Bendigo and Tarras Groundwater Allocation Study

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Executive summary

The Bendigo-Tarras groundwater basin has a dry climate and an increasing demand for irrigation water. Groundwater in the basin occurs within Quaternary and Tertiary age sediments lying within a depression in the underlying schist rock. The permeability of the sediments varies greatly, and groundwater not only occurs within the highly permeable sandy-gravel glacial outwash deposits close to the Clutha River/Mata-Au, but is also taken from the low yielding silty sand deposits around the Tarras settlement.

Geophysical data was used to define the depth of the groundwater basin. The low permeability silts underlying the area have a strong signature in the geophysical data. A combination of cross-sections and spatial maps was used to interpret the data.

Bores abstracting groundwater near the rivers can induce more water to replenish the groundwater system. In areas connected to the Clutha River/Mata-Au, this promotes more recharge to enter the aquifer and become available for allocation. However, in areas close to the Lindis River, this can affect river flows and connection to the Clutha River/Mata-Au.

To determine the amount of recharge from rainfall, modelling of the land-surface recharge over the last 24 years was carried out. Irrigated land contributed significantly more recharge to the underlying aquifer than non-irrigated land, due to the soil having less soil moisture deficit during periods of rainfall. Rainfall recharge occurs sporadically and requires large rainfall events to bring the soils to field capacity. In the last ten years, there have been low volumes of rainfall recharge to the groundwater system.

Groundwater modelling was carried out to assess the effect of cumulative long-term abstraction on river flows and groundwater levels. The model is based on current knowledge of the aquifer system and river investigations. Six different scenarios were constructed under different river flows and groundwater abstraction rates. Groundwater abstraction was increased significantly. It highlighted that pumping location is the most significant factor to cause an impact on the lower Lindis River. If the area surrounding the lower Lindis River reach is given a significant buffer, there are large quantities of groundwater potentially available for allocation on the Clutha Valley lower terraces.

The lower terraces on the eastern side of the Clutha River/Mata-Au are sub-divided into two allocation zones (Figure 1). The recommended limit for groundwater abstraction from the Lower Tarras allocation zone is **18.8Mm^3/year** and for the Bendigo allocation zone it is **29Mm^3/year**. Current consented allocation is only 12% of the Lower Tarras allocation zone recommended limit and only 13% of the Bendigo allocation zone recommended limit.

Groundwater takes within the Lindis alluvial ribbon aquifer are closely connected to the Lindis River and will be managed as surface water takes, with restrictions imposed during periods of low river flow. Outside of the ribbon aquifer but still within the Ardgour Valley an annual groundwater allocation of **189,600m^3/year** is recommended.

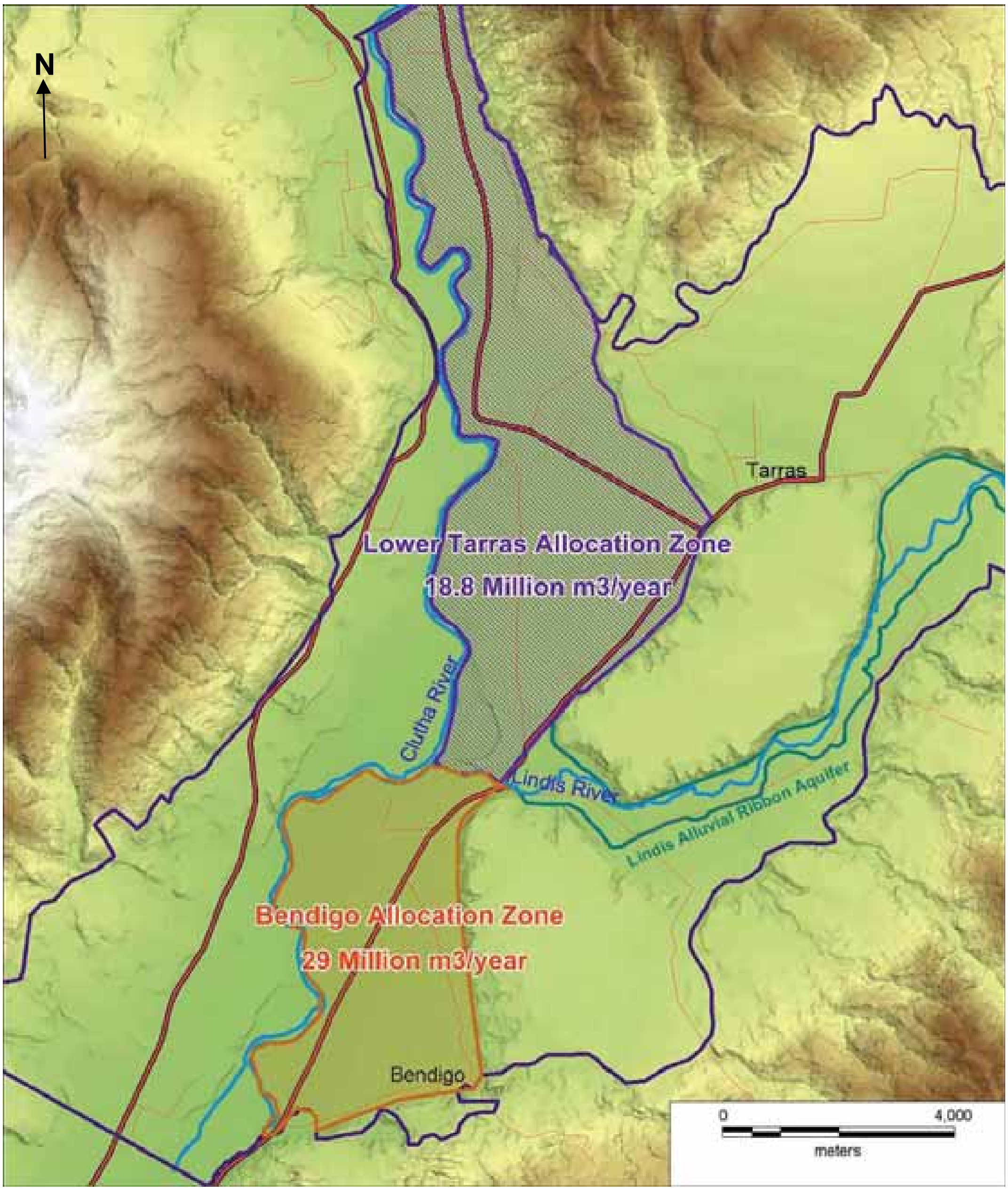

Figure 1 **Location of allocation zones and the recommended annual allocation limits**

Outside of the allocation zones mentioned above, there are only a few consented groundwater takes. These are concentrated on the west side of the Clutha River/Mata-Au. Takes within this area are buffered by recharge from the Clutha River/Mata-Au and abstraction will be balanced by induced river recharge. If there is further drilling to the western side of the basin for irrigation water, the groundwater model can be further refined to investigate allocation limits for this area. There is currently not enough information on the hydraulic properties of the aquifer on the western side of the basin to accurately define a limit. The Tarras settlement area has limited groundwater availability, due to the local lithology, which restricts the abstraction to small quantities under the permitted volume of 25,000 litres per landholding per day.

It is suggested that an automatic groundwater level monitoring site be established in a central location of the Bendigo allocation zone.

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1. Introduction

The Bendigo-Tarras groundwater basin is being increasingly relied upon for irrigation water to irrigate pasture and grape vines. Previous reports on groundwater allocation limits have indicated that the limits are close to being exceeded. This report builds on previous groundwater studies and geophysical data to develop a groundwater model of the aquifer. The modelling investigated the rate of recharge and how the system responded to increases in abstraction, including the impact of groundwater pumping on significant surface water bodies in the area. The objective of the study was to recommend an annual allocation limit for groundwater abstraction and future groundwater monitoring.

The Bendigo-Tarras area has a dry climate, which has created a demand for more irrigation water. Groundwater in the basin occurs within several different geological deposits. For example, it is found within the highly permeable sandy gravel glacial outwash deposits on the lower terraces. Bores tapping these sediments are widely used for irrigation water. Low yielding clay rich deposits around the Tarras settlement contain a limited groundwater resource. Bores here are used for domestic and stock water supplies. Bores within the Ardgour Valley tap the Lindis alluvial ribbon aquifer, which is closely connected to the Lindis River. Abstraction in this area can affect the flow in the Lindis River. These aspects have lead to a concentration of production bores for irrigation in the southern Bendigo area.

The Clutha River/Mata-Au and Lindis River are both significant rivers for the groundwater system in the area. They are both highly integrated with the groundwater system, but contrast in the size of their flows and their sensitivity to stream depletion effects. The Clutha River/Mata-Au flows at approximately 250 cumecs (250,000l/s), whereas the lower Lindis River dries out most summers. Careful groundwater resource management is required to lessen impacts upon the lower Lindis River, while allowing resource development in those areas which are buffered by recharge from the Clutha River/Mata-Au.

2. Setting and background information

The Bendigo-Tarras groundwater basin is located in Central Otago (Figure 2.1). Groundwater is situated within Quaternary and Tertiary age sediments which are resting in a depression formed in the underlying schist basement rocks. Two major river systems flow through the basin; the Clutha River/Mata-Au and Lindis River.

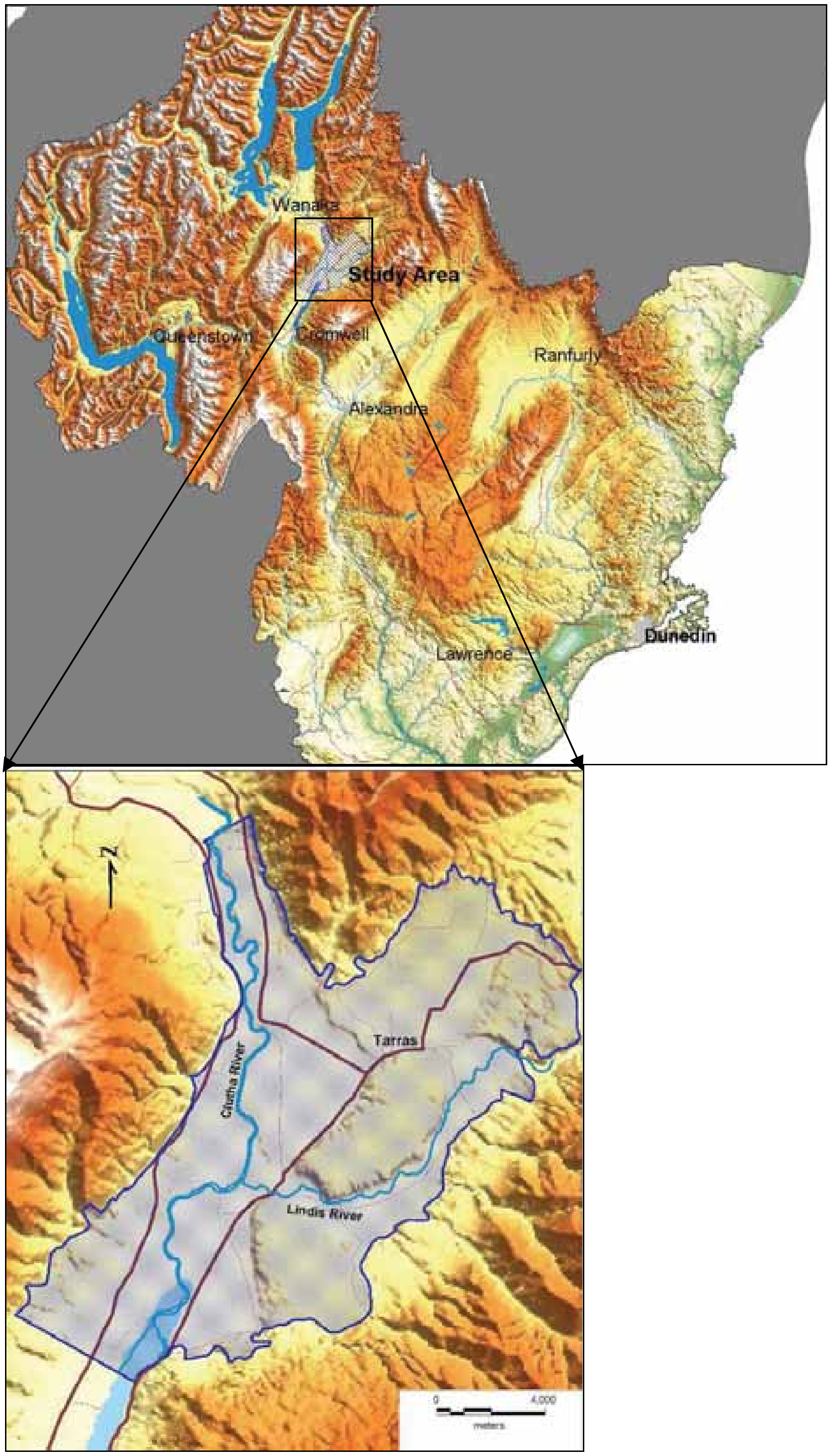

Figure 2.1 Location of the Bendigo-Tarras groundwater basin study area

2.1 Geology

The Bendigo-Tarras basin is underlain by Haast Schist of the Rakaia Terrane. The schist acts as basement rock to the basin. The faults and folds through the schist form the shape of the basin. Overlying the basement rocks throughout Central Otago are non-marine Miocene quartz conglomerate, sandstone, mudstone and lignites of the Manuherikia Group. In this area the Manuherikia Group is represented by silt deposits and quartz sands which underlie the Quaternary deposits of sand, silt and gravel. This silty sandy layer is found at the ground surface just north of Tarras settlement (Figure 2.2).

