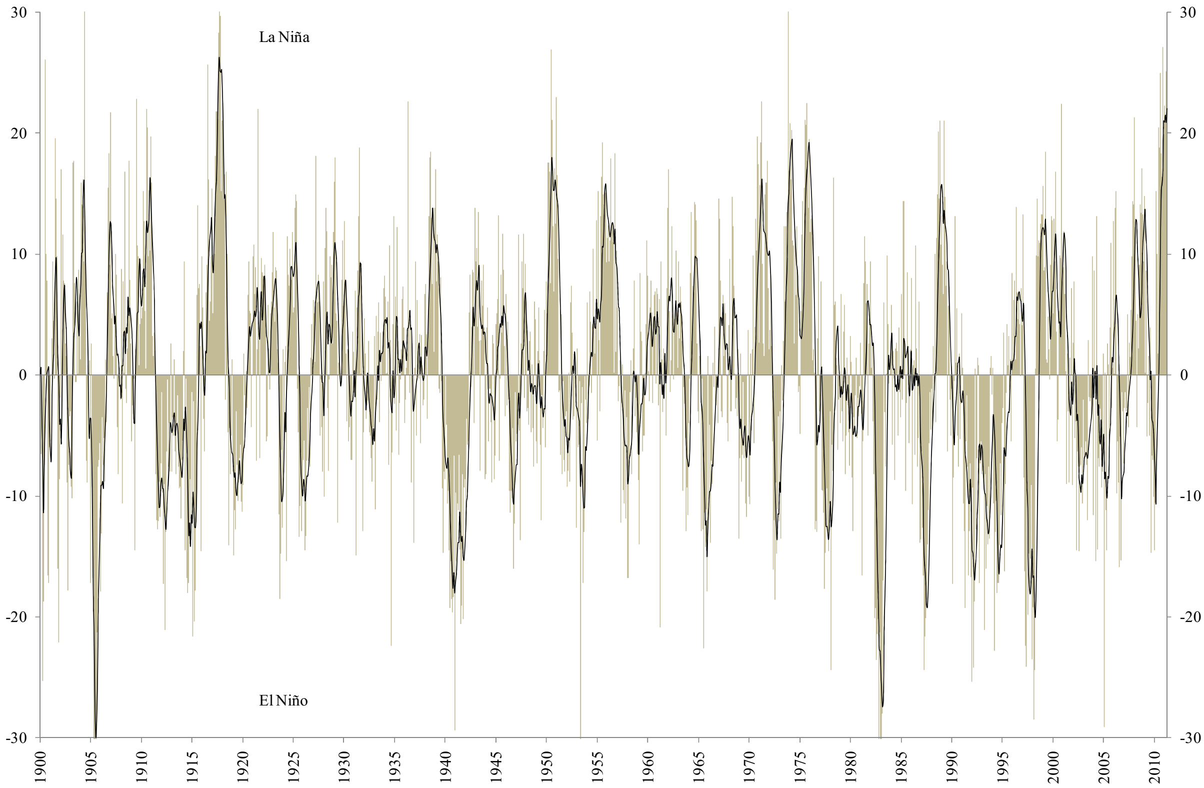

Figure 1 Monthly values of the Southern Oscillation Index plotted with a six month moving average[2]

Some caution is advised when predicting Otago's climate from the southern oscillation. For example, we would expect annual rainfall at Maniototo to be fairly predictable, with higher rainfall occurring during La Niña events. Scrutiny of the long-term records showed this to be the general long-term pattern, particularly if the SOI is large. However, there were quite marked departures where the opposite pattern occurred. For example, the period between mid-2002 to early 2004 was consistently wet, but this was a moderate El Niño period.

A prevailing southern oscillation event usually lasts between two and seven years. However, if we assume that the southern oscillation is a good indication of climate variability, we would prefer to have at least 14, if not 28, years to characterise the climate at any site.

These aspects of precipitation variability were examined in detail by Mojžíĕk (2006). He found that the precipitation variability in the South Island was governed largely by the local circulation characteristics, mainly the strength and position of the westerly flow. The increase in precipitation in the west and south-east was thought to be associated with enhanced westerlies.

Rainfall sites

The list of rainfall sites used for our recharge study is provided in Table 1. The median record duration is 36 years, which is sufficient to characterise climate variability. Some sites have fewer than 10 years of record, and these needed to be combined with sites in a similar climatic setting to generate an adequate length of record.

[2] Data sourced from Australian Bureau of Meteorology: http://www.bom.gov.au/climate/current/soi2.shtml

Table 1 NIWA rainfall sites used in this study

Sites Name	Agent Num.	Start	End	Duration (year)	Easting	Northing	Altitude
Arrowtown	25376	Apr-2004	Mar-2011	7.0	1270394	5014662	409
Arrowtown	5175	Jul-1927	Jan-1991	63.6	1270207	5015210	360
Arrowtown, Zelkova	7451	Apr-1992	Apr-2000	8.1	1268450	5014005	413
Balclutha	5866	Jul-1949	Mar-2011	61.7	1349373	4874548	12
Balclutha Finegand	5867	Jun-1964	Mar-2011	46.8	1348744	4870450	6
Baverstock Waiwera	5849	Oct-1954	Mar-2011	56.5	1331942	4882202	91
Blackstone Hill	5252	Oct-1915	Jun-2007	91.7	1356364	5019075	637
Cambrian	5248	May-1944	Apr-1973	29.0	1343405	5023018	549
Clinton PO	5859	Jan-1967	Dec-1987	21.0	1320354	4876785	122
Clinton School	5861	Nov-1983	Jan-1994	10.3	1320791	4877362	120
Cromwell 2	5529	Jul-1984	Jul-2007	23.1	1300290	5006115	213
Cromwell EWS	26381	Apr-2006	May-2011	5.1	1300432	5006455	213
Cromwell M.W.D.	5526	Jun-1949	Jun-1985	36.1	1300290	5006115	213
Enfield	5271	Jun-1977	Oct-1999	22.3	1431500	5009778	107
Ettrick No.2	5645	Feb-85	Apr-11	26.2	1315307	4941349	91
Inchclutha, T'Graph Rd.	5886	Jan-1967	Mar-2011	44.2	1355422	4867494	8
Kelso, The Holt	5677	Jan-1967	Jan-2003	36.1	1302370	4913020	180
Nenthorn	5316	Apr-1969	Jul-2008	39.2	1391346	4962934	360
Glenedi Road	5703	Aug-1984	Mar-2011	26.6	1374865	4882497	61
Lauder EWS	5535	Mar-1985	May-2011	26.2	1338831	5007244	375
Lauder Flat	5537	Jan-1945	Mar-2011	66.2	1340182	5010871	366
Lovells Flat	5872	Jan-1977	Feb-2011	34.2	1357637	4879712	91
Lovells SH1	5855	Jun-1987	Jan-1990	2.7	1355361	4882061	15
Matakanui	5530	May-1947	Feb-2011	63.8	1325142	5004476	357
Middlemarch, Garthmyl	5329	Oct-1896	Jan-2011	114.3	1376247	4955310	200
Milton	5856	Nov-1929	Nov-1985	56.1	1365943	4888825	18
Moa Creek	5545	Sep-1913	Apr-1984	70.7	1306667	4930221	620
Mooyman Homestead	5372	Jun-1983	Sep-1999	16.3	1308471	4919600	50
Naseby Forest 1	5257	Jan-1923	Mar-1983	60.2	1370775	5009375	610
Naseby Forest 2	5258	Oct-1983	Apr-2011	27.6	1374856	5009965	607
Kilmory Lug Creek	5315	Jan-1972	Mar-1994	22.2	1376141	4964817	343
Oamaru Airport	5141	Jan-1950	Oct-1985	35.8	1448848	5017928	30
Oamaru Airport AWS	5142	Dec-1981	May-2011	29.4	1448692	5018491	0
Ophir 2	5544	Apr-1924	Apr-2011	87.1	1333389	4999674	305
Oturehua	5253	Feb-1917	Feb-1974	57.1	1358662	5014712	549
Poolburn Edl	5549	May-1984	Mar-1986	1.9	1341771	4997027	412
Queenstown Aero AWS	5451	Jan-1982	May-2011	29.4	1264121	5005723	354
Ranfurly	5278	Apr-1943	Dec-2000	57.8	1372122	4998189	424
Ranfurly EWS	18593	Nov-2000	May-2011	10.5	1371959	4999028	450
Ranfurly Maniototo	5280	Mar-1975	Jul-1989	14.4	1371623	4998950	427
Roxburgh	5621	Jun-1987	Sep-2000	13.3	1312248	4950115	97
Roxburgh Power Stn	5612	Aug-1950	Dec-1987	37.3	1311931	4957003	110
Tapanui	5686	May-1897	Apr-2011	114.0	1309885	4905360	180
Taumata	23940	Nov-2001	Mar-2011	9.4	1322109	4990568	80
Te Houka	5864	Nov-1970	Mar-2011	40.4	1342368	4875835	82
Waipiata	5279	Aug-1915	Jan-1994	78.5	1376136	4993771	360
Warepa	5863	Sep-1967	Mar-2006	38.6	1338463	4870797	70
Wedderburn	5255	Jul-1957	Nov-1983	26.4	1363184	5009875	549

While many of the available rainfall sites do have long records, most contain considerable gaps typically ranging from a day to a month in duration. Some sites had longer gaps; for example, Ophir 2 and Waipiata both have very long records, but also have gaps of over two years.

Data preparation for this report mostly involved filling in the gaps in the rainfall records. To do this, data was sourced from a nearby suitable site to ensure a continuous record as an input to the daily soil moisture balance model.

Potential evapotranspiration

There are considerably fewer PET sites in Otago than there are rainfall sites (Table 2). The earliest PET records begin in 1972, and the median duration is only 15 years. This means that in most basins, the length of the recharge modelling period was constrained by the available PET data.

Therefore, to make the most of the available rainfall data, we decided, where possible, to extend the PET records. Fortunately, PET is cyclic on a seasonal basis and is fairly predictable. This seasonal predictability means that gaps in records can be filled with confidence.

Table 2 PET records used for this study

Name	Start	End	Duration (year)	E	N	Altitude
Alexandra	Jan-1972	Jan-1983	11.1	1316678	4982224	141
Balclutha, Finegand	Jan-1975	Aug-2004	29.6	1348744	4870450	6
Clyde	Jan-1983	Jun-1996	13.3	1310482	4987653	171
Clyde Ews	Jun-1996	Feb-2011	14.7	1310614	4987604	171
Cromwell EWS	Apr-2006	May-2011	5.1	1300432	5006455	213
Dunedin Aero Aws	Nov-1991	Feb-2011	19.2	1382684	4910200	1
Gore Aws	Jul-1986	Feb-2011	24.6	1282189	4885125	123
Gore, Grassland DSIR	Jan-1972	Oct-1986	14.8	1282576	4885145	123
Lauder EWS	Sep-1985	Feb-2011	25.5	1338831	5007244	375
Middlemarch EWS	Aug-2000	Feb-2011	10.5	1376319	4955683	213
Queenstown Aero Aws	Oct-1991	Feb-2011	19.3	1263993	5005529	354
Ranfurly Ews	Nov-2000	Feb-2011	10.2	1371936	4999209	450
Ranfurly Maniototo	Mar-1975	Jan-1990	14.8	1371802	4999122	427
Windsor Ews	Nov-2000	Feb-2011	10.2	1428446	5014004	81

Some site records can be extended by simply appending data from a nearby PET site to create a composite record. Sites where this was possible are:

- Gore: Gore AWS and Grassland DSIR
- Central Otago composite: Lauder EWS (primary site), Alexandra Clyde EWS, Clyde
- Maniototo: Ranfurly Ews and Ranfurly Maniototo.

For other sites, with no suitable neighbour, we had to derive a correlation with another PET site. Correlations were also made to remove gaps in PET records; for example, at Ranfurly, from 1990 to 2000.

For this study we made correlations between PET sites by plotting median PET values for each day of the year for the full available record at two sites. The correlation could then be used to fill in the gaps at the primary site. This method provides a seamless long-term PET record for sites with insufficient record.

Figure 2 illustrates this technique, using Balclutha and Gore as an example. The relationship with the Gore record was used to fill gaps in the Balclutha record.

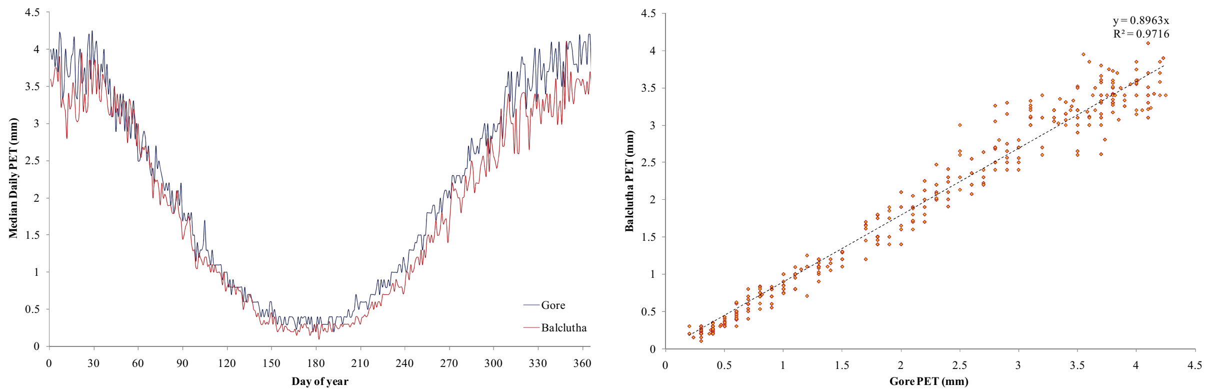

Figure 2 Relationship between PET at two sites (Gore and Balclutha)

Correlations and regression coefficients are provided in Table 3. The relationship between two PET sites is listed as:

Primary site = correlation coefficient x secondary site.

To avoid negative PET values, the intercept for the trend line was set to zero. This is a realistic assumption to make, because in winter, PET values of 0 mm/day typically occur throughout the region.

Overall, the results of the correlations are very good. The exception is the Lower Waitaki, which had the lowest regression coefficient of 0.87. The reason for this is that the Windsor site record has only been in existence for ten years and showed considerable fluctuation on a daily basis.

Table 3 Correlations made between primary and secondary PET sites

Basin	Primary Site	Secondary Site	Correlation	r^2
Kuriwao	Balclutha	Combined Gore	0.90	0.97
Lower Waitaki	Windsor	Central Otago composite	0.88	0.87
Maniototo	Ranfurly	Central Otago composite	0.94	0.98
Roxburgh	Middlemarch	Central Otago composite	0.98	0.94
Strath Taieri	Middlemarch	Lauder	0.92	0.95
Wakatipu	Queenstown	Lauder	1.05	0.98

2.2 Soil classes

Rainfall recharge to groundwater is largely influenced by the hydraulic properties of the overlying soil profile. A soil's storage capacity is its main physical characteristic that determines how readily rainfall is recharged.

The storage capacity of permeable soils tends to be low because they allow rainfall to pass through more readily. Soils with a lower storage capacity also tend to allow more recharge because they require less rainfall to become saturated.

Soils with a high storage capacity are typically clay rich. These soils tend to impede drainage and are more prone to surface ponding of water. Soils with a higher storage capacity can take longer to saturate and are more prone to evapotranspiration losses.

The Otago region has a large number of mapped soil types. One reason for this is that different areas in Otago have been mapped by different soils scientists over many years. Over time, this has led to a proliferation of local names for what are essentially the same regional soils.

