Dunstan – Earnscleugh Groundwater Basin: Model Results and Scenarios

Prepared for

Otago Regional Council

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PATTLE DELAMORE PARTNERS LTD
Level 2, 134 Oxford Terrace
Christchurch Central, Christchurch 8011
PO Box 389, Christchurch 8140, New Zealand

Office +64 3 **345 7100**
Website **http://www.pdp.co.nz**
Auckland Tauranga **Hamilton** Wellington
Christchurch Invercargill

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DOCUMENT CONTRIBUTORS

Prepared by

SIGNATURE

Tom Garden

Reviewed by

SIGNATURE

Neil Thomas

Approved by

Hilary Lough

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Executive Summary

The Earnscleugh Flat and Dunstan Flats aquifers are located in the Alexandra Basin in Central Otago, on opposite sides of the Clutha River / Mata-Au ('Clutha River') (Figure 1). The area has a semi-arid climate, and direct rainfall infiltration comprises a relatively small proportion of recharge. Water losses relating to irrigation (both related to application of irrigation water, and losses from water transport and storage) comprise a significant proportion of recharge to both aquifers. Changes in abstraction pressure and associated surface water management practices in the last 10 years mean that reassessment of the existing water allocation settings is necessary.

The Earnscleugh Flat and Dunstan Flats aquifers present unique challenges in terms of freshwater management and being consistent with the National Policy Statement for Freshwater Management (NPS-FM), due to most of the recharge being from "inefficient" irrigation water race transport. It is possible that future measures to improve the efficiency of surface water take usage and reduce water race losses could significantly reduce the recharge to the aquifers and adversely affect groundwater users and surface water receptors.

The purposes of the Earnscleugh Flat and Dunstan Flats groundwater models are as follows:

- Estimate the water balance and overall groundwater flow pattern of the aquifers;
- Constrain which parameters and boundary conditions the modelled aquifer water balance and flow pattern are most sensitive to, to guide future investigations;
- Investigate the possible implications of reduced irrigation race losses on the aquifers in terms of effects on groundwater levels and groundwater receptors (e.g. stream flows).

The model results indicate a reasonable calibration to both stream flows and groundwater levels, where this data was available. The modelled water balance and groundwater flow pattern for each aquifer is generally consistent with our conceptual understanding, with some differences for each aquifer. Due to the importance of "artificial" recharge from irrigation water race losses for both aquifers, a scenario was also modelled for each where irrigation water race recharge was reduced to zero, to simulate potential more efficient piped water transport.

The Earnscleugh Flat scenario results indicate that without irrigation water race recharge, groundwater infiltration to the lower Fraser River would reduce groundwater levels in the southern part of Earnscleugh Flat by up to 1 – 1.5 m, and groundwater infiltration to the lower Fraser River would reduce by at least 7 L/s. The Dunstan Flats scenario results indicate that without irrigation water race recharge, groundwater levels in the central Flats could reduce by up to 3.5 m, which could have an adverse effect on some bore owners. Surface water flows would not be expected to change significantly, though slightly greater recharge to the aquifer from the Clutha and Manuherekia Rivers would be expected.

The existing groundwater allocation limits for the Earnscleugh Flat and Dunstan Flats aquifers are based on an estimated 50% of recharge (assuming efficient irrigation methods). It is preferred for groundwater allocation decisions to be based on acceptable environmental effects on existing groundwater users or surface water receptors. Limited information is available regarding the location and/or sensitivity of surface water receptors in either aquifer, however it is expected that there could be potentially significant reductions in groundwater levels and inflow to the lower Fraser River if the full current allocation limit was abstracted. However, the magnitude of the effects would be dependent on the location of any increased abstraction, with abstraction from the southern half of Earnscleugh Flat expected to have a larger effect on inflow to the lower Fraser River, while abstraction from the northern part of Earnscleugh Flat would be expected to mostly affect the magnitude of outflow to the Clutha River. Consideration should be made to splitting the allocation zone based on where abstraction is expected to have a greater effect on inflow to the lower Fraser River.

The groundwater modelling for the Dunstan Flats aquifer indicates that a reduction in irrigation water race losses could have a significant adverse effect on bores in the central part of the Flats, even without additional abstraction pressure. It is also important to note that groundwater inflow from the Manuherekia Claybound Aquifer would also be likely to reduce if water race losses lessen, due to those losses also being a significant source of recharge to the Manuherekia Claybound Aquifer. There are no known surface water receptors that would be sensitive to changes in groundwater levels. The groundwater levels in the southern part of Dunstan Flats are largely controlled by the Clutha and Manuherekia Rivers, therefore reduced recharge or abstraction in this part of the aquifer is expected to cause increased inflow from the Clutha and Manuherekia Rivers but is not likely to cause significant widespread adverse effects on existing groundwater users. Consideration could be given to splitting the allocation zone between the northern half where groundwater levels are sensitive to changes in recharge or abstraction, and the southern part where groundwater levels are strongly controlled by the adjacent river levels.

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1.0 Introduction

1.1 Background

The Earnscleugh Flat and Dunstan Flats aquifers are located in the Alexandra Basin in Central Otago, on opposite sides of the Clutha River / Mata-Au ('Clutha River') (Figure 1). The area has a semi-arid climate, and direct rainfall infiltration comprises a relatively small proportion of recharge. Water losses relating to irrigation (both related to application of irrigation water, and losses from water transport and storage) comprise a significant proportion of recharge to both aquifers. Changes in abstraction pressure and associated surface water management practices in the last 10 years mean that reassessment of the existing water allocation settings is necessary.

Pattle Delamore Partners (PDP) have been engaged by Otago Regional Council (ORC) to build numerical groundwater models for the Earnscleugh Flat Aquifer and Dunstan Flats Aquifer that will provide a basis for allocating groundwater, for consultation and inclusion in the proposed Land & Water Regional Plan for Otago.

This report covers the following scope:

- A brief summary of the hydrogeological setting of the aquifers (refer to the PDP conceptual model report (PDP, 2022) for a full description of the hydrogeological setting);
- A summary of the approach used for modelling the Earnscleugh Flat and Dunstan Flats aquifers;
- The model calibration and results;
- The results of scenario modelling that simulates a potential future reduction in recharge to the aquifers as a result of reduced irrigation race water losses.

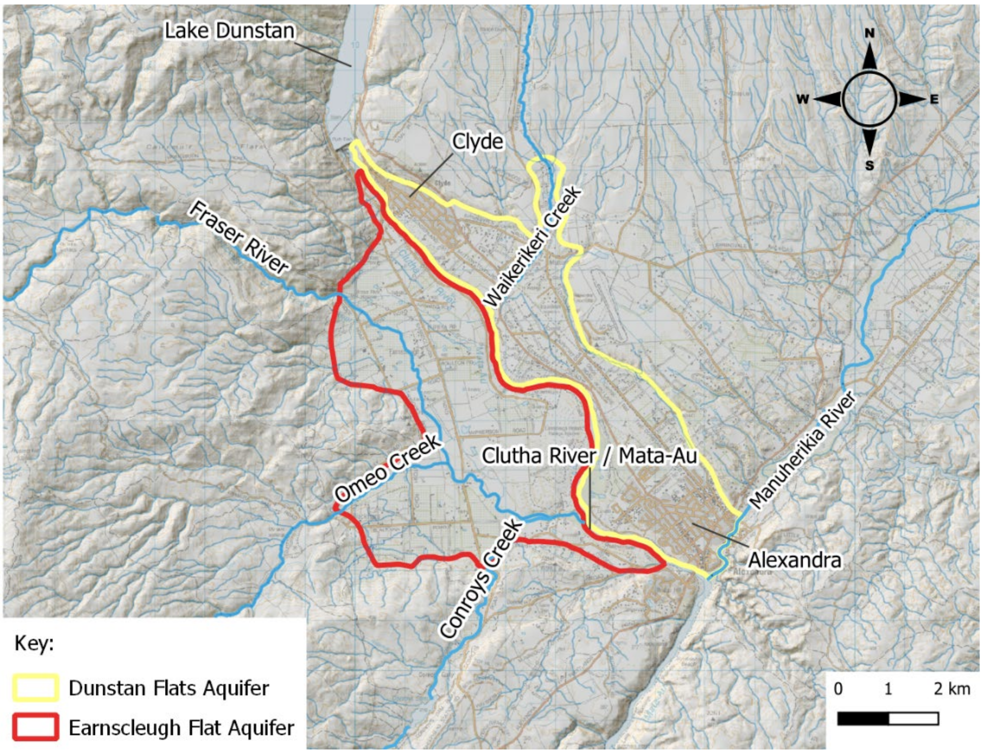

Figure 1: The study area, showing the approximate extent of the Earnscleugh Flat Aquifer (red) and Dunstan Flats Aquifer (yellow).

1.2 Purpose of the model

The National Policy Statement for Freshwater Management 2020 (NPS-FM) sets out the objectives and policies for freshwater management in New Zealand under the Resource Management Act 1991. Policy 11 of the NPS-FM is that "*Freshwater is allocated and used efficiently, all existing over-allocation is phased out, and future over-allocation is avoided."* Section 3.28 of the NSP-FM includes the statement that every regional council must make or change its regional plan(s) to include criteria for deciding how to improve and maximise the efficient allocation of water. Section 3.29 of the NSP-FM includes the statement that every regional council must operate for every freshwater management unit a freshwater quantity accounting system to provide the baseline information required for setting target attribute states, environmental flows and levels, and limits.

In the NPS-FM, overallocation is defined as:

> *over-allocation, in relation to both the quantity and quality of freshwater, is the situation where: (a) resource use exceeds a limit; or (b) if limits have not been set, an FMU or part of an FMU is degraded or degrading*

Whilst this is the formal definition of overallocation in the NPS-FM and this report is focussed on water quantity, water quality is also an important issue which is closely related to water quantity. For example, the current recharge to the aquifers via good quality water from the irrigation race losses may help dilute the effect of nitrate losses from landuse across the areas. Therefore, changes in the pattern and sources of recharge to the aquifers will also impact on water quality. This aspect is not part of the scope of this report, but may need to considered as water quantity allocation limits are defined for the aquifers at a later stage.

ORC's current management of the aquifers of the Alexandra Basin is based largely on the 2012 groundwater allocation review (ORC, 2012), which was primarily based on land surface recharge modelling and estimates of other recharge sources. The 2012 review highlighted that losses from water races used for transport of irrigation water (diverted from rivers) make up a large proportion of the recharge to both the Earnscleugh Flat Aquifer and Dunstan Flats Aquifer, as discussed further in section 2.0 below.

Abstraction pressure and significant changes to surface water management practices in the area mean the 2012 review no longer serves the requirements for supporting allocation settings. ORC has indicated that future technical documents to support the proposed Land & Water Regional Plan for Otago, which is to be notified in December 2023, would need to include groundwater flow modelling and provide information on safe yield thresholds for the groundwater system.

The Earnscleugh Flat and Dunstan Flats aquifers present unique challenges in terms of freshwater management and being consistent with the NPS-FM, due to most of the recharge being from "inefficient" irrigation water race transport. It is possible that future measures to improve the efficiency of surface water take usage and reduce water race losses could significantly reduce the recharge to the aquifers and adversely affect groundwater users and surface water receptors.

The purposes of the Earnscleugh Flat and Dunstan Flats groundwater models are as follows:

- Estimate the water balance and overall groundwater flow pattern of the aquifers;
- Constrain which parameters and boundary conditions the modelled aquifer water balance and flow pattern are most sensitive to, to guide future investigations;
- Investigate the possible implications of reduced irrigation race losses on the aquifers in terms of effects on groundwater levels and groundwater receptors (e.g. stream flows).

2.0 Hydrogeological setting

This section summarises the hydrogeological setting of the modelled aquifers. A full description of the setting of each aquifer is provided in the PDP conceptual model report (PDP, 2022).

2.1 Geology

The Earnscleugh Flat and Dunstan Flats aquifers are hosted in glacial outwash of Pleistocene age, associated with the Albert Town and Luggate glacial advances (AquaFirma, 1997). This outwash consists primarily of sandy gravels and rests on older low permeability sediments of the Manuherekia Group, which in turn is underlain by basement schist (Turnbull, 2000). A geological map of the Alexandra Basin is provided in Figure 2.

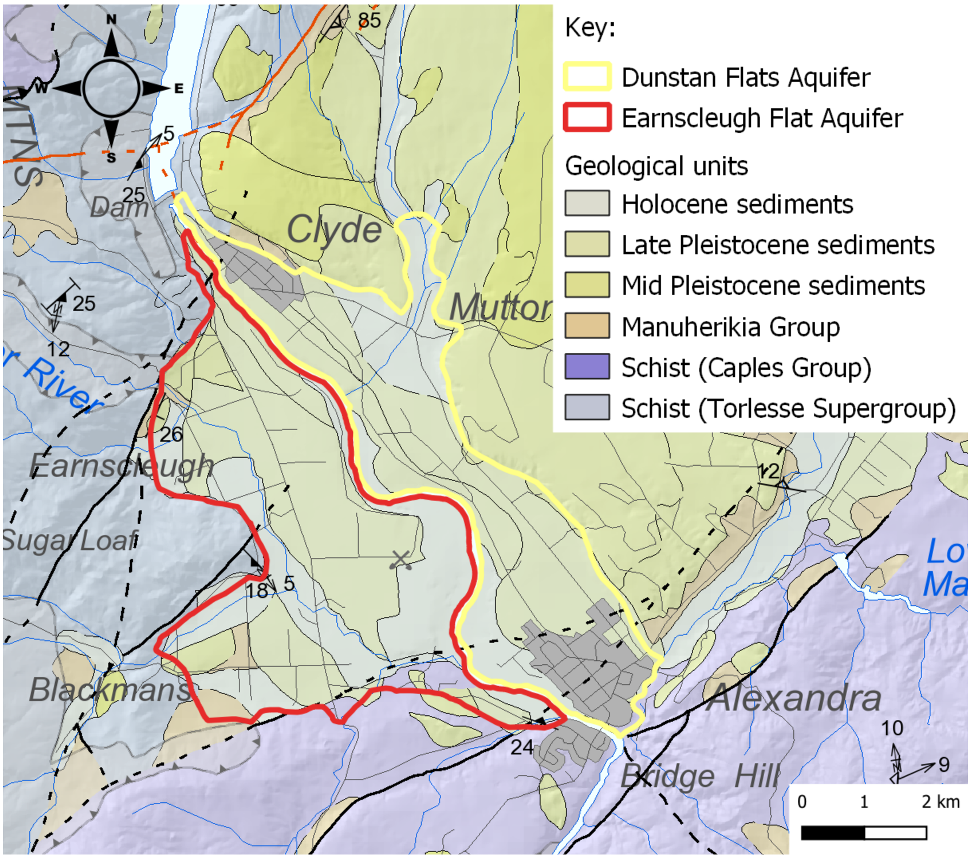

Figure 2: Simplified geological map of the Alexandra Basin (Turnbull, 2000).

2.2 Hydrogeology

Groundwater in both aquifers generally flows towards the Clutha River. There are 189 bores recorded on Earnscleugh Flat, and they range in depth from 2 – 54.4 m below ground level (bgl), though many of the bores are of unknown depth. Aquifer tests conducted in the Earnscleugh Flat Aquifer have estimated transmissivities of 1,100 to 8,900 m^2/day, based on three tests near the centre of Earnscleugh Flat. There are 289 bores recorded on Dunstan Flats, and they range in depth from 6 – 204 m below ground level (bgl) with most bores up to 39 m deep, though many of the bores are of unknown depth. Aquifer tests conducted in the Dunstan Flats Aquifer have estimated transmissivities of 1,200 to 7,000 m^2/day based on three tests in the central Dunstan Flats.

2.2.1 Groundwater levels

Static water level records in bores on Earnscleugh Flat show that the groundwater table is generally deeper towards the Clutha River across most of the terrace (Figure 3). At the southern end of the terrace groundwater levels are closer to the surface where the Fraser River has incised into the terrace. This coincides with the gaining reach of the Fraser River, as discussed further in the sections below.

There are relatively few long-term records of groundwater levels available for the Earnscleugh Flat Aquifer. Bore G42/0190 in the southern central part of the terrace has a sporadic monitoring record, with one to five measurements per year since 2015. This bore is 21.3 m deep, and the groundwater level record shows that seasonal fluctuations of up to approximately 2.6 m per year are common (9.7 – 12.3 m bgl). Average groundwater levels across much of Earnscleugh Flat were contoured by AquaFirma (1997) and indicate that groundwater across at least the northern part of the Flat flows directly towards the Clutha River (Figure 4).

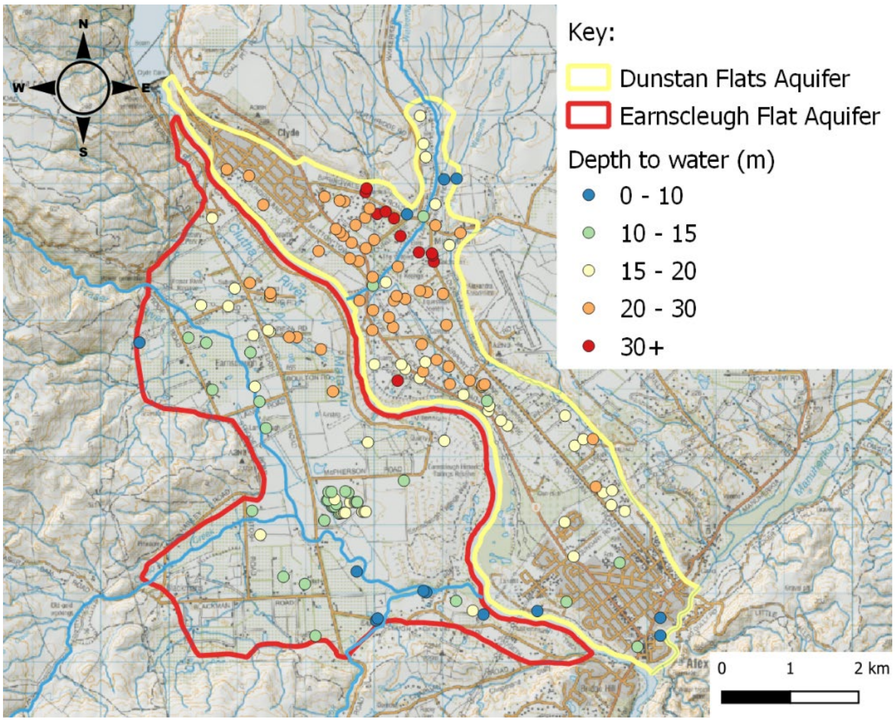

Figure 3: The depth to water at the time of drilling, recorded in bores across the Dunstan Flats Aquifer and Earnscleugh Flat Aquifer.

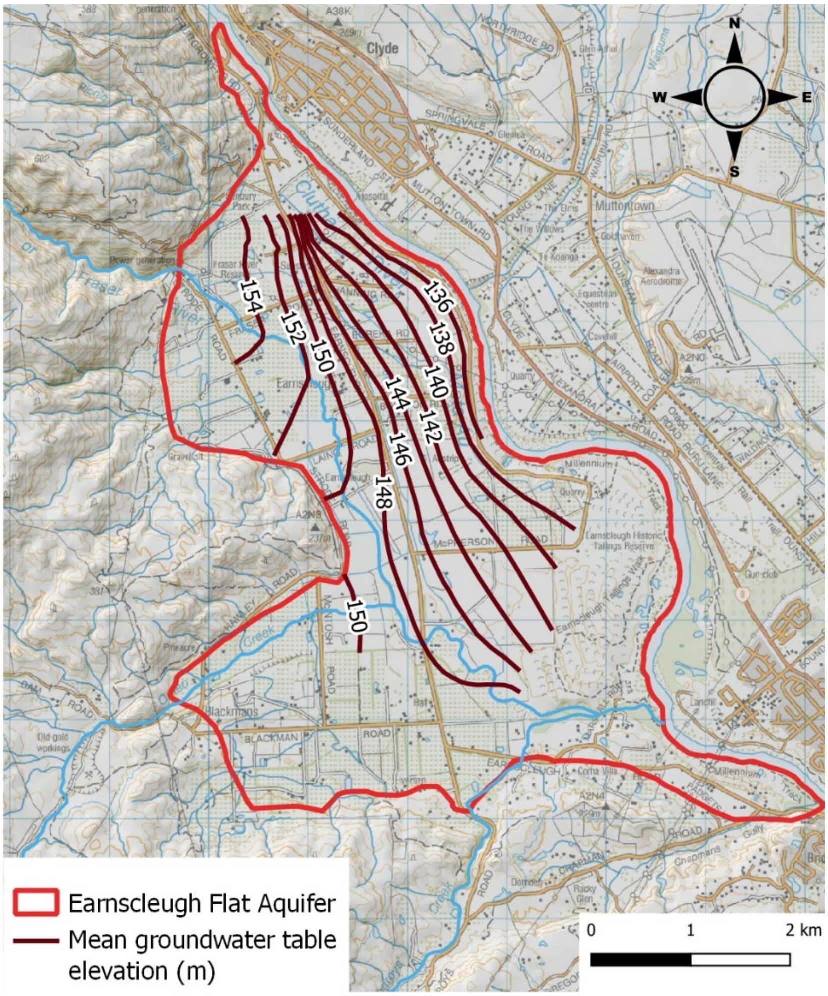

Figure 4: Average groundwater level contours produced from monitoring of groundwater levels across Earnscleugh Flat in the 1990's (after AquaFirma, 1997).

Static water level records in bores on Dunstan Flats show that the groundwater table is shallowest both at the upper margins of the terrace near Waikerikeri Creek and on the lower margins of the terrace near the Clutha River (Figure 3).

Long-term groundwater level records in the Dunstan Flats Aquifer are available from bore G42/0695 on the north-western side of Dunstan Flats. This bore is 17.8 m deep and has a record from April 1986 to present. Groundwater level data is currently recorded at 5-minute intervals. The record shows that seasonal fluctuations are generally on the order of 2 metres. Comparisons of groundwater level records with the flow in the Clutha River show that generally there is not a strong correlation between the two, except for times when floods in the Clutha River mean that the river stage exceeds the adjacent groundwater level, and the groundwater table rises in response (AquaFirma, 1998). This pattern has been observed in several bores in the Dunstan Flats Aquifer, with the bores closest to the river showing the strongest correlation with river stage (AquaFirma, 1998). This occasional relationship suggests that, on average, groundwater in the Dunstan Flats is not directly connected to the Clutha River at least in the area around the monitoring bore G42/0695. Based on the data from bore G42/0695, groundwater levels are typically highest in late summer and lowest in spring, which correlates with the pattern of irrigation and reflects irrigation losses contributing to groundwater recharge in the area.

2.2.2 Recharge

The study area has a semi-arid climate; the floor of the Alexandra Basin has a typical annual rainfall of 350 mm per year (mm/y), while rainfall is significantly higher at higher elevations (ORC, 2012). The mean annual pan evaporation is just over 1000 mm and typically a small soil moisture excess, totalling on average 38 mm/yr for June – August, recharges groundwater from rainfall under natural conditions (ORC, 2005). Rainfall is therefore a minor source of recharge for both the Earnscleugh Flat and Dunstan Flats aquifers.

The most significant source of recharge for the Earnscleugh Flat Aquifer is losses from the Fraser River in the northern end of Earnscleugh Flat. Smaller losses also occur from Omeo Creek. The Fraser River gains from groundwater in its lower reaches where it incises down into the terrace, from approximately 2 km above the confluence with the Clutha River (AquaFirma, 1998; ORC, 2012). Flows in the Fraser River are partially controlled by a dam in the upper catchment, which stores water for irrigation and electricity generation (Landpro, 2020). Irrigation provides a significant source of groundwater recharge on Earnscleugh Flat, both as a result of direct application to ground and via losses from water races and storage ponds. Irrigation races and irrigated areas are shown in Figure 5. It is also expected that runoff recharge from the Old Man Range to the west of Earnscleugh Flat, particularly from the Cairnmuir Flats and Shepherds Flat, may also be a source of recharge to the aquifer. This appears to have not been estimated in the ORC (2012) report.