The Quaternary sediments were deposited during a series of glacial periods. There were times when ice extended to cover all of the entire study area between 600 to 400 thousand years ago. The till deposits which form the high terraces in the area are related to a glacial terminal moraine near Lowburn. A large lake formed behind the terminal moraine which then filled with laminated silt and sand (Turnbull, 2000). During later glacial periods, the ice did not reach as far as the study area, but large amounts of sand, gravel and silt were moved down to this area as glaciers in Wanaka and Hawea eroded out the schist rock. These sediments are referred to as glacial outwash. Clutha River/Mata-Au alluvial deposits of sandy gravel also form the lower terraces through the basin (Figure 2.2). The gravels and sands within the Clutha Valley are "cleaner" and more sorted so have a higher permeability.

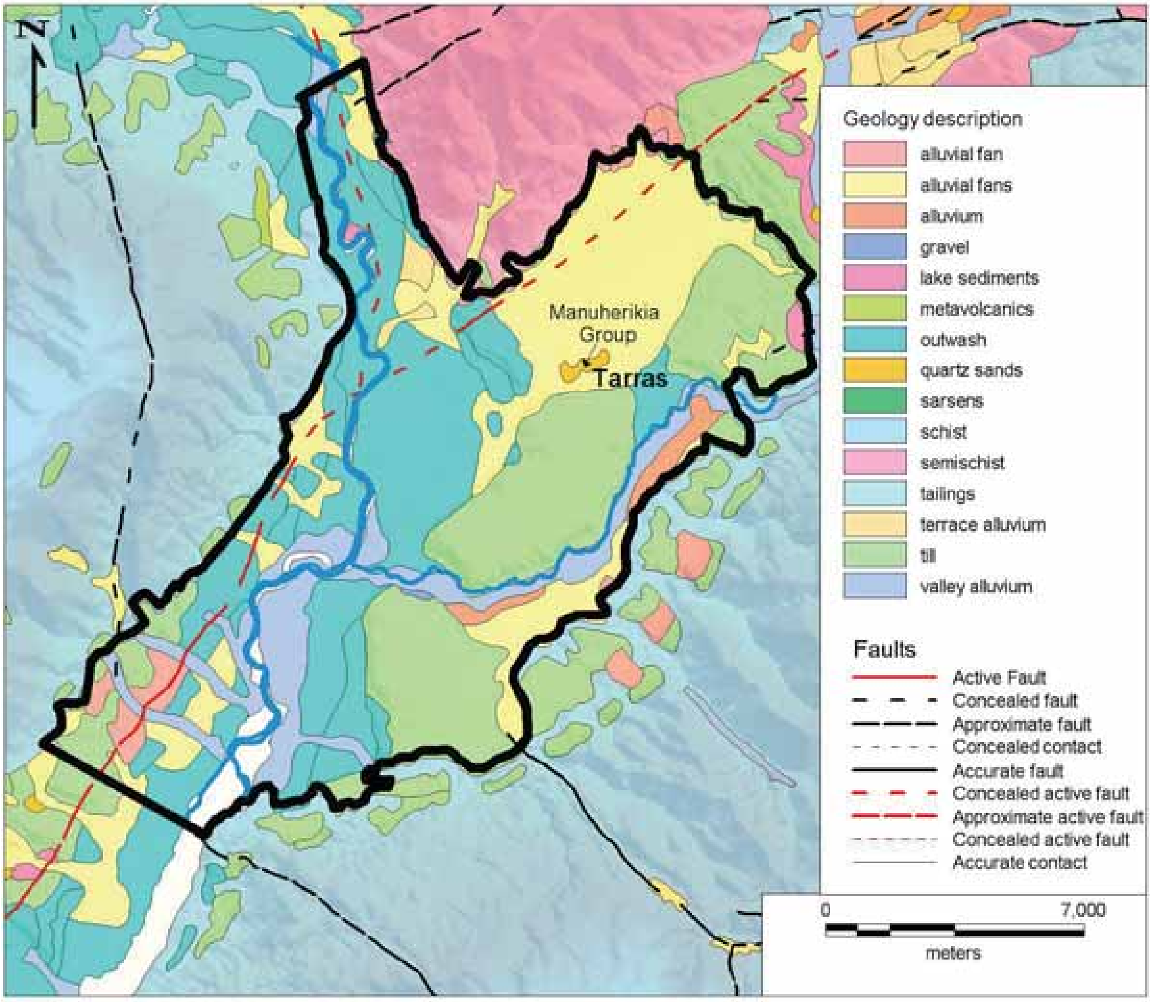

Figure 2.2 Map of geological units in the study area. Geological information is from Turnbull, 2000

2.2 Surface water bodies

There are two major river systems flowing through the Bendigo – Tarras basin (Figure 2.3). These are the Clutha River/Mata-Au and the Lindis River. They are both highly integrated with the groundwater system but contrast in the size of their flows and their sensitivity to stream depletion affects. The Clutha River/Mata-Au flows at approximately 250m^3/s; whereas the lower reaches of the Lindis River are dry for much of the irrigation season most years. Recent studies on the Lindis River have investigated the flows required to maintain an acceptable habitat for the fish species which are present. The Lindis River has significant habitat for trout spawning, juvenile and adult trout, Clutha flathead galaxiid and eels (ORC, 2008).

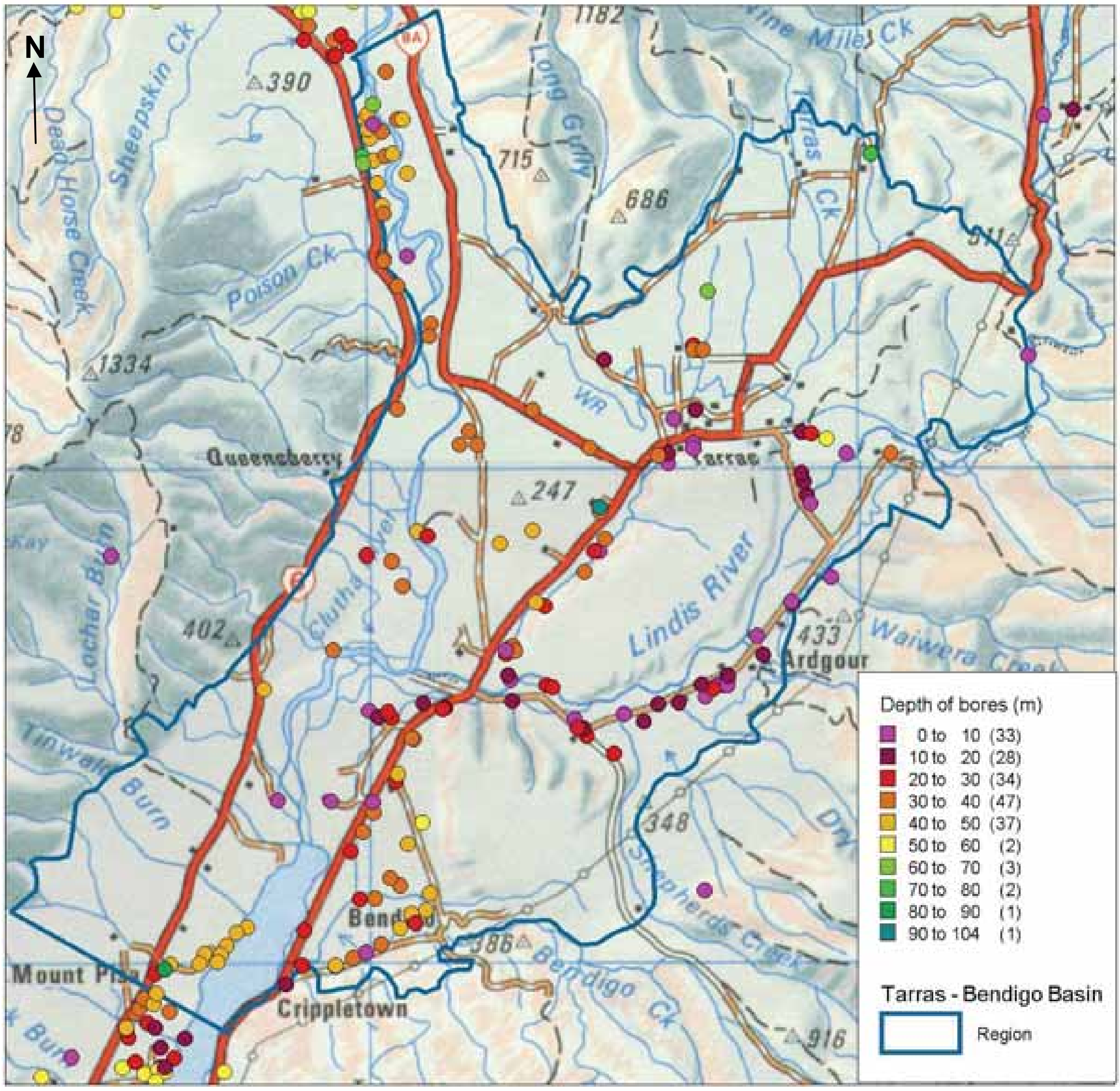

Figure 2.3 General map of study area, with bore locations and depths

2.3 Climate and land use

The Bendigo-Tarras area has a dry climate, with average rainfall in the area between 400 and 550mm. Summer rainfall can be as low as 60mm per season (January to March). Median summer air temperatures for the area are between 16 and 17^{o}C. Winter median temperatures are 5 to 6^{o}C.

Vineyards are expanding in the basin, and large central pivot irrigators are increasingly being used for irrigation of pasture. Many of the large groundwater takes in the area are for irrigation of pasture and grapes. Flood irrigation of pasture with surface water also occurs within the basin.

2.4 Bore locations and current abstraction

There are currently 150 bores located within the Bendigo-Tarras basin (Figure 2.3). Bores are found within several different geological deposits, which control the bore productivity. For example, bores tapping the highly permeable sandy-gravel glacial outwash deposits on the lower terraces are widely used for irrigation water. Bores in the Tarras settlement area are used for domestic and stock water supplies as they tap low yielding clay rich deposits. Bores within the Ardgour Valley are generally less than 20m deep and tap the Lindis alluvial ribbon aquifer, which is closely connected to the Lindis River. Abstraction in this area can affect the flow in the Lindis River.

There are 35 bores within the Bendigo allocation zone, 20 of which have groundwater take consents to abstract more than permitted 25,000 litres per day. Consented groundwater abstraction is concentrated in these lower terraces of the basin. To distinguish between the two higher permeability areas they are referred to here as the Lower Tarras allocation zone and Bendigo allocation zone. These zones are outlined in Figure 2.4.

There are 43 current consents from the basin, and the total current groundwater allocation from the entire basin is **8.89Mm^3/year**. The annual consented volume from the Lower Tarras Allocation Zone is 2.3Mm^3/year and from the Bendigo allocation zone is currently 3.62Mm^3/year.

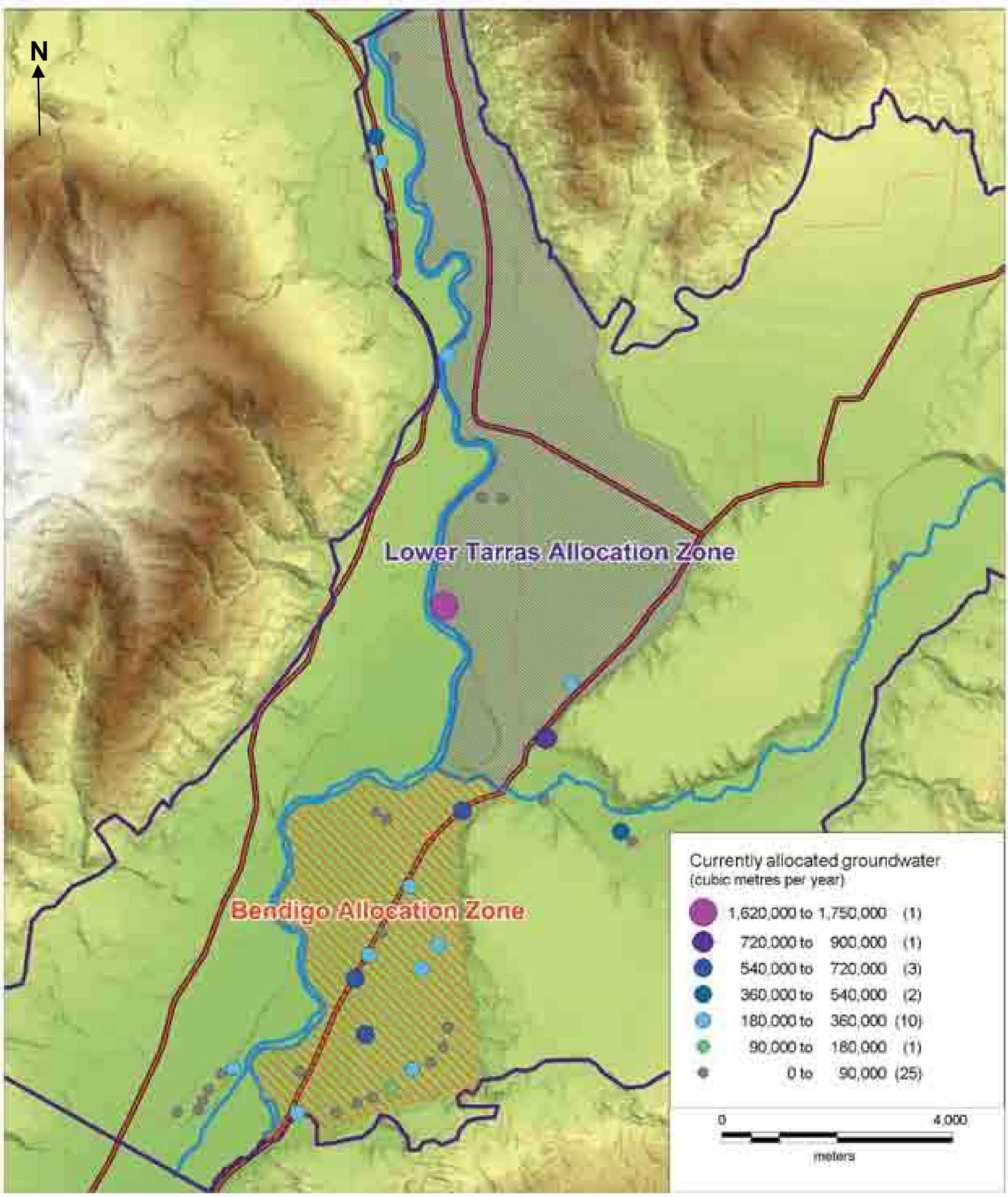

Figure 2.4 **Currently consented groundwater takes (maximum annual volume) and proposed allocation zones**

3. Groundwater hydrology

3.1 Aquifer extent

The extent of the aquifer and the boundaries to groundwater movement were based on geological information, lithological bore logs and analysis of geophysical data. The boundary of the basin is shown in Figure 2.2 and Figure 2.3. The low permeability schist rocks are considered to limit the extent of groundwater flow.