The experience of contemporary soil scientists at Landcare Research has shown that many of Otago's soils have similar hydraulic properties. This enables the number of mapped soils to be reduced, which simplifies the recharge modelling considerably.

A total of 12 soil hydrological classes were used for the recharge modelling. The spatial distribution of these soils was provided by Landcare Research as a GIS layer. Up to 10 classes were used in any one groundwater basin. A summary of these soils and their hydraulic properties is provided in Table 4. More detailed characteristics of the soil classes are provided in Table A.1. of Appendix 1A.

PAW and PRAW values refer to the soil properties of profile available water and profile readily available water, respectively. These properties are equivalent to TAW (total available water) and RAW (readily available water), as reported in international literature. Lower PAW values indicate a more sensitive recharge response to rainfall events. Near-surface soil retention (Fracstor) values are based on field observations provided by Rushton *et al*. (2006) and (de Silva and Rushton, 2007).

Table 4 Soil Classes used for Otago recharge assessments

Class	Soil	Drainage	PAW (mm)	PRAW (mm)	Fracstor
1	Stony sand	Very free	30	21	0
2	Deep sands	Very free	80	64	0.1
3	Shallow stony soils and moderately deep sands	Free	80	48	0.2
4	Mod. deep sandy loam to silt loam	Free	150	90	0.3
5	Mod. deep fine sandy loam, silt loam, silty clay	Slow	150	90	0.5
6	Mod. to deep fine sandy loam, silt loam, silty clay	Poor	180	90	0.7
7	Shallow stony soils	Slow	60	36	0.4
8	Shallow stony old clay-bound gravels	Very slow	60	36	0.6
9	Shallow to moderately deep hill soils	Slow	80	65	0.5
10	Shallow hill soils	Free to rock	30	21	0.3
11	Deep silt loam	Slow to poor	100	45	0.6
12	Deep sandy loam to silt loam	Free	200	125	0.3

The soils found in any area are a product of the local geology, local climate, vegetation cover and land stability. In Otago, there are distinct geographical settings where the factors that form soils are broadly consistent. This is why the number of soil classes can be simplified to 12. It also means that certain soil types predominate in particular regions.

Table 5 shows the soils classes as a percentage of the area within each basin. The South Otago basins have an abundance of poorly drained deep silt loams, particularly Soil Class 11, which is the most prevalent soil in Otago. By contrast, Central Otago soils are typically quite free-draining sandy soils (Types 1-3). In north-eastern areas of Otago (Ida, Manuherikia, Strath Taieri, Maniototo and Lower Waitaki), no one soil type appears to dominate.

Table 5 Summary of percentage soil coverage for each basin

Class	Soil description	Inch Clutha	Clydevale	Cromwell	Ida Valley	Manuherikia	Kuriwao	Waitaki	Maniototo	Pomahaka	Roxburgh	Strath Taieri	Tokomairiro	Wakatipu
1	Stony sand			44.4	4.7	11.8		22.5	4.6		3.8			2.4
2	Deep sand	0.9		29.9				0.3						0.1
3	Shallow stony soil and mod. deep sand		0.1	18.5	16.8	20.1		27.4	12.2	4.8	50.9	13.3	0.7	4.2
4	Mod. deep sandy to silt loam	3.6	1.2	5.1	2.5	0.1	0.4	9.1	4.5	5.2	16.0	6.9		16.4
5	Mod. deep fine sandy loam, silt loam, silt clay	8.6	10.6		10.6	5.9	1.8	33.7	9.8	10.2		3.3		10.6
6	Mod. to deep fine sandy loam, silt loam, silt clay	54.6	5.9		6.7	7.3	15.6	0.5	5.9	13.1		8.5	1.6	4.1
7	Shallow stony soils				16.7	9.2	1.2	5.8	3.0	0.6		1.7		21.9
8	Shallow stony clay-bound gravels			0.3	23.3	20.1			28.7		28.3	3.9		
9	Shallow to mod. deep hill soils		4.1		17.9	24.7	1.0		23.2		0.5	0.9	1.6	
10	Shallow hill soils		2.5	1.8	0.8	1.0	0.9		0.5	1.3	0.5	42.5	1.3	32.3
11	Deep silt loam	11.2	68.7				70.1	0.7	7.7	48.4		13.8	91.6	
12	Deep sandy to silty loam	21.1	7.0				9.0			16.3		5.2	3.2	8.0

2.3 Soil moisture balance model

The land-surface recharge model selected for this report is a simple spread-sheet model, based on the soil moisture balance model described by Rushton *et al*. (2006). This model has been verified with lysimeter data from Canterbury (Appendix 2). The Rushton model was found to predict lysimeter recharge accurately, as long as the soil hydraulic properties are known.

A key assumption made in the recharge calculations is that water is able to freely drain from the soil profile into underlying permeable geology. In many areas, the estimated rainfall recharge can only be considered to be potential recharge. For groundwater recharge to occur, there needs to be a suitable receiving medium underlying the soil profile.

For example, in the Manuherikia and Ida Valleys, much of the valley floor consists of Tertiary mudstones. These mudstones tend to form a barrier to drainage, so that rainfall moving through the soil profile is impeded. In these areas, rainfall infiltration either moves laterally towards the nearest surface water body, or surface ponding occurs once the soil moisture reaches field capacity. Likewise, we assumed that recharge would not be intercepted by drainage before reaching the water table.

Spread-sheet calculations for soil moisture balance follow the algorithms provided in Rushton *et al*. (2006). The Rushton model consists of a two-stage process: calculation of near-surface storage and calculation of the moisture balance in the subsurface soil profile. The near-surface soil storage reservoir provides moisture to the soil profile once all the near-surface outputs have been accounted for. If there is no moisture deficit in the soil profile, recharge to groundwater occurs.

The Rushton model has been adapted for this report to incorporate run-off, which was calculated using the US Department of Agriculture, Soil Conservation Service (SCS) run-off curve number model. The SCS run-off model is described in Rawls *et al*. (1992).

There are three steps to describe the soil moisture balance:

1. Calculation of infiltration to the soil zone (*In*), and near-surface soil storage for the end of the current day (*SOILSTOR*). Note that infiltration (*In*), as specified by the Rushton algorithms, is not just infiltration (rainfall-run-off), it also includes *SOILSTOR* from the previous day.
2. Estimation of actual evapotranspiration (AET). PET is derived by the Penman-Monteith equation (Allen *et al*., 1998). A crop coefficient is not applied here since the crop is assumed to be pasture, which is the reference crop for the Penman-Monteith equation. Most pastures in New Zealand behave like the reference crop for most of the year (Scotter and Heng, 2003).
3. Calculation of soil moisture deficit and groundwater recharge. Recharge occurs only when the soil moisture deficit is negative, i.e. when there is surplus water in the soil moisture reservoir. The soil moisture deficit for the first day of the model is set to zero. Note that the soil moisture deficit equation, section (d) of Rushton, is ambiguous. *SURFSTOR* for this equation should be for the end of the current day.

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

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

Curve Number: A curve number is estimated for each soil, which is then used to calculate maximum soil retention of run-off. The same method is used for the HortResearch SPASMO model: the lower the curve number, the greater the soil retention threshold, which results in reduced run-off. Pasture in good condition on free-draining soil has a low curve number (39). Pasture in poor condition on a poorly drained soil has a high curve number (89). Additional values are given in Table 5.5.1 of Rawls *et al*. (1992). The SCS run-off calculation also has the capacity to incorporate slope and soil moisture (Williams, 1991).

Profile Available Water: PAW or TAW is calculated from field capacity, wilting point and rooting depth data. Typical values for field capacity and wilting point are given in Table 19 of Allen *et al*. (1998), and many values for New Zealand soils can be found in the literature (e.g. McLaren and Cameron, 1996). It is more difficult to determine appropriate values for rooting depth. Values quoted in the literature are usually for uninhibited root penetration. Some knowledge of the soil profile is required to estimate rooting depth, because root penetration at a particular site may be limited by the presence of a resistive layer such as a loess or clay pan. If rooting depth is not known, it may be estimated from the profile thickness for thicker soil units. However, because rooting depth is also a function of water capacity and aeration properties of the soil, some caution is needed in using profile thickness as a proxy.

Profile Readily Available Water: PRAW or RAW is related to PAW by a depletion factor, *p*. The depletion factor is the average fraction of RAW 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 pasture. (See Table 22 of Allen *et al*. (1998) for more values.)

Fracstor: This is the near-surface soil retention. Values are estimated for Otago soils based on values obtained elsewhere. The contribution of Fracstor to the soil moisture balance is small, so errors resulting from estimations are considered to be negligible. Typical values are 0 for a coarse sandy soil, 0.4 for a sandy loam and 0.75 for a clay loam (Rushton, 2006, p. 388). Appropriate values can be estimated from field observations (de Silva and Rushton, 2007). If the soil dries quickly, then Fracstor will be less than 0.3. If the soil surface remains wet after heavy rainfall, so that it is not possible to work the soil for several days, then Fracstor is likely to be in the range 0.6–0.8.

3. Rainfall recharge assessments

3.1 Introduction

This section details how rainfall recharge to groundwater was estimated for each of the 13 groundwater basins. A summary of the calculated annual recharge volume is also provided for each basin. Statistics are given for data with full calendar years only.

From an allocation perspective, the two most important statistics to study are mean annual recharge and the standard deviation from the mean. The standard deviation is a measure of the variation around the mean. Values quoted here are for one standard deviation, which accounts for ±34% variation from the mean. A low standard deviation means that in most years, the annual recharge volume is close to the mean. A large standard deviation indicates that there is often considerable variation away from the mean.

In terms of groundwater allocation, the standard deviation is important because it provides an indicator of the vulnerability of an aquifer to drier conditions. Groundwater basins with a standard deviation less than 50% of the mean will be fairly robust in their ability to provide sufficient water during dry years. Basins with a high standard deviation are more vulnerable to water stress.

For example, the mean annual recharge of the Cromwell aquifer is predicted to be 1.2 million m^3/year. If we apply a default groundwater allocation of 50% of the mean, the allocation limit would be 600,000 m^3/year. The standard deviation for the recharge data is 700,000 m^3/year, which is ±61% of that mean. This implies that there would be a 100,000 m^3 shortfall for the driest 16% of years, which would need to be met from water sources other than rainfall recharge. In this case, groundwater abstractions would be buffered by inflow from the Clutha River / Mata Au, so there would in reality be no shortfall in the Cromwell aquifer.

Many of the basins were divided into two separate recharge areas to account for prevailing local rainfall gradients. These rainfall gradients were taken from the mean annual rainfall contours provided on the Grow Otago website.

The boundaries for each basin were defined by the limits of tertiary or quaternary geology. A departure from this rule occurs in South Otago, where there are fractured rock aquifers. Basins where the substrate consists predominantly of bedrock are Clydevale-Wairuna and Kuriwao. The boundaries of these basins were delineated in previous groundwater investigations (ORC, 2002 and ORC, 1999). The Pomahaka basin also has a significant area of bedrock as a substrate within its middle portion.

3.2 Assumptions

The following assumptions have been made for the recharge assessments:

- Recharge is entirely sourced from rainfall. Increased soil moisture from irrigation has not been included in the calculations.
- The soil moisture balance model assumes that water leaves the bottom of the soil zone if the soil moisture deficit is zero at the end of the day.
- Daily rainfall and PET totals produce a soil moisture balance that is consistent at an hourly level. This assumption has to be made because the available data is for daily totals. PET has a regular cycle throughout the day, and rainfall can fall at any time during the day and at any intensity. This means that at an hourly level, the soil moisture balance is variable on any given day.
- All of the calculated recharge can drain freely into a permeable subsurface medium (aquifer). However, in many areas, this is not the case, and the calculated recharge has to be considered as potential recharge only.
- Snow is considered to be rainfall in the calculations. Note that snow does not greatly influence the recharge calculations, because it occurs at a time when PET is low and soil is saturated.
- Soil properties and PET and rainfall values are consistent over the calculated areas.
- Land cover is assumed to be pasture.
- Rainfall run-off from around the perimeter of the recharge area is not included in the recharge assessment.

3.3 Inch Clutha

The Inch Clutha basin receives more rainfall near the coast than at Balclutha. For recharge modelling, the basin was divided into northern and southern parts along the 700 mm mean annual rainfall contour (Figure 3). The mean annual rainfall for the northern and southern areas during the modelling period was 687 mm and 760 mm, respectively (Table 6).

The primary rainfall site used for representing the northern part of the basin was Balclutha, at Finegand. This record has a large number of small gaps of two to four days duration. The majority of these gaps were filled by Balclutha (5866), which has a longer record but more significant gaps than Finegand. The remaining gaps were filled by using the rainfall data from Inch Clutha at Telegraph Road.

Rainfall in the southern section is represented by the Telegraph Road site. While this site is geographically located on the boundary between the northern and southern parts of the basin, it is more representative of the southern area than any other sites in the region. All gaps in this site's record were filled by rainfall data from both Balclutha (5866) and Balclutha, Finegand.

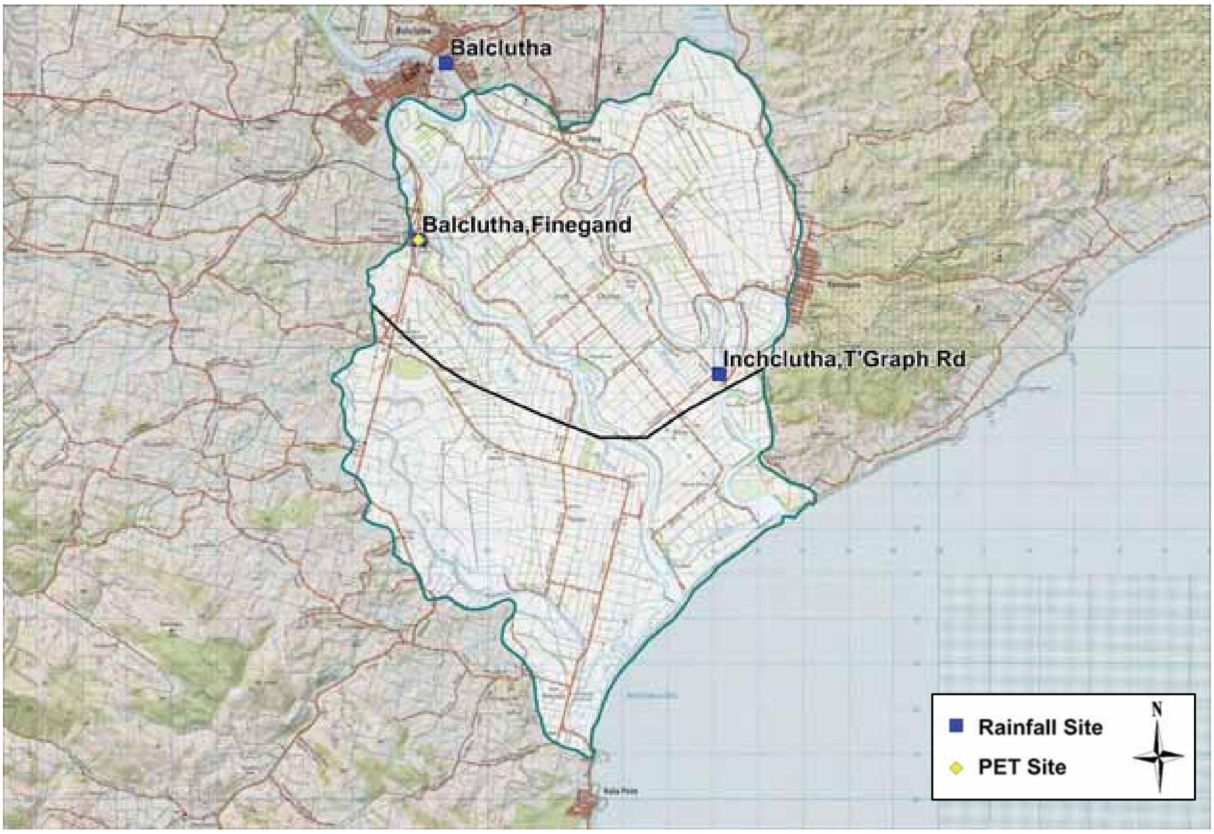

Figure 3 **Inch Clutha basin boundary and sites used for the recharge assessment**

The PET data for Inch Clutha came from the NIWA climate station at Balclutha, Finegand. The duration of this record limited the recharge modelling period to between January 1975 and August 2004.