The most significant source of recharge for the Dunstan Flats Aquifer is losses from irrigation water races related to the Manuherekia Irrigation Scheme. Subsurface through-flow from the adjacent Manuherekia Claybound Aquifer are also considered to be a significant source of recharge. Irrigation excess soil drainage losses and losses from Waikerikeri Creek are other smaller sources of recharge.

Irrigation methods across the Alexandra Basin are becoming more efficient over time, with most irrigation reported to be occurring via border dyke and wild flooding methods in 2012 (ORC, 2012), while the 2021 irrigated area GIS layer indicates that micro drip is now the most common method.

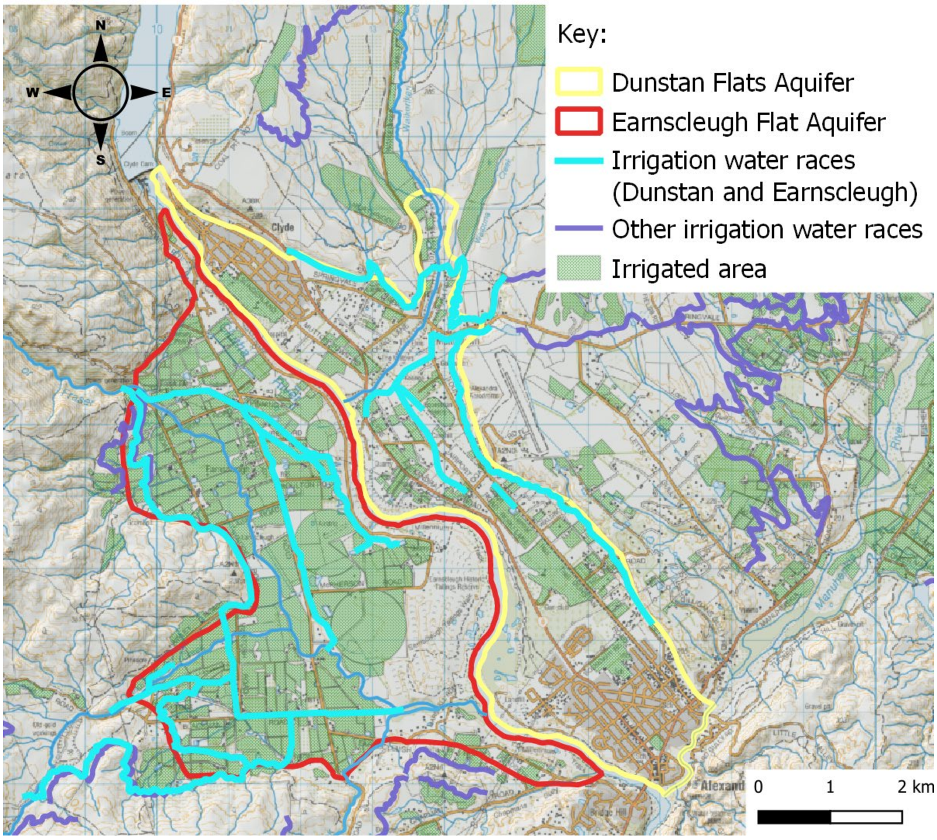

Figure 5: The location of irrigation water races and irrigated land area across the study area.

2.2.3 Outflow

All outflow from the Earnscleugh Flat Aquifer occurs either as groundwater abstractions, flow to the lower Fraser River and thence to the Clutha River, seepage directly into the Clutha River, or else as springs along the bank of the Clutha River. Flow to the lower Fraser River comprises the largest outflow, estimated at 56% of total discharge from the aquifer in 2012 (ORC, 2012).

All groundwater that is not abstracted from the Dunstan Flats Aquifer via bores ultimately discharges to the Clutha River via groundwater seepage. In 2012, groundwater abstractions were estimated to total 4% of total outflow, with discharge to the Clutha River comprising the other 96%.

2.3 Water balance

The overall water balance of the Earnscleugh Flat Aquifer as estimated by ORC in 2012 is provided in Table 1 below. It is noted that aspects of this water balance, in particular inflow due to irrigation and outflow from groundwater abstraction, may have changed since 2012 and were refined during the modelling process (section 5.2.1). However, this water balance is considered a useful starting point for the conceptual model of the aquifer.

Table 1: Water balance of the Earnscleugh Flat Aquifer (after ORC, 2012)

Water balance component	Mean annual inflow (Mm^3/y)	Mean annual outflow (Mm^3/y)
Rainfall recharge	0.35 (1.2%)	
Excess soil drainage related to Fraser Irrigation Scheme	0.55 (1.9%)	
Infiltration of water from Fraser River to the aquifer	24.60 (85.1%)	
Water race losses to the aquifer	3.40 (11.8%)	
Seepage into the lower Fraser River		16.20 (56.1%)
Pumping from the Earnscleugh Flat Aquifer[1]		0.15 (0.5%)
Seepage into springs cascading into the Clutha River / Mata-Au		4.00 (13.8%)
Seepage directly into the Clutha River / Mata-Au		8.5 (29.4%)
Total	28.9	28.9

Notes:

1. *Actual pumping estimated as 30% of groundwater take consent allocation for the aquifer.*

The overall water balance of the Dunstan Flats Aquifer as estimated by ORC in 2012 is provided in Table 2 below. It is noted that aspects of this water balance may have changed since 2012, in particular inflow due to irrigation, inflow from the Manuherekia Claybound Aquifer and outflow from groundwater abstraction. Some of these aspects were refined during the modelling process (section 6.2.1). However, this water balance is considered a useful starting point for the conceptual model of the aquifer.

Table 2: Water balance of the Dunstan Flats Aquifer (after ORC, 2012)

Water balance component	Mean annual inflow (Mm^3/y)	Mean annual outflow (Mm^3/y)
Rainfall recharge	0.48 (4.5%)	
Excess soil drainage related to the Manuherekia irrigation scheme	0.70 (6.5%)	
Subsurface through-flow from the Manuherekia Claybound Aquifer	2.20 (20.6%)	
Infiltration of water from Waikerikeri Creek into the Dunstan Flats Aquifer	0.30 (2.8%)	

Table 2: Water balance of the Dunstan Flats Aquifer (after ORC, 2012)

Water balance component	Mean annual inflow (Mm^3/y)	Mean annual outflow (Mm^3/y)
Water race losses to the aquifer	7.00 (65.4%)	
Pumping from the Dunstan Flats Aquifer[1]		0.43 (4.1%)
Seepage directly into the Clutha River / Mata-Au		10.20 (96.2%)
Totals	10.7	10.6

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

3.0 Groundwater model structure and design

The Earnscleugh Flat and Dunstan Flats Aquifers are separated by the Clutha River, and there is no evidence of a direct connection between them. Therefore it was considered most appropriate to model the two aquifers separately. The following sections briefly outline the modelling approach, in light of the conceptual setting described in the sections above. A full description of the modelling approach is provided in the conceptual model report (PDP, 2022).

Both models were set-up as steady state, with a single stress period representing average conditions. In this context, average conditions represented average annual recharge, average groundwater levels and average stream flows. Both models were developed using the USGS MODFLOW 6 code.

The model grid for both models was based on a cell size of 100 x 100 m, and both aquifers were modelled as two layers.

Recharge to the groundwater system for both aquifers was calculated using a soil moisture model developed for the area as part of this modelling project, which incorporated losses from application of irrigation water (see section 4.0 below). In addition to these losses, further losses were allowed for from the irrigation race network and from runoff from the ranges to the west for the Earnscleugh Flat model. These network losses are poorly defined and are based on estimates from the ORC 2012 work (noting that these may have changed since that time), though they likely represent a significant part of the water balance for both modelled aquifers.

Groundwater abstractions in both models were represented via the MODFLOW well package (WEL). Actual groundwater abstraction rates are not well defined for takes in the area and based on discussions with ORC a value of 30% of the consented annual volume was used as the abstraction rate for each take. However, abstraction is a relatively minor part of the overall water balance.

Further specific details of the structure and design of each model are discussed in sections 3.1 and 3.2 below.

3.1 Earnscleugh

The extent of the groundwater model is shown in Figure 6 and the recharge grid used for the model is shown in Figure 7. The overall extent of the active model area was based on surface water boundaries (the Clutha River) and the extent of the Quaternary gravels of Earnscleugh Flat. The Manuherekia Group and basement schist that outcrop adjacent to the Quaternary gravels are assumed to be impermeable for modelling purposes, therefore the other boundaries of Earnscleugh Flat were modelled as no flow boundaries.

Across most of the aquifer the map of the thickness of the gravels produced by AquaFirma (1998) was used to define the thickness of the cells. These contours were extrapolated further across the aquifer using geological judgement based on the available pattern of gravel contours. The lower cells were set to be 6 m thick, and the upper cells' thickness determined based on the gravel thickness map. Across the parts of the terrace not covered by the gravel thickness map the gravel thickness was be assumed to be 24 m, and layers 1 and 2 were both set to be 12 m thick. This approach enables surface waterways to be modelled in an upper aquifer and also allows for variable topography across the area, particularly in the Earnscleugh tailings area towards the south of the model area.

Surface water boundaries in the Earnscleugh Flat Aquifer include the Fraser River, Omeo Creek, Conroys Creek and the Clutha River. The Fraser River, Omeo Creek and Conroys Creek were modelled as stream cells using the MODFLOW stream package (SFR) as this ensures that only the available flow in the river can be lost to the underlying aquifer. The stage in these streams was set based on LiDAR data for the stream. The flow at the top end of the Fraser River where it enters the model area was set at 3,717 L/s (321,149 m^3/day), which was determined as follows:

- An estimated mean flow of the Fraser River at the lower intake weir between the Fraser Dam and Earnscleugh Flat of 3,150 L/s, as reported by LandPro (2020).
- An estimated average irrigation surface water take from the Fraser River between the weir and Earnscleugh Flat of 197 L/s.
- An estimated average inflow to the Fraser River from the Clyde Dam irrigation pipeline of 764 L/s. 3,150 – 197 + 764 = 3,717 L/s.

The flows at the top of Omeo Creek and Conroys Creek, where they enter the model area, were based on modelled mean stream flows sourced from the Ministry for the Environment (available at https://data.mfe.govt.nz/layer/53309-river-flows/). The flow at the top of Omeo Creek was set at 420 L/s (36,288 m^3/day) and the flow at the top of Conroys Creek was set at 280 L/s (24,192 m^3/day). We are not aware of any flow gauging studies on these creeks which could be used to validate these values.

There are areas of the hills to the west of Earnscleugh Flat that drain directly to the Flat (i.e. not to the Fraser River, Omeo Creek or Conroys Creek). Runoff from these areas likely to contribute recharge to the Earnscleugh Flat Aquifer. The two largest areas of potential runoff recharge are the Cairnmuir Flats area (which is drained by Picnic Stream) and the Shepherds Flat area (which is drained by an unnamed stream). The streams draining these areas do not appear to reach the Fraser River, based on available LiDAR data and aerial photography. Allowance was made for runoff recharge to the model by inclusion of a second stream file (SFR-2), with four stream cells included to represent Picnic Stream, and five cells included to represent the stream draining Shepherds Flat. The initial flows at the top of these streams were based on the modelled mean annual low flow sourced from the Ministry for the Environment (available at https://data.mfe.govt.nz/layer/53309-river-flows/). The flow for Picnic Stream was set at 5.2 L/s while the flow for the stream draining Shepherds Flat was set at 6.5 L/s.

The irrigation water race losses were applied as recharge in addition to the soil water balance recharge, which is described in section 4.0 below. The total magnitude of losses was taken to be 3.4 Mm^3/year based on the ORC allocation study (ORC, 2012). This volume was divided by 365 days and distributed evenly across the cells in the model that are defined as irrigation water races for an irrigation race recharge of 0.00261 m/day per cell. The location of irrigation water races was determined from a LINZ NZ water race centrelines shapefile and manual tracing of races from aerial imagery.

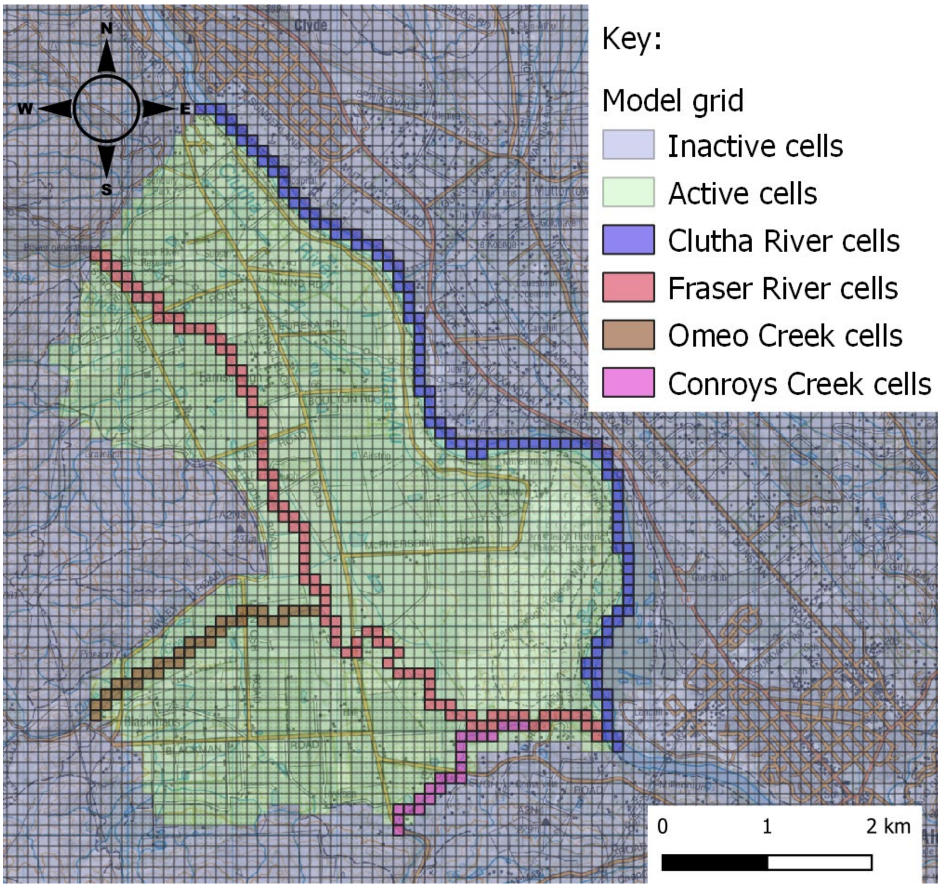

Figure 6: Overall model structure of the Earnscleugh Flat Aquifer model.

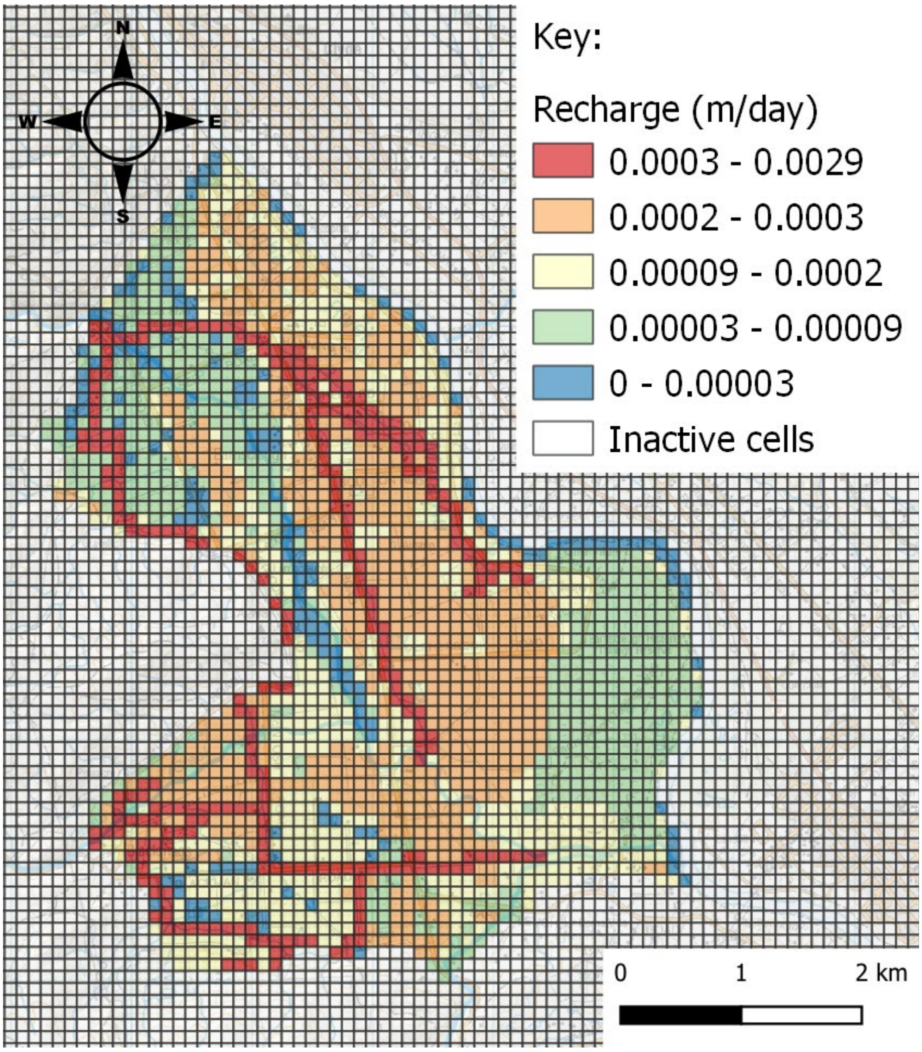

Figure 7: Recharge distribution across the Earnscleugh Flat Aquifer model area, including both assumed water race losses and modelled soil moisture balance.

The Clutha River was modelled using the MODFLOW River package (RIV). Again, the stage of the river was based on LiDAR elevation data, but no specified flow is required for the river package. The streambed conductance parameter for all streams and the Clutha River was determined via calibration as discussed further in section 5.1 below.

Surface water takes within the model area were modelled using the MODFLOW Mover package (MVR). All consented surface water takes within the model area are under the one consent RM18.266.02, which authorises a combined maximum daily take of 54,043.2 m^3/day. Two takes from the upper Fraser River have maximum instantaneous take values of 1,200 and 800 L/s, while three takes in the middle Fraser have a combined maximum take of 470.667 L/s. To determine the take to assign to the Mover package, it was assumed that 50% of the daily maximum take was used for a total of an assumed 90-day irrigation season, and it was assumed that the total take was apportioned in proportion to the maximum instantaneous rate of take. One take on this consent is outside of the model area, while the other four were included, with a take of 1,562.2 m^3/day assigned to the No. 1 Race, 1,838.2 m^3/day assigned to the combined VDV1 and VDV2 takes (which were located in the same model cell) and 919.1 m^3/day assigned to the VDV3 take. Inevitably, there is uncertainty around these values.

3.2 Dunstan

The extent of the groundwater model is shown in Figure 8 and the recharge grid used for the model is shown in Figure 9. The overall extent of the active model area was based on surface water boundaries (the Clutha and Manuherekia Rivers) and the outcrop of the Manuherekia Claybound aquifer to the north-east. Both the surface water boundaries represent flow boundaries to the aquifer, however, the Dunstan Flats aquifer receives throughflow from the adjacent Manuherekia Claybound aquifer and this boundary was represented as a general head boundary in the model with a fixed head of 18 m below ground level, which is the approximate average depth to groundwater measured in bores near the boundary. This head was not varied during the calibration process, however the conductance of the general head boundary was varied, as discussed in section 6.1 below.

Accurate information on the depth to the basement strata beneath the Dunstan Flats aquifer is not available, however four bores on Dunstan Flats were reported to encounter rock, at depths varying from 19.3 m to 58 m below ground level. Based on this information, and evidence from the depth of bores in the area (the vast majority of which are shallower than 40 m) it is estimated that the permeable strata extend to a depth of around 40 m across most of the model area. Therefore, the model was split into two layers with the upper model layer 10 m thick and the lower model layer 30 m thick. This approach enables some vertical anisotropy to be modelled in the aquifer where it is required and also allows surface waterways to be modelled in an upper aquifer.

Surface water boundaries in the Dunstan Flats Aquifer include the Waikerikeri Creek, Manuherekia River and the Clutha River. The Waikerikeri Creek was modelled using the MODFLOW stream package (SFR) as this ensures that only the available flow in the river can be lost to the underlying aquifer. The stage in the creek was set based on LiDAR data for the stream and the flow at the top end of the creek where it enters the model area was set to 26 L/s (2,246.4 m^3/day) based on gauged flows in the creek (ORC, 2012). The Clutha River was modelled using the MODFLOW River package (RIV). Again the stage of the river was based on LiDAR elevation data, but no specified flow is required for the river package. Likewise, the Manukerekia River was simulated using the MODLOW River package. The streambed conductance parameter for both the Waikerikeri Creek and the Clutha River was determined via calibration, as discussed further in section 6.1 below.

The irrigation water race losses were applied as recharge in addition to the soil water balance recharge, which is described in section 4.0 below. The total magnitude of losses was taken to be 7 Mm^3/year based on the ORC allocation study (ORC, 2012). This volume was divided by 365 days and distributed evenly across the cells in the model that are defined as irrigation water races for an irrigation race recharge of 0.0171 m/day per cell. The location of irrigation water races was determined from a LINZ NZ water race centrelines shapefile and manual tracing of races from aerial imagery.

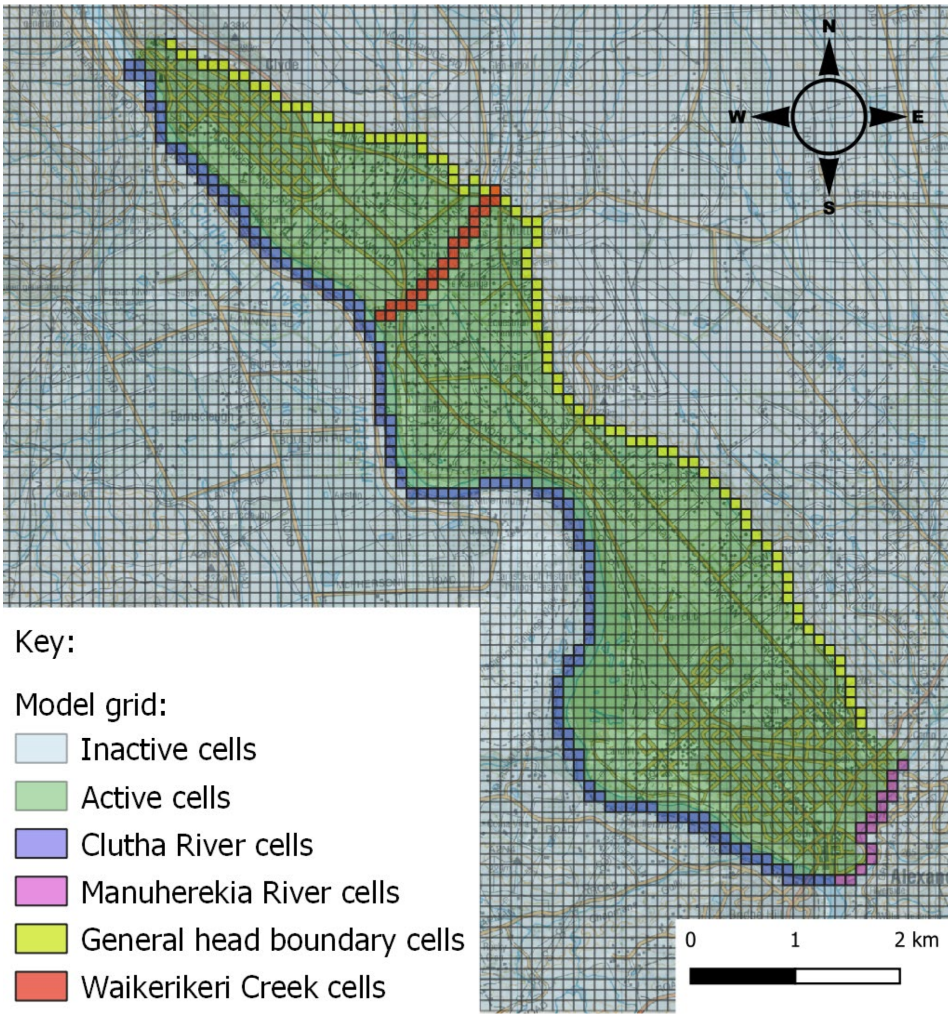

Figure 8: Overall model structure of the Dunstan Flats Aquifer model.