Lithological bore logs show well-sorted gravels in the Clutha Valley to approximately 50m deep and thinly-layered silts and clay-bound sands in the Tarras area. The Tarras deposits are low permeability, and bores in this area are low-yielding and predominantly used for domestic and stock water supplies.

The geophysical data were used to define the base of the aquifer. The depth to the silty mudstone layer varied from 20-30m in the Ardgour valley, to over 120m deep within the Clutha Valley. The application of geophysical data in defining the extent of the basin is described in detail in Section 3.2.

3.2 Application of airborne geophysics to define aquifer boundaries and permeabilty

An airborne geophysical survey was carried out in this area in 2008 by Glass Earth Ltd. The geophysical data included earth resistivity, a measure of the response of the earth to the penetration of electro-magnetic radiation. Resistivity is known to be a surrogate indicator of the clay or silt content of alluvium, the saturation or non-saturation of sediments and the presence of bedrock.

The fine-grained silt layer underlying the highly permeable sandy gravels of the Clutha Valley gives an obvious signature in the geophysical resistivity data. The data could therefore be used to define the extent and depth of the aquifer system, and to define the shape of the lower bounding surface.

The geophysical data could be viewed as vertical cross-sections (CDI profiles) or as a horizontal map layer (spatial grid). Both of these views were used to interpret the data in terms of permeability. The CDI profiles and spatial map layer show high permeability gravels as green and yellow shades. It should be noted that schist is also displayed in these colours, although with a mottled appearance. Fine grained silts and clays show as orange to red and even purple hues.

Resistivity map layers are available in different frequencies, which correlate to different depths below ground surface. Figure 3.1 shows the resistivity at 40,000 Hertz (Hz) which has been used to define deeper areas of saturated sand and gravel within the basin. The mottled green and yellow hues of schist can be seen outside of the basin boundary (outside blue line on map). The deeper areas of saturated gravels and sands show as areas of yellow or green (inside dashed outline on map). Where the underlying silt layer is closer to the surface (within 50m deep), the resistivity map layer shows an orange hue. The Manuherikia Group silty sand deposit is displayed as red to purple hues about the Tarras settlement. Within the basin, the silty gravely terraces also show up as yellow, although these sediments are dry. The relationship between the saturated basin sediments and the dry gravel terraces is better shown through the CDI profiles.

The spatial resistivity map layers represent the rocks at a depth below the ground surface; therefore, the topography needs to be taken into consideration when analysing the data. For example, where the survey was flown over the higher terraces in the Bendigo-Tarras area, the map layer refers to topographically higher sediments than the lower-lying Clutha Valley sediments.

As the frequency of the resistivity data increases, the map layers represent deeper sediments. The maps shown in Figure 3.2 of 8200 Hz and 1800 Hz reflect progressively deeper saturated silty sediments underlying the saturated sands and gravels. The areas of higher permeability slowly shrinks from the initial outline (dashed line), as seen in the 40,000 Hz data to the smaller areas of yellow hue, as seen in Figure 3.2.

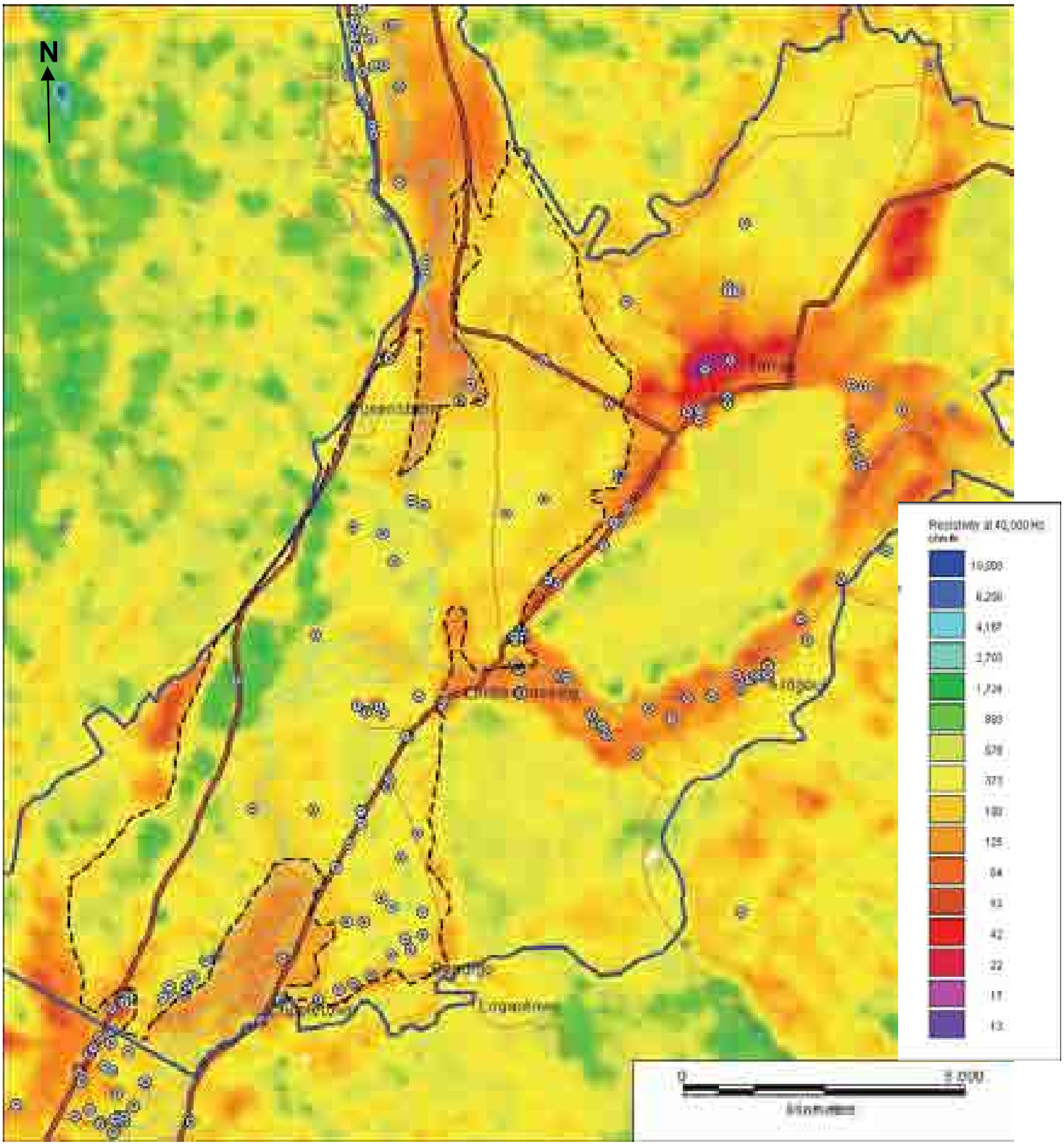

Figure 3.1 **Spatial resistivity data at 40,000 Hz. The blue line defines the edge of the sedimentary basin based on geology. The dashed outline contains the deepest saturated sands and gravels. Bore locations are shown with blue markers**

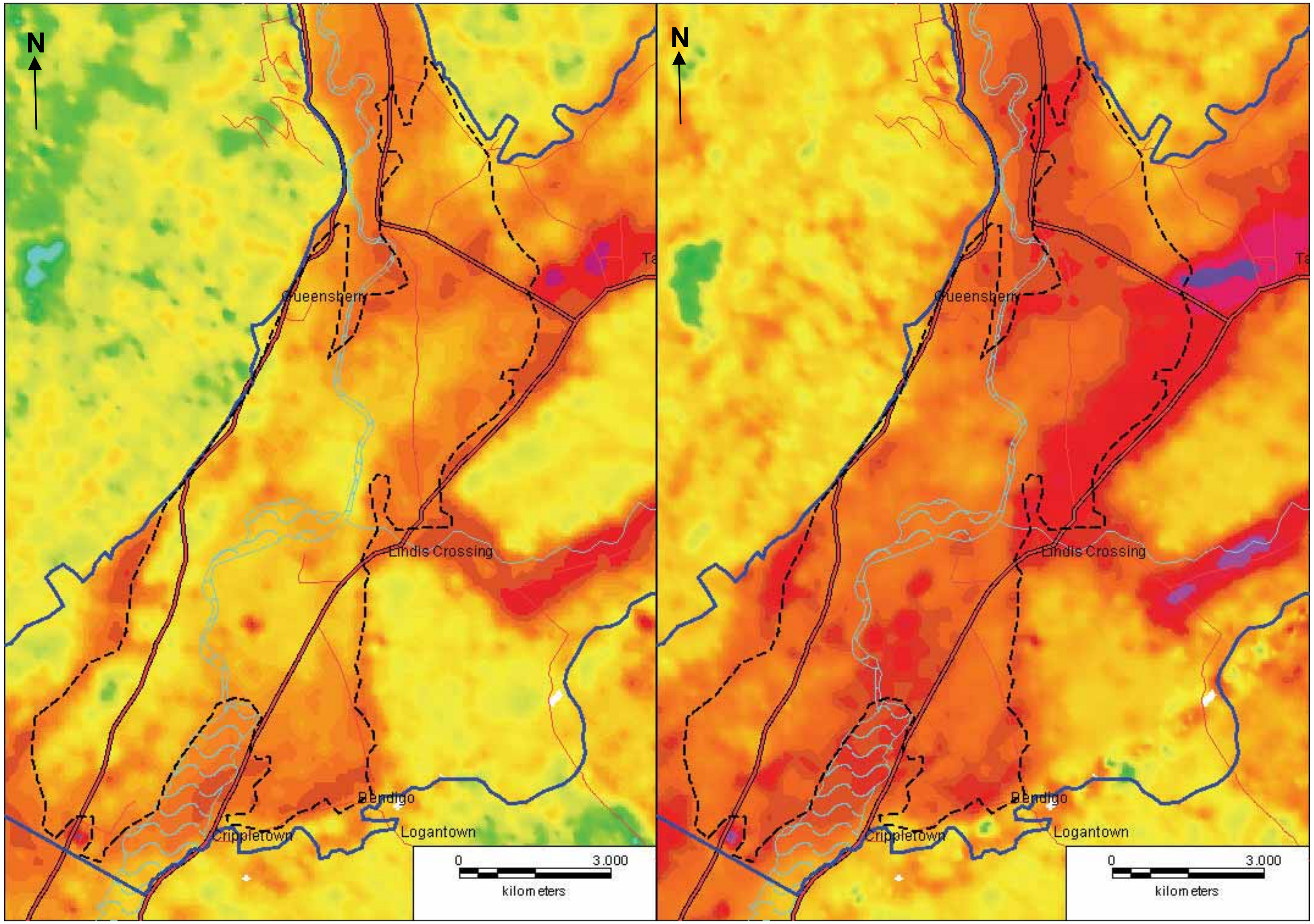

Figure 3.2 **Spatial resistivity data at 8200 Hz (left) and 1800 Hz (right)**

The CDI profiles have been projected onto maps, so that the underlying features can be related to geology and topography. However, it should be noted that the CDI profiles are off-set from the flight lines which are shown on the following maps as thick black lines. The CDI profile shown in Figure 3.3 indicates that the underlying silt deposits of Bendigo area dipping to the north-east and rising again at the edge of the terrace. These silt deposits underlie the dry Quaternary terraces and restrict horizontal groundwater movement below them. The silt deposits contain the shallow groundwater within the Lindis alluvial ribbon aquifer in the Ardgour Valley.