Table 6 **Inch Clutha recharge modelling site records**

		Site	Start	End	Duration (years)
Rainfall	**North**	Balclutha Finegand (5867)	Jun-1964	Mar-2011	46.8
	South	Inch Clutha, Telegraph Rd (5886)	Jan-1967	Mar-2011	44.2
PET		Balclutha Finegand (5867)	Jan-1975	Aug-2004	29.6
Modelling period			Jan-1975	Aug-2004	29.6

The climate at Inch Clutha is marked by a moderate to high rainfall and low PET. Mean annual recharge was calculated to be 10.4 Mm^3/year (Table 7). This is 25% higher than the median, indicating that long-term recharge volumes were strongly influenced by wetter years. The standard deviation is 62% of the mean.

Table 7 **Inch Clutha recharge modelling results (million m^3/year)**

	Area (Ha)	Mean	Std dev	Max.	Median	Min.
Inch Clutha	9,634	10.4	6.5	23.6	7.8	1.4

3.4 Clydevale-Wairuna

These two basins collectively form the largest area modelled in South Otago. The boundaries for Clydevale and Wairuna basins were originally defined in 2002 and treated as two separate 'aquifers' (ORC, 2002). Groundwater is mostly sourced from fractured Murihiku group rock, so from a groundwater perspective, the boundary is somewhat arbitrary. For this reason, the two basins are treated as a single entity (Figure 4).

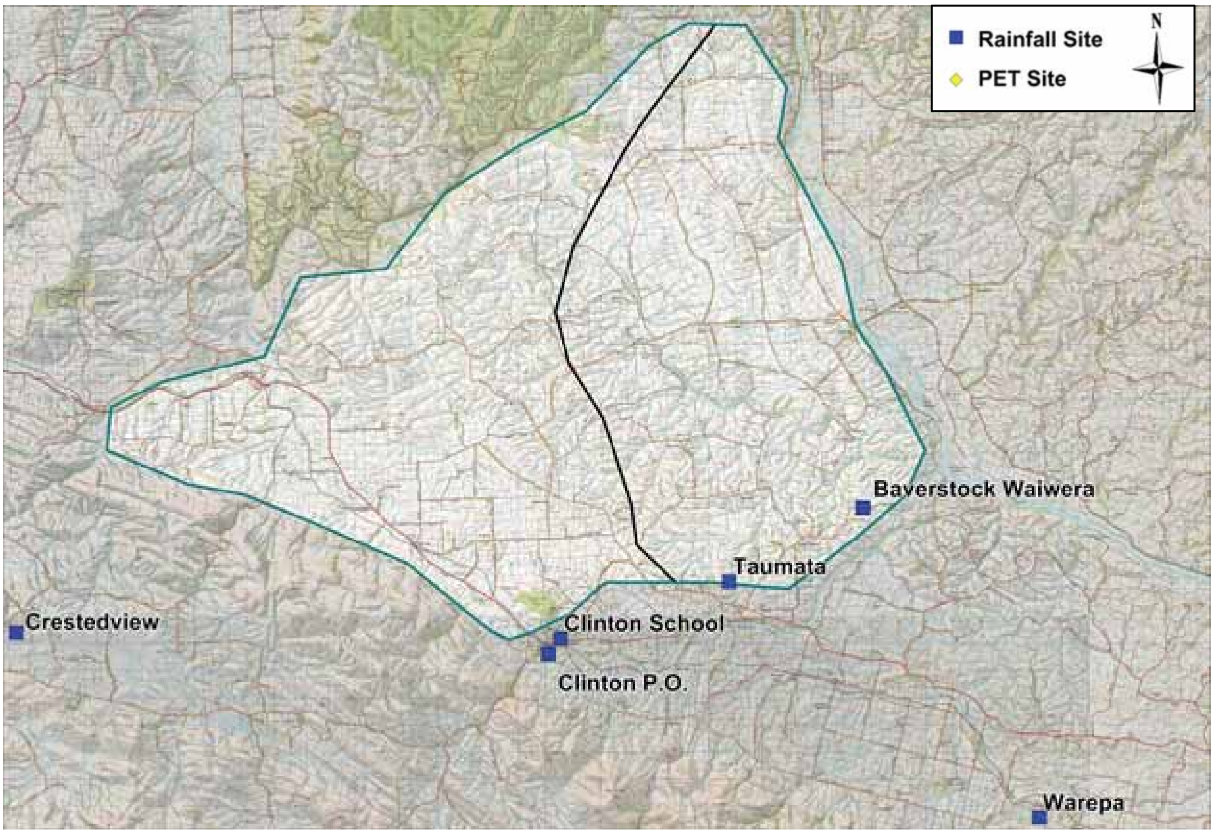

Figure 4 **Clydevale-Wairuna basin boundary and sites used for the recharge assessment**

The basin was divided into two parts along the trend of the mean annual rainfall contour line. There is a strong rainfall gradient across the Murihiku Range, with mean annual rainfall being much higher in the south-west (771 mm) than in the north-east (627 mm).

Rainfall data for the south-western part of the basin came from the two Clinton rainfall sites, which were combined to form the primary rainfall record (Table 8). Gaps for this combined record were filled by data from Warepa.

Table 8 **Clydevale-Wairuna recharge modelling site records**

		Site	Start	End	Duration (years)
Rainfall	**East**	Warepa (5863)	Sep-1967	Mar-2006	38.6
		Baverstock Waiwera (5849)	Oct-1954	Mar-2011	56.5
	West	Clinton PO (5859)	Jan-1967	Dec-1987	21.0
		Clinton School (5861)	Nov-1983	Jan-1994	10.3
PET		Combined Gore	Jan-1972	May-2011	39.4
Modelling period			Jan-1972	Feb-1994	22.1

Rainfall for the eastern part was primarily sourced from the Baverstock site, at Waiwera. Gaps were also filled from the Warepa record. PET was sourced from the combined Gore record. The recharge modelling period was limited by the rainfall record for Clinton, which ends in January 1994.

Clydevale-Wairuna has the greatest calculated recharge volume of all the basins considered in this report (Table 9). This is mainly due to its large area, combined with high annual rainfall totals. However, recharge at this basin does need to be considered as potential recharge only, as the basin's substrate is predominantly Murihiku group greywacke.

Table 9 Clydevale-Wairuna recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std dev	Max.	Median	Min.
Clydevale	35,454	64.6	34.4	157.5	55.3	3.1

Seasonal variability of recharge is high and is volumetrically greater than the mean annual recharge of all other sites, except Pomahaka. However, the standard deviation is equivalent to around 50% of the mean, so there is little risk of water stress on a regular basis. The lowest calculated annual recharge is only 5% of the mean, which does indicate that the basin can become water stressed during extremely dry seasons.

3.5 Cromwell

The Cromwell aquifer is very small, covering an area of 1,799 Ha (Figure 5). This is also one of the few basins studied than can truly be considered an aquifer.

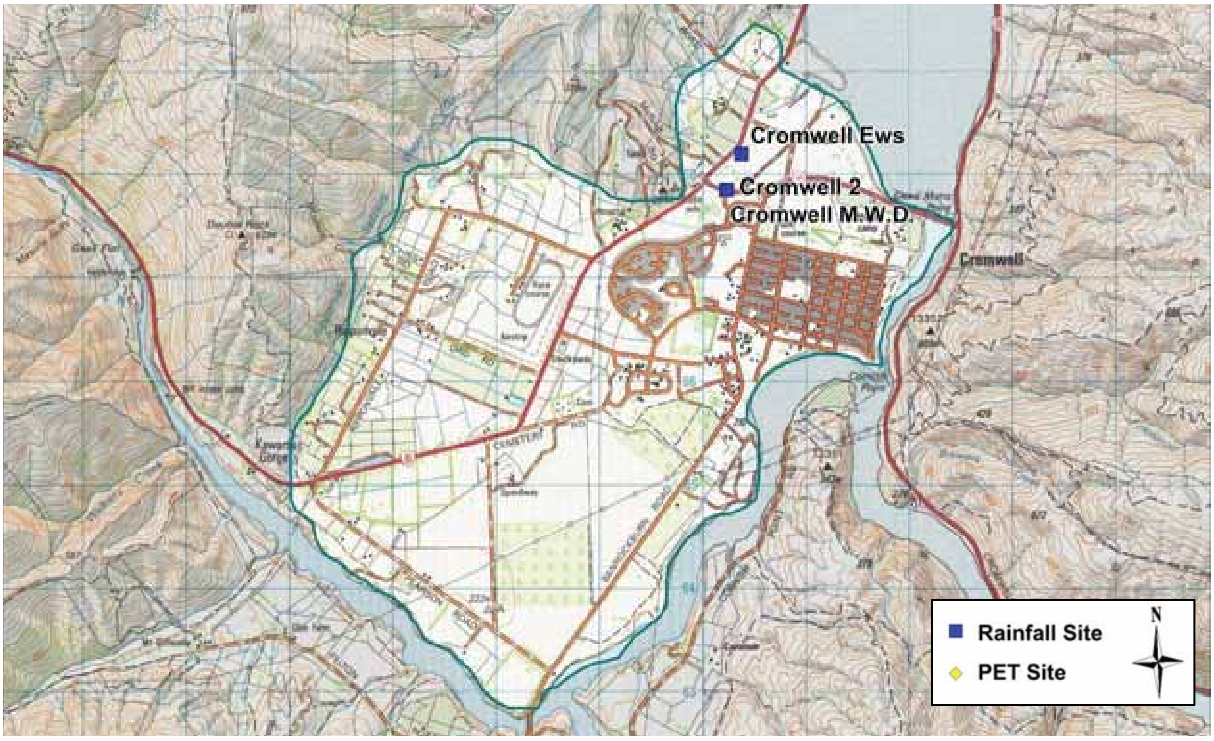

Figure 5 Cromwell aquifer boundary and sites used for the recharge assessment

Rainfall data for this aquifer was sourced from the three sites located at Cromwell: Cromwell EWS, Cromwell 2 and Cromwell M.W.D. When combined, these sites form a continuous record from July 1984 to the present day, with a small overlap between one site ending and the next one starting (Table 10).

The Central Otago composite record was used as the PET input for the model. This composite record gives 39 years of continuous PET, which is the longest PET record available in Otago. The recharge modelling period begins in 1972, at the start of the PET record.

Table 10 Cromwell recharge modelling site records

	Site	Start	End	Duration (years)
Rainfall	Cromwell 2 (5529)	Jul-1984	Jul-2007	23.1
	Cromwell EWS (26381)	Apr-2006	May-2011	5.1
	Cromwell M.W.D. (5526)	Jun-1949	Jun-1985	36.1
PET	Central Otago Composite	Jan-1972	Jan-2011	39.1
Modelling period		Jan-1972	Jan-2011	39.1

Mean annual rainfall during the recharge modelling period was 423 mm, which is the lowest of all the basins studied. The calculated mean annual recharge volume of 1.2 Mm^3/year is also volumetrically small because of the aquifer's small land surface area (Table 11). The standard deviation is 61% of the mean.

Table 11 Cromwell recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Cromwell	1,779	1.2	0.7	2.8	1.0	0.2

3.6 Ida Valley

The Ida Valley was divided into northern and southern areas to cater for the increased rainfall near the Hawkdun Range. The boundary between these two areas was drawn along the drainage divide in the vicinity of Boundary Road (Figure 6). This divide naturally separates water resources within the catchment and also lies along the 500 mm/year mean annual rainfall contour. The mean annual rainfall for the northern and southern parts during the modelling period was 611 mm and 424 mm, respectively.

Rainfall data for the northern part of the basin came from Oturehua, which was extended by appending the record for Blackstone Hill (Table 12). Gaps in these records were filled with data from the nearby rainfall sites.

Rainfall data for the southern part of the basin was mostly sourced from Moa Creek. This record contained numerous small gaps, ranging from two to ten days, which were filled by rainfall data from Lauder Flat (5537). The Moa Creek record was extended to 1986 by including Poolburn Edl, which had no gaps. The lack of recent rainfall records for the southern part of the basin meant that recharge modelling had to end in 1986.

The PET record for the Ida Valley was sourced from the composite record created for Central Otago. Unlike other basins, the modelling period for the Ida Valley was limited by short rainfall, rather than PET, records. At 14 years, this basin has the shortest modelling period, which barely provides sufficient duration for a reliable dataset.

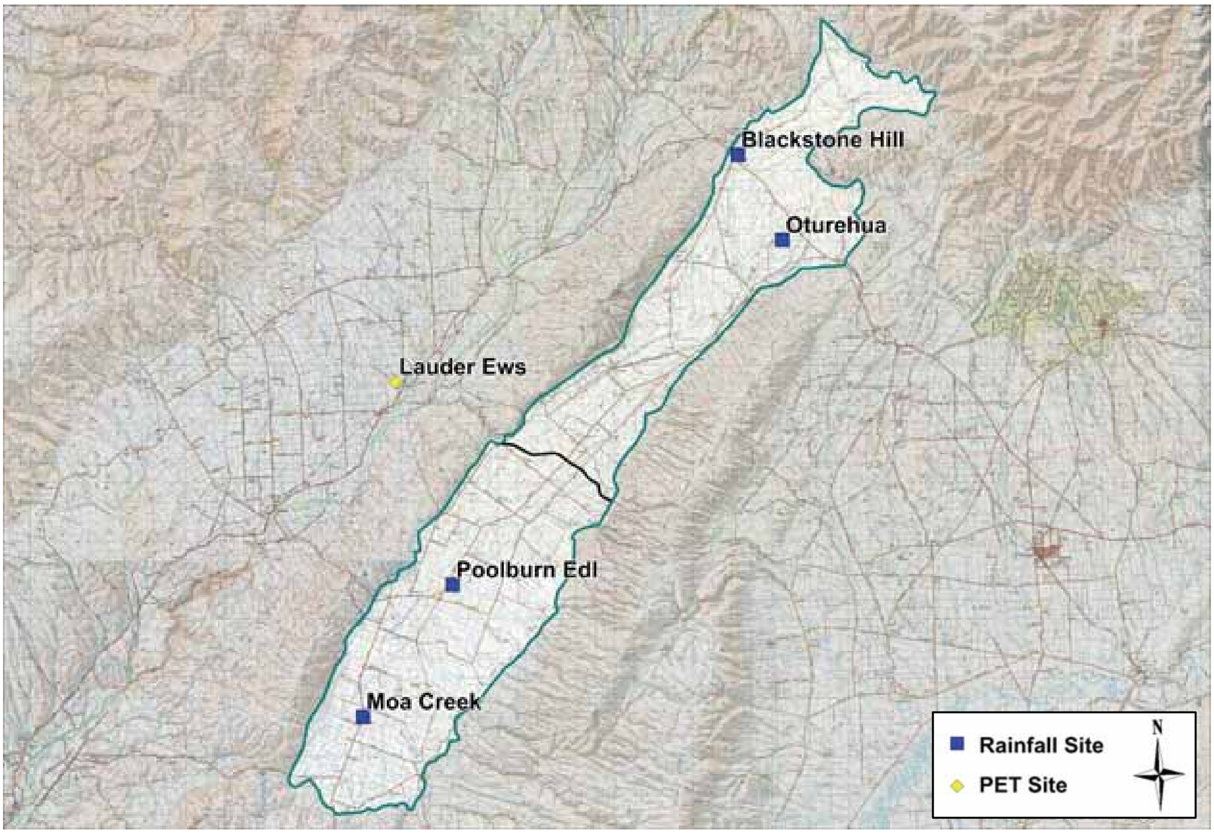

Figure 6 Ida Valley basin boundary and sites used for the recharge assessment

Table 12 Ida Valley recharge modelling site records

		Site	Start	End	Duration (years)
Rainfall	**North**	Oturehua (5253)	Feb-1917	Feb-1974	57.1
		Blackstone Hill (5252)	Oct-1915	Jun-2007	91.7
	South	Moa Creek (5545)	Sep-1913	Apr-1984	70.7
		Poolburn Edl (5549)	May-1984	Mar-1986	1.9
PET		Central Otago Composite	Jan-1972	Jan-2011	39.1
Modelling period			Jan-1972	Apr-1986	14.2

Ida Valley is calculated to receive 18.8 Mm^3/year of potential recharge. This is far in excess of what the basin can practically yield as a groundwater resource. Drainage is certainly impeded by the underlying Tertiary sediments, which cause water to pond or route laterally towards surface water bodies. For this reason, the calculated recharge volume is not a clear indication of what the basin can practically yield as a resource.