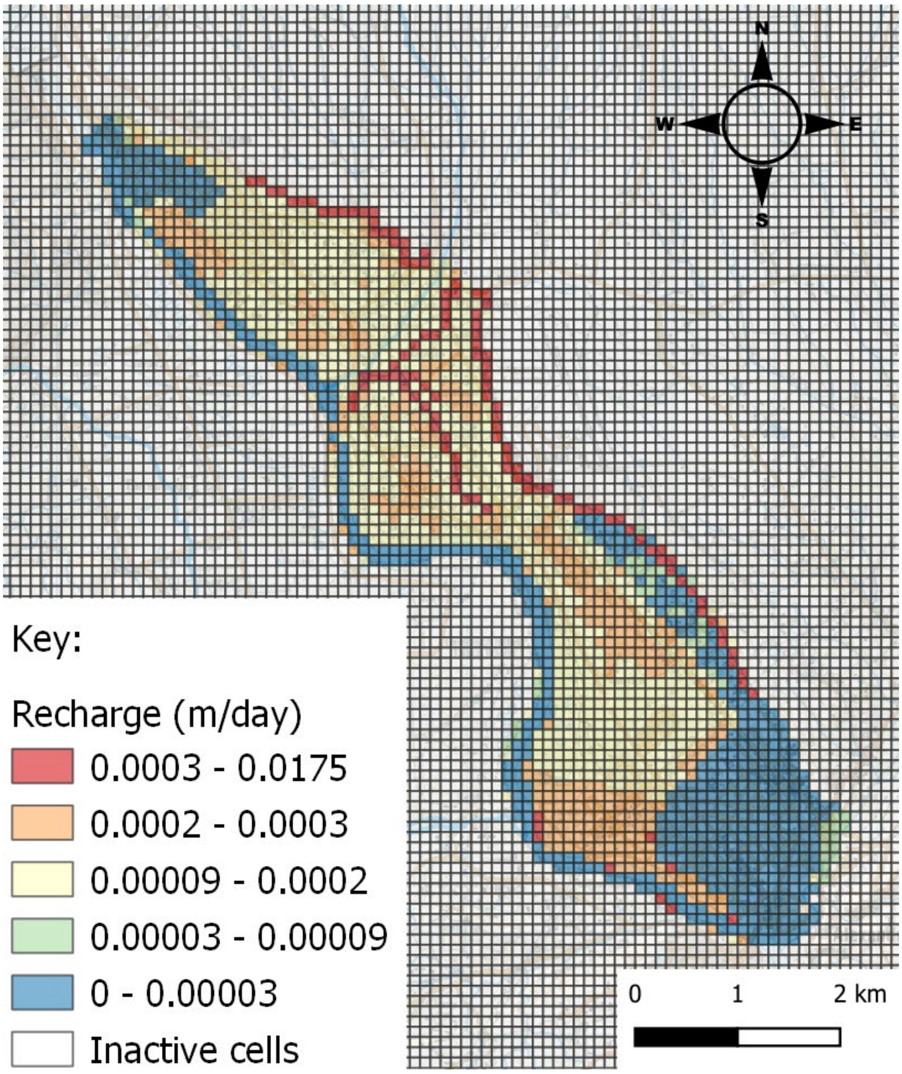

Figure 9: Recharge distribution across the Dunstan Flats Aquifer model area, including both assumed water race losses and modelled soil moisture balance.

4.0 Recharge model

4.1 Soil water balance model

Rainfall and irrigation recharge to groundwater in the Dunstan and Earnscleugh groundwater models was calculated using a spatially distributed daily soil moisture balance model covering both the Dunstan Flats Aquifer and Earnscleugh Flats Aquifer. The model uses the same 100 m grid as the as the groundwater models, therefore the outputs of the recharge model were able to be used directly in the groundwater flow model.

The soil water balance model calculates recharge using a daily 'bucket' approach, where grid cell has a specific water holding capacity. The water holding capacity of each grid cell is determined by the profile available water (PAW) of the overlying soil. This is calculated as the difference in soil water content at field capacity (FC) and permanent wilting point (PWP).

On a daily basis, the model calculates the movement of water in and out of each grid cell. Rainfall and irrigation contribute water while evapotranspiration (ET) removes water from the grid cells. If the net total water in a grid cell at the end of a day exceeds the water holding capacity of the grid cell, water is lost either as overland runoff or drainage to groundwater. As the land above the Dunstan and Earnsleugh aquifers is relatively flat, all excess water was assumed to be lost to subsurface drainage (and then to become groundwater recharge).

Irrigation inputs to irrigated grid cells are calculated on the basis of start and stop soil moisture triggers consistent with irrigation best management practices to minimise excess drainage. When the soil moisture content of an irrigated grid cell falls below the start trigger, irrigation begins and then continues (at the specified application rate and return period) until the stopping trigger point is reached. This approach assumes there are no water supply restrictions preventing irrigation from occurring during the irrigation season (assumed to be 1 September – 30 April each year).

4.2 Input data

The recharge model required continuous series of daily rainfall and potential evapotranspiration (PET) data. These were developed by combining the available rainfall and PET records for the NIWA climate stations shown in Figure 10 in a single timeseries for the model grid. Average annual rainfall is estimated to be approximately 402 mm/year while average annual PET is approximately 845 mm/year.

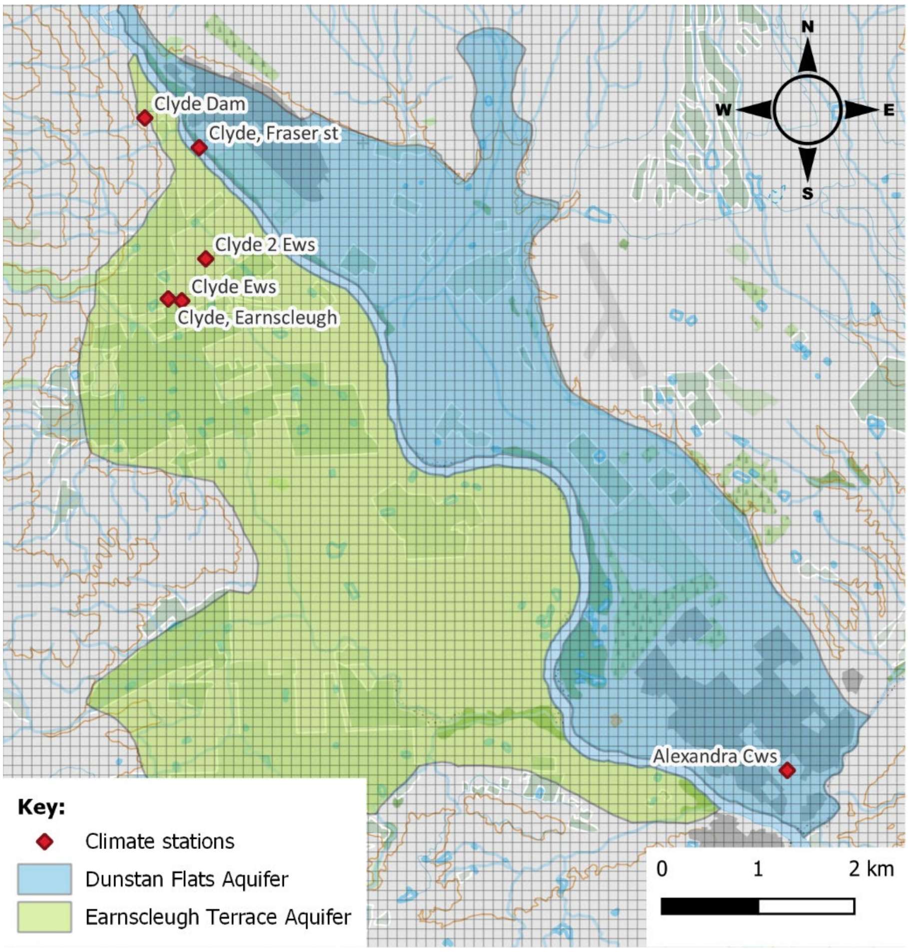

Figure 10: Climate stations used for soil water balance model.

The PAW for each grid cell was determined for a rooting depth of 90 cm using data from the Fundamental Soil Layer (Manaaki Whenua – Landcare Research) as shown in Figure 11. For cases where multiple polygons overlapped a grid cell, a single value was calculated by taking the area-weighted average across the grid cell.

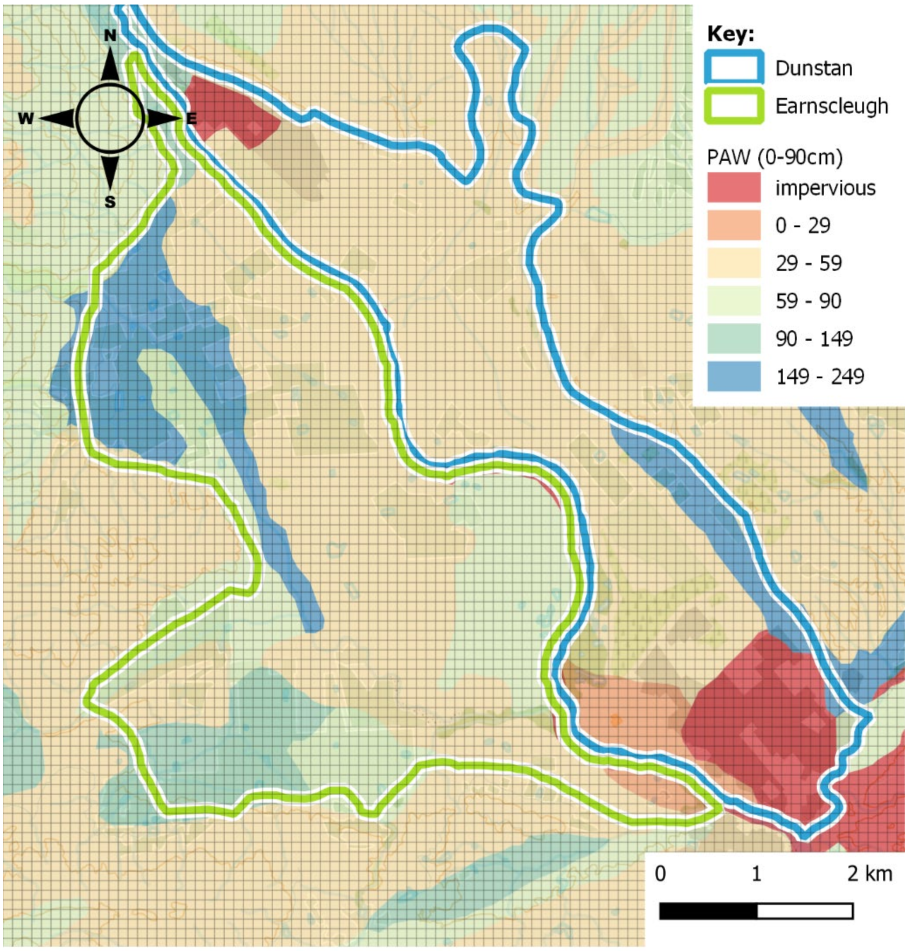

Figure 11: Profile available water (PAW) used in soil water balance model.

Irrigated grid cells in the model were defined using data provided by ORC and shown in Figure 12. A grid cell was considered irrigated if more than half of the grid cell area intersected an irrigation area polygon. For cases where multiple irrigation methods intersected in a single grid cell, the dominant (by area) irrigation method was assumed to apply for the entire grid cell.

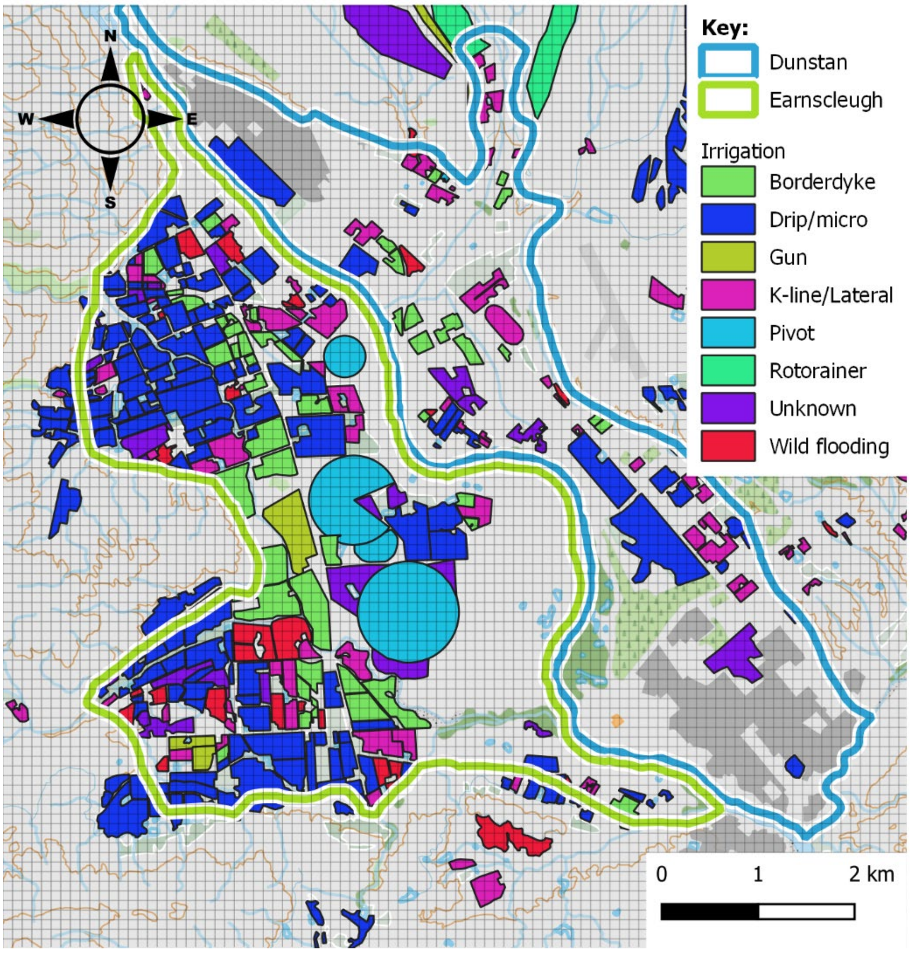

Figure 12: Irrigated areas and types used in soil water balance model.

The irrigation inputs shown in Table 3 were assumed for each irrigation method based on prior experience.

Table 3: Irrigation input data

<table>
<tr><th rowspan="2">Method</th><th rowspan="2">Efficiency (%)</th><th rowspan="2">Application rate (mm/day)</th><th rowspan="2">Return period (days)[1]</th><th colspan="2">Irrigation trigger (% of PAW)</th></tr>
<tr><th>Start</th><th>End</th></tr>
<tr><td>Drip/micro</td><td rowspan="3">90%</td><td rowspan="3">5</td><td rowspan="3">1</td><td rowspan="8">50%</td><td rowspan="8">90%</td></tr>
<tr><td>Pivot</td></tr>
<tr><td>Unknown</td></tr>
<tr><td>Rotorainer</td><td rowspan="3">80%</td><td rowspan="3">15</td><td rowspan="3">5</td></tr>
<tr><td>K-line/Long lateral</td></tr>
<tr><td>Gun</td></tr>
<tr><td>Wild flooding</td><td rowspan="2">70%</td><td rowspan="2">50</td><td rowspan="2">21</td></tr>
<tr><td>Borderdyke</td></tr>
</table>

Notes:

1. *Note a return period of 1 means irrigation can be applied every day, a return period of 5 means there will be 4 days of no irrigation with irrigation applied on the 5^{th} day, etc.*

4.3 Results

The recharge model was run over the 33-year period from 1 July 1978 to 30 June 2021 (period dictated by climate data availability) and the average daily recharge for each grid cell was calculated and used as an input to the groundwater models. The daily average data was then post-processed to calculate separate average daily recharge numbers for all grid cells within the Dunstan and Earnscleugh aquifers. These figures were then converted to an estimate of annual total recharge and the results are shown in Table 4.

Table 4: Recharge model predictions

<table>
<tr><th></th><th>Cell type</th><th>Dunstan</th><th>Earnscleugh</th></tr>
<tr><td rowspan="3">PDP Modelled daily average recharge (mm/day)</td><td>Dryland</td><td>44</td><td>30</td></tr>
<tr><td>Irrigated</td><td>89</td><td>71</td></tr>
<tr><td>All cells</td><td>51</td><td>53</td></tr>
<tr><td rowspan="3">PDP Modelled aquifer total recharge (Mm³/year)</td><td>Dryland</td><td>0.56</td><td>0.31</td></tr>
<tr><td>Irrigated</td><td>0.23</td><td>0.89</td></tr>
<tr><td>All cells</td><td>0.79</td><td>1.2</td></tr>
<tr><td>ORC groundwater allocation</td><td>Rainfall</td><td>0.48</td><td>0.35</td></tr>
</table>

Table 4: Recharge model predictions

	Cell type	Dunstan	Earnscleugh
study aquifer total recharge (Mm³/year)[1]	only		
	Rainfall + irrigation	1.18	0.9

Notes:
1. (Otago Regional Council (ORC), 2012)

These recharge figures are comparable to modelled recharge estimates from a previous groundwater allocation study for the Alexandra Basin (Otago Regional Council (ORC), 2012) which are also shown in Table 4. This study predicted average annual rainfall recharge of 0.48 Mm³/year for the Dunstan Aquifer and 0.35 Mm³/year for the Earnscleugh Aquifer. These values compare well to the model results in Table 4 for dryland cells of 0.56 Mm³/year and 0.35 Mm³/year given the different modelling periods, modelling assumptions and input datasets used in the two assessments.

The total recharge (including irrigated areas) predicted for the Dunstan Aquifer of 0.79 Mm³ is underestimated compared to the ORC study at 1.18 Mm³, while the predicted recharge of 1.2 Mm³ for the Earnscleugh Aquifer is overestimated compared to the ORC study at 0.9 Mm³. This difference is thought to be due to assumptions around irrigation behaviour and changes in irrigation practices over the past several years. The PDP recharge model assumes irrigation is managed efficiently to minimise drainage and as the input data shows (see Figure 12), irrigation is largely efficient pivots or micro/drip. It is possible when the study was completed there was a larger proportion of border-dyke and wild flooding irrigation which could account for the extra excess irrigation water predicted by the ORC study for the Dunstan Aquifer. New irrigation may also have been developed since the ORC study was undertaken in 2014 which could account for the higher predicted recharge volume for the Earnscleugh Aquifer.

5.0 Earnscleugh model

5.1 Model calibration

5.1.1 Model parameterisation

The model was calibrated using Parameter Estimation software (PEST) (Doherty, 2010) to a total of 33 groundwater level observations (the groundwater level in bores at the time of drilling) and surface water flow observations (the flow in the middle Fraser River at the Earnscleugh Road bridge and the flow in the lower Fraser River at Marshall Road). Due to the uncertainty in the initial flow in the Fraser River where it exits the gorge, the modelled flow at this point was allowed to vary by around 15% from the initial estimate. Therefore, the model was calibrated to the difference between flow observations (i.e. the flow losses and gains) at the following sites (as estimated by Aquafirma (1997):

- Frasers Domain to Fraser Road – average flow loss of around 600 L/s
- Fraser Road to Laing Road – average flow loss of around 50 L/s

River flow gauging described in Aquafirma (1997) indicated that overall net gain and loss in the Fraser River at Marshall Road (close to the Clutha River confluence) is approximately 0 i.e. the river gains approximately as much as it loses with the main gains occurring between Earnscleugh Road and Marshall Road. Therefore the final flow calibration point was the difference between flows where the river enters the model area, and flows at Marshall Road, where the calibration target was a difference of 0 L/s.

Aquifer properties for the modelled area were defined by pilot points, where the hydraulic conductivity at each pilot point is varied during the model calibration process using PEST. The point estimates are then spatially interpolated to generate a hydraulic conductivity field across the model area. Such an approach was employed for the Earnscleugh model and a map showing the location of pilot points used to generate the hydraulic conductivity field is shown in Figure 13. Figure 14 shows a plot of the calibrated hydraulic conductivity field for layer 1 and 2 of the model. The calibrated hydraulic conductivities varied from 32.2 to 358.9 m/day. It is noted that this hydraulic conductivity field is the result of PEST calibration and simply represents a distribution that best ‘fits’ the observed groundwater levels and flows, however due to the paucity of pumping test data across the model area it is difficult to determine whether this distribution provides a good representation of the real distribution.

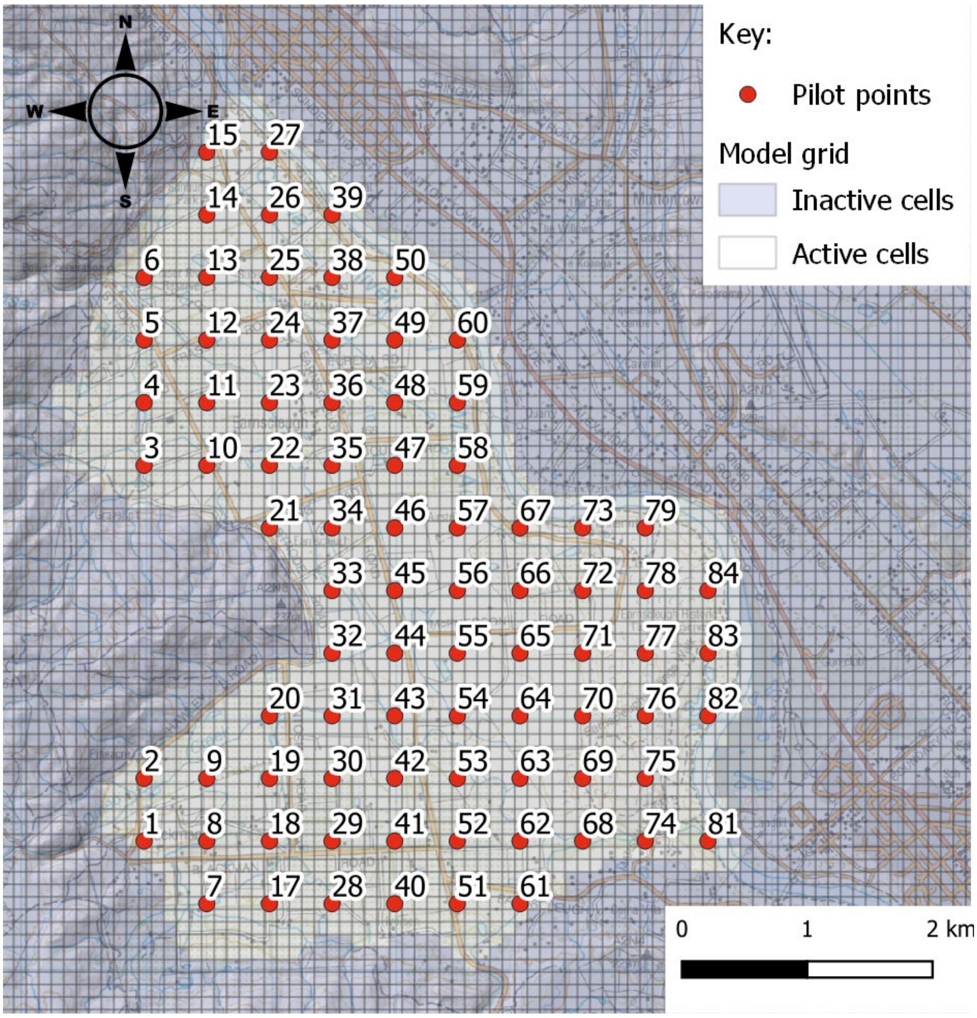

Figure 13: The location of pilot points (and associated pilot point IDs) used for hydraulic conductivity calibration across Earnscleugh Flat.