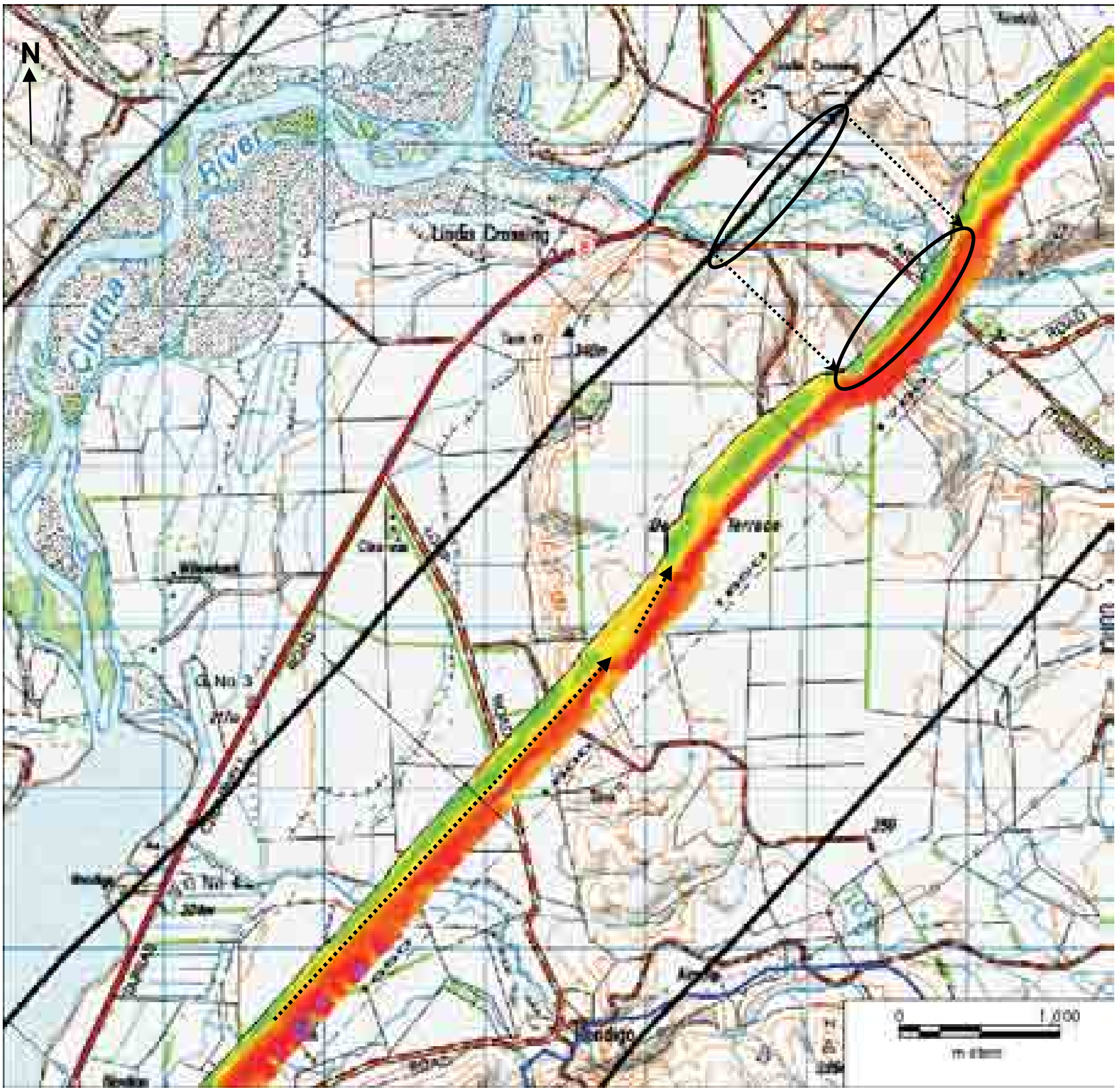

Figure 3.3 **CDI profile along flight line 10700. Highlighted on the section are the dips seen in the underlying silt and the Lindis alluvial ribbon aquifer contained by the underlying silty sediments**

In the Tarras area, there are three flight lines which show the significant variability in sediment permeability (Figure 3.4). Flight line 10500 (top left corner of map) shows yellow-green to blue hues within the Clutha Valley, reflecting highly permeably coarse gravel and sand deposits. The underlying silts can again be seen in red to purple shades. As the flight line rises out of the basin, the mottled schist pattern is observed. Flight line 10600 starts in the south-west, with highly permeable gravels overlying the distinctive silt layer. The gravel layer thins to the north-east and the silty sediments can be seen rising under the terrace. The overlying silty sandy sediments are layered with clay, and are often dry or low water-yielding (Figure 3.5). The Manuherikia Group silty sediments lie below these Quaternary sediments. The available flight lines with CDI profiles miss the outcropping area around the Tarras settlement. This area is shown by the distinctive dark red and purple hues in the map layer.

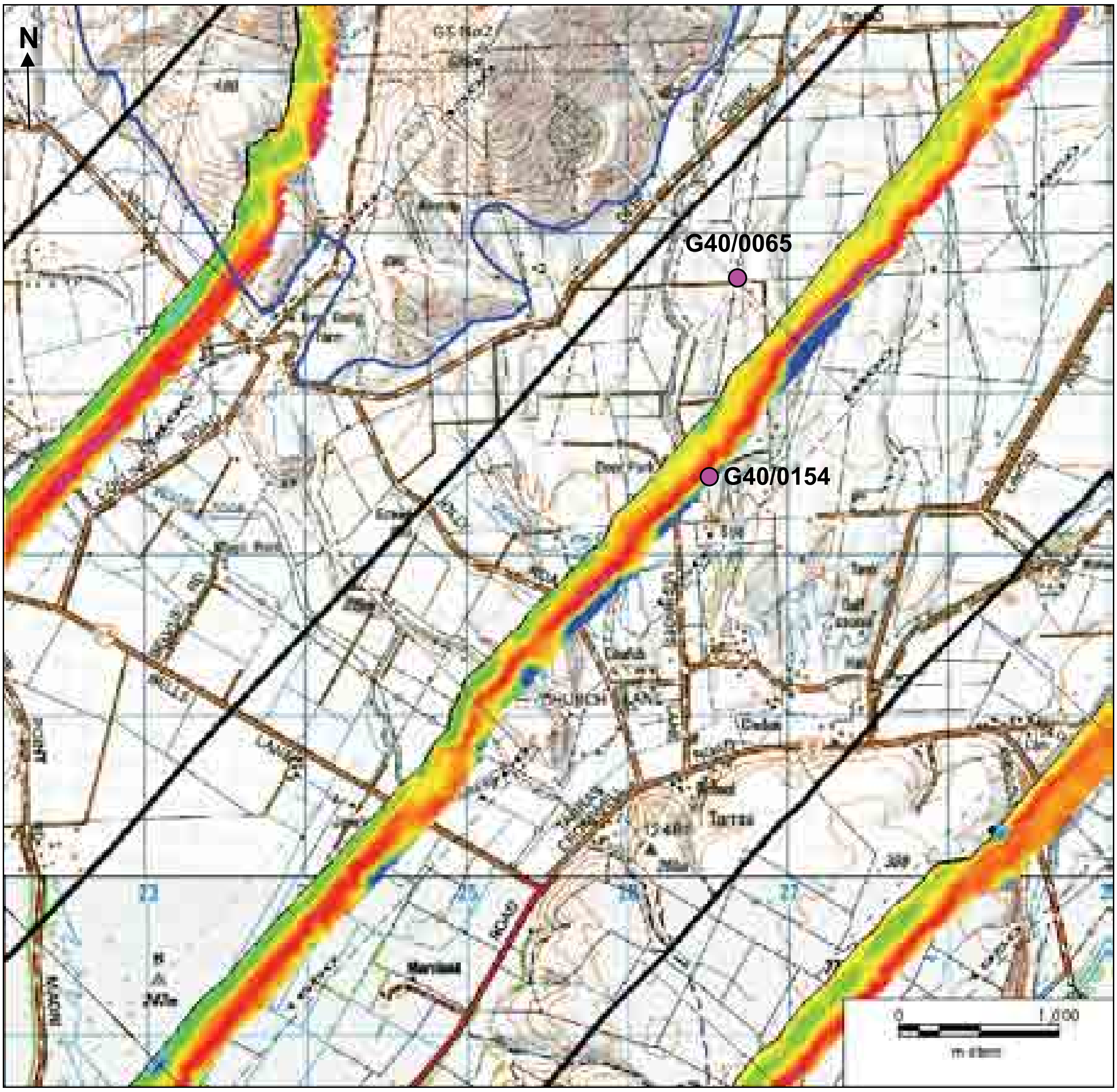

Figure 3.4 **CDI profiles along three flight lines in the Tarras area: Flight lines 10500, 10600 and 10700**

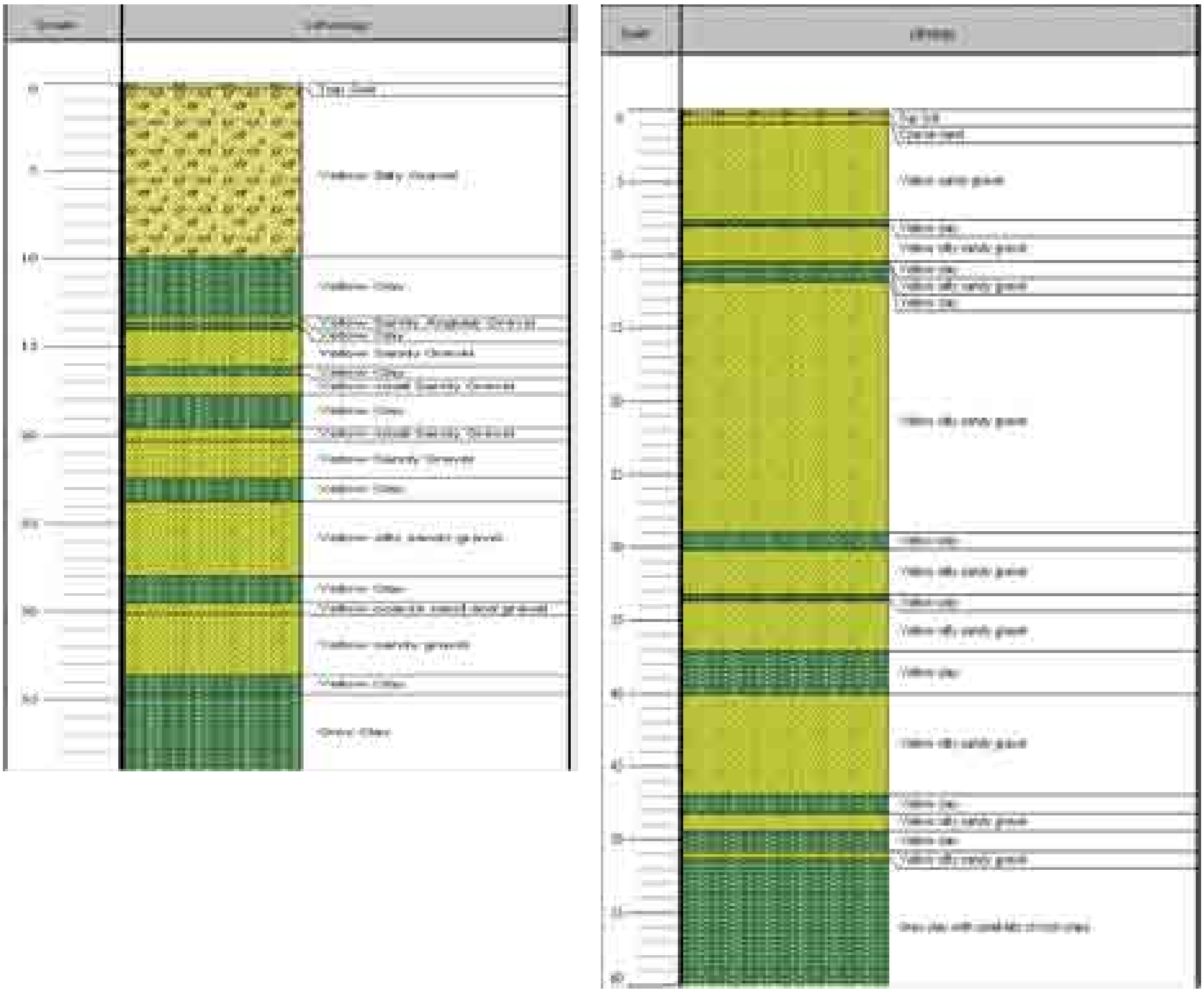

Figure 3.5 Bore logs for bore G40/0154 (left) and G40/0036 (right), showing a lithology of silty sandy gravel layered with clay sediments. Locations are shown in Figure 3.4

3.3 Groundwater flow patterns

Surveys of groundwater levels give a contour surface for the top of the water table in the area (Appendix A). This surface is known as a piezometric surface (water table). The slope on the piezometric surface indicates the direction of groundwater flow. Figure 3.6 shows the monitoring bores for the groundwater level survey and piezometric surface contours. Generally groundwater flows into the aquifer from the Clutha River/Mata-Au in the northern area of the Tarras or Bendigo allocation zones, and then back into the Clutha River/Mata-Au in the southern area.

There is a strong influence from the Lindis River as water moves into the deeper gravels after exiting the Ardgour Valley at the Lindis Crossing (Figure 3.7). The Lindis River levels are about seven metres above the height of the Clutha River/Mata-Au at the Lindis Crossing bridge. So the groundwater levels drop a significant amount between the bridge and the confluence with the Clutha River/Mata-Au.