The standard deviation is 52% of the mean, which indicates that an allocation of 50% mean annual rainfall recharge would be met most years. This assumes that the water infiltrates into the ground, where it is stored as groundwater and can be pumped at a useful rate. However, experience indicates that all three of these assumptions are unlikely to be true in the Ida Valley because of its Manuherikia group silt substrate.

Table 13 Ida Valley recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Ida Valley	27,247	18.8	9.8	39.9	17.8	5.1

3.7 Lower Waitaki Plain

The area covered by the Lower Waitaki Plain is represented by the flat land south of the Canterbury boundary and the Waitaki River floodplain (Figure 7). The substrate consists of permeable alluvium, and the entire area can be considered to be an aquifer.

Two rainfall sites were combined to form a composite rainfall record for the aquifer (Table 14). The gaps for this combined dataset were filled by the rainfall data from Enfield (5271). The mean annual rainfall for this aquifer during the modelling period was 520 mm.

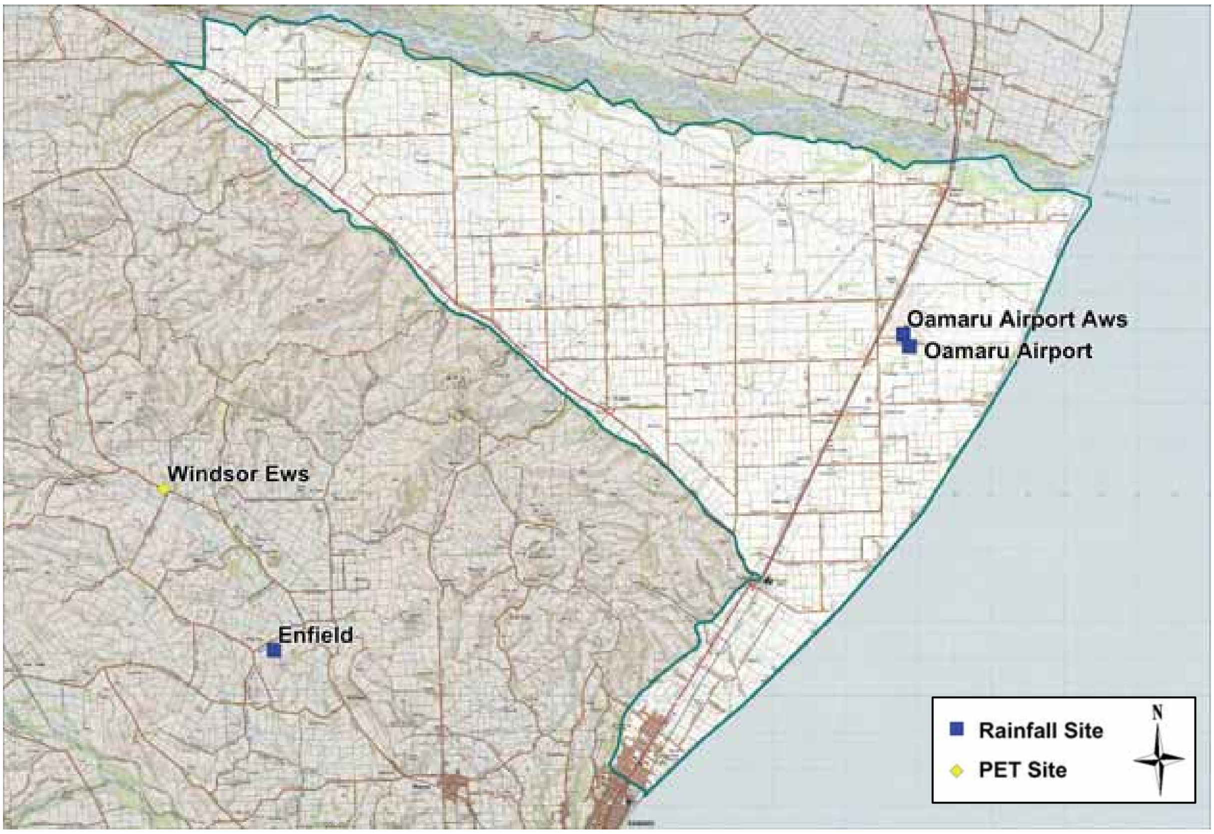

Figure 7 Lower Waitaki basin boundary and sites used for the recharge assessment

The primary PET site used was Windsor. A correlation was made with the Central Otago composite record to extend the record back to 1972.

Table 14 Lower Waitaki Plain recharge modelling site records

	Site	Start	End	Duration (years)
Rainfall	Oamaru Airport AWS (5142)	Dec-1981	May-2011	29.4
	Oamaru Airport (5141)	Jan-1950	Oct-1985	35.8
PET	Windsor (18594)	Nov-2000	Jan-2011	10.2
	Central Otago composite	Jan-1972	Jan-2011	39.1
Modelling period		Jan-1972	Jan-2011	39.1

The modelling results show that the Waitaki Plain aquifer has a mean annual rainfall recharge of 18.5 Mm^3/year (Table 15). The mean is higher than the median, suggesting that this value is skewed by wetter years. The standard deviation is 76% of the mean, which is relatively high. This indicates that recharge can be quite variable and that the aquifer receives very little rainfall recharge during drier years. The calculated minimum recharge is only 0.3 Mm^3/year, which is 2% of the mean.

Table 15 Lower Waitaki recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std dev	Max.	Median	Min.
L Waitaki	19,443	18.5	14.1	56.0	14.2	0.3

3.8 Kuriwao

The limits of the Kuriwao basin were originally defined by ORC (1999). Like the Clydevale-Wairuna system, the Kuriwao basin is underlain by Murihiku group greywacke, so calculated recharge can only be considered as potential recharge.

For this study, the basin was divided into two parts along the 800 mm mean annual rainfall contours (Figure 8). The mean annual rainfall for the northern and southern parts during the modelling period was 670 mm and 911 mm, respectively.

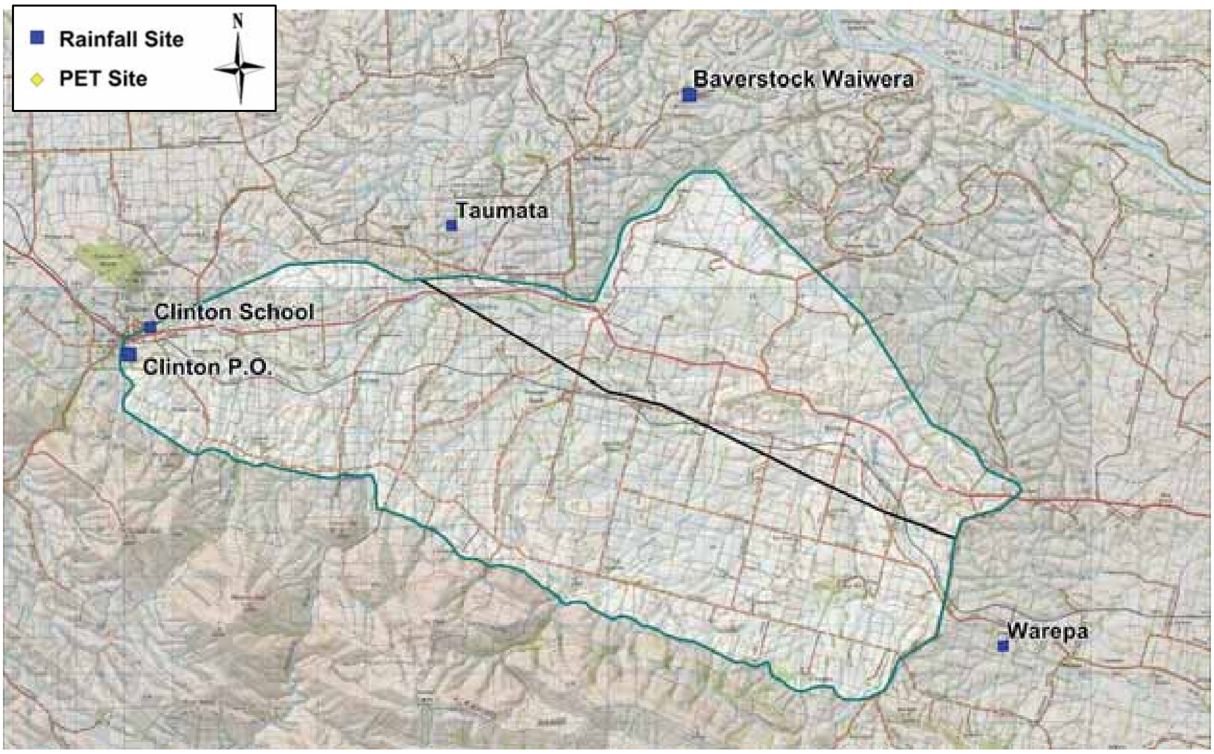

Figure 8 Kuriwao basin boundary and sites used for the recharge assessment

The primary rainfall site used for the northern section was Baverstock, at Waiwera (Table 16). Gaps were filled from two nearby sites: Taumata (23940) and Te Houka (5864).

A composite of two Clinton rainfall sites and Warepa were used to form a continuous rainfall record for the southern section. Any remaining gaps were filled with data from the ORC rainfall site at Crestedview.

Table 16 Kuriwao recharge modelling site records

		Site	Start	End	Duration (years)
Rainfall	**North**	Baverstock Waiwera (5849)	Oct-1954	Mar-2011	56.5
		Taumata (23940)	Nov-2001	Mar-2011	9.4
	South	Clinton PO (5859)	Jan-1967	Dec-1987	21.0
		Clinton School (5861)	Nov-1983	Jan-1994	10.3
		Warepa (5863)	Sep-1967	Mar-2006	38.6
PET		Combined Gore	Jan-1972	May-2011	39.4
		Balclutha Finegand (5867)	Jan-1975	Aug-2004	29.6
Modelling period			Jan-1972	Apr-2006	34.2

Balclutha, at Finegand, was used as the primary PET site. A correlation was made with the combined Gore record to extend the Finegand record back to August 2004.

The Kuriwao basin typically receives a high annual rainfall and has relatively low PET. Accordingly, its calculated mean annual recharge is high at 24.2 Mm^3/year (Table 17). This is equivalent to 25% of median annual rainfall, which is the highest of all the basins in this study. However, like Clydevale-Wairuna, these statistics come with the caveat that calculated recharge can only be considered to be potential recharge in an area underlain by a fractured rock aquifer.

Table 17 Kuriwao recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Kuriwao	10,424	24.2	10.4	52.7	22.2	4.2

3.9 Maniototo

The Maniototo basin is the largest area modelled in this report. The Maniototo shares many characteristics with the Strath Taieri basin, including a high diversity of soil cover, a mean annual rainfall of under 500 mm/year and a high average PET, caused by a strong wind run. The Maniototo basin is completely surrounded by mountain ranges, which creates an interesting orographic effect. These characteristics made this basin one of the more challenging areas to model.

The Maniototo was divided into a northern and southern section to reflect the higher rainfall observed along the Ida Range and Kakanui Mountains (Figure 9). More rainfall sites are available to divide the basin up further, although their periods of records are typically short and do not align well over time. To include these additional sites would require sacrificing the length of the modelling period considerably. We decided to compile a longer record at the expense of spatial variability.

Rainfall for the northern Maniototo section was mainly sourced from Naseby Forest 1 and 2. Gaps were filled from Wedderburn and the three Ranfurly sites (Table 18). For the southern section, the Ranfurly sites were combined to form the primary rainfall record. Remaining gaps were filled by the rainfall data from Waipiata. During the modelling period, mean annual rainfall for the northern and southern sections was 598 mm and 439 mm, respectively.

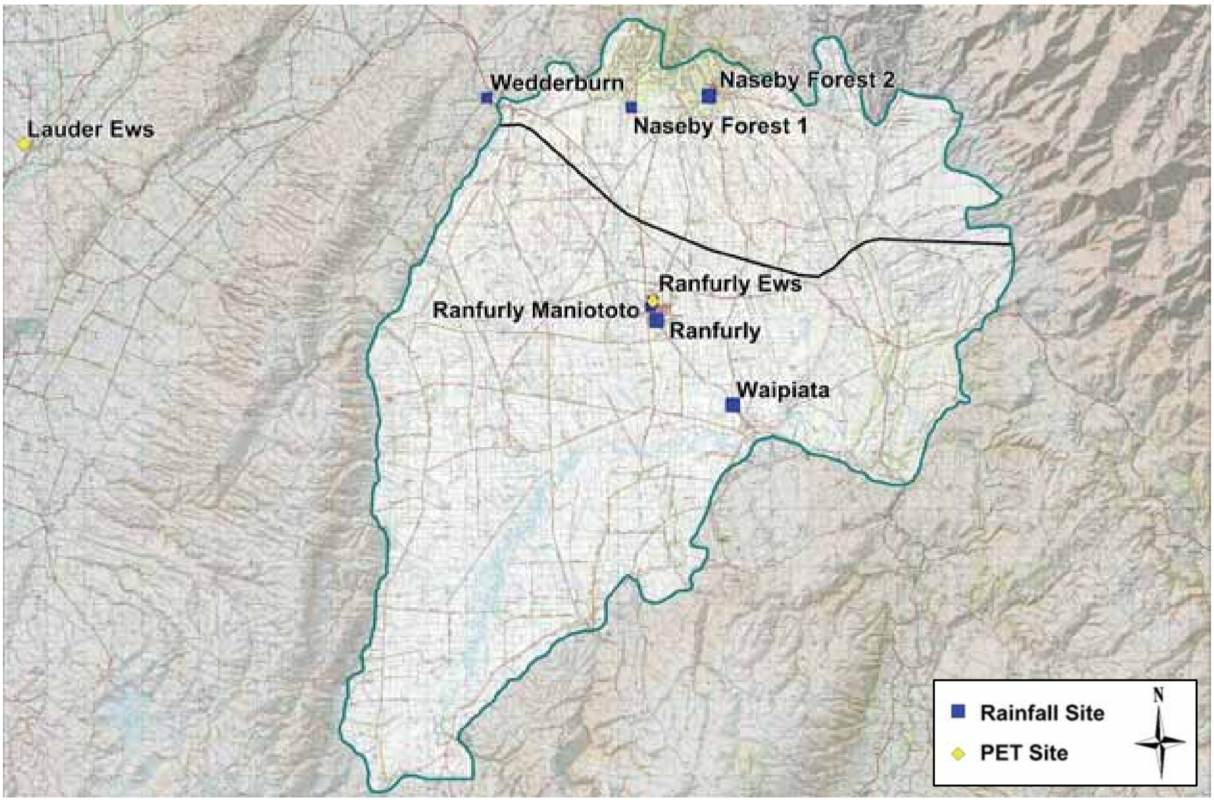

Figure 9 **Maniototo basin boundary and sites used for the recharge assessment**

To create a continuous PET record, the two available Ranfurly PET sites were combined to form a record for Ranfurly. A correlation was made with the Central Otago composite record to fill the gap between Oct 1988 and Nov 2000 in the Ranfurly record.