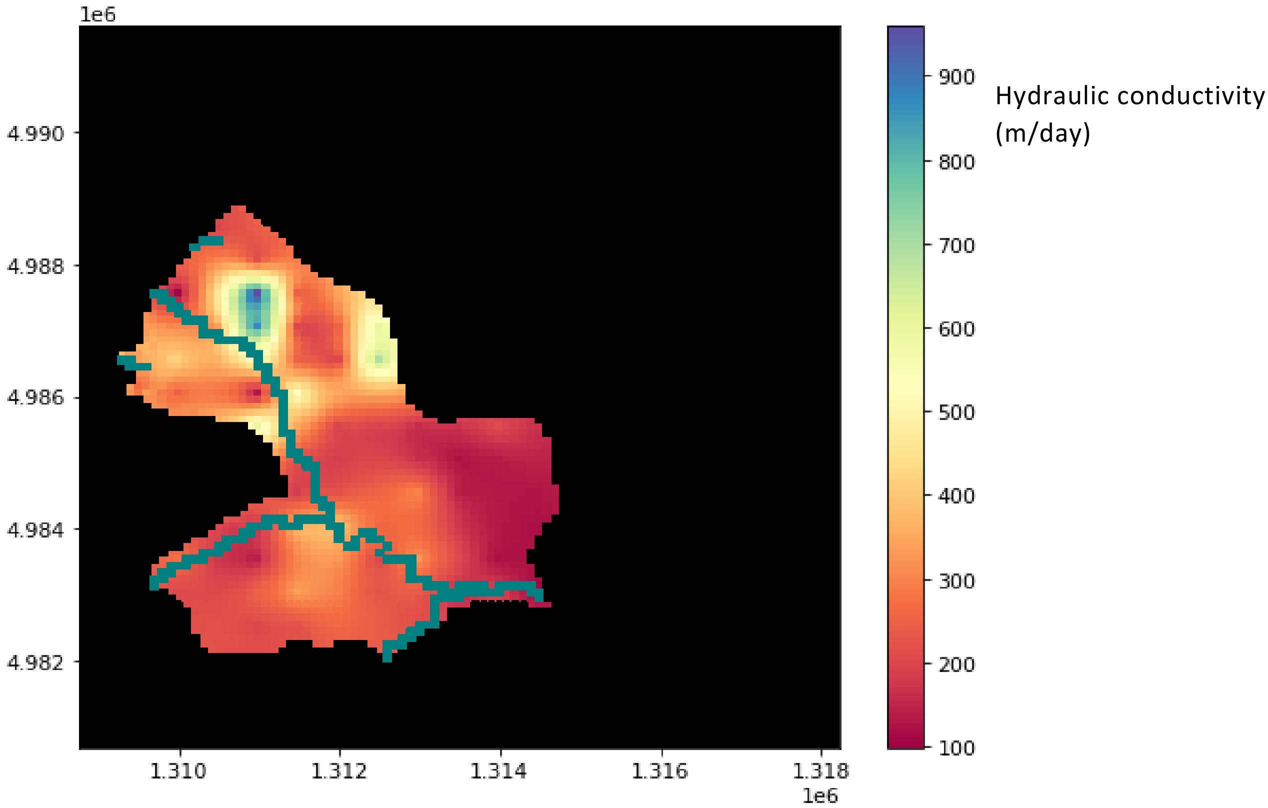

Figure 14: Calibrated horizontal hydraulic conductivity field for the Earnscleugh Flat Aquifer model, in m/day.

Streambed conductance values were also varied in a similar way during the calibration process, with the Fraser River split into four segments (described in Table 5 below), and Omeo Creek and Conroys Creek each represented as a single segment. The streambed conductance of each segment was varied during the calibration process and the final calibrated streambed conductance values are provided in Table 5. The Clutha riverbed conductance value was also varied in a similar way (as a single segment) during the calibration process, and the final calibrated conductance value is also provided in Table 5.

Table 5: Calibrated streambed conductance values for the Earnscleugh Flat Aquifer model.

Parameter	Calibrated streambed conductance (m/day)
Clutha River	8,063
Lower Fraser River [1]	0.2
Middle Fraser River [2]	0.08

Table 5: Calibrated streambed conductance values for the Earnscleugh Flat Aquifer model.

Parameter	Calibrated streambed conductance (m/day)
Upper Fraser River 2 [3]	0.8
Upper Fraser River 1 [4]	5.1
Omeo Creek	3.5
Conroys Creek	0.7

Notes:

1. *This segment is from approximately Marshall Road to the confluence with the Clutha River.*
2. *This segment is from approximately the Earnscleugh Road bridge to Marshall Road.*
3. *This segment is from approximately the Laing Road bridge to the Earnscleugh Road bridge.*
4. *This segment is from the top of Earnscleugh Flat to the Laing Road bridge.*

The average calibrated streambed conductance value for the upper Fraser River (from the upper boundary of the model to approximately the Earnscleugh Road bridge) when weighted by reach length (the Upper Fraser River 1 segment encompasses 42 reaches while the Upper Fraser River 2 segment encompasses 32 reaches) was around 3.2 m/day. As an independent check, the streambed conductance of this reach of the Fraser River was estimated using the gauged losses along this reach, the average head difference between the river stage and the groundwater level (estimated at 15 m based on the depth to water recorded in bores near the Fraser River), and the length of the river along this reach, using the equation provided in the Environment Canterbury stream depletion guidelines (PDP & ECan, 2000). The streambed conductance estimated using this method was 1.04 m/day, which is considered a reasonably close match to the modelled value.

It should be noted that the calibration has relied on the ORC (2012) estimate of irrigation water race losses being approximately correct. If these losses are inaccurate, then this would affect the resulting calibrated aquifer parameters such as hydraulic conductivity and streambed conductance.

5.1.2 Calibration statistics

The model was calibrated using PEST to a total of 33 groundwater level observations (the groundwater level in bores at the time of drilling) and surface water flow observations relating to the observed losses along the river (as described in Section 5.1.1 above).

Calibration statistics are provided in Table 6. In a model where both groundwater levels and flows are used as calibration targets there is frequently some trade-off between ensuring a good match to flows or groundwater levels. The model results in terms of groundwater levels are discussed further in section 5.2.2 below.

Table 6: Calibration statistics for the Earnscleugh Flat Aquifer model				
Observation group	**Number of observations**	**Root Mean Squared error (m) (RMS)**	**R^2 value**	**Normalised Root Mean Squared Error**
Groundwater heads	33	1.9	0.9	5.6%
	Observed value	**Modelled value**		
Surface water loss between Fraser Domain and Laing Road	600 L/s	580 L/s		

5.2 Model results

5.2.1 Mass balance

The overall modelled mass balance is generally consistent with our conceptual understanding of the Earnscleugh Flat Aquifer. The model mass balance is summarised in Table 7 below. The results show that most recharge to the aquifer (92%) is modelled to be sourced from losses from streams, with recharge from a combination of rainfall, recharge from irrigation-related excess soil moisture and irrigation water race losses comprising most of the remainder (11.0%). The model predicts a very small (0.4%) recharge contribution from the Clutha River. The 92% of recharge from streams is generally similar to the 85.1% of recharge from the Fraser River that was estimated by ORC in 2012 (see Table 1), however it is noted that the 2012 study did not account for potential losses from Omeo Creek and Conroys Creek.

Although allowance was made in the model for runoff recharge from the Old Man Range via stream cells, the model cells were dry in these areas. As MODFLOW considers dry cells inactive, no streamflow losses to groundwater could be applied from these areas. It is noted that the magnitude of runoff recharge is likely to be very small in comparison to losses from the Fraser River.

The pattern of outflow indicates that most outflow from the aquifer (93%) is modelled to discharge to the Clutha River. A much smaller portion of the modelled outflow (6%) comprises streamflow gains to the lower Fraser River from groundwater. Groundwater abstractions were modelled to comprise 1% of outflow from the aquifer. It is noted that the modelled distribution of outflows differs from those estimated by ORC in 2012 (see Table 1); ORC estimated 56.1% of outflow to be seepage into the lower Fraser River. It is noted that the 2012 ORC water balance assumed that all streamflow gain to the lower Fraser River was due to groundwater seepage, and did not include surface water flows from

Omeo Creek or Conroys Creek. The water balance determined from the model also indicates a greater total inflow from streams compared to the water balance determined by ORC (2012). This is due to additional losses in the model from Omeo Creek and Conroys Creek, which were not considered in the ORC estimate from 2012. This is discussed further in section 5.2.3 below.

Table 7: Modelled mass balance summary for the Earnscleugh Flat Aquifer

Water balance component	Inflow		Outflow	
	m^3/day	%	m^3/day	%
Rainfall, irrigation race and irrigation excess soil moisture recharge	7,847	7.6		
Runoff recharge from Old Man Range	0			
Streams (losses from Fraser River, Omeo Creek and Conroys Creek)	94,789	92	6,208	6
Groundwater abstraction			986	1
Clutha River	367	0.4	95,816	93
Total	103,004.3		103,011.9	

Note: Some differences in totals appear due to rounding

5.2.2 Groundwater levels

The modelled groundwater heads in bores across Earnscleugh Flat generally match observed heads reasonably well (Figure 15). It is noted that the measured groundwater levels presented in Figure 15 and used for calibration were the levels measured at the time of drilling, due to the lack of available average groundwater level data. Due to seasonal fluctuations, it is expected that these levels would not all represent the average groundwater level in those locations, and therefore some variation from the modelled heads is expected.

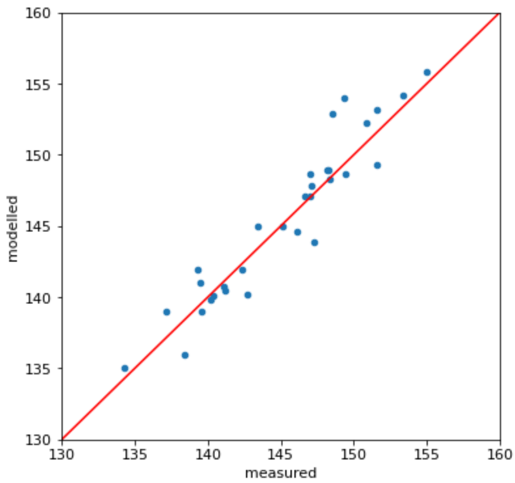

Figure 15: Modelled versus observed groundwater levels (in metres above sea level) in bores across Earnscleugh Flat.

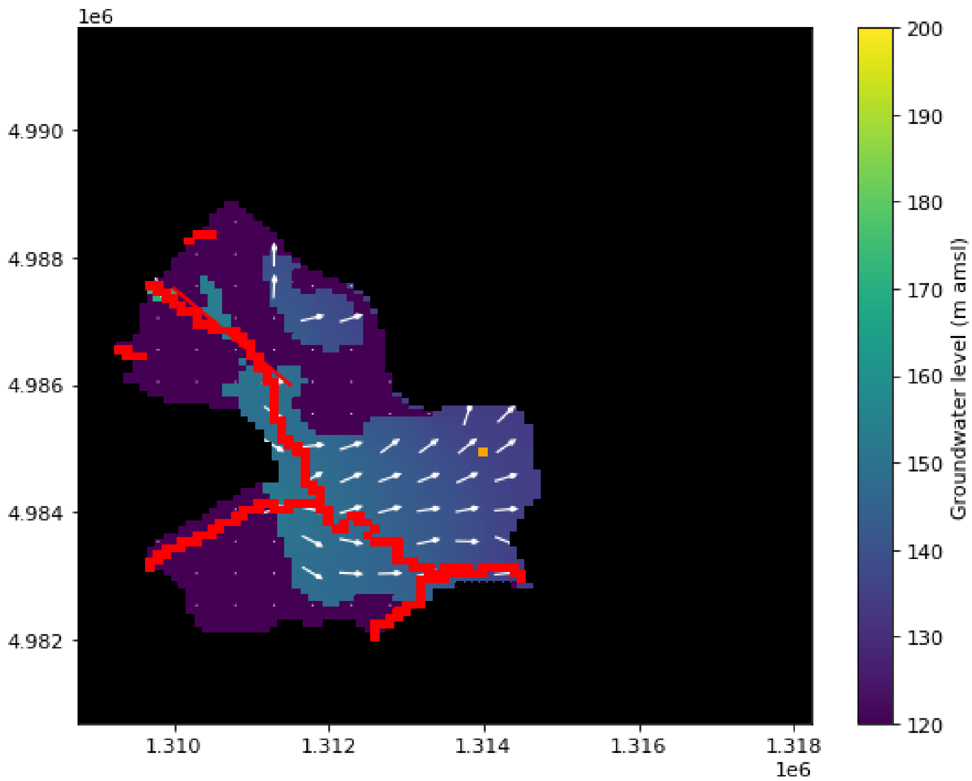

Figure 16: Modelled groundwater levels in layer 1 of the Earnscleugh Flat Aquifer model. Contours and colour bar are in metres above sea level. Orange squares denote the location of groundwater abstractions. Dark purple areas represent dry cells.

The distribution of groundwater levels across the upper layer of the model (layer 1) is shown in Figure 16, while the levels in the lower layer (layer 2) are shown in Figure 17. Modelled groundwater levels are shown to be closer to the surface in the southern end of Earnscleugh Flat and near the lower reaches of the Fraser River, while the upper layer of the model is dry beneath the upper Fraser River and upper Omeo Creek. This is consistent with our conceptual understanding of the hydrogeology of Earnscleugh Flat. There are also parts of the northwestern and southwestern ends of Earnscleugh Flat where both model layers are dry.

The modelled groundwater level contours show that groundwater flow across most of Earnscleugh Flat has a steep gradient towards the Clutha River. This generally matches the average groundwater level contours produced by AquaFirma (1997) and shown in Figure 4. The modelled contours indicate that groundwater in the southern part of Earnscleugh Flat, particularly in layer 2 of the model, generally flows towards the lower Fraser River.

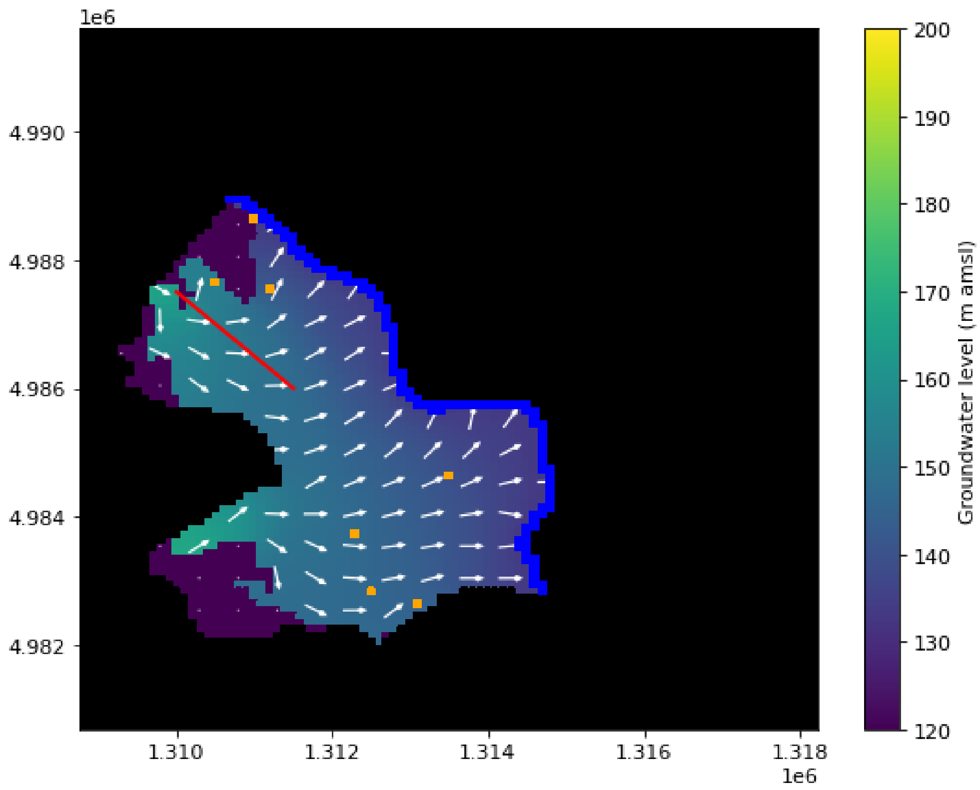

Figure 17: Modelled groundwater levels in layer 2 of the Earnscleugh Flat Aquifer model. Contours and colour bar are in metres above sea level. Orange squares denote the location of groundwater abstractions. Dark purple areas represent dry cells.

5.2.3 Surface water flows

The distribution of modelled stream flows across the model area is shown in Figure 18 below. The flows generally match stream gauging results reasonably well, with the Fraser River losing significant flow across the northern to central parts of Earnscleugh Flat, and gaining flow in its lower reaches. A graph of the flows along the length of the Fraser River is provided in Figure 19. The graph shows that the Fraser River gains significant flow due to surface flows in Omeo Creek and Conroys Creek. A relatively small gain in flow in the lower Fraser River is due to streamflow gains from groundwater. Therefore the overall patterns of streamflow changes in the Fraser River are similar to those measured by stream gaugings, however in ORC (2012) it was assumed that the entirety of the gain in the Fraser River was due to groundwater inflow, whereas our model indicates most of the gains as being due to surface water flows in Omeo Creek and Conroys Creek. Further flow gaugings including of Omeo Creek and Conroys Creek would be helpful.

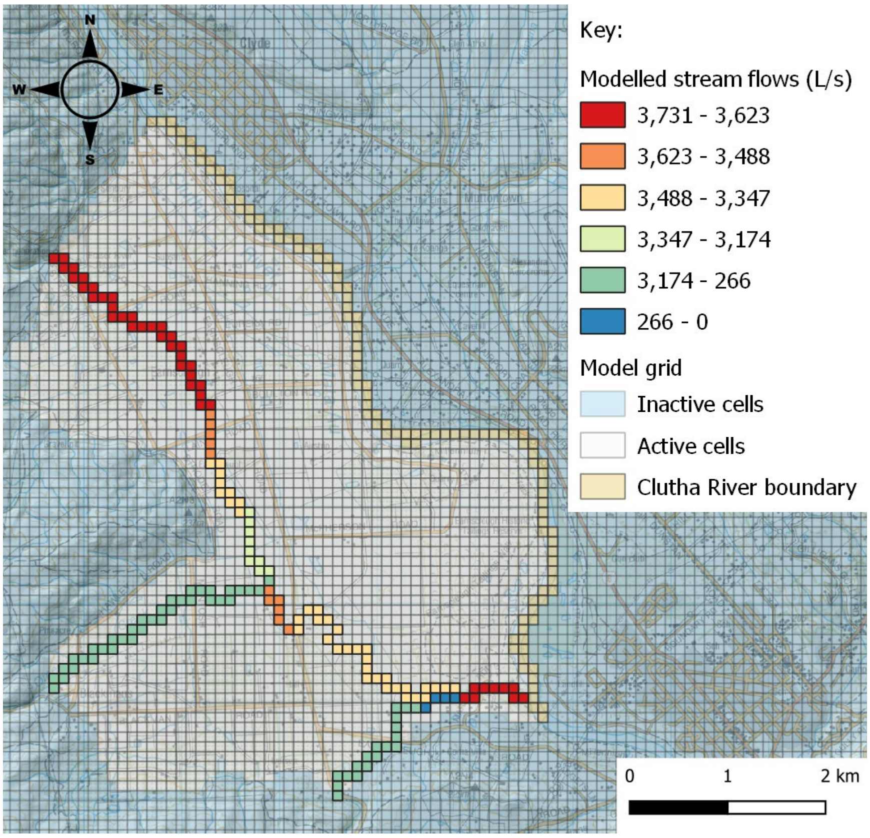

Figure 18: Modelled stream flows across the Earnscleugh model area.

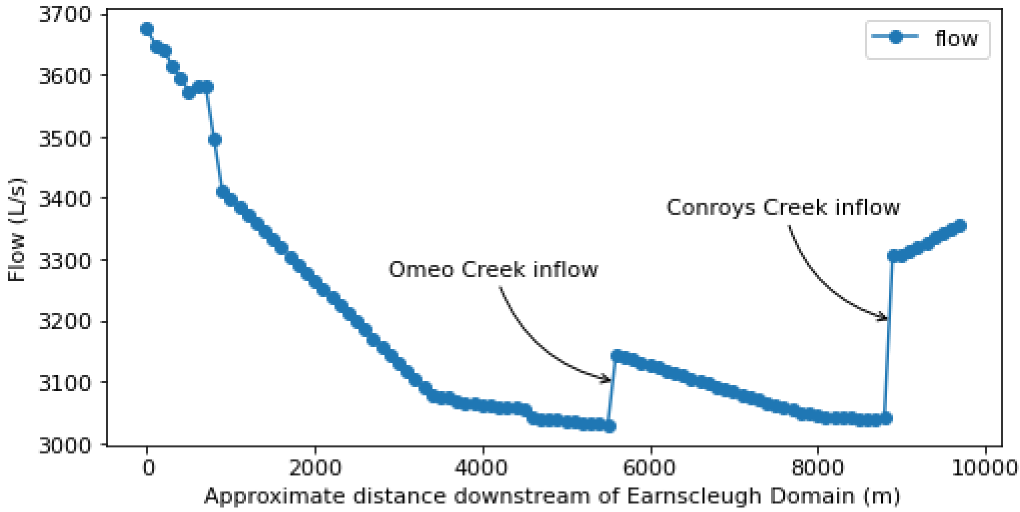

Figure 19: Modelled stream flows along the length of the Fraser River inside the model area.

The distribution of modelled streamflow gains and losses to groundwater is shown in Figure 20. The pattern of gains and losses generally matches those expected from our conceptual understanding of the Earnscleugh Aquifer. As discussed above, the magnitude of the gains to the lower Fraser River are lower than those estimated by ORC in 2012. As we are not aware of any flow gauging data from Omeo Creek and Conroys Creek it is difficult to ascertain which estimate is the more correct. It is noted that the average measured groundwater level contours (Figure 4) imply that most groundwater in the vicinity of the upper Fraser River (where most measured streamflow losses from the Fraser River occur) flows directly towards the Clutha River, and this is consistent with the modelled groundwater contours shown in Figure 17. Therefore the model results, with most outflows occurring to the Clutha River rather than to the lower Fraser River, may be realistic.

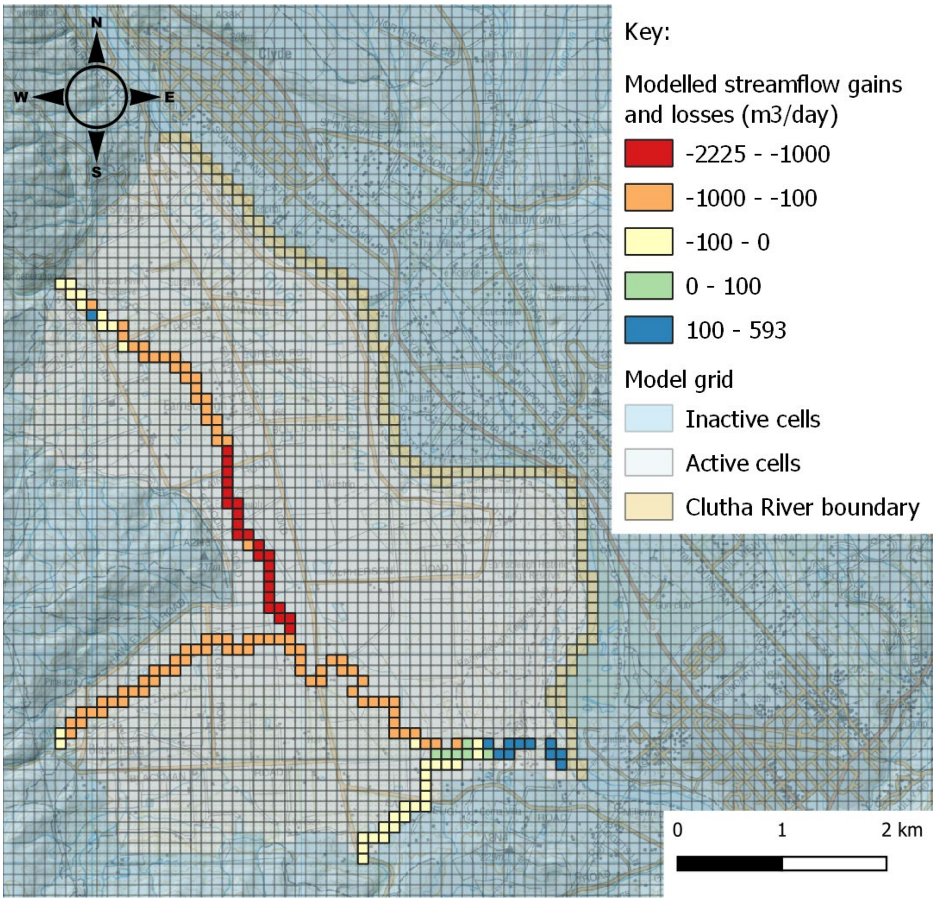

Figure 20: Modelled streamflow gains and losses to groundwater. Positive values indicate streamflow gains from groundwater, negative values indicate streamflow losses to groundwater.