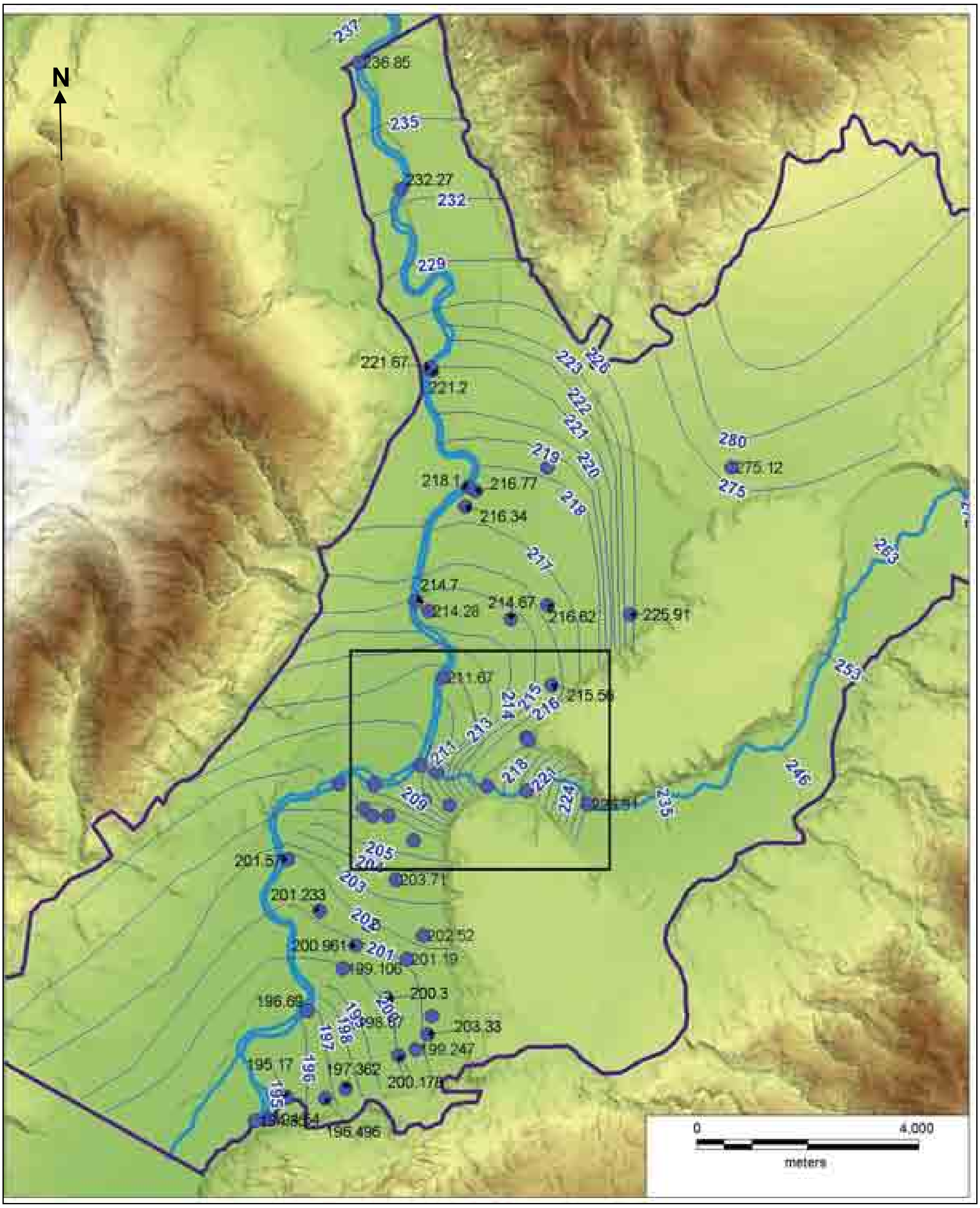

Figure 3.6 **Contoured water table surface from December 2009 survey of groundwater levels and river levels**

Note: Purple points indicate survey location and level. Groundwater flow is perpendicular to the contour lines. Contour lines outside of the Lower Tarras and Bendigo allocation zones are estimated groundwater levels. See Figure 3.7 for inset

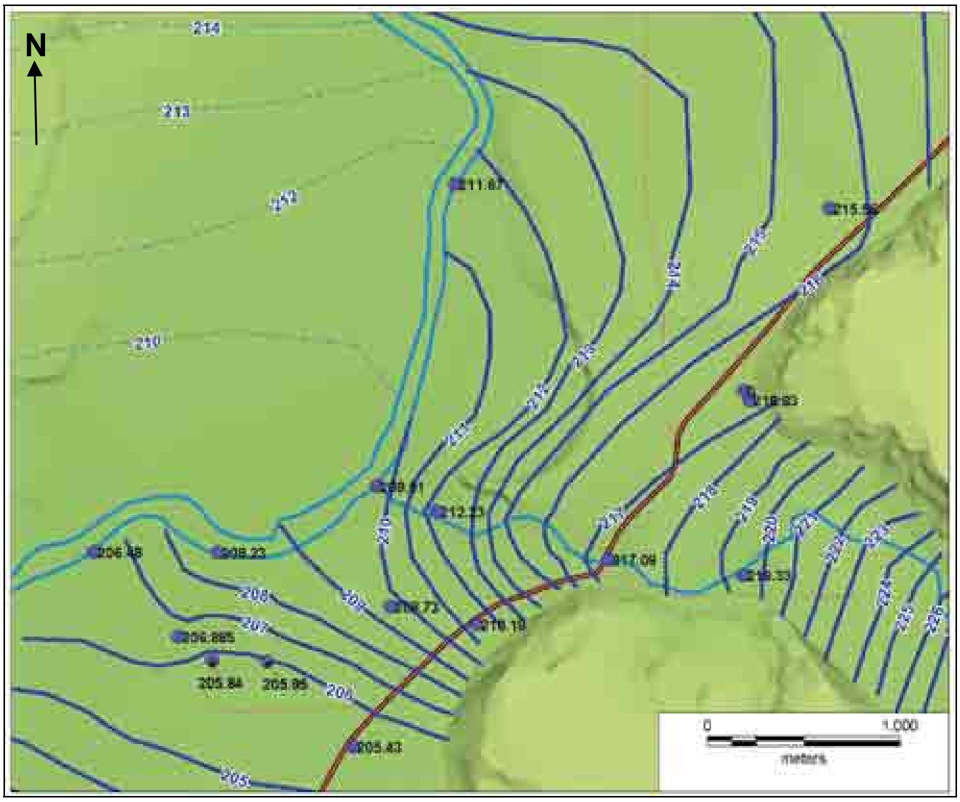

Figure 3.7 Groundwater piezometric surface in the area of the lower reach of the Lindis River. See Figure 3.6 for location within basin

The levels in December 2009 were on average 32cm lower than during September 2009. Surveys at the end of summer (March 2010) show another drop of 17cm in groundwater levels from the December 2009 levels. So there is an average of 0.5m fall in groundwater levels from the end of winter peak to end of summer low. The groundwater levels in the bores just south of the lower Lindis River fell by 1.5 to 1m over the six months (G41/0129 and G41/0236). Even those a little further away dropped by 0.6 to 0.7m. This reflects the strong influence that the Lindis River has over the groundwater levels in this area.

In the Tarras settlement area, the groundwater levels are nearly 60m higher than on the lower terraces. This significant height difference is caused by the lower permeability of the sediments in this area (Figure 3.5).

3.4 Aquifer properties

There are four aquifer tests that have been carried out as part of groundwater take applications, which can be relied upon for relatively accurate information as to the hydraulic properties. The permeability of the gravels and sands in the more recent alluvium is high. Aquifer testing of the Perriam bore G41/0231, Davidson bore G41/0316 and Bascorich bore G41/0286 showed a transmissivity values from 3000m^2/day to 5000m^2/day. This indicates that the gravels and sands of the lower terraces have relatively high permeability in this area.

In comparison, bores drilled in the Tarras area struggle to supply even household supplies. The sediments are poorly sorted in this area, as there has not been any reworking of the glacial desiments into alluvial deposits.

The "specific capacity" of a bore is related to the pumped discharge rate divided by the drawdown. This value can be used as a general indicator as to aquifer permeability in an area.

However, the results are highly dependent on the construction of the bore, the pumping time and the tested flow rate. Therefore, results should only be only used as a general indication of relative permeability.

A map of specific capacity is shown in Figure 3.8. The general distribution of higher values can be seen in a paleo-channel (old river channel) running parallel to the Clutha River/Mata-Au in the Bendigo area. The low values in the more northern areas around Tarras settlement can also be seen. In the Ardgour Valley, the values can vary greatly even between close bores which indicates that this may be due to other factors as described above rather than aquifer permeability.

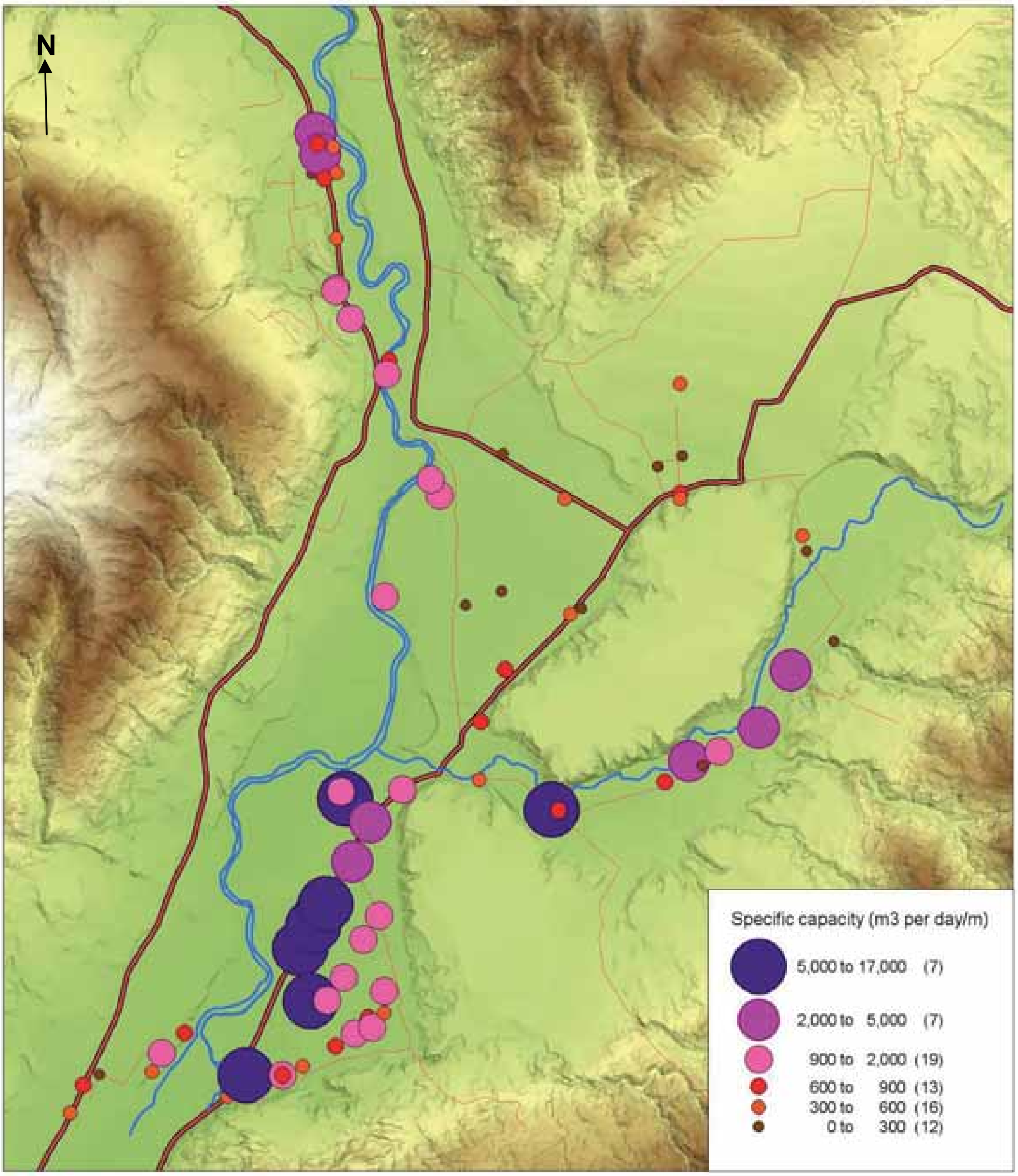

Figure 3.8 Specific capacity of bores in the Bendigo-Tarras area

4. Groundwater recharge

Recharge is water entering the aquifer system. It can do this through river flow losses or rainfall percolation down through the soil profile. It is important to quantify recharge so as to be able to determine groundwater abstraction limits. Recharge sources in this location will be from land-surface recharge and flow losses from the Clutha and Lindis Rivers.

4.1 Rainfall recharge

Rainfall recharge occurs when soils are wetter than field capacity and water can percolate down through the soil profile to the underlying water table. In the dry climate of Bendigo-Tarras, this occurs only sporadically and not in every year. Irrigation of the soil can increase the recharge to the groundwater system by maintaining soil moisture levels close to field capacity before rainfall events. However, generally only low volumes of water recharge the aquifer system via rainfall recharge.

The rainfall recharge to the groundwater system was modelled using a soil moisture balance model by Rushton *et al.* (2006). The recharge to the system was modelled over a 24-year period (from 1985 to 2009). The method involves calculating the amount of recharge on a daily basis over this period using the climate and soil data. When the modelled soils breach field capacity due to rainfall they drain through the soil profile and down to the water table. More detail on the recharge modelling is covered in Appendix B.

Soils of the Bendigo-Tarras area were classified into 13 recharge zones, based on their hydraulic properties. The soil properties were defined with the assistance of Landcare Research. The distribution of the soil recharge zones is shown in Figure 4.1.