Table 18 **Maniototo recharge modelling site records**

		Site	Start	End	Duration (years)
Rainfall	**North**	Naseby Forest 1 (5257)	Jan-1923	Mar-1983	60.2
		Naseby Forest 2 (5258)	Oct-1983	Apr-2011	27.6
		Wedderburn (5255)	Jul-1957	Nov-1983	26.4
	South	Ranfurly EWS (18593)	Nov-2000	May-2011	10.5
		Ranfurly (5278)	Apr-1943	Dec-2000	57.8
		Ranfurly Maniototo (5258)	Mar-1975	Jul-1989	14.4
		Waipiata (5279)	Aug-1915	Jan-1994	78.5
PET		Central Otago composite	Jan-1972	Jan-2011	39.1
		Ranfurly EWS (18593)	Nov-2000	Jan-2011	10.2
		Ranfurly Maniototo (5258)	Apr-1975	Oct-1988	13.5
Modelling period			Jan-1972	Jan-2011	39.1

The results of the Maniototo recharge calculation are shown in Table 19. Despite its relatively low rainfall, the Maniototo has one of the largest annual recharge volumes. This is mostly attributed to its large area, as recharge is equivalent to just 5% of median annual rainfall. Recharge variability is also extremely high, with a standard deviation of 86% of the mean.

Table 19 **Maniototo recharge modelling results (million m^3/year)**

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Maniototo	77,822	31.6	27.2	129.7	24.4	1.4

3.10 Manuherikia

This Manuherikia Valley was divided into two sections, based on the annual rainfall contours (Figure 10). Rainfall is significantly higher in the northern part of the area adjacent to the Hawkdun and St Bathans ranges. During the modelling period, the mean annual rainfall for the northern and southern parts was 611 mm and 509 mm, respectively.

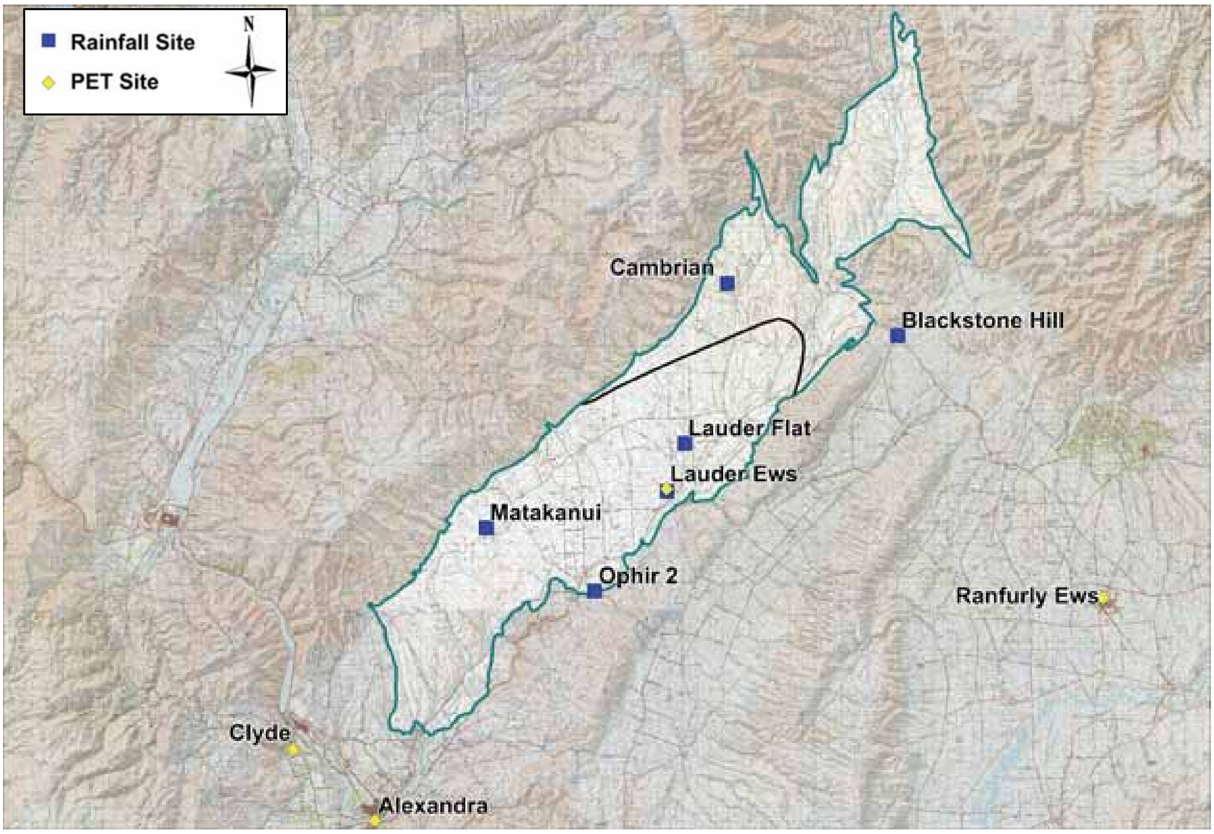

Figure 10 **Manuherikia basin boundary and sites used for the recharge assessment**

The primary rainfall record used in the northern section was obtained from Cambrian. This record was extended, and gaps were filled using data from Blackstone Hill, which extended the available record to 2007. In the absence of other suitable sites, gaps from 1973 onwards were filled from nearby Manuherikia sites at Lauder.

Table 20 **Manuherikia recharge modelling site records**

		Site	Start	End	Duration (years)
Rainfall	**North**	Cambrian (5248)	May-1944	Apr-1973	29.0
		Blackstone Hill (5252)	Oct-1915	Jun-2007	91.7
	South	Lauder EWS (5535)	Mar-1985	May-2011	26.2
		Matakanui (5530)	May-1947	Feb-2011	63.8
		Ophir 2 (5544)	Apr-1924	Apr-2011	87.1
		Lauder Flat (5537)	Jan-1945	Mar-2011	66.2
PET		Central Otago Composite	Jan-1972	Jan-2011	39.1
Modelling period			Jan-1972	Jul-2007	35.5

The rainfall record for the southern section was compiled from four sites: Lauder EWS, Lauder Flat, Matakanui and Ophir 2. Data from these sites were combined to form a single continuous record.

The Central Otago composite record was used for PET. This record limits the start of the modelling period to 1972. The end of the modelling interval was limited to 2007, due to the length of the rainfall record in the northern section.

The Manuherikia Valley gives a surprisingly high potential recharge value of 45.1 Mm^3/year (Table 21). This is largely due to its large area, the Manuherikia being the second largest basin studied. Median annual rainfall was relatively low at 531 mm/year, which gives an equivalent recharge of 13%.

Like the Ida Valley, as much of the Manuherikia is underlain by low permeability Tertiary sediments, rainfall recharge can only be considered as potential recharge.

Table 21 Manuherikia recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Manuherikia	58,896	45.1	25.6	104.5	40.5	11.3

3.11 Pomahaka

The Pomahaka basin was treated as a single entity for recharge modelling (Figure 11). Rainfall distribution is fairly even throughout the basin. The mean annual rainfall was 925 mm, which is by far the highest of any basin included in this report.

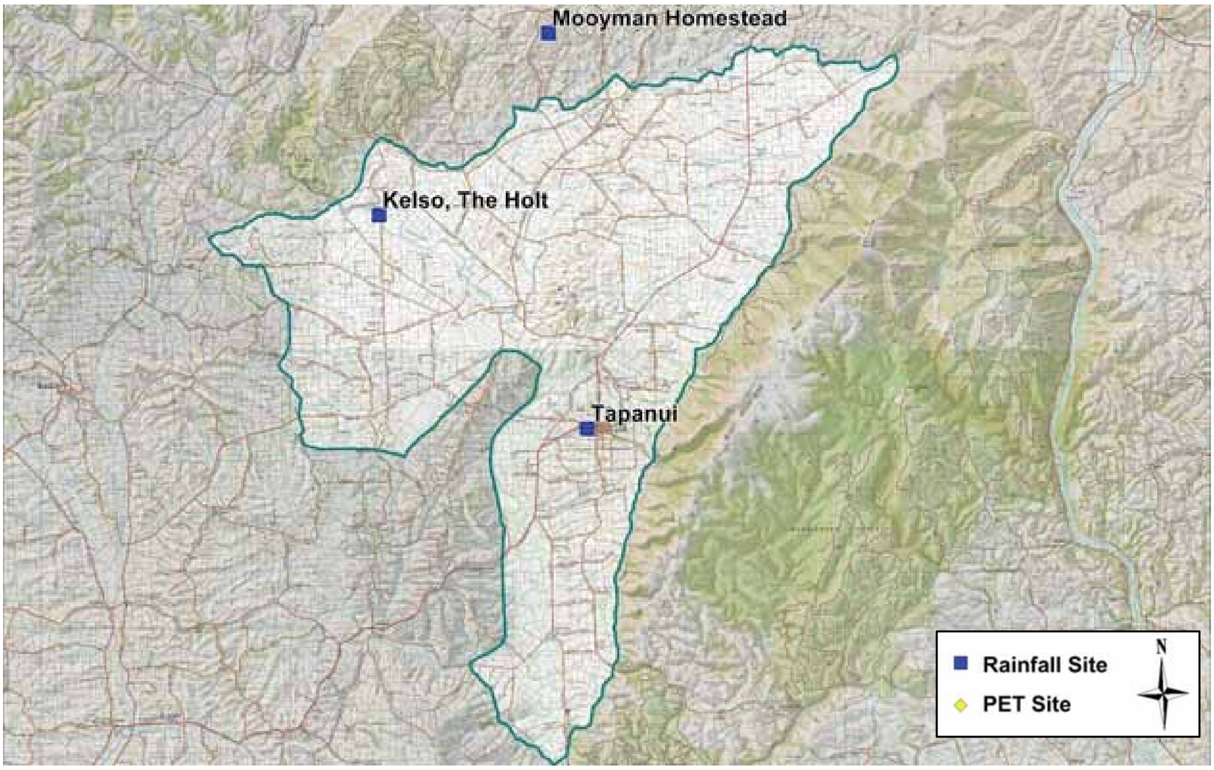

Figure 11 Pomahaka basin boundary and sites used for the recharge assessment

A continuous rainfall record was developed by combining data from the Mooyman, Kelso and Tapanui sites (Table 22). The PET record came directly from the combined Gore dataset. This gives a total recharge modelling duration of 39 years.

Table 22 Pomahaka recharge modelling site records

	Site	Start	End	Duration (years)
Rainfall	Mooyman Homestead (5372)	Jun-1983	Sep-1999	16.3
	Kelso, The Holt (5677)	Jan-1967	Jan-2003	36.1
	Tapanui (5686)	May-1897	Apr-2011	114.0
PET	Combined Gore	Jan-1972	May-2011	39.4
Modelling period		Jan-1972	Jan-2011	39.1

Mean annual recharge in the Pomahaka basin was calculated as 52.1 Mm^3/year (Table 23). Recharge is equivalent to 22% of median annual rainfall, which is one of the highest rates in this study.

The calculated median annual recharge volume is considerably lower than the mean, indicating that the calculated mean value is strongly influenced by wetter years. The standard deviation is about half the mean, which indicates a good recharge capacity even during drier conditions. Extreme values show that the calculated maximum is over twice the mean value, while the lowest annual recharge is only 6% of the mean.

Table 23 Pomahaka recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Pomahaka	21,894	52.1	25.3	116.0	47.4	8.1

3.12 Roxburgh

The Clutha Valley, in the vicinity of Roxburgh, marks a transition from a semi-arid environment in the north-east to a high rainfall area in the south-west. Roxburgh is the smallest area covered in this report, being slightly smaller than the Cromwell aquifer. The Roxburgh aquifer is clearly defined by an alluvial terrace sitting between the Roxburgh power station and Roxburgh township (Figure 12). This terrace is almost entirely bounded by Schist bedrock.

The aquifer was considered to be a single entity for recharge modelling. There is a small orographic gradient across the aquifer. However, this gradient was not considered to be sufficient to warrant dividing the aquifer into two. Mean annual rainfall for the modelling period was 598 mm.

A continuous rainfall record for Roxburgh was available at Roxburgh (5621) from 1950 to 2000. Gaps for this record were filled with data from Roxburgh Power Station and Ettrick No. 2.

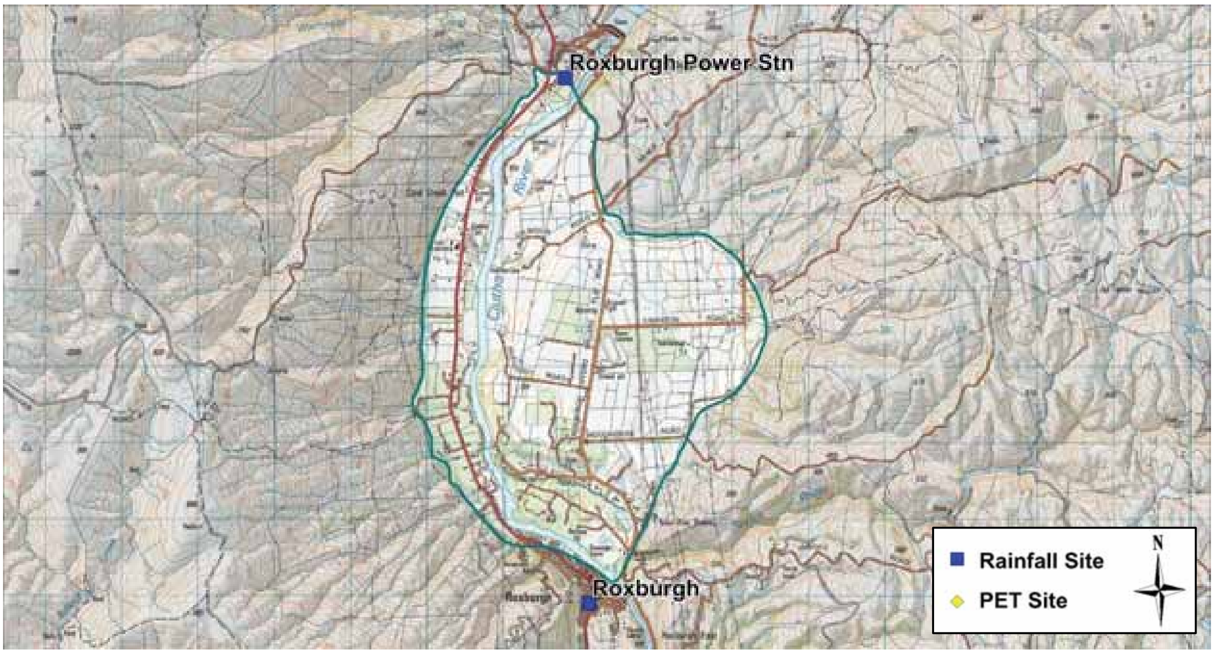

Figure 12 Roxburgh basin boundary and sites used for the recharge assessment

Middlemarch was used as the primary PET site. There are no other suitable evapotranspiration sites available to use at Roxburgh. Middlemarch was considered to provide the best estimate of PET at Roxburgh because its median PET values are shown on the Grow Otago maps to be most similar. A correlation was made between Middlemarch and the Central Otago composite record to extend the record back to 1972. This provided a record for modelling of 28-years duration.