5.3 Sensitivity analysis

As stated in section 5.1 above, the Earnscleugh Flat Aquifer model was calibrated to 33 groundwater level observations and two streamflow observations, and the model parameters included the hydraulic conductivity at each pilot point and streambed conductance for each stream or river.

5.3.1 Parameter sensitivity

The sensitivity of selected observations used for calibration to model parameters are shown in Figure 21 to Figure 24 below. Simulated flows in the Fraser River were highly sensitive to the streambed conductance of the upper Fraser River (Figure 21), with the sensitivity of all other parameters much lower. The simulated flows in the lower Fraser River at the Marshall Road are similarly sensitive to the streambed conductance of the upper Fraser River, though the streambed conductance of Omeo Creek also had an influence on simulated flows in the lower Fraser River (Figure 22).

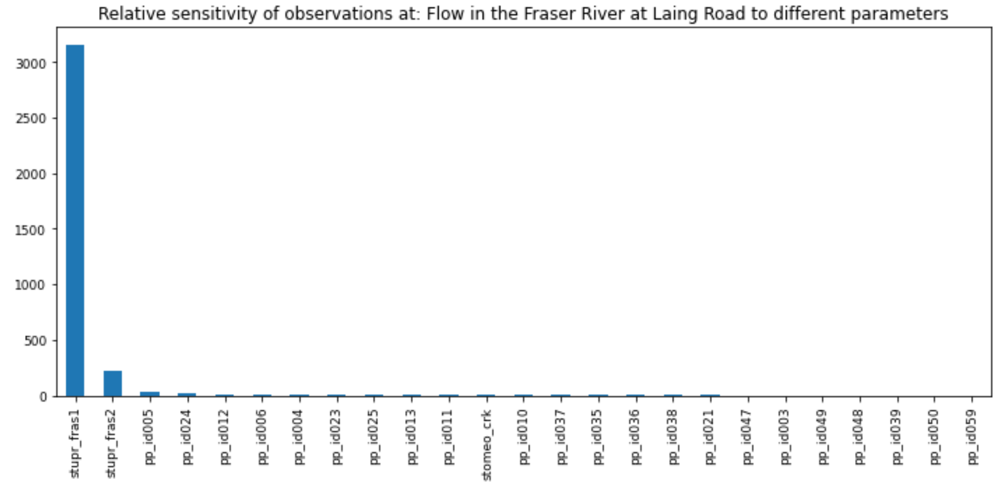

Figure 21: Relative sensitivity of observed flow in the upper Fraser River (Laing Road) to different model parameters.

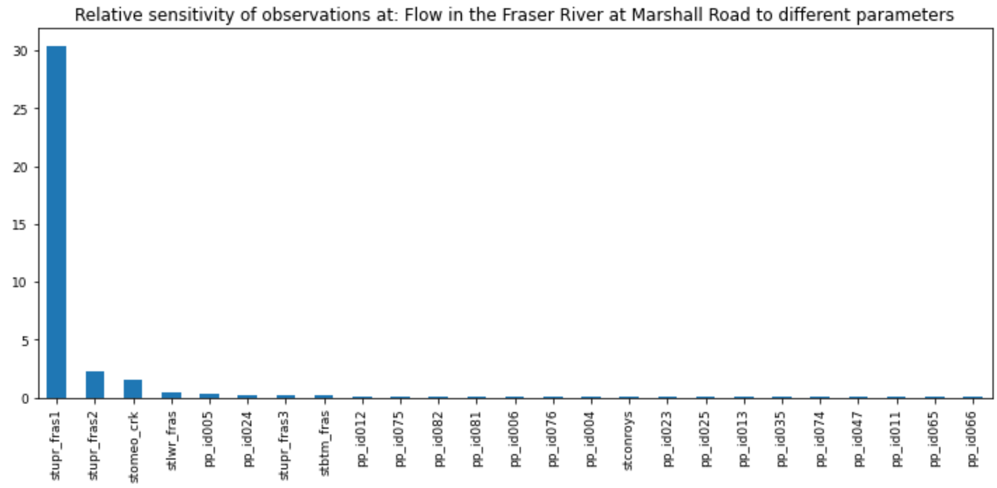

Figure 22: Relative sensitivity of observed flow in the lower Fraser River (Marshall Road) to different model parameters.

The heads in groundwater bores are also generally most sensitive to the streambed conductance of the upper Fraser River, however they are also sensitive to other parameters such as the hydraulic conductivity at certain pilot points and the streambed and riverbed conductance of the Omeo Creek and the Clutha River, depending on the bore. Figure 23 shows the overall sensitivity of groundwater heads in bores to different model parameters.

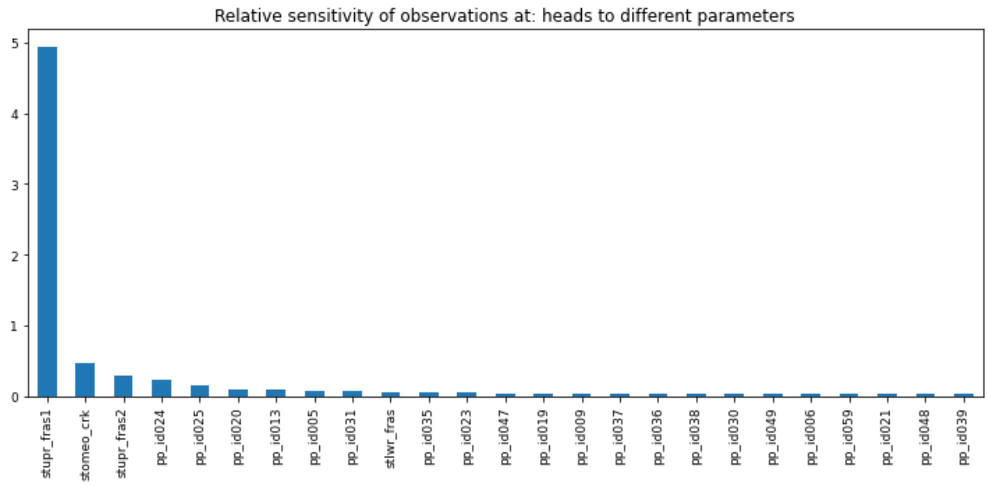

Figure 23: Relative sensitivity of model heads to different model parameters.

The overall compositive relative sensitivity of the model calibration to different parameters shows that the streambed conductance of the upper Fraser River is by far the most sensitive parameter (Figure 24). Other sensitive parameters include the streambed conductance of Omeo Creek and the lower Fraser River, and the hydraulic conductivity at pilot point 5 and 24 near the upper Fraser River.

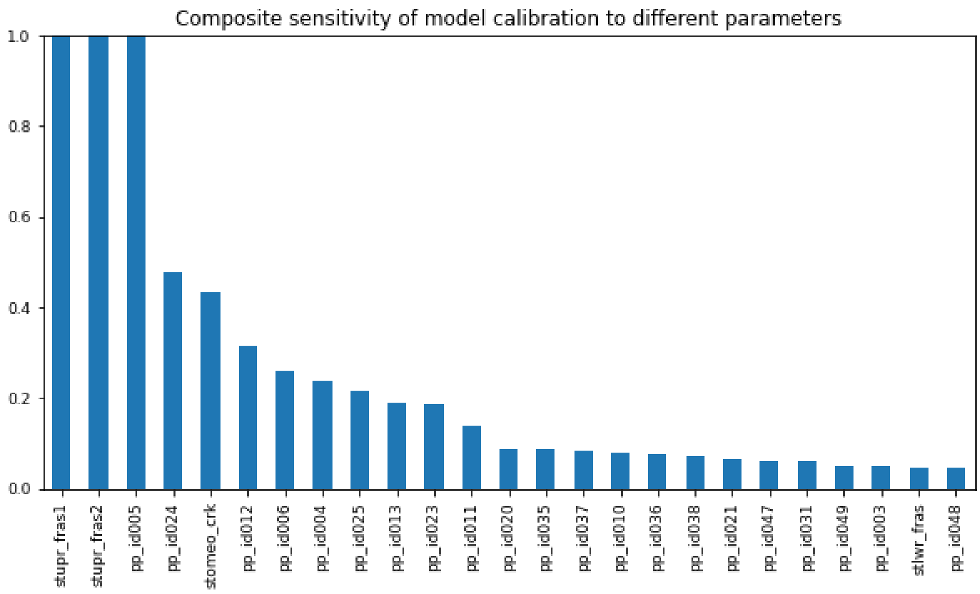

Figure 24: The composite sensitivity of the Earnscleugh Flat Aquifer model calibration to different model parameters.

5.3.2 Parameter uncertainty

The uncertainty of model parameters can be calculated based on a combination of the prior parameter variability (i.e. the estimated parameter uncertainty before the model is calibrated) and the reduction in that variability achieved by calibrating the model to observations (groundwater levels and flows). Greater reductions in the parameter variability imply more certainty in the modelled value of a particular parameter. Conversely, little or no reduction implies a greater uncertainty.

Prior estimates of the uncertainty in hydraulic conductivity (at pilot points) were determined based on the range of values observed from pumping tests in the area as well as reasonable bounds based on the lithology of the strata in the area. Prior estimates of the uncertainty in other parameters, including conductance across the model boundaries (river cells and streambed conductance) are not well constrained by observed data, and the standard deviation of those parameters was set conservatively high to one order of magnitude beyond the expected value based on the strata. Note that the variance of a parameter is equal to the square of the standard deviation.

Figure 25 presents the relative reductions in parameter variance for the 25 greatest reductions. In general, greater reductions in uncertainty correspond to the most sensitive parameters, including the streambed conductances of the upper Fraser River (stupr_fras), and Omeo Creek (stomeo_crk), and the hydraulic conductivity at certain pilot points, particularly pilot points 24 and 25 near the upper Fraser River (see Figure 13 for pilot point locations). Figure 26 shows the prior versus posterior variance for the ten parameters that had the largest percentage reductions in uncertainty. It can be seen that the posterior variance of the upper Fraser River streambed conductance is very low, while in comparison there is still considerable uncertainty in the streambed conductance of Conroys Creek.

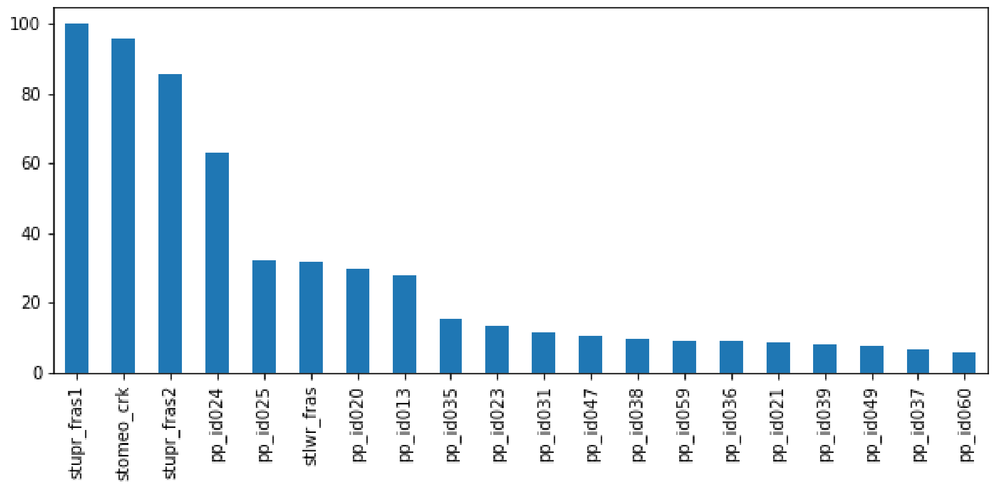

Figure 25: The 25 Earnscleugh Flat model parameters that had the largest percent reduction in uncertainty during the model calibration process.

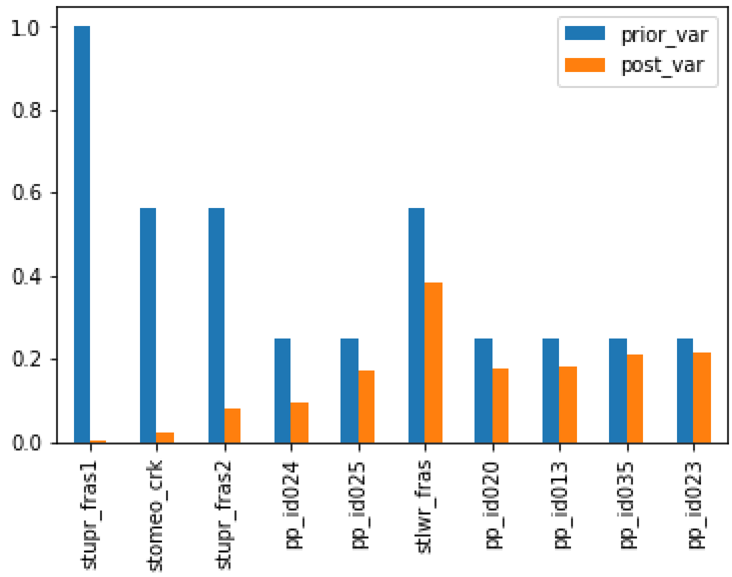

Figure 26: The prior versus posterior variance for the Earnscleugh Flat model parameters that had the largest percentage uncertainty reductions during calibration.

6.0 Dunstan model

6.1 Model calibration

6.1.1 Model parameterisation

Aquifer properties for the modelled area were defined by pilot points, where the hydraulic conductivity at each pilot point is varied during the model calibration process using PEST (Doherty, 2010). The point estimates are then spatially interpolated to generate a hydraulic conductivity field across the model area. Such an approach was employed for the Dunstan model and a plot showing the location of pilot points used to generate the hydraulic conductivity field is shown in Figure 27. Figure 28 shows a plot of the calibrated hydraulic conductivity field for layer 1 of the model. It should be noted that this hydraulic conductivity field is the result of PEST calibration, however due to the lack of pump test data across the model area it is difficult to determine whether this hydraulic conductivity distribution provides a good representation of the real distribution.

The vertical hydraulic conductivity was assumed to equal 1/1000 of the horizontal hydraulic conductivity.

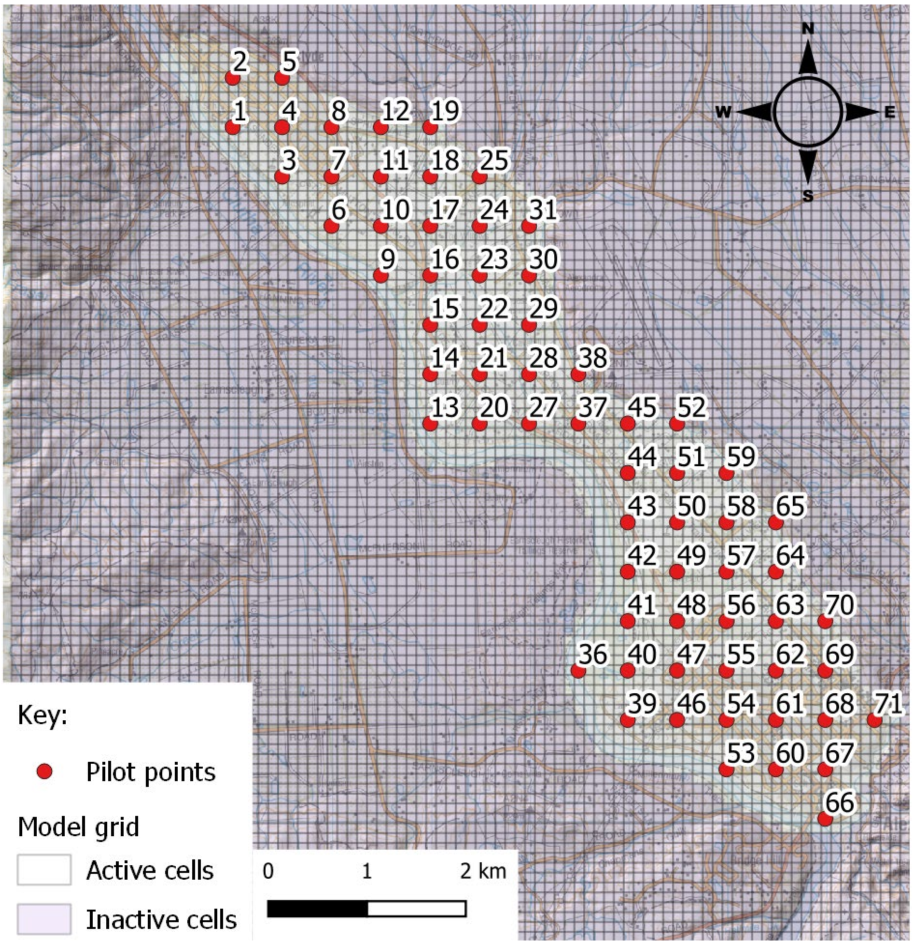

Figure 27: Location of pilot points (and corresponding pilot point IDs) used for calibration of the hydraulic conductivity field across Dunstan Flats.

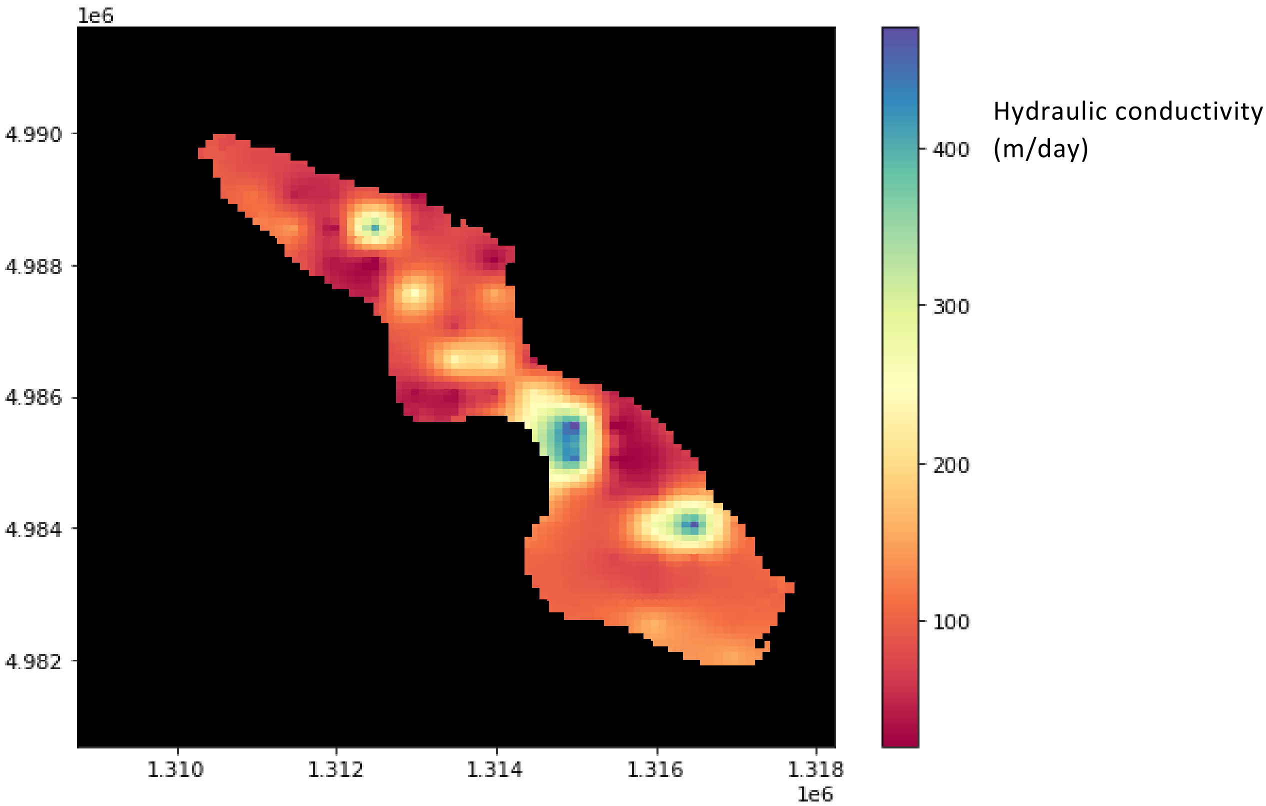

Figure 28: Calibrated horizontal hydraulic conductivity field for the Dunstan Flats Aquifer model, in m/day.

Other parameters that were varied in a similar way during the calibration process were the streambed conductance for Waikerikeri Creek, the riverbed conductance values for the Clutha and Manuherekia Rivers, and the conductance of the general head boundary between the Dunstan Flats Aquifer and the Manuherekia Claybound Aquifer. The calibrated values for each of these parameters are provided in Table 8 below.

It should be noted that the calibration has relied on the ORC (2012) estimate of irrigation water race losses being approximately correct. If these losses are inaccurate, then this would affect the resulting calibrated aquifer parameters such as hydraulic conductivity and streambed conductance.

Table 8: Calibrated conductance values for the Dunstan Flats Aquifer model.

Parameter	Calibrated conductance (m/day)
Clutha River	8408
Manuherekia River	998
General head boundary	43.0
Waikerikeri Creek	0.07

6.1.2 Calibration statistics

The model was calibrated using PEST to a total of 74 groundwater level observations (the groundwater level in bores at the time of drilling) and one surface water flow observation (the flow in Waikerikeri Creek at the State Highway 8 bridge).

Calibration statistics are provided in Table 9. In a model where both groundwater levels and flows are used as calibration targets there is frequently some trade-off between ensuring a good match to flows or groundwater levels. As only one surface water flow observation point was available, which had a weighting of 0.05 the weighted residual was low (0.0031 m^3/day). The variance for the groundwater heads, 0.780, is considered reasonable, and it should be noted that due to the groundwater observations not being average values it is expected that there would be some variance. The model results in terms of groundwater levels are discussed further in section 6.2.2 below.

Table 9: Calibration statistics for the Dunstan Flats Aquifer model

Observation group	Number of observations	Mean value of weighted residuals	Standard error of weighted residuals	Variance of weighted residuals [1]	Correlation coefficient
Groundwater heads [2]	74	-0.0319 m	0.883	0.780	
All (measurement observations only) [4]					0.999

Notes:

1. *Variance was obtained by dividing the sum of squared residuals by the number of items with non-zero weight.*
2. *All groundwater heads had a weight of 1*
3. *All surface water flows had a weight of 0.05*
4. *I.e. does not include regularisation points*

6.2 Model results

6.2.1 Mass balance

The modelled mass balance is generally consistent with our conceptual understanding of the Dunstan Flats Aquifer. A summary table of the model mass balance is provided in Table 10 below. The results show that most of the modelled recharge is sourced from groundwater throughflow (43%) and a combination of rainfall, irrigation excess soil moisture and irrigation water race losses (39.5%, combined). The Clutha River is modelled as contributing a significant amount of inflow (13.3%). Waikerikeri Creek is modelled as contributing 3.0% of recharge, while the remainder is from the Manuherekia River (1.1%). Most of the outflow from the aquifer (91.5%) is modelled as occurring as seepage to the Clutha River. Groundwater abstraction comprises the next highest outflow at 7.0%. Outflow to the Manuherekia River (1.0%), groundwater outflow out the general head boundary (0.5%). No groundwater inflow to Waikerikeri Creek occurred in the model.