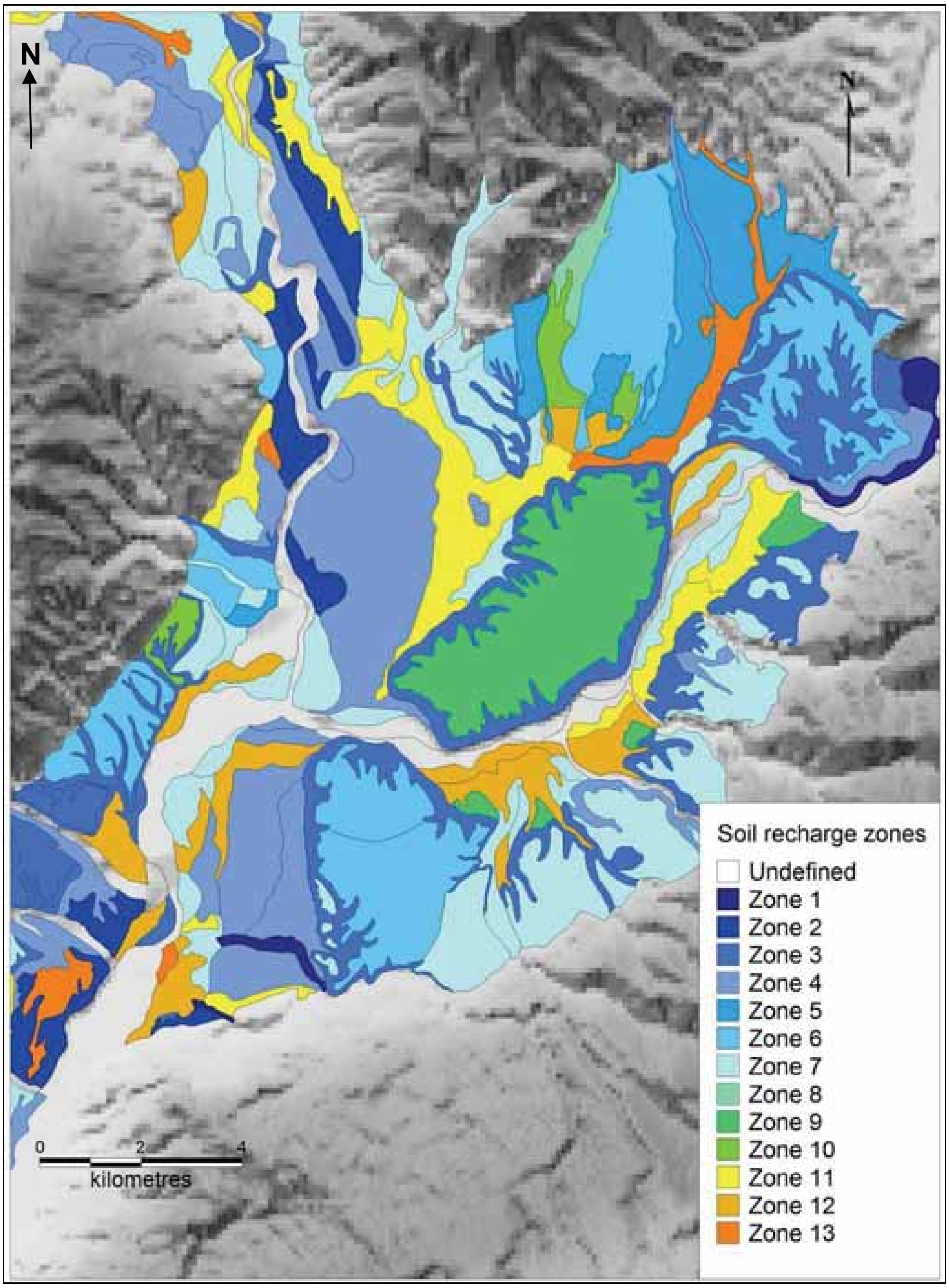

Figure 4.1 Soil recharge zones for the Bendigo-Tarras area

Some recharge soil zones in the Bendigo-Tarras area only have a thin layer of sandy stony soil overlying the unsaturated zone and require little rainfall to allow water to drain down to the water table, (for example, soil recharge zone 2 (Figure 4.2)). Other soils have high water storage potential and it takes a substantial amount of rainfall for them to become saturated, (for example soil recharge zone 10 (Figure 4.3)). There is significantly less recharge under soil zone 10 than soil zone 2 (Table 4.1). Soil zone 2 shows 20% of annual rainfall contributing to rainfall recharge for the aquifer, i.e. average recharge rate of 87mm per year. In comparison, soil zone 10 shows less than 2% of rainfall reaching the water table at an average rate of 7mm per year.

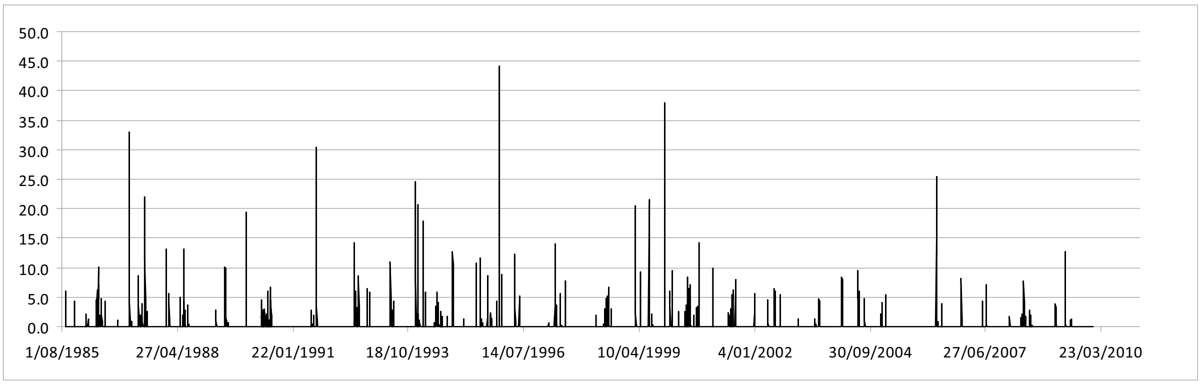

Figure 4.2 **Daily recharge calculated for Soil Zone 2**

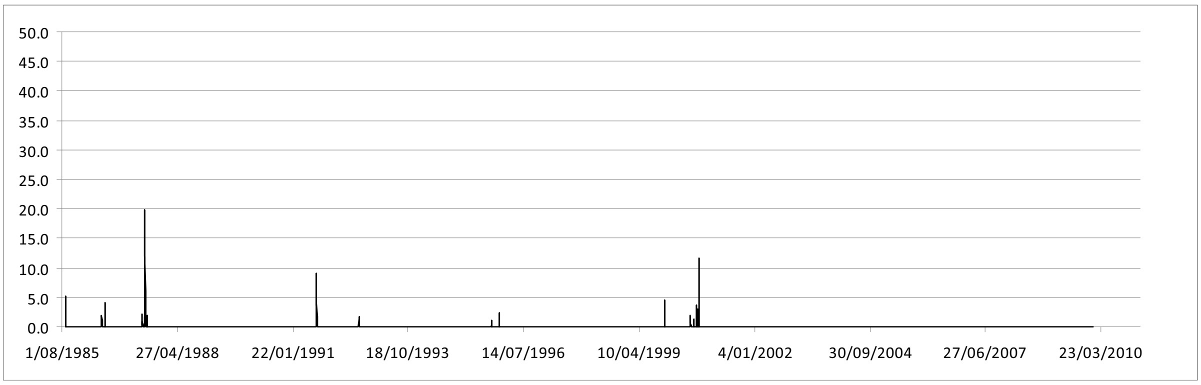

Figure 4.3 **Daily recharge calculated for soil zone 10**

Another feature of the modelled recharge is that recharge in the zones with higher water storage occurs sporadically (or episodically) and only after major rainfall events. Figure 4.3 indicates that, over recent years, there has been very little recharge over these soil zones. Table 4.1 also shows that, over the last nine years, many of the soil zones have shown no recharge at all.

Table 4.1 **Soil recharge zones for the Bendigo-Tarras area**

Zone name	Annual recharge (mm)	Recharge over last 10 years (mm)	Recharge over last 9 years (mm)
Zone 1	**335**	**341.7**	**344.56**
Zone 2	**86.7**	**54.07**	**45.04**
Zone 3	66.5	36.81	29.42
Zone 4	44.1	21.1	14.1
Zone 5	34.2	14.8	8
Zone 6	21.9	8.75	2.29
Zone 7	19	7.18	1.27
Zone 8	14	5.41	0.37
Zone 9	8.34	4.25	0
Zone 10	7.1	4.1	0
Zone 11	5.3	2.6	0
Zone 12	3.1	1.04	0
Zone 13	1.7	0	0

4.2 Irrigation contribution to recharge

Irrigation of substantial areas of Bendigo and Tarras contributes to the land-surface recharge through the soil (Figure 4.4). The irrigation of these areas over the summer months allows the soils to fill to field capacity more frequently when rainfall events occur. The traditional irrigation areas have concentrated on soils with higher total available water (TAW) values, such as recharge soil zone 11. More recent irrigation has moved into areas of lower TAW, such as recharge soil zone 4, in the Bendigo area. The irrigation contribution can significantly increase the amount of recharge to the aquifer. On recharge soil zone 11, irrigation is predicted to increase the recharge from an average 5.3mm per year to 63mm per year. On the recharge soil zone 4, the average annual recharge increases from 44mm to 338mm. These increases are based on water being applied at the rates suggested in the Aqualinc (2005) report on irrigation requirements for Otago.

The average application depths are conservative for pasture irrigation (zone 11 = 3.5mm/day, zone 4 = 5.6mm/day). More recharge would be experienced under higher daily application rates, especially where areas are flood irrigated. However, from a long-term allocation perspective, it is regarded as unsuitable to allocate recharged water that has entered the aquifer through an excess irrigation application rate. Therefore, the conservative and recommended application depths were used from Aqualinc (2005). The increased recharge rates are achieved through lower soil moisture deficits during periods of rainfall, allowing the soil to reach field capacity faster than non-irrigated soils, rather than irrigating to the point where soils breach field capacity and drain to the water table.

It should be noted that allocating groundwater based on recharge rates under irrigation, assumes that irrigation in this area is permanent or at least a long-term activity. Given the long-established tradition of irrigation in the area and the reliance on irrigation for farming practices, this would be a reasonable assumption.

Application depths for irrigating vines are much lower. Aqualinc (2005) recommends 2.2mm/day on the stony low PAW soils (e.g. soil zone 4) where much of the vine irrigation is occurring. Under vine irrigation, the recharge in soil zone 4 increases from 44mm to 60mm per year.

More detail on the results of irrigation recharge modelling and methods used to estimate increased recharge under irrigation is given in Appendix B.

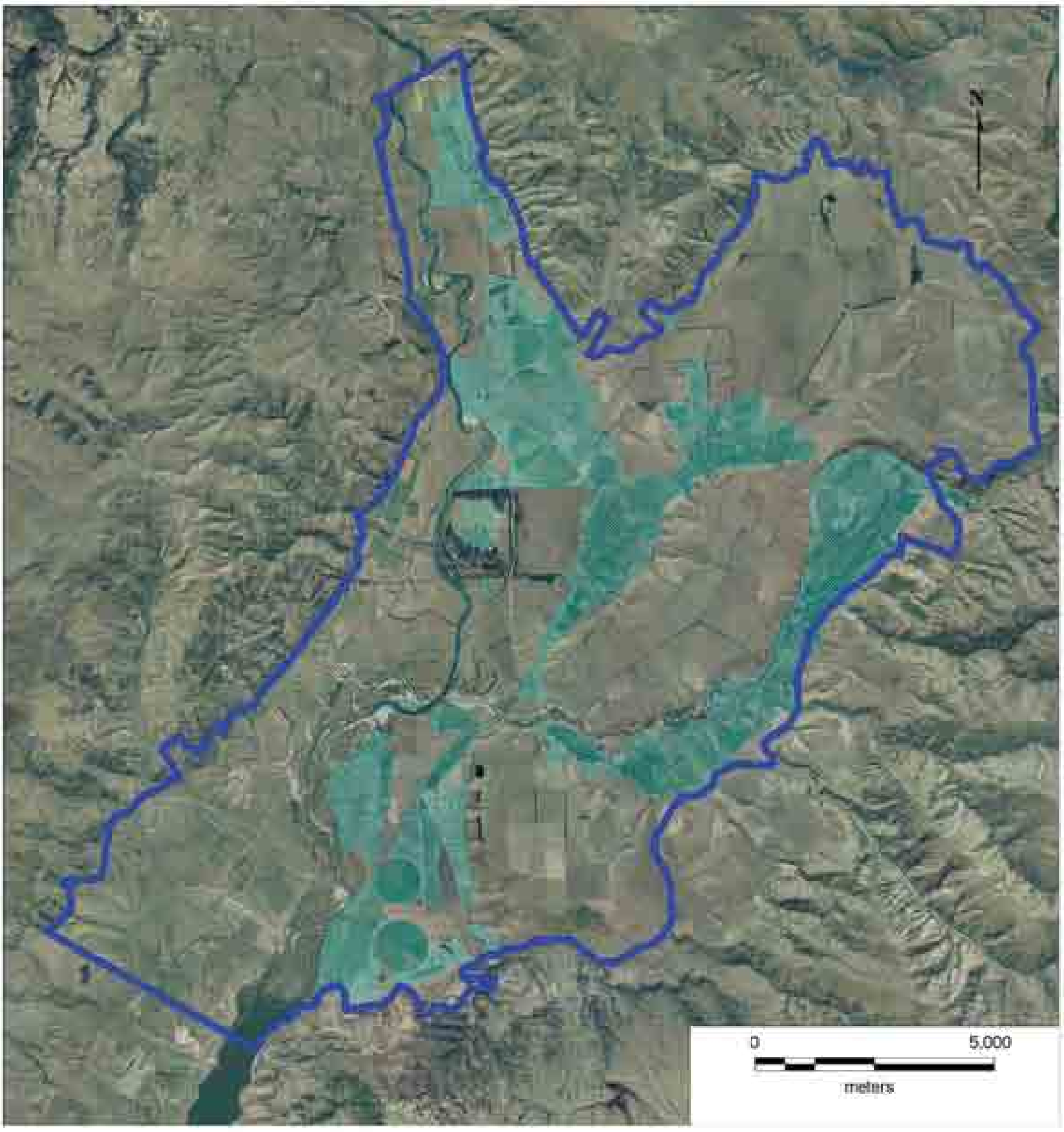

Figure 4.4 **Irrigated areas estimated from 2006 aerial photos and areas of proposed irrigation for which water take consents have been granted up to 2009**

4.3 River recharge

The Lindis River and Clutha River/Mata-Au contribute large quantities of recharge water to the Tarras – Bendigo aquifer. Flow losses from the Clutha River/Mata-Au cannot be measured due to the large flows in the river. They were investigated through modelling discussed in Section 5. The lower Lindis River has been studied in detail in terms of flow gauging and flow monitoring for determining a proposed minimum flow level on the river (ORC 2008).