Table 24 Roxburgh recharge modelling site records

	Sites Name (Agent num.)	Start	End	Duration (year)
Rainfall	Roxburgh (5621)	Jun-1987	Aug-2000	13.2
	Roxburgh power stn (5612)	Aug-1950	Dec-1987	37.3
PET	Middlemarch EWS (18437)	Aug-2000	May-2011	10.7
	Central Otago composite	Jan-1972	Jan-2011	39.1
Modelling period		Jan-1972	Aug-2000	28.7

Mean annual rainfall recharge for Roxburgh has been calculated as 1.8 Mm^3/year (Table 25). There is considerable annual variation, with a standard deviation of 1.1 Mm^3/year, which is 61% of the mean. The calculated median annual recharge for Roxburgh is equivalent to 17% of median annual rainfall.

Table 25 Roxburgh recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Roxburgh	1,706	1.8	1.1	4.5	1.6	0.1

For its size, Roxburgh has fairly average statistics overall. The exception is its lowest historical recharge estimate of 100, 000 m^3/year, which is only 4% of the mean.

3.13 Strath Taieri

The Strath Taieri basin covers an area of 22.5 KHa (Figure 13). The basin was first defined as a groundwater resource by Stone Environmental (1997). The climate is fairly dry for Otago, with a mean annual rainfall of 497 mm over the modelling period. Evapotranspiration rates are also high, averaging 2.3 mm/day, which is mostly due to a high wind run.

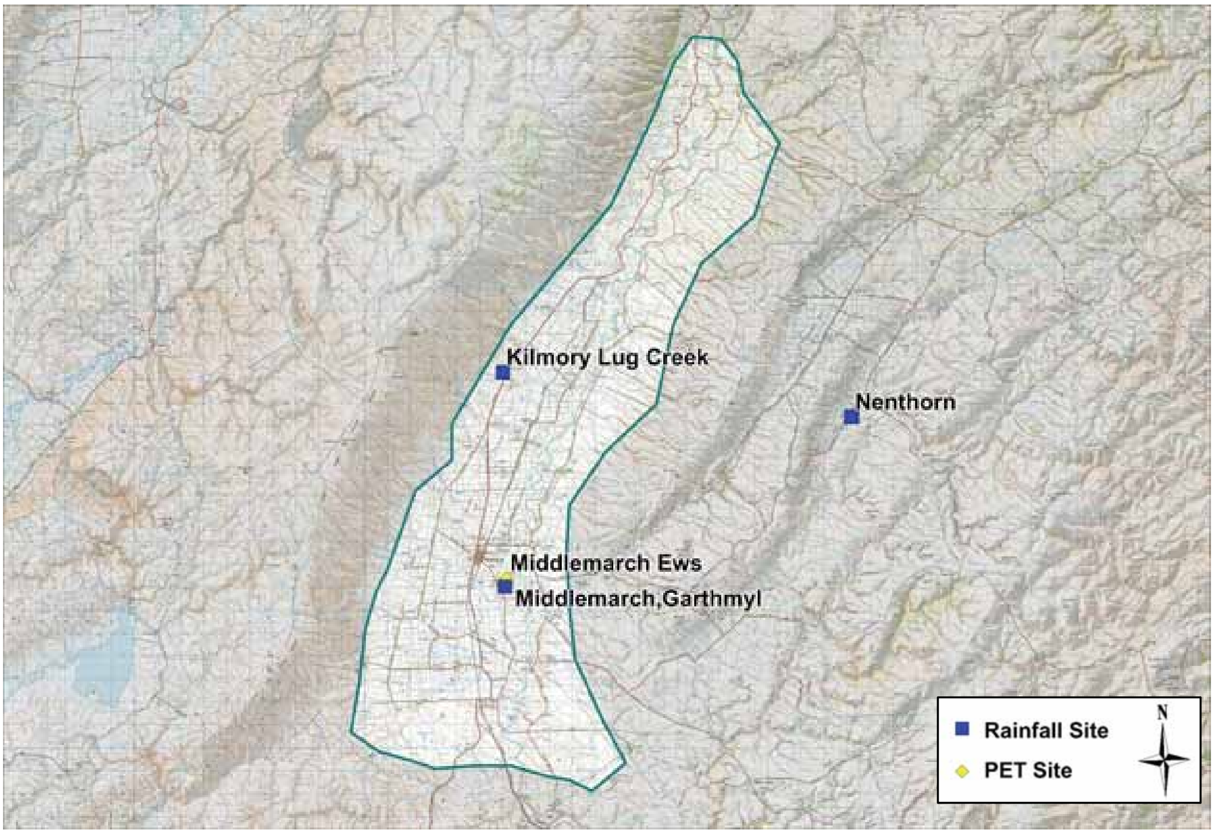

Figure 13 Strath Taieri basin boundary and sites used for the recharge assessment

Rainfall in the Strath Taieri basin is best represented by the Middlemarch site, at Garthmyl, which has over 114 years of record (Table 26). This record has numerous gaps of two days to a month, mostly during the 1970s and 80s. A secondary site, Kilmory, at Lug Creek (5315), was used to fill these gaps because it falls inside the aquifer boundary. Any remaining gaps were filled by rainfall data from Nenthorn (5316).

Table 26 Strath Taieri recharge modelling site records

	Site	Start	End	Duration (years)
Rainfall	Middlemarch, Garthmyl (5329)	1/10/1896	Jan-2011	114.3
PET	Middlemarch EWS (18437)	Aug-2000	May-2011	10.7
	Lauder EWS (5535)	Sep-1985	Jan-2011	25.4
Modelling period		Sep-1985	Jan-2011	25.4

PET data was sourced from the Middlemarch EWS climate station record. This record started in 2000, so a correlation was made with Lauder EWS to generate a continuous record from 1985 onwards.

Rainfall recharge modelling predicts a mean annual recharge of 8.3 Mm^3/year for the Strath Taieri aquifer (Table 27). This constitutes 5% of the median annual rainfall, which is the lowest of all the basins modelled. There is also considerable variability in the recharge results, with a standard deviation that is 91% of the mean. This makes the Strath Taieri basin highly dependent on water sources other than storage from rainfall recharge during drier years.

The mean is clearly influenced by wetter years, as the median recharge estimate is considerably lower at 6.2 Mm^3/year, which is 25% below the mean.

Table 27 Strath Taieri recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std Dev	Max.	Median	Min.
Strath	22,512	8.3	7.5	26.7	6.2	0.0

The Strath Taieri basin is the only basin in this study that did not receive any recharge for an entire year. This occurred in 1998 and again in 2003, a year in which there was only 335 mm of rain, and was thus the driest year in the basin for the modelling period. Only one year has been drier in the 114 years of rainfall record at Middlemarch; this was 1964, in which there was 330mm of rain. All of these low rainfall events occurred during mild El Niño conditions.

The Strath Taieri basin shares many characteristics with the Maniototo basin, which also returned a recharge estimate of 5% of median annual rainfall. For instance, both basins have high PET values caused by a strong wind run, fairly low annual rainfall totals and a mixed soil cover.

3.14 Tokomairiro

The Tokomairiro basin forms the low lying flats around Milton and covers the smallest area of the South Otago basins (Figure 14).

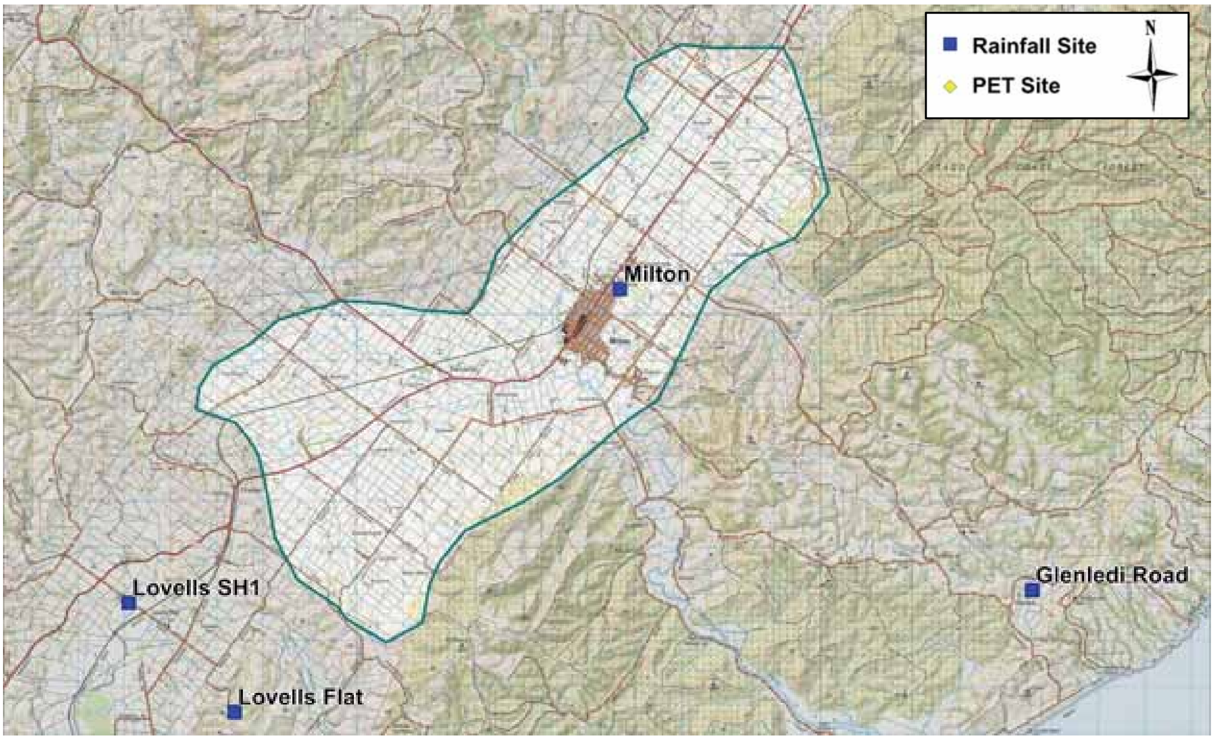

Figure 14 Tokomairiro basin boundary and sites used for the recharge assessment

Rainfall data for the Tokomairiro basin was primarily sourced from the Milton and Lovells Flat sites (Table 28). Two additional sites were used to fill in gaps in the record: Lovells SH1 (5855) and Glenledi Road (5703). The mean annual rainfall for the 32-year modelling period was 762 mm.

PET data came directly from the Balclutha, at Finegand, and the Dunedin aero climate station records, with Balclutha being the primary site. PET at these two sites is very similar, and a correlation between the two records was not considered necessary.

Table 28 Tokomairiro recharge modelling site records

	Site	Start	End	Duration (year)
Rainfall	Milton (5856)	Nov-1929	Nov-1985	56.1
	Lovells Flat (5872)	Jan-1977	Feb-2011	34.2
PET	Dunedin Aero (5397)	Jan-1972	Dec-1991	19.9
	Balclutha, Finegand (5867)	Jan-1975	Aug-2004	29.6
Modelling period		Jan-1972	Aug-2004	32.6

Mean annual rainfall recharge was calculated to be 10.3 Mm^3/year (Table 29), which is 19% of median annual rainfall. Recharge in the Tokomairiro basin was maintained even during dry conditions, with the standard deviation only forming half of the mean recharge value.

Table 29 Tokomairiro recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std dev	Max.	Median	Min.
Tokomairiro	6,873	10.3	5.0	20.4	9.7	2.7

3.15 Wakatipu

The Wakatipu basin has the highest PET of any of the basins covered in this report, at 2.6 mm/day. This is offset by a fairly high mean annual rainfall of 746 mm/year, together with a high coverage of freely draining soils. A groundwater investigation, carried out by ORC in 2003, estimated that annual rainfall recharge was 6.3 Mm^3/year, based on 10% infiltration to the water table (ORC, 2003).

The Wakatipu basin was divided into northern and southern parts, based on the mean annual rainfall pattern (Figure 15). Rainfall contours show a strong orographic effect, with rainfall being higher towards Coronet Peak than in the south. The mean annual rainfall for the northern and southern parts during the modelling period was 786 mm and 729 mm, respectively.

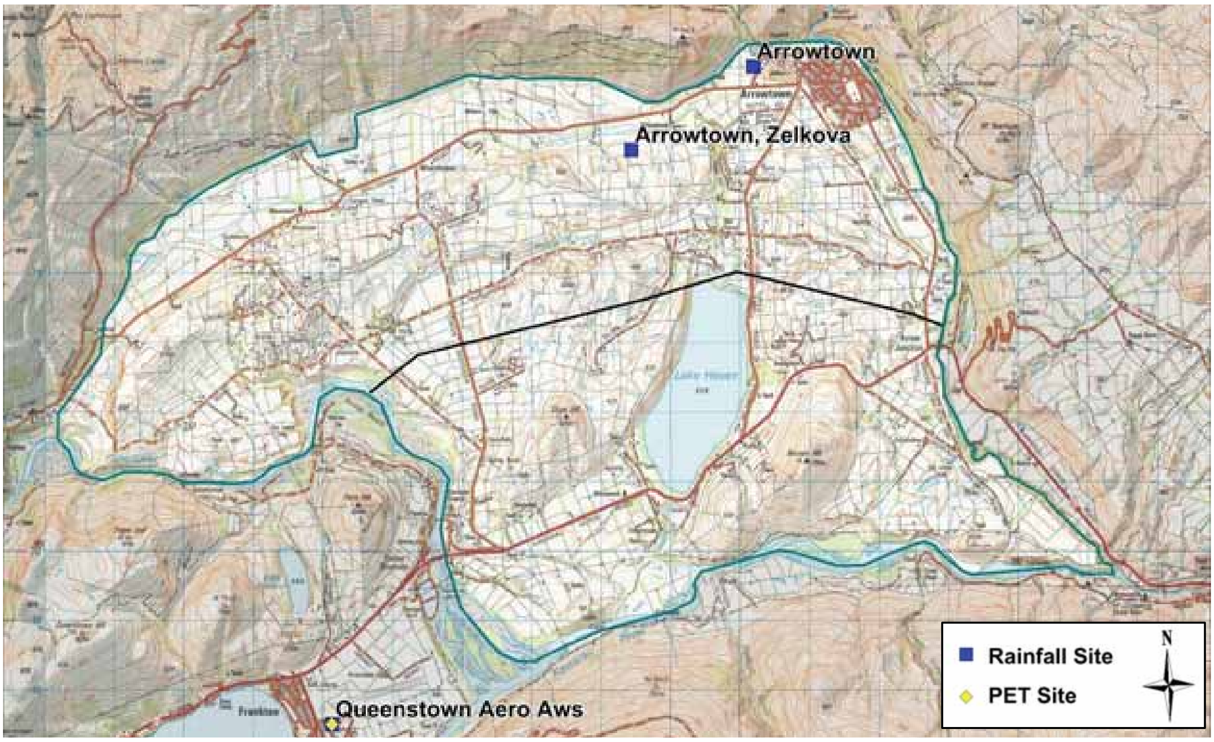

Figure 15 Wakatipu basin boundary and sites used for the recharge assessment

Rainfall data for the northern section was sourced from three Arrowtown sites (Table 30). These records were combined to form a series starting in 1927. Unfortunately, the records of the three sites do not overlap, so it was necessary to fill gaps with data from Queenstown aero. Rainfall for the southern part was sourced entirely from this site, which forms a complete record.