Comparison with the mass balance estimated by ORC (2012), provided in Table 2 above, indicates that the modelled outflow proportions are generally similar to those estimated by ORC, although the ORC estimate did not include outflow to the Manuherekia River. However, there are some significant differences in the modelled inflows compared to those estimated by ORC. The modelled groundwater inflow (43%) is a much larger proportion than the 20.6% that was estimated by ORC. The ORC estimated water balance indicates that the combined inflows from rainfall, irrigation related excess soil drainage and water race losses were estimated to total 76.4% of recharge, compared to 39.5% for the modelled water balance. Inflow from the Clutha and Manuherekia Rivers were not included in the ORC estimated water balance, though the occasional correlation between Clutha River stage height and groundwater levels measured in bores close to the river discussed in section 2.2.1 above suggests that it is reasonable to assume that the Clutha River and Manuherekia River are a source of recharge to the aquifer, particularly to areas close to the rivers. The total inflow to the aquifer in absolute terms was estimated to be lower than the modelled total inflow, with the 10.7 Mm^3/year estimated by ORC the equivalent to 29,315 m^3/day, compared to the modelled total inflow of 45,561 m^3/day. The bulk of the difference is due to the larger modelled groundwater inflow and modelled inflow from the Clutha River.

Table 10: Modelled mass balance summary for the Dunstan Flats Aquifer

Water balance component	Inflow		Outflow	
	m^3/day	%	m^3/day	%
Rainfall, irrigation race and irrigation excess soil moisture recharge	18,017	39.5	0	0
Streams	1,382	3.0	0	0
Groundwater abstraction	0	0	3,197	7.0
Clutha River	6,061	13.3	41,693	91.5
Manuherekia River	505	1.1	448	1.0
Groundwater throughflow (general head boundary)	19,596	43.0	224	0.5
Total	45,561	100	45,561	100

Note: Some differences in totals appear due to rounding

6.2.2 Groundwater levels

The modelled groundwater heads in bores across Dunstan Flats generally match observed heads reasonably well (Figure 29), with some outliers. It is noted that the measured groundwater levels presented in Figure 29 and used for calibration were the levels measured at the time of drilling, due to the lack of available average groundwater level data. Due to seasonal fluctuations, it is expected that these levels would not all represent the average groundwater level in those locations, and therefore some variation from the modelled heads is expected.

The distribution of groundwater levels across the upper layer of the model (layer 1) is shown in Figure 30Figure 16, while the levels in the lower layer (layer 2) are shown in Figure 31. Modelled groundwater levels are shown to be closer to the surface in the southern end of Dunstan Flats and near the Clutha River, while the upper layer of the model is dry beneath the Waikerikeri Creek and across the northern Dunstan Flats. This is consistent with our conceptual understanding of the hydrogeology of Dunstan Flats and the distribution of the depth to water recorded in bores (Figure 3).

The modelled groundwater level contours show that groundwater flow across most of Dunstan Flats has a gradient towards the Clutha River. The hydraulic gradient in the southern parts of the flats has a shallow to near-horizontal gradient, and it is most likely that it is in this part of the model that the modelled inflow from the Manuherekia River and Clutha River occurs.

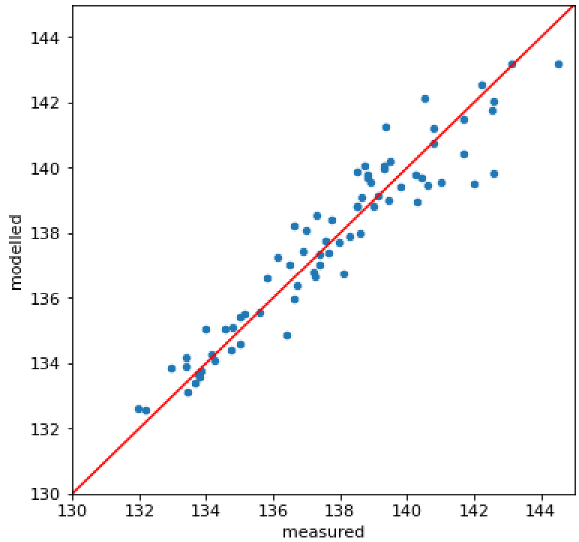

Figure 29: Modelled versus observed groundwater levels in bores across Dunstan Flats.

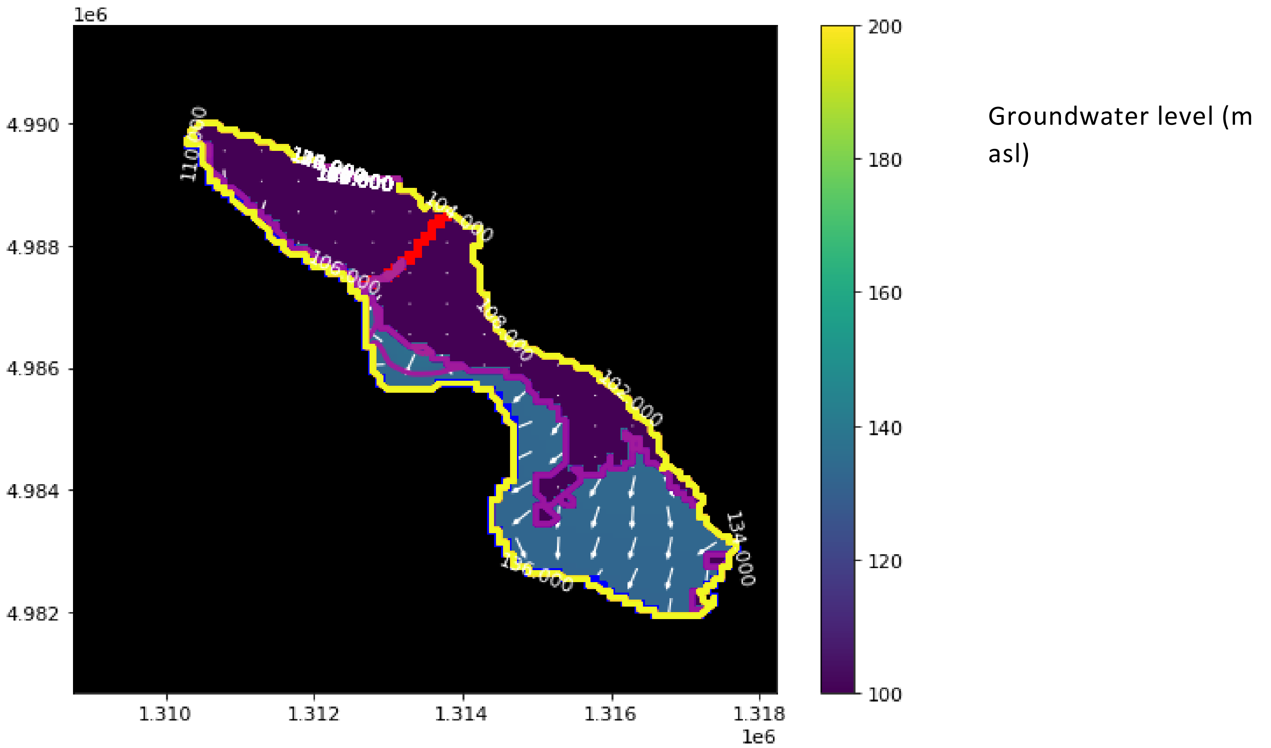

Figure 30: Modelled groundwater levels in layer 1 of the Dunstan Flats Aquifer model. Contours and colour bar are in metres above sea level.

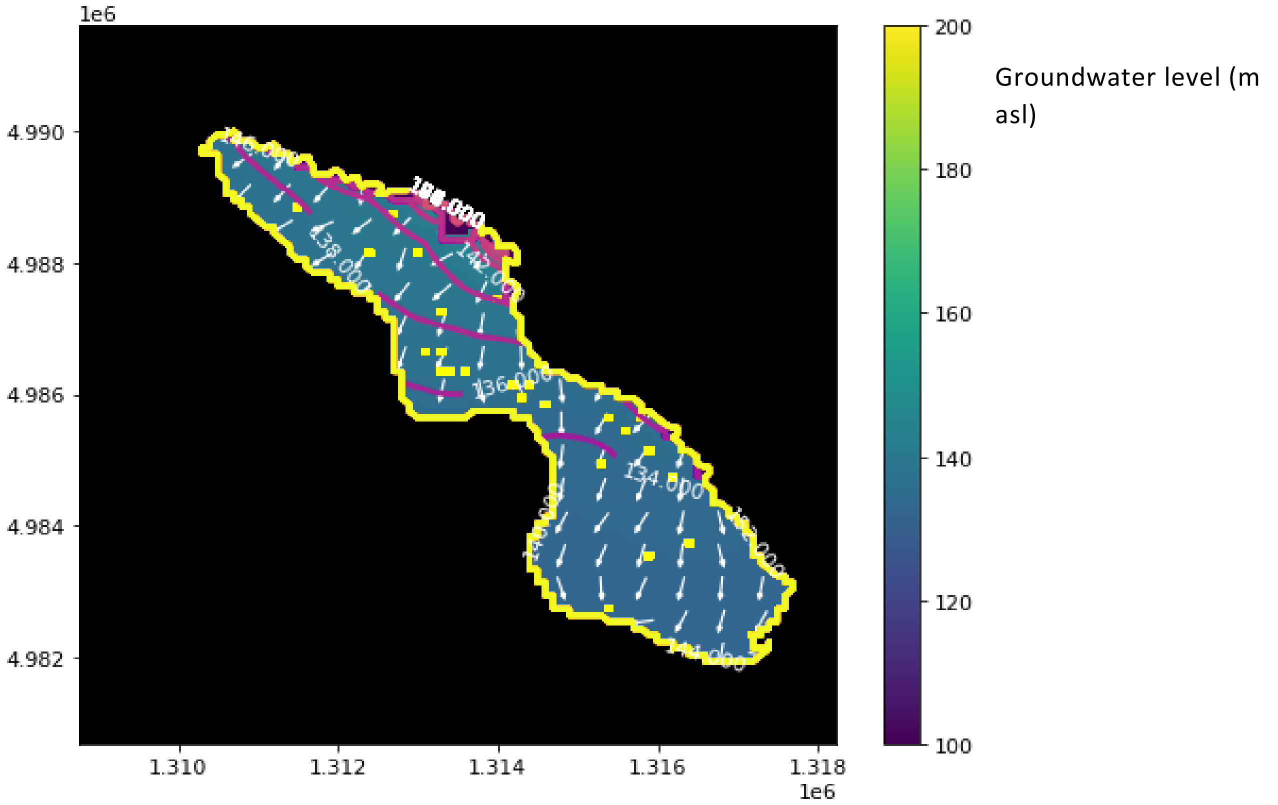

Figure 31: Modelled groundwater levels in layer 2 of the Dunstan Flats Aquifer model. Contours and colour bar are in metres above sea level. Yellow squares indicate the location of modelled groundwater abstractions.

6.2.3 Surface water flows

The modelled flows in Waikerikeri Creek show the flows steadily decreasing with distance across Duntan Flats, due to infiltration to groundwater. The modelled stream flows are shown in Figure 32. The streamflow gains and losses to groundwater indicate that Waikerikeri Stream loses a constant 59.2 m^3/day to groundwater in each cell along its length except for the final stream cell, in which it loses 40.6 m^3/day. The stream flows generally match the available streamflow gauging data reported by ORC (2012), which measured 10 L/s of streamflow loss between Springvale Road (approximately near the upgradient end of the model) and the State Highway 8 bridge.

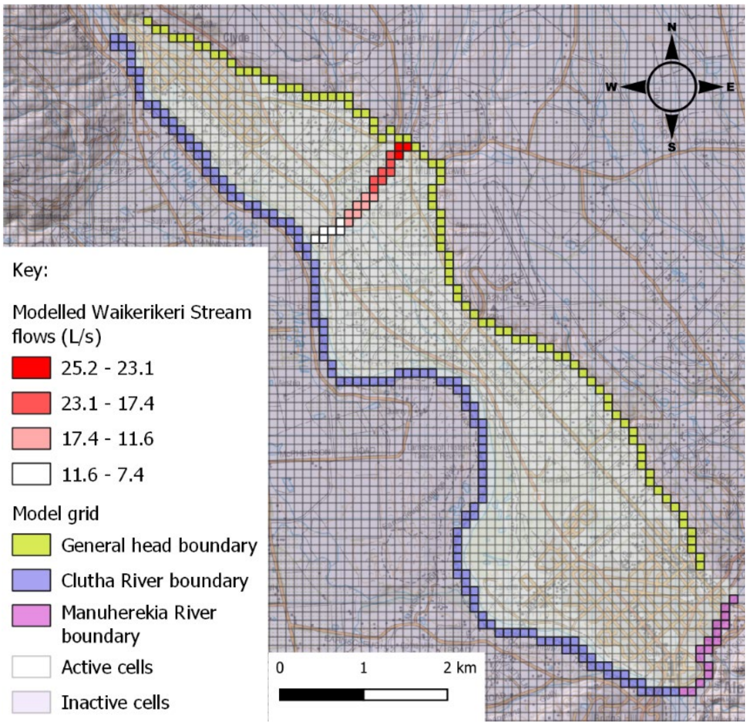

Figure 32: Modelled stream flows in Waikerikeri Creek.

6.3 Sensitivity analysis

As stated in section 6.1 above, the Dunstan Flats Aquifer model was calibrated to 77 groundwater level observations and one streamflow observation, and the model parameters included the hydraulic conductivity at each pilot point and streambed conductance for each stream or river.

6.3.1 Parameter sensitivity

The sensitivity of selected observations used for calibration to model parameters are shown in Figure 33 to Figure 35 below. Simulated flows in Waikerikeri Creek at State Highway 8 were only sensitive to the streambed conductance of the Creek (Figure 33), indicating that simulated flows across the upper part of Dunstan Flats are mostly influenced by the rate of infiltration to groundwater through the streambed, which is disconnected from groundwater for most of its length.

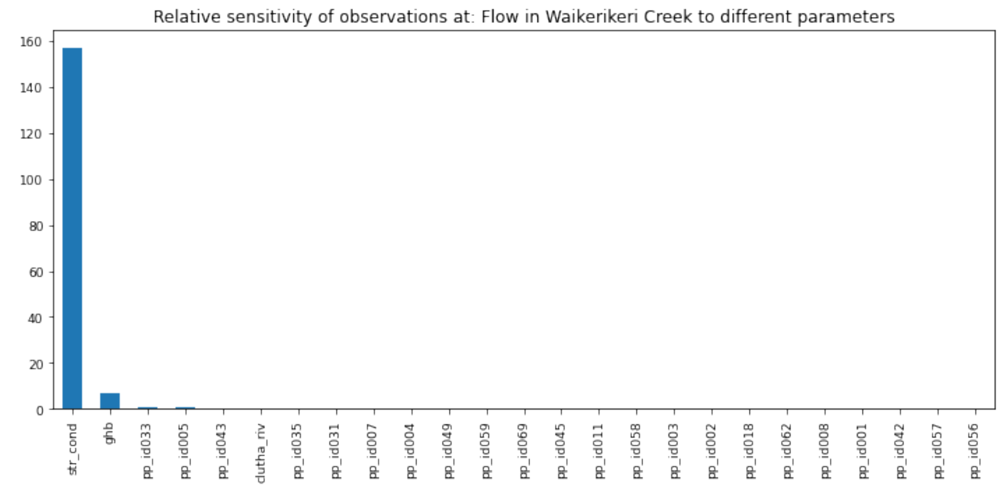

Figure 33: Relative sensitivity of flow in the middle Waikerikeri Creek (State Highway 8 bridge) to different model parameters.

The heads in groundwater bores are also generally most sensitive to the conductance of the general head boundary, however they are also slightly sensitive to other parameters such as the hydraulic conductivity at certain pilot points and the streambed conductance of Waikerikeri Creek, depending on the bore. Figure 34 shows the overall sensitivity of groundwater heads in bores to different model parameters.

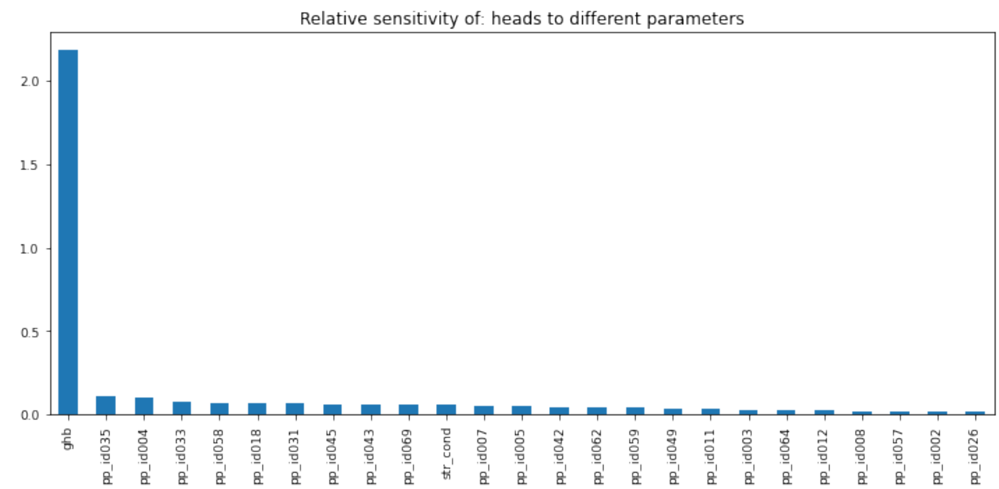

Figure 34: Relative sensitivity of model heads to different model parameters.

The overall compositive relative sensitivity of the model calibration to different parameters shows that the conductance of the general head boundary and the streambed conductance of Waikerikeri Creek are the most sensitive parameters (Figure 35). Other sensitive parameters include the hydraulic conductivity at certain pilot points.

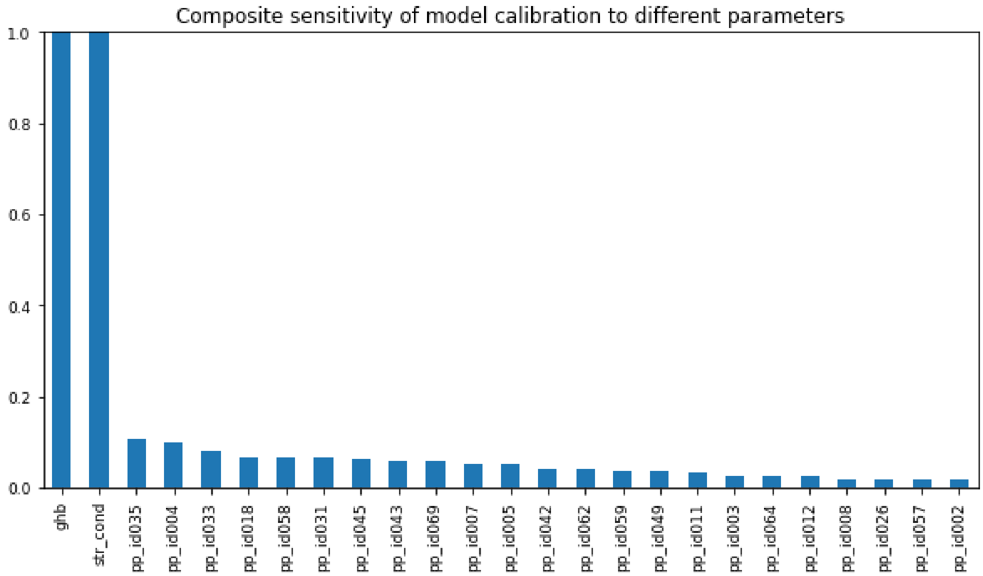

Figure 35: The composite sensitivity of the Dunstan Flats Aquifer model calibration to different model parameters.

6.3.1 Parameter uncertainty

The uncertainty of model parameters can be calculated based on a combination of the prior parameter variability (i.e. the estimated parameter uncertainty before the model is calibrated) and the reduction in that variability achieved by calibrating the model to observations (groundwater levels and flows). Greater reductions in the parameter variability imply more certainty in the modelled value of a particular parameter. Conversely, little or no reduction implies a greater uncertainty.

Prior estimates of the uncertainty in hydraulic conductivity (at pilot points) were determined based on the range of values observed from available pumping tests in the area as well as reasonable bounds based on the lithology of the strata in the area. Prior estimates of the uncertainty in other parameters, including conductance across the model boundaries (river cells and streambed conductance) are not well constrained by observed data, and the standard deviation of those parameters was set conservatively high to one order of magnitude beyond the expected value based on the strata. Note that the variance of a parameter is equal to the square of the standard deviation.

Figure 36 presents the relative reductions in parameter variance for the 25 greatest reductions. In general, greater reductions in uncertainty correspond to the most sensitive parameters, including the streambed conductance of Waikerikeri Creek, the conductance of the general head boundary, and the hydraulic conductivity at certain pilot points (see Figure 27 for pilot point locations). Figure 37 shows the prior versus posterior variance for the ten parameters that had the largest percentage reductions in uncertainty. It can be seen that the posterior variance of the Waikerikeri Creek streambed conductance and the general head boundary conductance is very low, while in comparison there is still considerable uncertainty in the hydraulic conductivity at many of the pilot point locations.

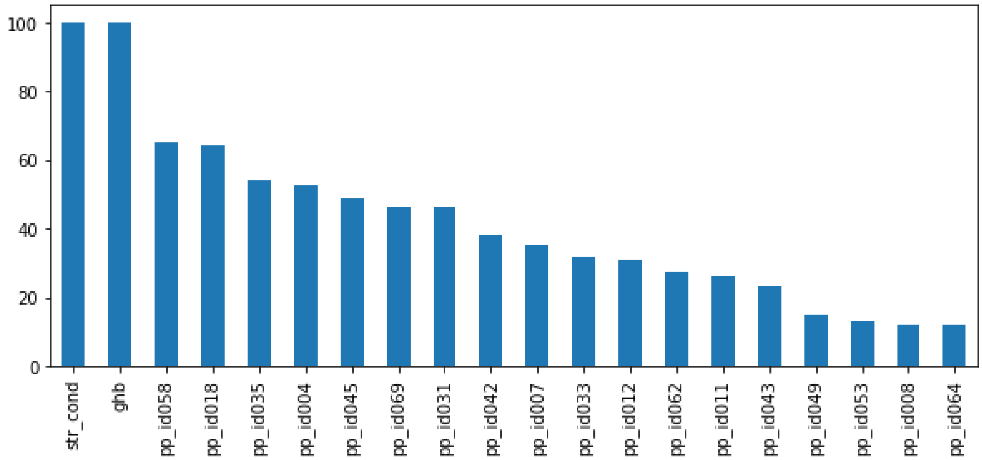

Figure 36: The 25 Dunstan Flats model parameters that had the largest percent reduction in uncertainty during the model calibration process.

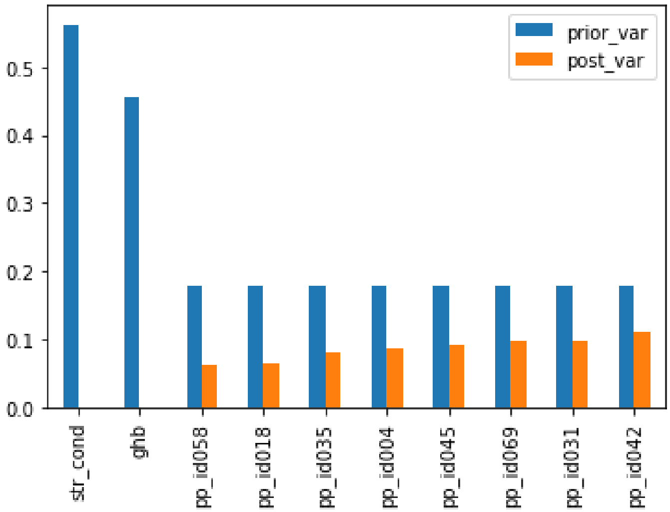

Figure 37: The prior versus posterior variance for the Dunstan Flats model parameters that had the largest percentage uncertainty reductions during calibration.

7.0 Model scenarios

Both the Earnscleugh Flat Aquifer and Dunstan Flats Aquifer provide challenges for sustainable water resource management due to the existing water balances of both aquifers being highly modified by recharge related to human activities. In order to investigate the potential effects of changing water usage and guide future groundwater allocation decision making, the groundwater model for each aquifer was altered to simulate potential changes in recharge, as described below.