4.3.1 Lindis River recharge

Lindis River flow monitoring was carried out during the summer period of 2007/2008 between the Ardgour Road flow site and the Clutha River/Mata-Au confluence, which included a flow site at Lindis Crossing bridge (Figure 4.5 and Figure 4.6). The flow data showed that the low flow at Ardgour Road stabilised at approximately 200l/s (Figure 4.5). At this flow rate the river is dry within a kilometre downstream and all the river flow recharges to the aquifer (Figure 4.5). At higher flows, the recharge (flow loss) is approximately 450l/s.

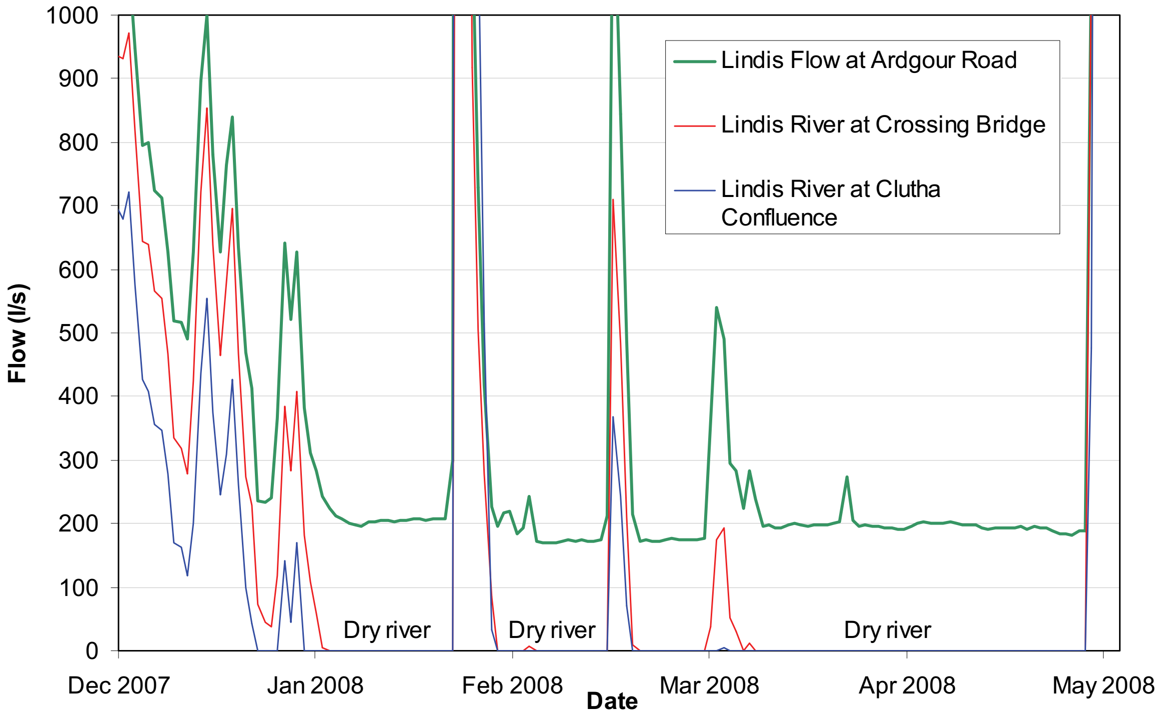

Figure 4.5 Daily average flows at three sites on the lower Lindis River between the Ardgour Road Flow site and the Clutha River/Mata-Au confluence

The Ardgour Road flow site was moved further upstream in November 2009 (Figure 4.6).

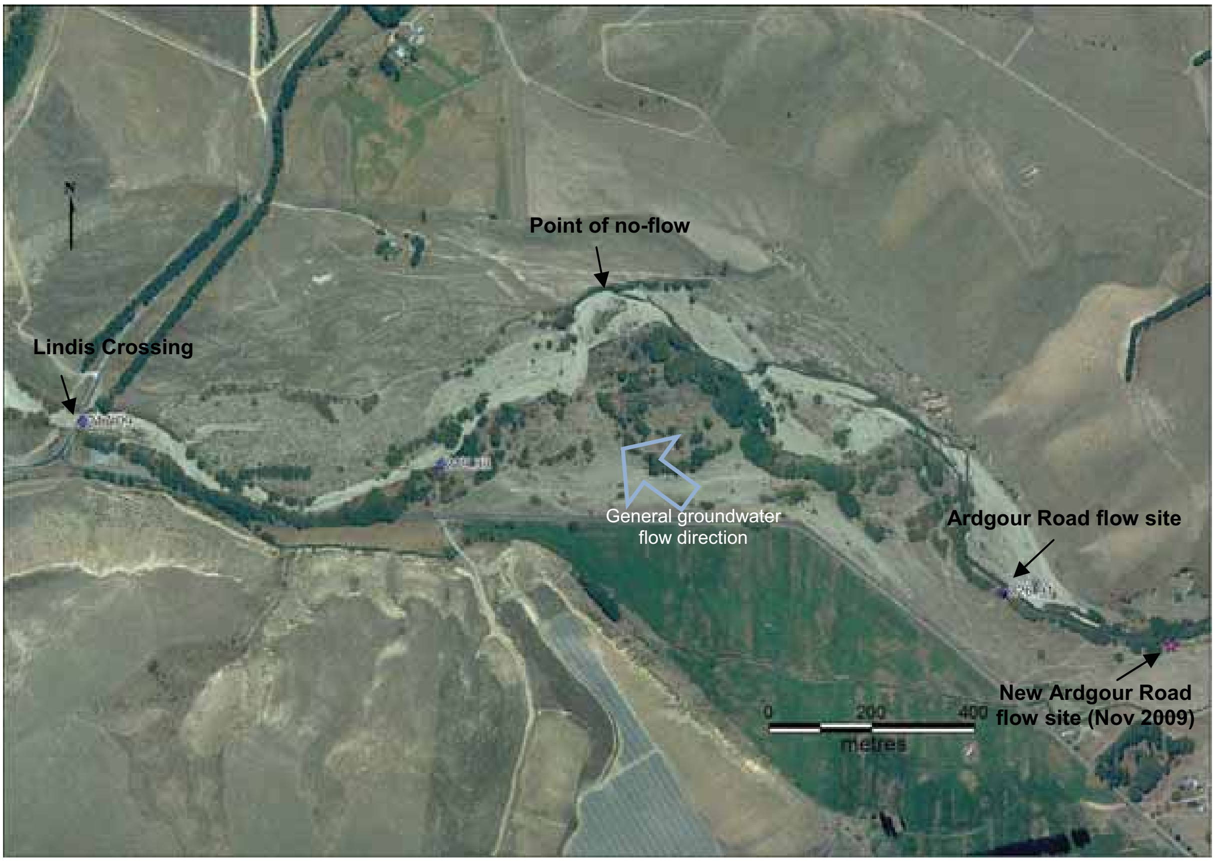

Figure 4.6 **Aerial photo of the Lindis River between the Ardgour Road flow site and the Lindis Crossing. Purple points show the location of survey points and water elevation in December 2009. The point of no-flow indicates the point at which the river dries up when flows at Ardgour Road flow site reaches 200 l/s**

The general groundwater flow direction is such that, during periods of higher groundwater levels (e.g. November) the aquifer will be discharging into the river (Figure 4.7). There will be river flow losses during this time occurring further downstream. Once the groundwater level drops below the level of the water in the river, the discharge stops and then the river only recharges the aquifer. When the river flow at Ardgour Road reaches 200l/s, the groundwater levels are low and all the river water below this point recharges the aquifer (Figure 4.5).

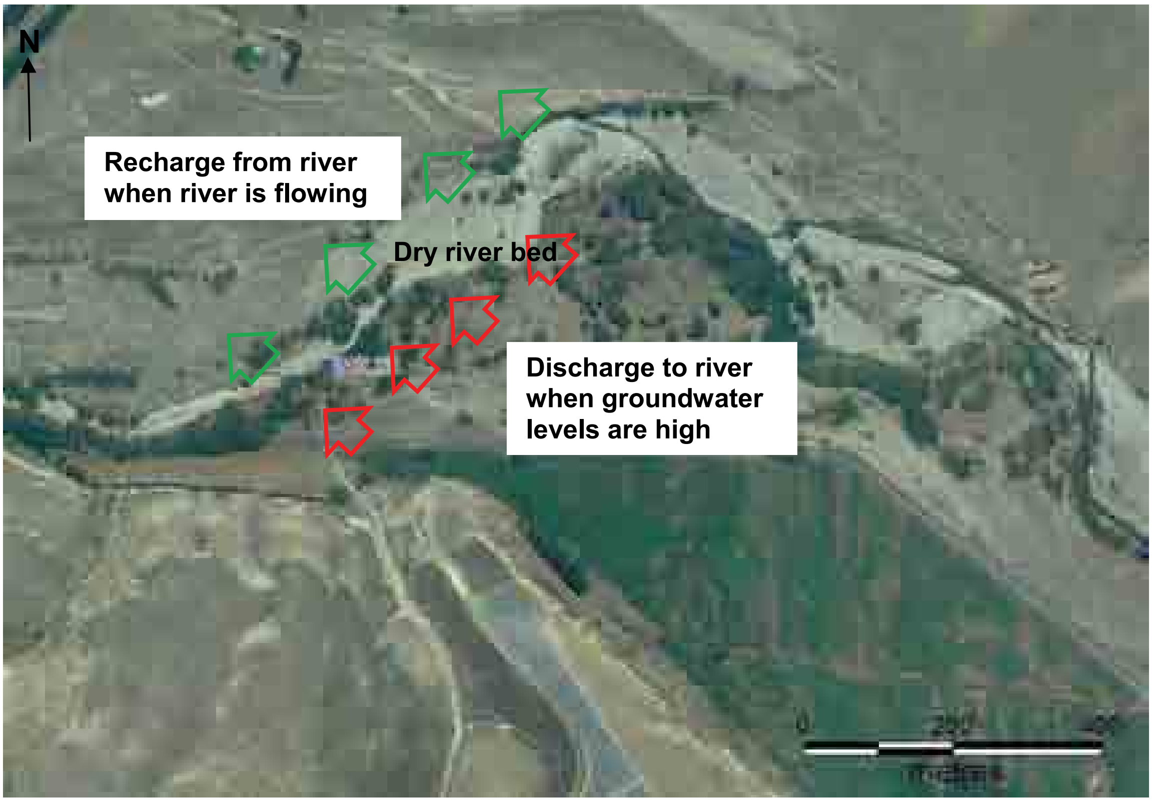

Figure 4.7 **Aerial photo of the Lindis River downstream of the Ardgour Road flow site, where the river bed becomes dry each summer**

Hydrographs show that during periods of higher groundwater level (e.g. November), the groundwater contributes flow into the river between the Ardgour Road flow site and the Lindis Crossing (Figure 4.8). In this situation the flow was occasionally higher at the Crossing Bridge site than at the upstream Ardgour Road site.

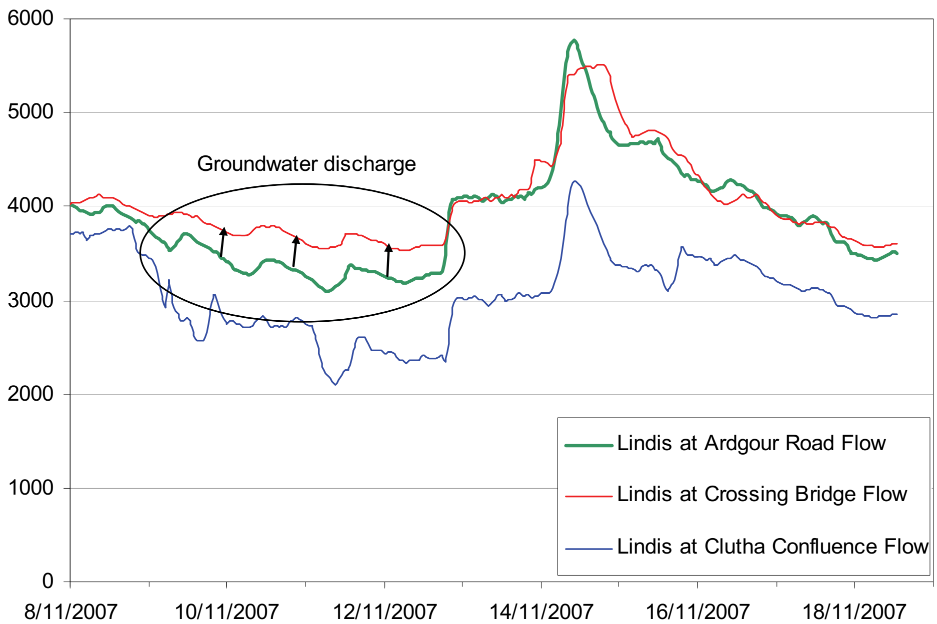

Figure 4.8 **Flow rates for three sites on lower Lindis River between Ardrgour Road flow site and the Clutha River/Mata-Au confluence during November (higher groundwater levels)**

4.3.2 Flow in lower Lindis River in comparison to shallow groundwater levels

Two piezometers are located between the Lindis Crossing bridge and the confluence with the Clutha River/Mata-Au (Figure 4.9). Groundwater level monitoring in these shallow piezometers beside the lower Lindis River reach showed the rapid response of groundwater levels to river flow (Figure 4.10 and Figure 4.11).