The primary PET site used was Queenstown aero AWS, which we correlated with Lauder EWS to extend the beginning of the record from 1991 to 1985. This correlation produced a regression coefficient of 0.98.

Table 30 Wakatipu recharge modelling site records

		Sites name (Agent num.)	Start	End	Duration (year)
Rainfall	North	Arrowtown (25376)	Apr-2004	Mar-2011	7.0
		Arrowtown, Zelkova (7451)	Apr-1992	Apr-2000	8.1
		Arrowtown (5175)	Jul-1927	Jan-1991	63.6
	South	Queenstown Aero (5451)	Jan-1982	May-2011	29.4
PET		Queenstown Aero AWS (18593)	Oct-1991	Jan-2011	19.3
		Lauder EWS (5535)	Sep-1985	Jan-2011	25.4
Modelling period			Sep-1985	Jan-2011	25.4

Groundwater in the Wakatipu basin is estimated to receive 12.5 Mm3/year of rainfall recharge. This is equivalent to 23% of median annual rainfall, which is one of the highest percentages in this report and over double the previous estimate made by ORC (2003).

Table 31 Wakatipu recharge modelling results (million m^3/year)

	Area (Ha)	Mean	Std dev	Max.	Median	Min.
Wakatipu	7,137	12.5	4.9	23.9	13.2	2.4

From a rainfall recharge perspective, the Wakatipu basin is the most robust of all the areas studied in this report. The standard deviation is only 39% of the mean, indicating that significant recharge is provided even during drier periods. Despite this, the Wakatipu basin was the only area where median was higher than the mean, indicating a bias in the mean towards drier conditions.

4. Regional summary

This section provides an overview of the modelling results. Median rainfall and recharge statistics are used to compare the results obtained from different basins throughout the region. Median values are used rather than the mean. The reason for this is that mean values tend to skew the statistics highly towards brief periods of high recharge. This makes median values a more representative indicator of long-term trends.

4.1 Recharge comparisons

Figure 16 shows the results of modelling as volume of recharge for each basin. The box and whisker plot is useful to display the variability of recharge in each basin because it graphs the median, upper and lower quartiles as a box. Extreme high and low values are shown by the whiskers. Areas with the highest median recharge also show the greatest variability.

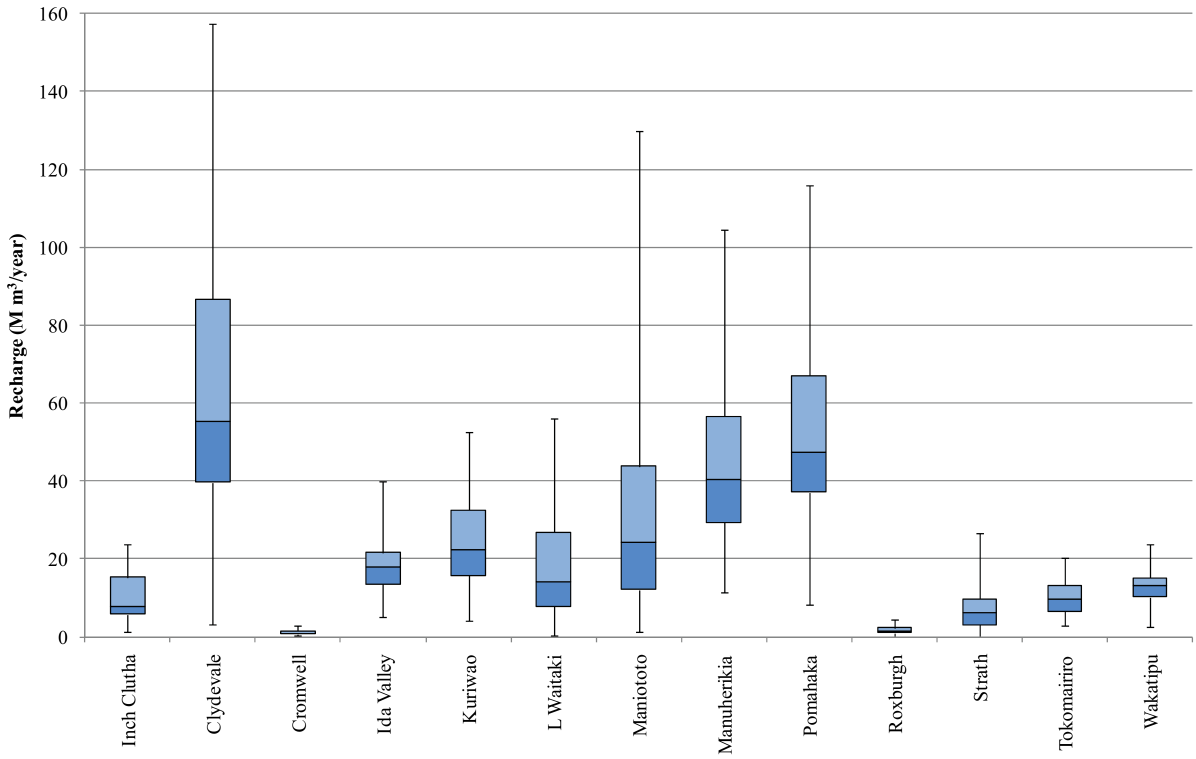

Figure 16 **Box and whisker plot of median annual recharge, upper and lower quartile and extreme values (million m^3/year)**

It is interesting to note that, in all of the basins studied, there were extremely dry periods where there was relatively little or even no recharge. In fact, for all basins, there was normally no or very little recharge occurring during the summer months. In drier years, recharge may not have occurred at all during spring and/or autumn. A useful way of studying seasonal variability is to look at the archived soil moisture deficit curves.

The largest recharge values were found in the Pomahaka, Clydevale-Wairuna, Manuherikia and Maniototo basins. The latter three cover extremely large areas, which distorts their recharge potential. A more useful way of comparing each basin is to look at recharge in millimetres or as a percentage of rainfall.

4.2 Climate and recharge variability

The results of the modelled recharge values compared to climate data are shown in Table 32. In this table, recharge is expressed in millimetres per year and also as a percentage of median annual rainfall. This allows recharge characteristics to be compared with those of the other basins.

The South Otago basins all have median annual rainfall value in excess of 700 mm/year, the highest being Pomahaka, with 944 mm/year. Rainfall at Wakatipu is also high, at around 750 mm/year. Strath Taieri and Wakatipu have the highest PET values, while Inch Clutha and Kuriwao have the lowest.

Recharge ranges from 25% to 5% of median annual rainfall and is between 10% and 20% in most basins. In general, the basins with the highest rainfall also have the highest percentage recharge. Variation within this overall trend is due to the differing composition of soil coverage in each basin.

Table 32 Climate and recharge statistics for Otago basins

	Mean recharge (Mm^3/year)	Median annual (mm/yr)			Percentage recharge
		Rainfall	PET (mm/d)	Recharge	
Kuriwao	24.2	836	1.9	205	25
Wakatipu	12.5	746	2.6	184	23
Pomahaka	52.1	944	2.1	212	22
Clydevale	64.6	781	2.1	152	20
Tokomairiro	10.3	771	2.1	137	19
Roxburgh	1.8	599	2.2	88	17
L Waitaki	18.5	521	2.0	75	17
Manuherikia	45.1	531	2.2	64	13
Cromwell	1.2	408	2.2	53	12
Ida Valley	18.8	499	2.2	61	12
Inch Clutha	10.4	726	1.9	76	10
Maniototo	31.6	483	2.2	29	5
Strath	8.3	486	2.3	25	5

The relationship between rainfall and recharge for each basin is shown in Figure 17. The highest percentage recharge occurs in Kuriwao, Wakatipu, Pomahaka and Clydevale-Wairuna. In these four basins, at least 20% of rainfall drains through the soil profile.

The South Otago basins are dominated by poorly drained deep silt loams, with a high water storage capacity (PAW). While these soils lack permeability, they maintain high recharge values because of consistent rainfall, which keeps the soil moisture deficit low for much of the year. In many of the wetter years, the soil is maintained at field capacity throughout the whole of July and August.

By contrast, the Wakatipu soils are typically free draining and have a lower water storage capacity. These soils tend to have a greater soil moisture deficit throughout the year, but their higher permeability makes them more responsive to individual rainfall events.

A low percentage of recharge occurs in the Maniototo and Strath Taieri basins, where only 5% of rainfall infiltrates to groundwater. These two areas have distinctly high PET, and rainfall of less than 500 mm/year. The Maniototo and Strath Taieri basins also have a mixture of soil types, and, in this respect, they differ from Cromwell, which has the lowest median annual rainfall, with just 408 mm/year. The percentage recharge at Cromwell was considerably higher because of a predominance of very free-draining sandy soils with low water storage capacity. As at Wakatipu, these soils readily allow rainfall to recharge groundwater, and this increases the recharge potential at Cromwell, despite its low annual rainfall.

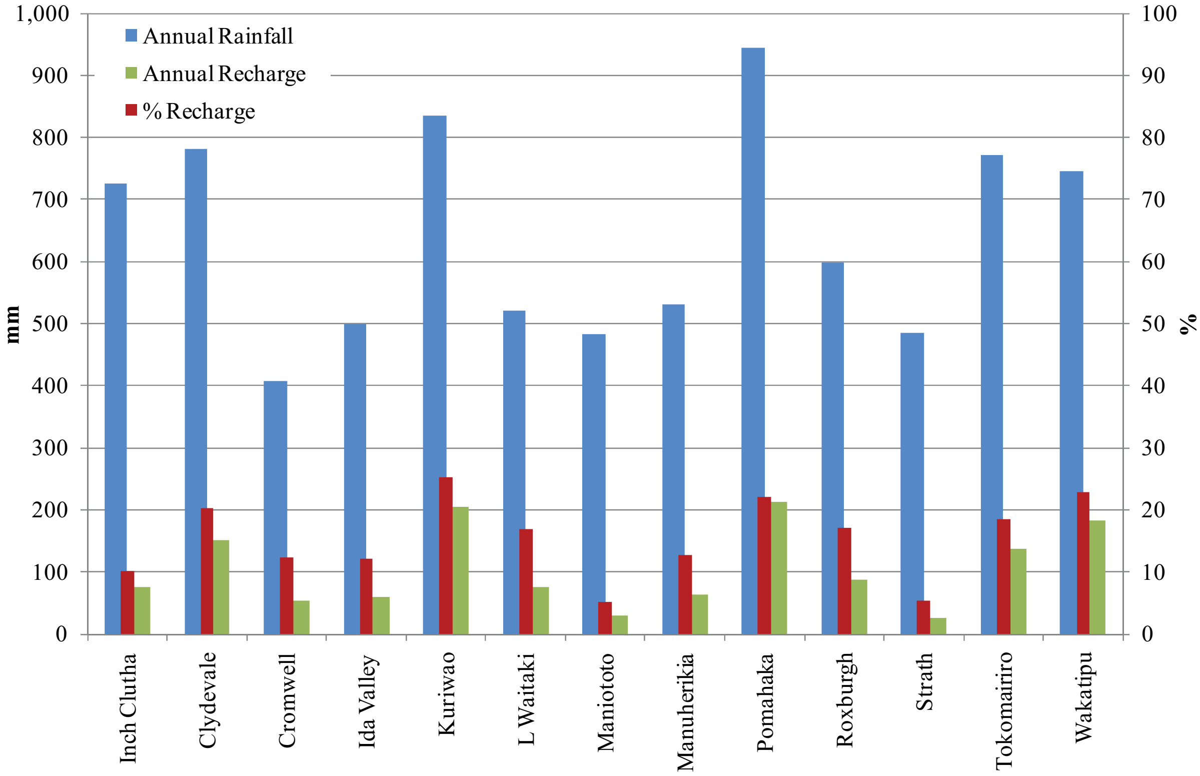

Figure 17 Comparative median annual rainfall and recharge depths

The variability of recharge as a percentage of rainfall is shown as a box and whisker plot in Figure 18. Variability varies greatly from basin to basin and does not depend on percentage of recharge.

In terms of volume, the greatest recharge variability is seen in the Waitaki and Clydevale-Wairuna basins. When variability is normalised to the mean, the Strath-Taieri and Maniototo basins are found to be by far the most variable. For these basins, the standard deviation comprises 85-90% of mean annual recharge. The standard deviation at Lower Waitaki is slightly lower, at 76% of the mean.

The Kuriwao, Pomahaka and Lower Waitaki basins have had years when over 40% of rainfall was recharged. The Strath Taieri basin has two years when no rainfall recharge occurred.

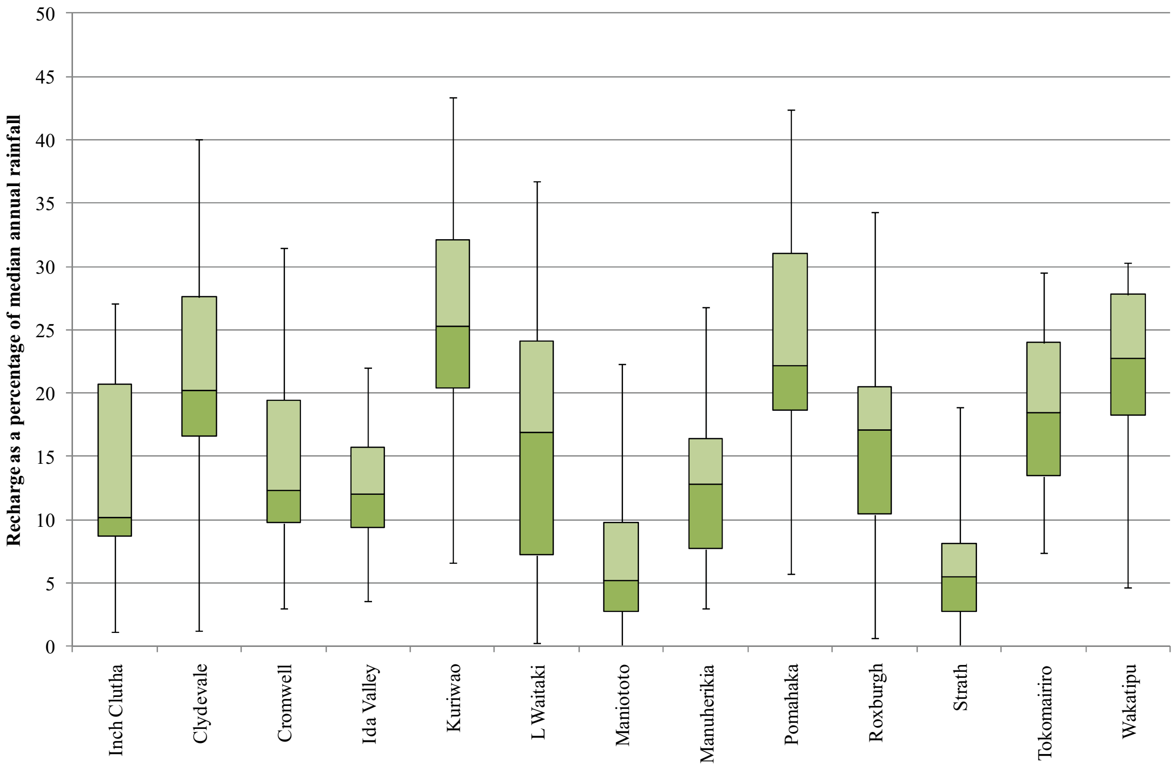

Figure 18 Box and whisker plot of annual recharge as a percentage of median annual rainfall

4.3 Comparison with previous studies

Between 1998 and 2004, Otago Regional Council carried out or commissioned a number of preliminary groundwater investigations. These studies provided the first groundwater assessments of most parts of Otago, which were carried out at a time when there was little groundwater information available. They also defined the boundaries of the aquifers that are now within the Regional Plan: Water.