7.1 Earnscleugh

7.1.1 Description of scenario

Our conceptual understanding of the Earnscleugh Flat Aquifer, and the model results, indicate that irrigation water race losses comprise a significant proportion of total recharge to the aquifer. Irrigation application methods across Earnscleugh Flat are becoming more efficient over time, however the water races associated with the Earnscleugh Irrigation Scheme are still a potentially inefficient means of transporting water, with the only published estimates of water losses from the races dating from the 1930s, when the losses were estimated at 22% (ORC, 2012). If demand for irrigation water increases in the future, piping of irrigation water would allow increased usage of water without necessitating an increase in surface water abstraction.

The effects of piping irrigation water were simulated by altering the model recharge file to only include the land surface recharge estimated using the soil moisture balance model described in section 3.0 above, with no recharge from irrigation water races. No other parameters of the model were changed, i.e. none of the parameters that were varied during calibration were changed. It is noted that the effects on the aquifer modelled with this scenario due to reducing recharge would be comparable to an increase in groundwater abstraction of equivalent volume to the reduction in irrigation race related recharge.

7.1.2 Scenario results

As expected, the modelled reduction in irrigation water race recharge generally resulted in lower modelled groundwater levels in parts of the aquifer and slightly lower groundwater-related seepage to the lower Fraser River. The scenario results are discussed further in the sections below.

Effects on overall water balance

A comparison of the base model and scenario water balance is provided in Table 11 below. The water balance comparison shows that total recharge to the aquifer is predicted to decrease by approximately 5,228 m^3/day. In addition, the model results indicate a reduction in stream seepage to the aquifer of around 6,533 m^3/day. The change in stream seepage to the model is an artefact of the model and represents the effect of 2 cells going dry along the upper Fraser River.

These cells therefore do not allow water to seep in to the river, resulting in an apparent effect of less stream seepage. In reality, we would expect very little change in stream seepage because stream seepage from the Fraser River is not controlled by groundwater levels beneath the river, as groundwater are already around 15 m below the base of the river.

This reduction in inflow is predicted to result in primarily a reduction in outflow to the Clutha River, however there is also a predicted 633 m^3/day reduction in outflow from the Fraser River due to reduced groundwater infiltration to the lower reaches of the river.

Table 11: Mass balance summary for base model versus scenario for the Earnscleugh Flat Aquifer

Water balance component	Inflow (m^3/day)		Outflow (m^3/day)	
	Base	Scenario	Base	Scenario
Rainfall, irrigation race and irrigation excess soil moisture recharge	7,847	2,618		
Streams	94,789	88,256	6,208	5,575
Groundwater abstraction	0	0	987	987
Clutha River	367	449	95,816	84,759
Total	103,004	91,324	103,011	91,321

Note: Some differences in totals appear due to rounding.

Effects on groundwater levels

A comparison of the modelled groundwater levels across the aquifer for the base model (with irrigation water race recharge) and the scenario model (without irrigation water race recharge) is shown in Figure 38 below. The results show reductions in groundwater levels of 0.5 – 1.5 metres across much of the southwestern part of Earnscleugh Flat. Available records of bore depths and recorded depth to water indicate that the bores in this area generally have 5 – 10 m of available groundwater from the water table to the bottom of the bore. Depending on the position of the bore screen, the available drawdown could be less. It is likely that a decrease in groundwater levels of up to 1.5 m could have an adverse impact on some owners of bores in the area. Decreases of generally less than 0.5 m were also modelled across parts of the northern half of Earnscleugh Flat. More cells are shown as being dry in the scenario model, which is partially why there are discreet cells shown with very large (>3 m) reductions in groundwater levels in Figure 38.

It is interpreted that most of the groundwater level change is in the southern part of the model because of the concentration of irrigation races in this area (see Figure 5) and the relatively higher proportion of recharge these provide to the area in comparison to infiltration from Omeo Creek and Conroys Creek.

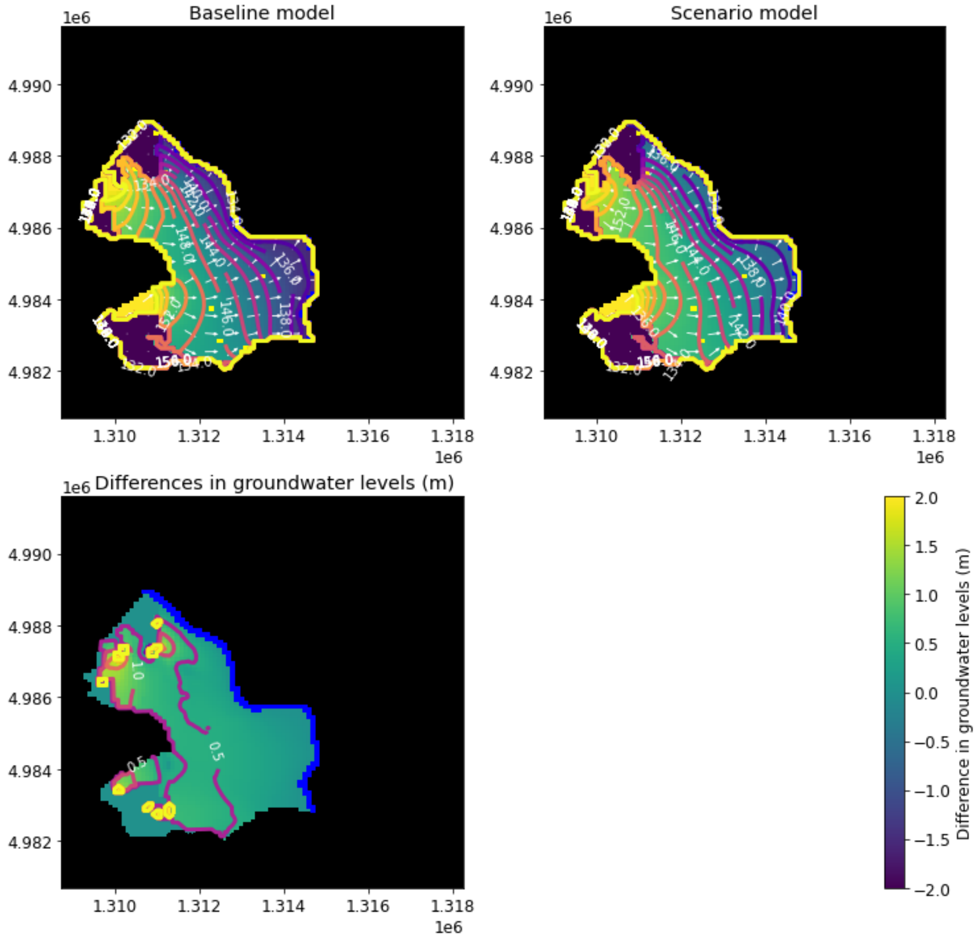

Figure 38: Comparison of modelled groundwater levels across layer 2 of the Earnscleugh Flat Aquifer for the base model including irrigation water race recharge (top left) with the scenario model without irrigation water race recharge (top right). The lower left figure shows the difference in groundwater levels between the base and scenario models, with 0.5 m contour intervals. Yellow areas depict greater than 3 m difference in groundwater levels between the base model and the scenario, due to few dry cells in the base model.

Effects on stream flows

Figure 39 shows the difference in flows along the Fraser River between the scenario model and baseline model. As discussed above, as a result of 2 cells going dry, there is less seepage to groundwater along the Fraser River in the scenario model, and therefore flows are apparently higher. However, this difference is an artefact of the model and does not represent an effect that would expected in reality. Overall, the main change is slight reduction in inflows to the lower Fraser River as a result of slightly lower groundwater levels

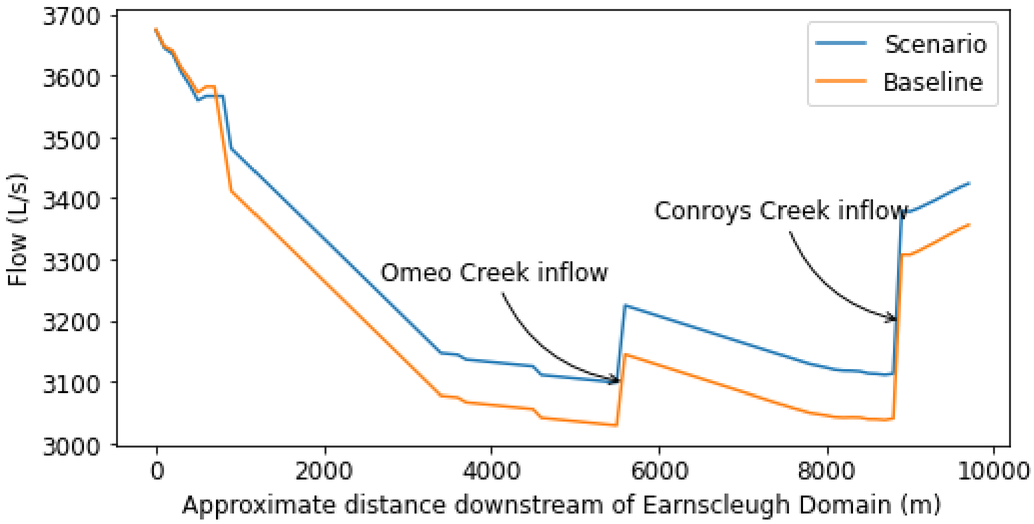

Figure 39: Difference in flows along the Fraser River between the scenario model and the baseline model.

The model is sensitive to changes in seepage from Omeo Creek (as described in Section 5.3.1) and therefore Figure 40 shows the difference in flows along Omeo Creek in the scenario model compared to the baseline model. The scenario model indicates slightly increased flows compared to the baseline model, but again this appears to be an artefact from model dry cells, rather than an actual expected effect. In general, the change in loss rates from Omeo Creek is very small due to the reduction in recharge to the model.

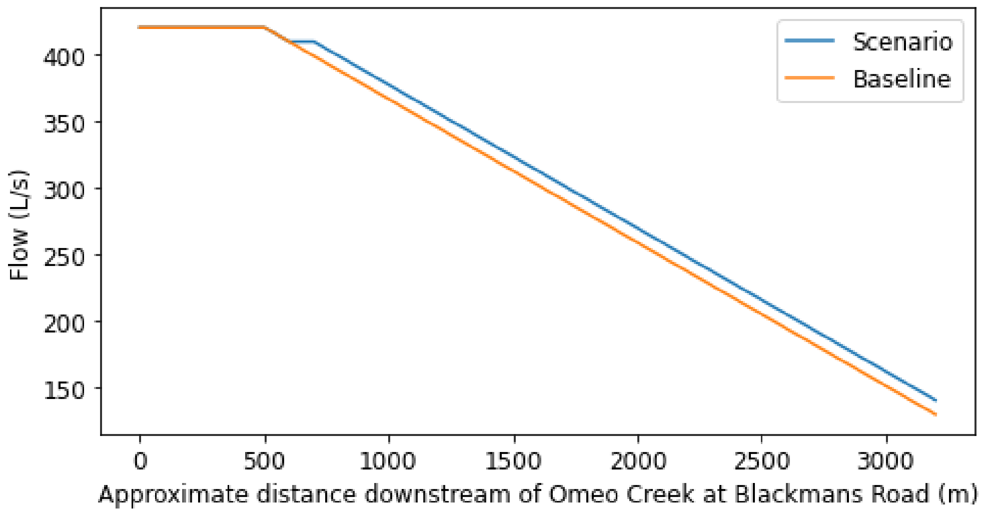

Figure 40: Difference in modelled stream flow along Omeo Creek for the scenario model compared to the base model.

7.2 Dunstan

7.2.1 Description of scenario

Our conceptual understanding of the Dunstan Flats Aquifer, and the model results, indicate that irrigation water race losses comprise a significant proportion of total recharge to the aquifer. Irrigation application methods across Dunstan Flats are becoming more efficient over time, however the water races on the Flat are still a potentially inefficient means of transporting water, with the only published estimates of water losses from the races dating from the 1930s. If demand for irrigation water increases in the future, or increased efficiencies are sought due to pressure on the water resources of the Manuherekia River, piping of irrigation water would be a feasible way to increase the efficiency of water use.

The effects of piping irrigation water were simulated by altering the model recharge file to only include the recharge estimated using the soil moisture balance model described in section 3.0 above, with no recharge from irrigation water races. No other parameters of the model were changed, i.e. none of the parameters that were varied during calibration were changed. It is noted that the effects on the aquifer modelled with this scenario due to reducing recharge would be comparable to an increase in groundwater abstraction of equivalent volume to the reduction in irrigation race related recharge.

7.2.2 Scenario results

As expected, the modelled reduction in irrigation water race recharge generally resulted in lower modelled groundwater levels across much of the aquifer, particularly the central area near Waikerikeri Creek. Modelled stream flows and gains and losses in Waikerikeri Creek were unchanged. The scenario results are discussed further in the sections below.

Effects on overall water balance

A comparison of the base model and scenario water balance is provided in Table 12 below. The modelled recharge from rainfall, excess soil moisture and irrigation races was greatly decreased in the scenario model (a decrease of approximately 16,100 m^3/day), which is consistent with our conceptual understanding of the importance of irrigation water race losses in terms of the overall aquifer water balance. The modelled inflows from the Clutha River, Manuherekia River and through the general head boundary were slightly higher in the scenario model, however the total inflows were still approximately 14,400 m^3/day lower in the scenario model compared to the base model.

The decrease in recharge inflow to the scenario model was partially balanced by a large decrease (approximately 14,200 m^3/day) in outflow to the Clutha River. There were also very small decreases in the outflow to the Manuherekia River and the general head boundary.

Table 12: Mass balance summary for base model versus scenario for the Dunstan Flats Aquifer

Water balance component	Inflow (m^3/day)		Outflow (m^3/day)	
	Base	Scenario	Base	Scenario
Rainfall, irrigation race and irrigation excess soil moisture recharge	18,017	1,888	0	0
Streams	1,382	1,401	0	0
Groundwater abstraction	0	0	3,197	3,197
Clutha River	6,061	7,423	41,693	27,529
Manuherekia River	505	619	448	298
Groundwater throughflow (general head boundary)	19,596	19,853	224	161
Total	45,561	31,184	45,561	31,184

Note: Some differences in totals appear due to rounding.

Effects on groundwater levels

A comparison of the modelled groundwater levels across the aquifer for the base model (with irrigation water race recharge) and the scenario model (without irrigation water race recharge) is shown in Figure 41 below. Groundwater levels were generally lower in the scenario model, particularly in the northern part of Dunstan Flats near Waikerikeri Creek. The hydraulic gradient is noticeably gentler across the aquifer in the scenario model. Differences in groundwater levels are not as pronounced in the southern part of Dunstan Flats, where the Clutha River and Manuherekia River have a strong control on groundwater levels.

Groundwater levels in the central to northern part of Dunstan Flats (e.g. near Muttontown) are up to approximately 3.5 m lower in the scenario model. Available records of bore depths and recorded depth to water indicates that many bores in this area have 9 – 10 m of available groundwater from the water table to the bottom of the bore. Depending on the position of the bore screen, the available drawdown could be less. It is likely that a decrease in groundwater levels of 3.5 m could have a significant adverse impact on the owners of bores in the area.

As indicated by Figure 41, significant adverse effects on groundwater levels are not predicted for bores in the southern part of Dunstan Flats, or for bores very close to the Clutha River. It is likely that any decrease in groundwater recharge from irrigation water losses would be at least partly compensated for by increased recharge from (or less discharge to) the Clutha and/or Manuherekia Rivers.

Implications of the scenario model results in terms of groundwater management and allocation are discussed further in section 8.0 below.

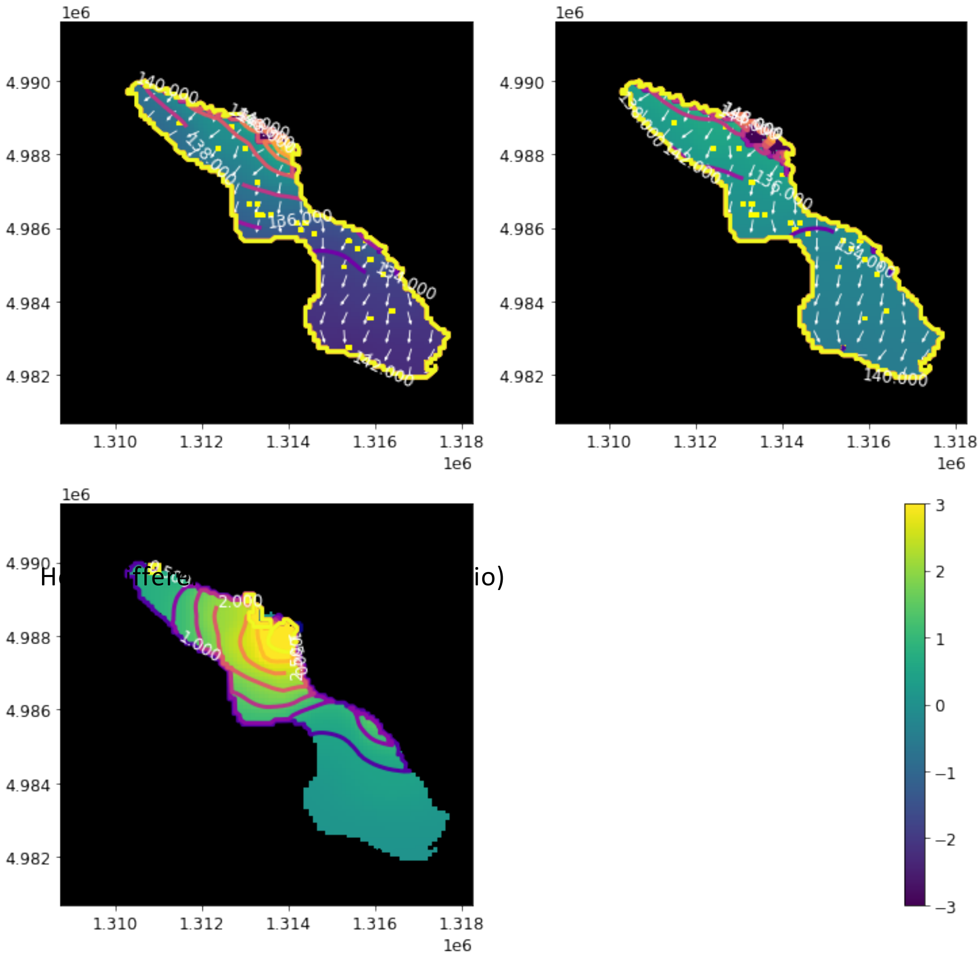

Figure 41: Comparison of modelled groundwater levels across layer 2 of the Dunstan Flats Aquifer for the base model including irrigation water race recharge (top left) with the scenario model without irrigation water race recharge (top right). The lower left figure shows the difference in groundwater levels between the base and scenario models, with 0.5 m contour intervals.

Effects on stream flows

The modelled groundwater table is well below the streambed of Waikerikeri Creek for most of its length across Dunstan Flats. Therefore, the rate of groundwater inflow and the stream flow in the Creek is unchanged between the base model and the scenario model for all stream cells except the final one, which had approximately 21.9 m^3/day of losses to groundwater in the base model. In the scenario model, the losses to groundwater in this final stream cell increase to 40.6 m^3/day.

The implications of the Dunstan Flats model scenario results in terms of groundwater management and allocation are discussed further in section 8.0 below.

8.0 Groundwater allocation

The purpose of the groundwater models that have been created for the Earnscleugh Flat Aquifer and Dunstan Flats Aquifer is to assist ORC with decisions regarding allocation of the aquifers.

Neither of the aquifers studied in this report currently have a maximum allocation limit set in Schedule 4A of the Regional Plan: Water for Otago (RPW), therefore the current allocation limits for the aquifer are set based on 50% of mean annual recharge (assuming efficient irrigation methods), in accordance with Policy 6.4.10A2(b) of the RPW.

The 2012 ORC allocation study estimated an allocation volume for each aquifer based on 50% of mean annual recharge in accordance with the RPW. The estimate of mean annual recharge considered the sources of recharge assumed to have a degree of permanence for the life of the groundwater management regime, therefore irrigation was assumed to be efficient (no more than 4 mm/day on average) and estimated water race losses were not included.

The resulting estimated mean annual recharge for the Earnscleugh Flat Aquifer was 25.5 Mm^3/year, therefore the allocation limit was set at 12.75 Mm^3/year. The consented allocation (as of 2012) was determined to be 0.514 Mm^3/year, therefore it was concluded that the Earnscleugh Flat Aquifer had substantial unused allocation. The Dunstan Flats Aquifer was estimated to have a mean annual recharge of 3.68 Mm^3/year, therefore the allocation limit was set at 1.84 Mm^3/year. The consented allocation (as of 2012) was determined to be 1.45 Mm^3/year, therefore it was concluded that the Dunstan Flats Aquifer had a relatively small volume of unallocated groundwater.

Although allocation limits are commonly set based on a certain percentage of recharge, ideally groundwater allocation should intend to achieve specific aims and outcomes, such as the protection of values assigned to surface water receptors that are dependent on groundwater discharges, or requirements for avoiding well interference. Numerical groundwater modelling is a tool that can be used to help estimate the sensitivity of receptors to changes in groundwater levels as a result of changes in recharge or abstraction. The implications of each of the models, and scenario results for each model, in terms of water management and allocation are discussed in the sections below.

8.1 Earnscleugh Flat Aquifer

The model for the Earnscleugh Flat Aquifer indicates that the primary sources of recharge to the aquifer are losses from the Fraser River, as well as Omeo Creek and Conroys Creek. These results are consistent with the previous ORC study (2012), although it is probable that the 2012 study overestimated the quantity of groundwater inflow to the lower Fraser River, due to a lack of surface water flow data for Omeo Creek and Conroys Creek. The 12.75 Mm^3/year allocation limit (equivalent to approximately 34,900 m^3/day) based on 50% of recharge estimated by ORC in 2012 is reasonably consistent with the Earnscleugh scenario mass balance results of a total inflow of 91,000 m^3/day (Table 11).

It is preferred for groundwater allocation limits to be based on the acceptable environmental effects of reduced groundwater levels or acceptable rates of stream depletion as a result of abstraction. We are not aware of any significant wetlands in the Earnscleugh Flat area, though it has been reported that there are springs along the bank of the Clutha River, through which groundwater discharges from the Earnscleugh Flat Aquifer (ORC, 2012; AquaFirma, 1998). The exact location of these springs is not known, nor whether they sustain any significant aquatic or terrestrial ecosystems. Further study to identify any potentially sensitive groundwater receptors could provide useful guidance for the setting of allocation limits.

Another potentially sensitive and ecologically important groundwater receptor is the lower Fraser River, which has been identified as having a relatively high fish species diversity (LandPro, 2020). The lower Fraser River receives groundwater inflow from the Earnscleugh Flat Aquifer, and our scenario model results show that reduced recharge or increased abstraction would decrease the groundwater inflow by at least 633 m^3/day (7 L/s) and therefore the flow of the lower Fraser River. However, the scenario model results suggest that the magnitude of the decrease in flow may be relatively minor compared to the magnitude of total average flow in the stream. It should be noted, however that our model was steady-state and therefore did not account for times of lowest flow in the Fraser River. At these times the reduction in baseflow due to reduced recharge or increased abstraction could be more significant as a proportion of total flow. For example, a streamflow gauging survey in February 1997 found that the flow of the Fraser River had reduced from approximately 2,100 L/s at the upper end of Earnscleugh Flat to 8 L/s at Earnscleugh Road in the approximate centre of the Flat (AquaFirma, 1997). The reduction was due to losses to groundwater and a 1,200 L/s irrigation take. The flow in the lower Fraser River at Marshall Road had recovered to 500 L/s, however it is not known how much of this recovery was due to groundwater inflow and how much was due to flows from Conroys Creek.

The scenario results show that an approximately 5,000 m^3/day reduction in recharge is expected to result in an approximately 600 m^3/day reduction in groundwater inflow to the lower Fraser River and Conroys Creek. If this approximate 1/8 ratio is assumed to hold for further decreases in recharge or increases in abstraction then the potential effects of the current full allocation limit being abstracted can be estimated, although this will be influenced by the spatial pattern of reduction in recharge or increased abstraction.