For most of the basins, a crude assessment of recharge was made to develop an estimate of the groundwater mass balance. These early recharge assessments typically consisted of estimating recharge as a percentage of mean annual rainfall. A summary of these preliminary estimations is provided in Table 33, along with the values determined in this report.

Table 33 Median recharge values compared to estimates from previous studies

	Clydevale	Kuriwao	Maniototo	Pomahaka	Roxburgh	Tokomairiro	Wakatipu
This study (m^3/yr)	55.3	22.2	24.4	47.4	1.6	9.7	13.2
Previous (m^3/yr)	8.1	22.7	35.1	54.5	1.9	3.7 to 4.7	6.3
Area (Ha)	35,454	10,424	77,822	21,894	1,706	6,873	7,137
Previous (Ha)	36,100	9,900	79,340	24,200	1,370	6,500	7,344
This study (mm)	152	205	29	212	88	137	184
Previous (mm)	23	230	44	225	138	57 to 72	85
Source	ORC, 2002	ORC, 1999	ORC, 2004	ORC, 1999	ORC, 1999	Irricon, 1998	ORC, 2003

The estimations made for Kuriwao and Pomahaka are similar to those made for this study. For the remaining basins, there are large differences between the old and new values. These differences are considered to be due to the differences in methodology used.

However, there are also differences caused by the assumptions inherent in the preliminary estimates, which vary in each report. The main assumptions that could influence recharge estimates are: whether the geology below the soil profile is permeable; and whether the recharge estimate takes into account lateral flow into the basin from the hillsides.

5. Conclusions

Rainfall recharge varies greatly throughout Otago, both spatially and through time. The most influential factors for rainfall recharge in any one basin are:

- rainfall volume and distribution
- soil type
- substrate geology.

Mean annual recharge volumes range from 1.2 to 64.6 million m^3/year. These volumes will be used to set default allocation limits for the 13 basins of 50% of mean annual recharge, which are calculated as follows:

Groundwater basin	Mean recharge (Mm^3/year)	Standard deviation (Mm^3/year)	Percentage recharge	Default allocation (Mm^3/year)
Clydevale-Wairuna	64.6	34.4	20	32.3
Cromwell	1.2	0.7	12	0.58
Ida Valley	18.8	9.8	12	9.40
Inch Clutha	10.4	6.5	10	5.22
Kuriwao	24.2	10.4	25	12.1
Lower Waitaki	18.5	14.1	17	9.24
Maniototo	31.6	27.2	5	15.8
Manuherikia	45.1	25.6	13	22.6
Pomahaka	52.1	25.3	22	26.0
Roxburgh	1.8	1.1	17	0.89
Strath Taieri	8.3	7.5	5	4.14
Tokomairiro	10.3	5.0	19	5.14
Wakatipu	12.5	4.9	23	6.26

Mean annual recharge volumes range from 5 to 25% of median annual rainfall. Higher recharge percentages are found in South Otago and Wakatipu. The Wakatipu basin also shows the least annual recharge variability in the region. The lowest percentage of rainfall recharge occurs in Strath Taieri and Maniototo, and these two sites also show the most annual variability.

Mean rainfall recharge values are 5 to 30% higher than the median, indicating that mean values are strongly biased towards wetter years. The exception was Wakatipu, which was biased towards drier years.

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Appendix A – Soil hydraulic data

These notes accompanied the soil physical and hydrological data provided by Sam Carrick of Landcare Research in November 2010.

i. Method used to estimate soil parameters

Field capacity (FC), wilting point (WP), profile available water (PAW) and profile readily available water (PRAW) data were derived from data recorded in the New Zealand Soils Database for individual horizons. The data of Rickard and Cossens (1968) have also been included.

Estimating soil parameters required the following steps:

1. Match the soil series with the same, or with 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 of less than 1 m. This provides an estimate of FC and WP in mm for the profile.
4. Calculate PAW by subtracting WP from FC. The PAW range indicates the likely variability of PAW across the map unit, taking into account the likely variation in the depth of fines over gravels.
5. Calculate PRAW 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 was modified according to expert opinion. As soils become shallower, the percentage of PRAW/PAW becomes larger.

ii. Method used to estimate field drainage

Drainage class was determined by soil classification and from personal knowledge of the soils. Definitions of drainage class may be found in Milne *et al*. (1995), and are as follows:

w = well drained

mw = moderately well drained

i = imperfectly drained

p = poorly drained (includes very poorly drained peat soils).

iii. Method used to assign run-off characteristics

Run-off characteristics are defined by the Hydrological Soil Group (HSG) and Soil Curve Number (SCS). 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 fairly confidently assigned to one of the four classes in this system.

The SCS number is a more difficult value to estimate. The intent of the classification is to help partition rainfall or irrigation into through-flow or run-off. The SCS number may be considered to be derived from a combination of soil permeability and infiltration capacity in a moist condition. The SCS number is not static but varies with antecedent moisture condition and with land use. I have rated soils according to the tables in SCS (1967) for land under pasture in a moist antecedent state. First, I rated a soil that I considered to be in the middle of a HSG class and then increased or decreased the curve number for other soils according to their relative permeability and air capacity.

iv. Method used to group soils into hydraulic classes

To simplify the land surface recharge modelling, the project specifications requested that individual soil map units are grouped into one of 12 classes (Table A.1.), with a maximum of 10 classes used for each aquifer/basin. The assignment to a hydraulic class was based on the dominant soil type in each map unit. These classes were developed for the first completed area (Alexandra basin) by grouping map units with similar attributes into the same class, where a modal value was assigned for each attribute. For each new aquifer area, the individual map units were either correlated to an existing hydraulic class or, if the soil was significantly different, a new hydraulic class was formed.

Table A.1 Hydraulic classes used to group similar soils throughout Otago, for the purpose of land surface recharge modelling

Hydraulic class	FC (mm)	WP (mm)	PAW (mm)	PRAW (mm)	Drainage	HSG	SCS
1	40	10	30	21	W	A	40
2	110	30	80	64	W	A	40
3	110	30	80	48	W	B	50
4	200	50	150	90	W	B	60
5	200	50	150	90	I	C	65
6	240	60	180	90	P	D	75
7	100	40	60	36	I	C	65
8	100	40	60	36	W	D	75
9	120	40	80	65	I	D	75
10	40	10	30	21	W	D	80
11	220	120	100	45	P	D	75
12	325	125	200	125	W	B	60

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Appendix B – Model verification

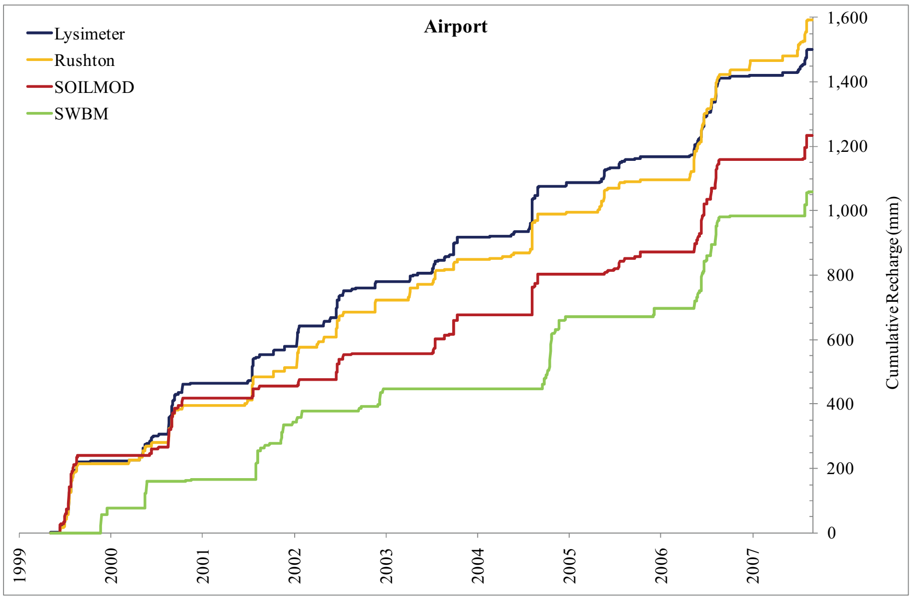
We verified the accuracy of the Rushton model by comparing calculated recharge with lysimeter data from Canterbury. Lysimeter data for three sites was provided courtesy of ECAN. The SOILMOD and Soil Water Balance Model, outlined in White *et al*. (2003), were also used as a means of comparing. Soil properties were kept consistent for the three models (Table B.1.) and are the same values as those used in White *et al*. (2003). No surface run-off has been incorporated into these simulations.

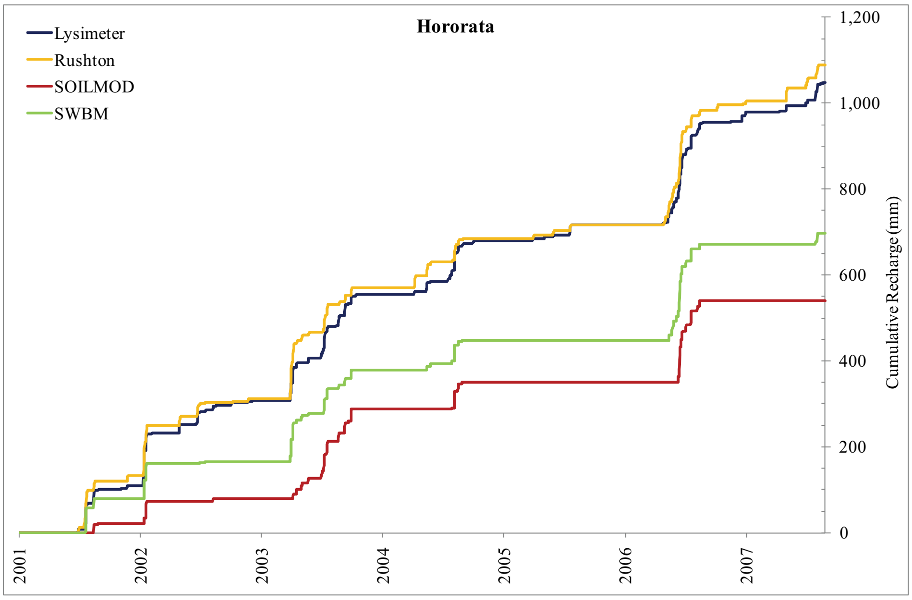
Table B.1 Soil properties used for Canterbury recharge simulations

	ChCh Airport	Lincoln University	Hororata
Soil series	Waimakariri	Templeton	Hororata
Soil type	V stony sandy loam	Silt loam on sand	Stony silt loam
Drainage	Excessively drained	Well drained	Well drained
Profile depth (mm)	300	650	300-400
PAW (mm)	45	170	75
FC (mm)	115	253	189
Rooting depth (mm)	650	650	400
FRACSTOR	0.4	0.45	0.6

Rooting depth is 650 mm at the airport and Lincoln sites. This is consistent with Scott (2004), who suggested that 600 mm is a realistic average rooting depth in Canterbury soils. The Hororata site has a rooting depth equivalent to the profile thickness. The reason for this is that the Hororata soils have a basal loess layer (Kear *et al*. 1967), which is expected to limit root penetration.

Results for the three models are compared with lysimeter data in Figure B.1. The Rushton model simulates recharge quite accurately, in terms of recharge response and recharge volume for each site.





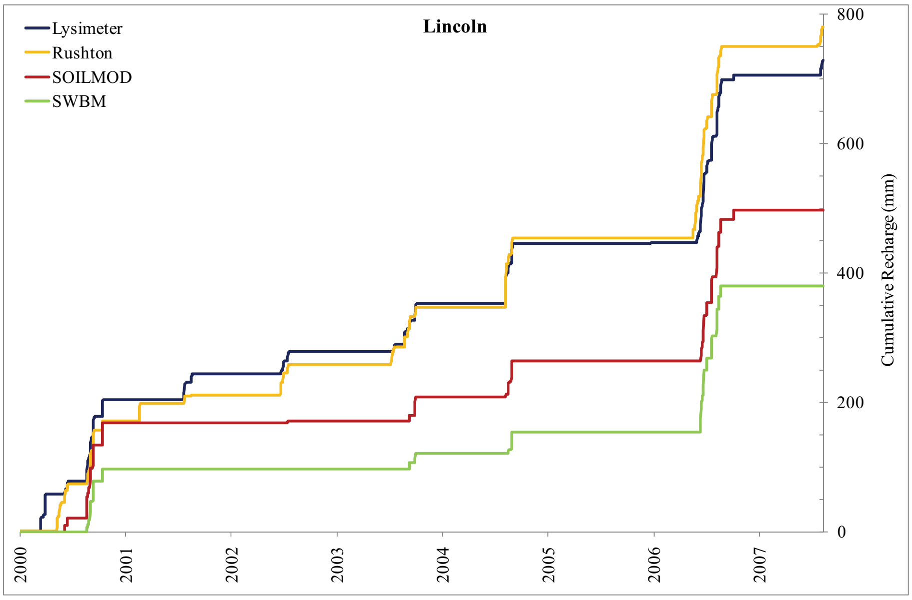


Figure B.1 Hydrographs of cumulative recharge for the three models compared to lysimeter data

Statistics to compare the three models are given in Table 36. The Rushton model gives the most accurate estimation of weekly rainfall recharge of all three models. Recharge at the airport site has been simulated most accurately, with an RMS error of 3.6 mm/wk. The estimate of recharge at the Hororata site is poorest, with an RMS error for the Rushton model of 4.2 mm/wk.

The period of record for this simulation is longer than reported in White *et al*. (2003), whose data only simulated the period between May 1999 and March 2001. Conditions were drier than normal from 2003 to 2005, and this resulted in an overall reduction in the percentage of rainfall recharge recorded at the three sites. The SOILMOD and soil water balance models have not responded well to drier conditions and, therefore, have greatly underestimated recharge. The simulation shows that the Rushton model is more sensitive to periods of low rainfall and accurately simulates rainfall recharge during these periods. However, the model will only be used with confidence if the soil hydraulic properties are characterised.

Table B.2 Observed and modelled recharge statistics for the three Canterbury lysimeter sites Lys = lysimeter, R = Rushton, SM = SOILMOD, WB = Soil water balance model

	Airport				Hororata				Lincoln			
	Lys	R	SM	WB	Lys	R	SM	WB	Lys	R	SM	WB
Total recharge (mm)	1502	1591	1234	1057	1047	1089	540	697	726	779	498	379
Mean weekly recharge (mm)	3.5	3.7	2.8	2.4	3.0	3.1	1.6	2.0	1.7	1.9	1.2	0.9
% of total rainfall	29	30	24	20	22	23	12	15	14	15	9	7
Max recharge (mm/wk)	65	67	69	85	82	81	87	85	47	65	49	46
RMS error (mm/wk)		3.6	4.7	11.3		4.2	7.0	4.4		4.0	4.1	4.1
Max weekly diff (mm/wk)		22	25	85		30	36	34		31	16	12
Min weekly diff (mm/wk)		-13	-42	-65		-16	-68	-38		-31	-41	-46
Period of record	May 1999 - August 2007				August 1999 - August 2007				January 2001 - August 2007			

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