The current allocation limit is equivalent to almost 35,000 m^3/day and if the ratio estimated above holds then the full allocation being abstracted would result in a 4,200 m^3/day (48 L/s) reduction in groundwater inflow, which is more than the entire base scenario modelled inflow to the lower Fraser River. This magnitude of flow reduction could have adverse ecological effects on the river, particularly at times of low flow. However, the location of any increased abstraction would affect groundwater inflows to the lower Fraser River. It is expected that abstraction from the northern side of Earnscleugh Flat (e.g. north of Laing Road) would have a much smaller impact on the lower Fraser River, as our groundwater model results indicate that groundwater in this area generally flows directly to the Clutha River. However abstraction from the southern part of Earnscleugh Flat (e.g. south of Omeo Creek) would be expected to have a proportionally greater effect on groundwater inflows to the lower Fraser River. If the lower Fraser River is considered an ecologically sensitive groundwater receptor, then consideration could be made to splitting the allocation zone based on where abstraction is likely to have greater effect on groundwater inflows to the lower Fraser River.

Another factor that can be important for setting allocation limits is the susceptibility of bores to well interference effects or not having enough available drawdown to allow use of the groundwater resource. The scenario model results indicated that groundwater levels could reduce by up to approximately 1.5 m in the southern part of Earnscleugh Flat if irrigation race recharge was reduced. An increase in bore abstraction of similar magnitude (5,000 m^3/day) would be expected to have similar effects, and if abstraction was at the total current allocation limit of equivalent to almost 35,000 m^3/day it is expected that there would be greater effects on groundwater levels.

8.2 Dunstan Flats Aquifer

The model for the Dunstan Flats Aquifer indicates that irrigation race losses and groundwater inflow from the Manuherekia Claybound Aquifer are the primary sources of inflow to the aquifer. These results are broadly consistent with the previous ORC study (2012), although our model estimates higher groundwater inflow than the ORC study.

The 1.84 Mm^3/year allocation limit set by ORC (2012), based on 50% of mean annual recharge not including irrigation water race losses and assuming efficient application methods, implies a total recharge of 3.68 Mm^3/year, which is equivalent to 10,082 m^3/day. This is much lower than the approximately 31,000 m^3/day estimated from the Dunstan Flats Aquifer scenario model, however it should be noted that there is great uncertainty in the groundwater inflow volume, which was modelled to account for most inflow to the aquifer and was a much larger volume in our model compared to the ORC estimate. The ORC estimate of 2.2 Mm^3/year is equivalent to approximately 6,000 m^3/day compared to the 19,900 m^3/day indicated by the scenario model water balance.

It should also be noted that previous work (ORC 2012; ORC 2005) indicates that much of the recharge to the Manuherekia Claybound Aquifer (which is the source of groundwater inflow) is itself sourced from irrigation race losses. Therefore, in a scenario in which irrigation races were piped it is likely that groundwater inflow would also significantly decrease. The approach used by ORC in 2012 is seemingly inconsistent, as total recharge to the Manuherekia Claybound Aquifer for the purposes of setting allocation (i.e. not including irrigation race losses) was estimated at 1.56 Mm^3/year, however the water balance estimate used to set the Dunstan Flats Aquifer allocation limit included 2.2 Mm^3/year of groundwater inflow from the Manuherekia Claybound Aquifer. A more consistent approach may have been to exclude or reduce the assumed groundwater inflow for the Dunstan Flats Aquifer water balance when setting allocation.

Sources of inflow from the soil moisture balance model (including both irrigated and non-irrigated areas) and Waikerikeri Creek (i.e. not including water race losses, groundwater inflow or inflow from the Clutha and Manuherekia River) total approximately 3,300m^3/day for the scenario model. If groundwater inflow was assumed to be the same as the 2012 ORC estimate, then the total recharge would be similar, at approximately 9,300 m^3/day. Our results imply that if the groundwater allocation for the Dunstan Flats Aquifer is to be based on recharge that would not be affected by potential future increases in efficiency, it could be more conservative to not include assumed groundwater inflow, as this is highly uncertain and potentially sensitive to changes in irrigation regime. Inclusion of inflow from the Clutha and Manuherekia Rivers could also be problematic, as this recharge would be expected to mainly affect the parts of the aquifer that are closest to these rivers. Therefore the 3,300 m^3/day scenario inflow (i.e. not including groundwater inflow) would imply a total recharge of 1.2 Mm^3/year, meaning the allocation limit would be 0.6 Mm^3/year: less than half of the existing amount.

The 50% of total recharge “default” allocation limit discussed above, and defined by the RPW, is essentially arbitrary and it is preferred for groundwater allocation limits to be based on the acceptable environmental effects of reduced groundwater levels or acceptable rates of stream depletion as a result of abstraction. We are not aware of any significant wetlands or springs in the Dunstan Flats area, though our model suggests there could be groundwater inflow at the lowest reaches of Waikerikeri Creek, immediately above the confluence with the Clutha River.

The scenario model for the Dunstan Flats Aquifer suggested that decreased recharge (or increased abstraction) would have the greatest impact on groundwater levels in the central to northern part of the Flats, near Muttontown. Any declines in groundwater levels in the southern part of the Flats are likely to be at least partially offset by increased recharge from the Clutha River and Manuherekia River. Therefore, it may be preferred for allocation in this part of Dunstan Flats (and potentially any parts of Dunstan Flats within a certain distance of the Clutha River) to be linked to any total surface water allocation from the Clutha River and/or Manuherekia River rather than an arbitrary percentage of total recharge. It is also important that the total groundwater allocation from the Dunstan Flats aquifer and other aquifers in the Clutha River catchment, including the Earnscleugh Flat aquifer, is factored into future surface water allocation decisions for the Clutha River.

The central to northern part of the Dunstan Flats Aquifer represents a challenge for water management and allocation because our model results suggest that groundwater levels may be quite sensitive to changes in recharge which could result from future improvements in irrigation efficiency, and related declines in groundwater levels could be significant enough to adversely affect bore owners. These bores abstract from an aquifer which is effectively “artificially” recharged to a significant degree. It may be inevitable that some future declines in groundwater levels occur and deepening of bores may be necessary, depending on the depth of gravels in this part of the aquifer. However, it is noted that the flow in Waikerikeri Creek is likely to be significantly reduced by irrigation-related surface water takes in its upper reaches (ORC, 2012), and if future increases in irrigation efficiency were accompanied by reductions in takes from Waikerikeri Creek then this could partially offset these effects to some degree although it is noted that there currently little available flow gauging data for this creek, which means the patterns of gains and losses are not well-understood.

The scenario model for the Dunstan Flats Aquifer shows that decreased recharge has a significant impact on the modelled groundwater levels near the bottom of Waikerikeri Creek. We do not know if there are any springs in this area, nor if they would be ecologically significant if they do exist. It is recommended that ORC confirm (either via review of existing data or via a new survey) whether there are any significant surface water features or ecosystems impacted by groundwater in this area, as if they did exist the acceptable impact on these would be a reasonable basis to use for allocation, at least in this part of the aquifer.

9.0 Conclusions

The aim of this modelling exercise was to create calibrated groundwater models for the Earnscleugh Flat Aquifer and the Dunstan Flats Aquifer that can be used to inform groundwater allocation decisions. The groundwater models were calibrated to flows (and gauged losses) in surface water bodies such as the Fraser River and Waikerikeri Creek, together with groundwater levels (measured at the time of drilling) in a number of bores across each aquifer.

The model results indicate a reasonable calibration to both stream flows and groundwater levels. The modelled water balance and groundwater flow pattern for each aquifer is generally consistent with our conceptual understanding, with some differences for each aquifer. Due to the importance of “artificial” recharge from irrigation water race losses for both aquifers, a scenario was also modelled for each where irrigation water race recharge was reduced to zero, to simulate potential more efficient piped water transport.

The Earnscleugh Flat scenario results indicate that without irrigation water race recharge, groundwater infiltration to the lower Fraser River would reduce groundwater levels in the southern part of Earnscleugh Flat by up to 1 – 1.5 m, and groundwater infiltration to the lower Fraser River would reduce by at least 7 L/s. The Dunstan Flats scenario results indicate that without irrigation water race recharge, groundwater levels in the central Flats could reduce by up to 3.5 m, which could have an adverse effect on some bore owners. Surface water flows would not be expected to change significantly, though slightly greater recharge to the aquifer from the Clutha and Manuherekia Rivers would be expected. Figure 42 shows indicative areas that may be at risk of declining groundwater levels due to increases in irrigation efficiency, based on the areas that were modelled to have a decrease in groundwater levels of at least 1 m.

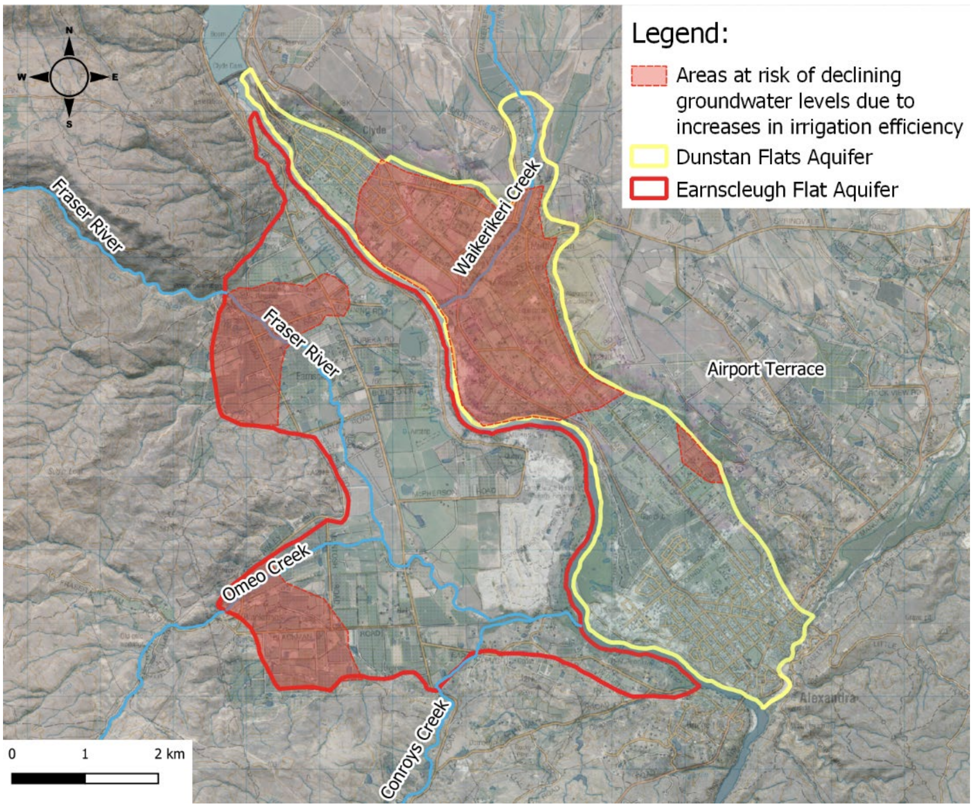

Figure 42: Map showing indicative areas that may be at risk of declines in groundwater levels of more than 1 m due to increases in irrigation efficiency.

The existing groundwater allocation limits for the Earnscleugh Flat and Dunstan Flats aquifers are based on an estimated 50% of recharge (assuming efficient irrigation methods). It is preferred for groundwater allocation decisions to be based on acceptable environmental effects on existing groundwater users or surface water receptors. Limited information is available regarding the location and/or sensitivity of surface water receptors in either aquifer, however it is expected that there could be potentially significant reductions in groundwater levels and inflow to the lower Fraser River if the full current allocation limit was abstracted. However, the magnitude of the effects would be dependent on the location of any increased abstraction, with abstraction from the southern half of Earnscleugh Flat expected to have a larger effect on inflow to the lower Fraser River, while abstraction from the northern part of Earnscleugh Flat would be expected to mostly affect the magnitude of outflow to the Clutha River. Consideration should be made to splitting the allocation zone based on where abstraction is expected to have a greater effect on inflow to the lower Fraser River.

The groundwater modelling for the Dunstan Flats aquifer indicates that there a reduction in irrigation water race losses could have a significant adverse effect on bores in the central part of the Flats, even without additional abstraction pressure. It is also important to note that groundwater inflow from the Manuherekia Claybound Aquifer would also be likely to reduce if water race losses lessen, due to those losses also being a significant source of recharge to the Manuherekia Claybound Aquifer. The predicted flow changes in the Clutha and Manuherekia rivers are small compared to their flows and there are no other known surface water receptors that would be sensitive to changes in groundwater levels, although there is some uncertainty on the connection to groundwater in the lower Waikerikeri Creek.. The groundwater levels in the southern part of Dunstan Flats are largely controlled by the Clutha and Manuherekia Rivers, therefore reduced recharge or abstraction in this part of the aquifer is expected to cause increased inflow from the Clutha and Manuherekia Rivers but is not likely to cause significant widespread adverse effects on existing groundwater users. Consideration could be given to splitting the allocation zone between the northern half where groundwater levels are sensitive to changes in recharge or abstraction, and the southern part where groundwater levels are strongly controlled by the adjacent river levels.

If ORC wished to revise the existing allocation limits based on the results of the modelling described in this report, then potential revised allocation limits are provided in Table 13. Note that, as discussed in section 8.1 above, abstraction from the Earnscleugh Flat aquifer could affect groundwater inflows to the lower Fraser River, the ecological significance of which are unknown at the current time. It may therefore be prudent to retain the existing allocation limit until an ecological survey of the lower Fraser River area has been undertaken.

Table 13: Potential revised allocation limits based on mean annual recharge

Aquifer	Basis of allocation limit	Potential revised allocation limit (Mm^3/year)	Existing allocation limit (Mm^3/year)
Dunstan Flats	50% of mean annual recharge, not including irrigation races or groundwater inflow [1]	0.60	1.84
Earnscleugh Flat	50% of mean annual recharge, **including streamflow recharge** but **excluding irrigation races**.	16.58	12.75
	50% of mean land surface recharge, **excluding** irrigation races **and** streamflow recharge.	0.48	

Notes:
1. *Includes recharge from Waikerikeri Creek but does not include recharge from the Clutha or Manuherekia Rivers.*

10.0 Monitoring Recommendations

ORC maintain a region-wide network of surface water and groundwater monitoring sites for State of the Environment (SOE) monitoring, to help monitor whether desired environmental outcomes are being achieved. The current SOE groundwater level monitoring network in the vicinity of the study area consists of a single bore (G42/0695, 17.85 m deep) on Dunstan Flats, at Muttontown near Waikerikeri Creek.

ORC have advised that they are in the process of upgrading their SOE network, and that there may be scope for additional sites in the vicinity of Earnscleugh Flat and Dunstan Flats. This section provides recommendations for potential additional monitoring sites that PDP consider would help reduce uncertainty around forecasts from modelling the Earnscleugh Flat and Dunstan Flats aquifers, and related groundwater allocation decisions. Further monitoring would also provide time series data that could potentially be used for calibration of transient groundwater models in the future if necessary.

It is recognised that there are limited resources available for SOE monitoring improvements, therefore we have ranked the recommended monitoring locations based on their priority. A summary of the recommended monitoring sites is provided in Table 14, and their locations are shown on Figure 43.

10.1 Surface Water Monitoring

As discussed above, a significant source of uncertainty in the models relates to uncertainty regarding surface water flows across both modelled aquifers. Long-term surface water flow monitoring sites would help reduce this uncertainty. It is recommended that surface water flow monitoring be established in each of the two modelled aquifers.

For the Dunstan Flats aquifer, the recommended highest priority site is upper Waikerikeri Creek, near the upslope boundary of the Flats. A long-term flow monitoring site would constrain the range of flows at this site, and how often the stream is dry, which would greatly increase our understanding of recharge to the Dunstan Flats aquifer. Another useful monitoring site, but of lower priority, would be the lower Waikerikeri Creek, for example at the State Highway bridge. This site in conjunction with a site in upper Waikerikeri Creek would allow stream recharge to the aquifer to be well constrained.

For the Earnscleugh Flat aquifer, the recommended highest priority site is the upper Fraser River, which is the primary source of recharge to the Earnscleugh Flat aquifer. PDP understands that there may already be monitoring in place in relation to the consent conditions of the Fraser Dam that controls flows in the river. If such monitoring is already in place this existing monitoring could potentially be incorporated into the SOE network, however it would be best if this site is below the point of take of the large surface water takes in this area.

A site in the middle Fraser River, ideally immediately upstream of the Omeo Creek confluence, would be useful to constrain the magnitude of losses from the River, and their seasonal fluctuation. This would be lower priority than the upper Fraser River site. Another useful monitoring location, if resources allow, would be a site in the lower Fraser River, ideally upstream of the Conroys Creek confluence. This would help constrain groundwater – surface water interaction in this area.

10.2 Groundwater Monitoring

A significant uncertainty discussed in the sections above is that the groundwater levels used for calibration in both modelled aquifers are not necessarily representative of the average groundwater levels necessary for accurate calibration of a steady-state groundwater model.

For the Dunstan Flats aquifer, a key recommended site for further groundwater level monitoring is the base of Airport Terrace in the middle part of Dunstan Flats. Monitoring of groundwater levels here would help constrain the likely groundwater throughflow from the Manuherekia Claybound aquifer, a highly uncertain source of inflow to the Dunstan Flats aquifer. It would be best if the bore monitored was relatively deep, screened near the base of the gravels in this area.

If sufficient resources are available, a monitoring site near the upper Waikerikeri Creek near the upslope edge of Dunstan Flats would be useful. This is the area that is likely to be most affected by future increases in irrigation transport efficiency, therefore monitoring of these affects would aid management of the aquifer. A monitoring site in this area may also help constrain and calibrate the magnitude of recharge from Waikerikeri Creek. Another lower priority potential monitoring site would be on the southern part of Dunstan Flats, near Alexandra town. Monitoring in this area would help constrain our understanding of the magnitude of seasonal fluctuation in this area, and the control of the Clutha and Manuherekia Rivers on groundwater levels.

For the Earnscleugh Flat aquifer, a key recommended groundwater level monitoring site is the upper Earnscleugh Flat, near the upper Fraser River. A reliable groundwater level record in this area would help to constrain the magnitude of recharge to the aquifer from the Fraser River, and potentially help constrain the groundwater flow direction in this area, i.e. whether most groundwater flows directly towards the Clutha River.

Another useful groundwater level monitoring site would be the middle Earnscleugh Flat area, near Omeo Creek. There is very little reliable groundwater level information in this area, which is a significant source of uncertainty in the model, and the degree to which recharge from Omeo Creek affects groundwater levels in this area is highly uncertain. If resources allow, a groundwater level monitoring site near the lower Fraser River would also help constrain groundwater – surface water interaction in this area.

Table 14: Recommended long-term monitoring sites

Site type	Site location	Reason for location	Priority [1]
Earnscleugh - Surface water	Upper Fraser River, immediately downstream of surface water takes [2]	Constrain stream flows into Earnscleugh Flat, and range of fluctuation	1
	Middle Fraser River, upstream of Omeo Creek	Constrain losses from the Fraser River, and their seasonal variation	2
	Lower Fraser River, ideally upstream of Conroys Creek confluence	Constrain gains to the Fraser River	3
Earnscleugh -	Upper Earnscleugh	Constrain groundwater	1

Table 14: Recommended long-term monitoring sites

Site type	Site location	Reason for location	Priority [1]
Groundwater	Flat, between the Fraser and Clutha Rivers	flows towards the Clutha River and surface water – groundwater interaction	
	Middle Earnscleugh Flat, near Omeo Creek	Constrain groundwater levels in part of aquifer with little data, and constrain interaction of Omeo Creek with groundwater	2
	Lower Earnscleugh Flat, near the lower Fraser River	Constrain groundwater – surface water interaction in lower part of aquifer	3
Dunstan – Surface water	Upper Waikerikeri Creek	Constrain stream flows onto Dunstan Flats and seasonal variation	1
	Lower Waikerikeri Creek	Constrain streamflow losses from Waikerikeri Creek	2
Dunstan – Groundwater	Base of Airport Terrace, in middle Dunstan Flats	Constrain groundwater levels at upper boundary of aquifer, and hence likely magnitude of recharge from groundwater throughflow	1
	Upper Dunstan Flat, near upper Waikerikeri Creek	Constrain groundwater – surface water interaction, and monitor any changes in groundwater levels due to changing land use practices	2
	Lower Dunstan Flat, near Alexandra	Constrain fluctuation in groundwater levels in lower flats	3

Notes:

1. *Ranked from 1 to 3, with 1 being highest priority and 3 being lowest.*
2. *Long-term monitoring may already be occurring at this site in relation to the consent conditions for Fraser Dam and irrigation on Earnscleugh Flat.*

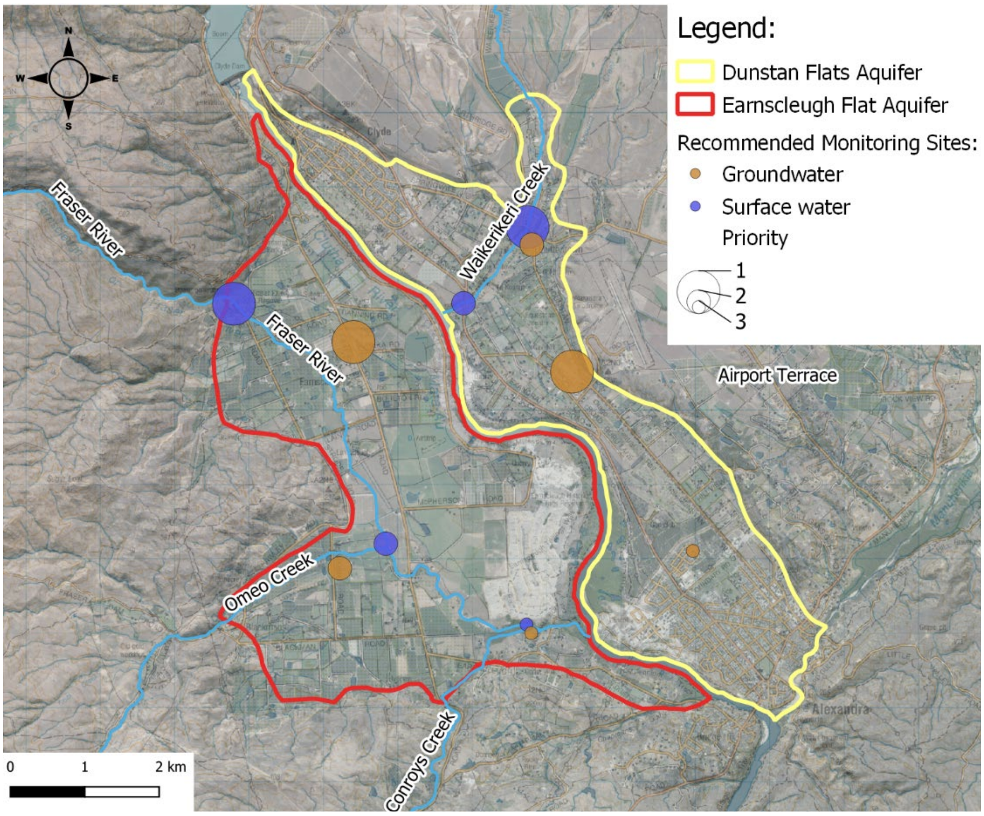

Figure 43: The location of recommended long-term surface water flow and groundwater level monitoring sites. Symbols are sized according to recommended priority, with highest priority sites largest.

10.3 Other Recommendations

It is recommended that concurrent flow gaugings be conducted in the area, particularly on the Fraser River, Waikerikeri Creek, Omeo Creek and Conroys Creek. The magnitude of losses from these streams are significant sources of uncertainty in the model.

Losses from irrigation water races are one of the most significant sources of recharge to both the Earnscleugh Flat and Dunstan Flats aquifers, however the magnitude of these losses are uncertain and in the modelling presented in this report irrigation race losses are based on estimates presented in the 2012 groundwater allocation study (ORC, 2012). To reduce this uncertainty, it is recommended that concurrent flow gaugings be conducted on the irrigation water races in order to constrain the magnitude and location of losses. Ideally these gaugings should be conducted in winter when water is not being taken for irrigation. There may also be useful existing information in consent documentation relating to the irrigation schemes that could help constrain these losses.

It is also recommended that a survey be conducted in the lower Fraser River and lower Waikerikeri Creek areas in order to ascertain whether there are any springs, wetlands or other ecologically sensitive receptors in these areas that could be adversely affected by changes in stream flows and/or groundwater levels.

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