Figure 4.9 Position of the two lower Lindis River groundwater level monitoring piezometers

The winter levels in piezometer 2 were only 2m below ground level and were at a similar level to the water levels in the river. Groundwater levels slowly decline in November and December as flow in the river dropped down to summer levels. When flow ceased in the lower section of the Lindis River in January and the constant recharge from the river stopped, the groundwater levels quickly dropped away (Figure 4.11). The level dropped by more than 2m in Piezometer 2 (near the bridge) and the levels in piezometer 1 dropped by 1.5m. There appears to be an additional groundwater abstraction effect on these piezometers as the levels start to rise in late March 2010, while river flow conditions remained static.

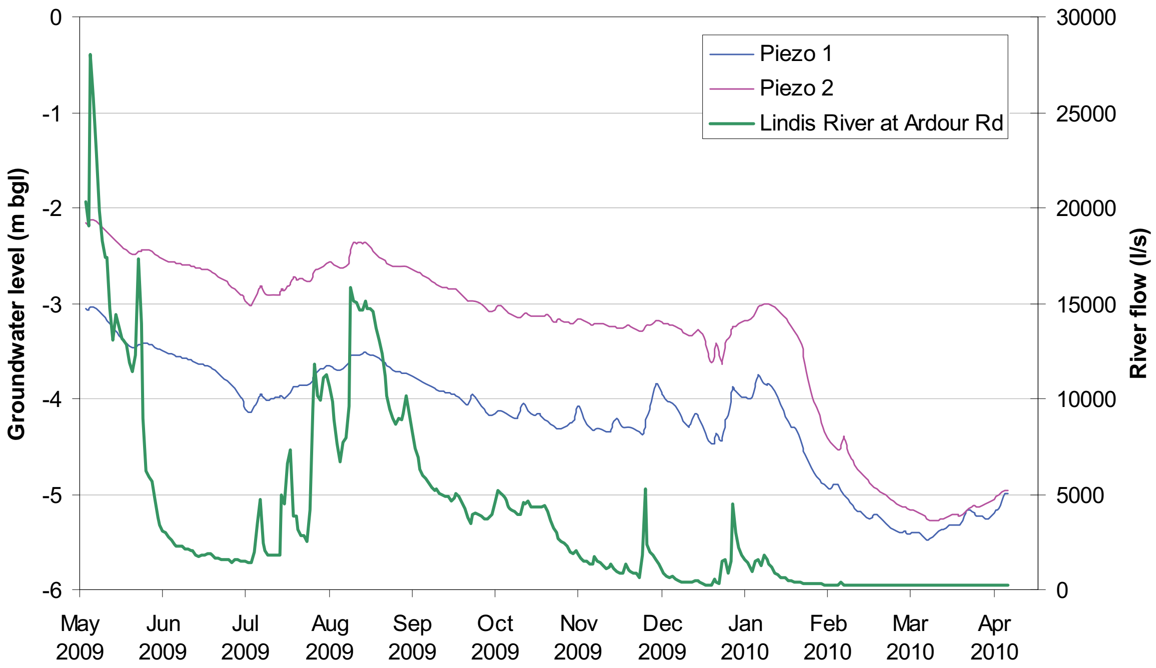

Figure 4.10 **Groundwater level data (in meters below ground level) from May 2009 to April 2010 in two piezometers located beside the lower Lindis River, compared to flow data from the Ardgour Road flow site, Lindis River**
Note: Groundwater data collected by Ken Higgie on behalf of John Perriam for consent 2007.342. See Figure 4.9 for locations

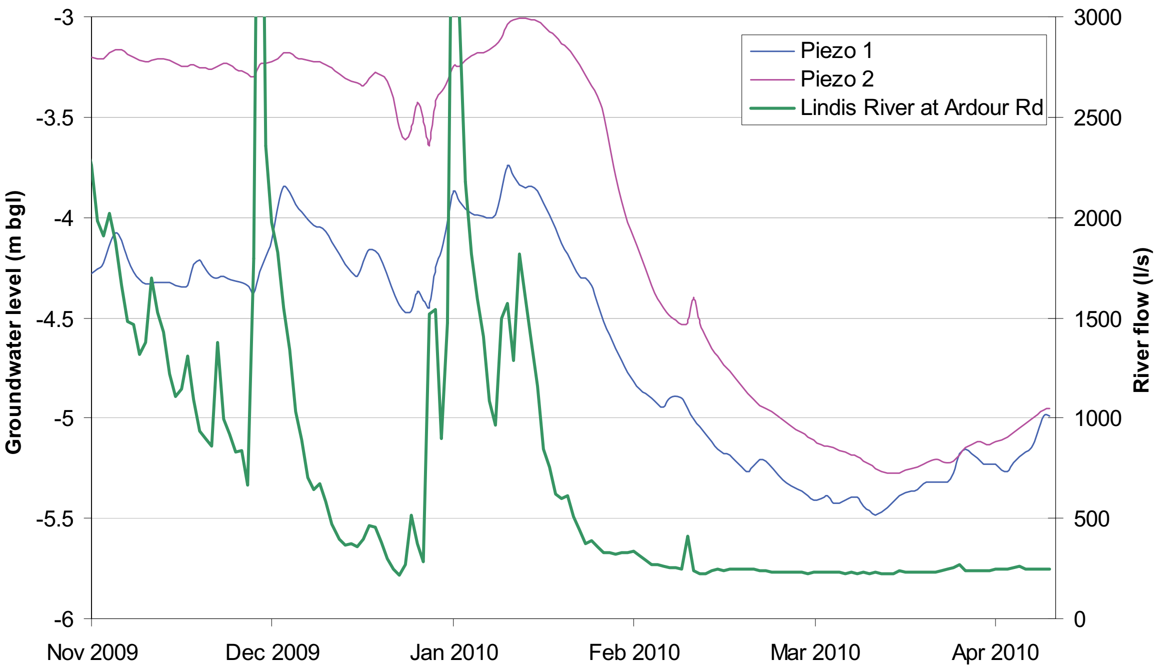

Figure 4.11 **Groundwater levels during summer, from November 2009 to April 2010, in two piezometers close to the lower Lindis River. Flow data from the Ardgour Road flow site, Lindis River**
Note: Groundwater data collected by Ken Higgie on behalf of John Perriam for consent 2007.342. See Figure 4.9 for locations

5. Numerical groundwater modelling

A steady-state numerical groundwater model was developed to investigate how the groundwater system currently operates, and how it responds to various pressures. Six different scenarios were used to observe how the groundwater system responded to variations in river flows and groundwater pumping (Table 5.1). The modelling results were used to determine a suitable allocation volume for the Bendigo and lower Tarras allocation zones. The modelling method and background is described in detail in Appendix D.

Table 5.1 Summary of modelling scenarios

Scenario	Lindis River flow	Pumping	Reason for scenario
1	1000l/s	None	Base scenario with December groundwater and river conditions
2	1000l/s	Current allocation	Impact of maximum consented groundwater abstraction with December river flows
3	500l/s	Current allocation	Impact of maximum consented abstraction at low flows
4	500l/s	None	Groundwater conditions during low flows without pumping
5	500l/s	Double current allocation	Increased abstraction during low flows
6	500l/s	Maximum pumping (2m water level drop)	Total groundwater volume that can be pumped without significant affects

5.1 Scenario 1: Base scenario

The base scenario has no groundwater pumping. December 2009 groundwater levels and river flows and average annual rainfall recharge over the last ten years under irrigated and non-irrigated conditions.

Groundwater levels are stable at the observed levels seen in the December monitoring. The groundwater flow directions and relative velocities are seen in Table 5.1 and Table 5.2. A similar pattern of groundwater flow directions is seen in both the Tarras and Bendigo allocation areas. Groundwater flows in from the Clutha River/Mata-Au in the northern area and then flows back into the Clutha River/Mata-Au at the southern end. Recharge from the Lindis River acts to lift the surrounding groundwater levels and split the aquifers.

The model has the Lindis River losing 447l/s from the Ardgour Road flow site to the Clutha River/Mata-Au, falling from 938l/s to 491l/s (Table 5.3). This loss is similar to what is measured in the field (ORC, 2008; Appendix D).

The water balance for this scenario shows that the largest contribution of recharge to the groundwater system comes from river recharge from the Clutha River/Mata-Au (Table 5.2).

Table 5.2 Water balance for Scenario 1

Flow component	Inflows (m^3/day)	Outflows (m^3/day)
Rivers: Lindis River and Clutha River/Mata-Au	 62,082 206,825	 17,458 274,371
Drains (spring)		17,011
Constant head	26,189	7,521
Rainfall recharge	21,265	
Total	**316,361**	**316,361**

The water balance can be further subdivided down by looking at defined areas. These areas are defined using the zone budget facility in the model. Most of the recharge (stream leakage) from the Lindis River is flowing to the Lower Tarras allocation zone in the section between the Ardgour Road flow site and the Lindis Crossing. From the Lindis Crossing to the confluence with the Clutha River/Mata-Au most stream leakage goes to the Bendigo Allocation Zone. The Bendigo allocation zone receives 4,590m^3/day in rainfall recharge and the Lower Tarras Allocation Zone receives 8,188m^3/day from rainfall recharge. These volumes are far less than the recharge from the Clutha River/Mata-Au (approximately 100,000m^3/day to each zone).

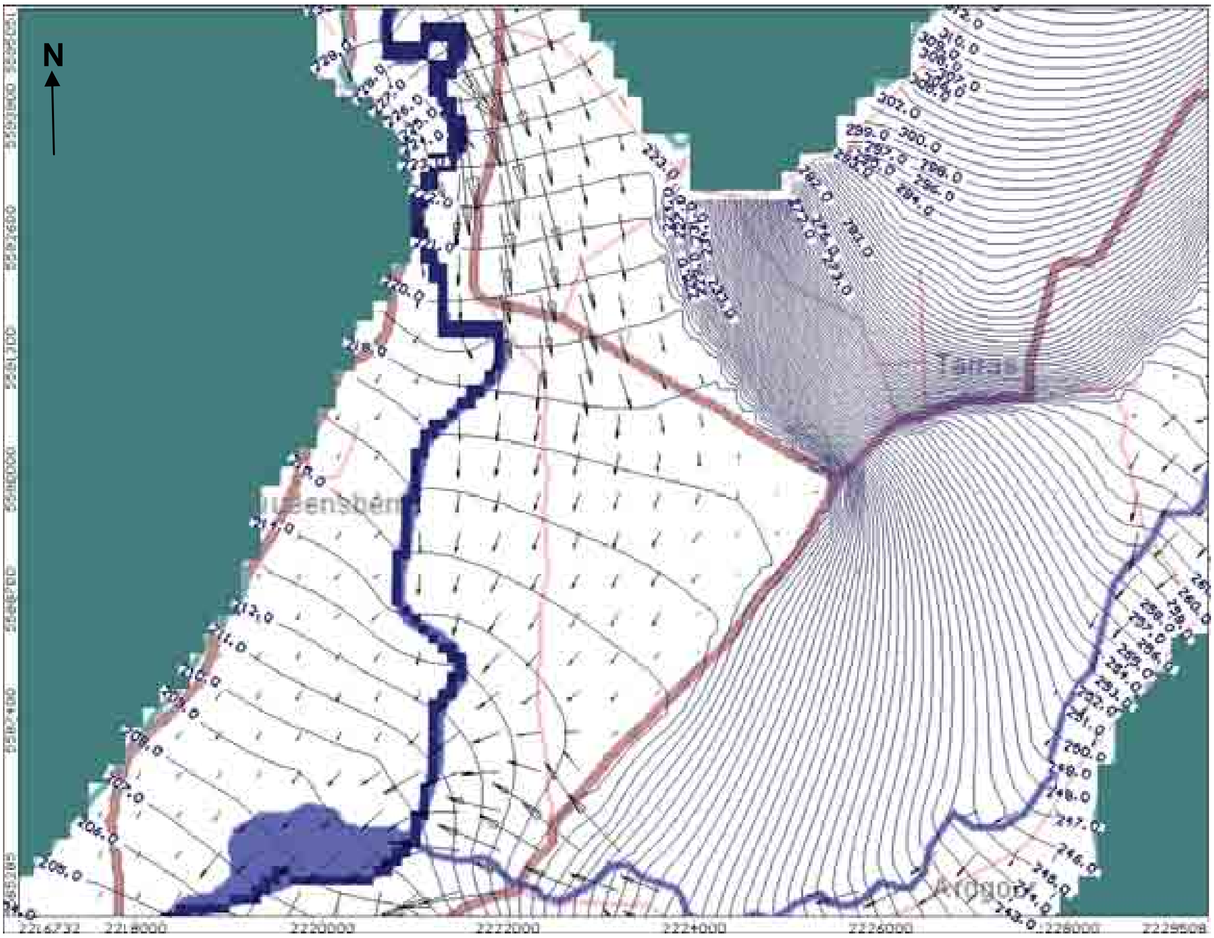

Figure 5.1 Tarras base scenario model contoured groundwater level (metres above mean sea level) and flow velocity vectors (arrow length is proportional to velocity and direction indicates groundwater flow direction)

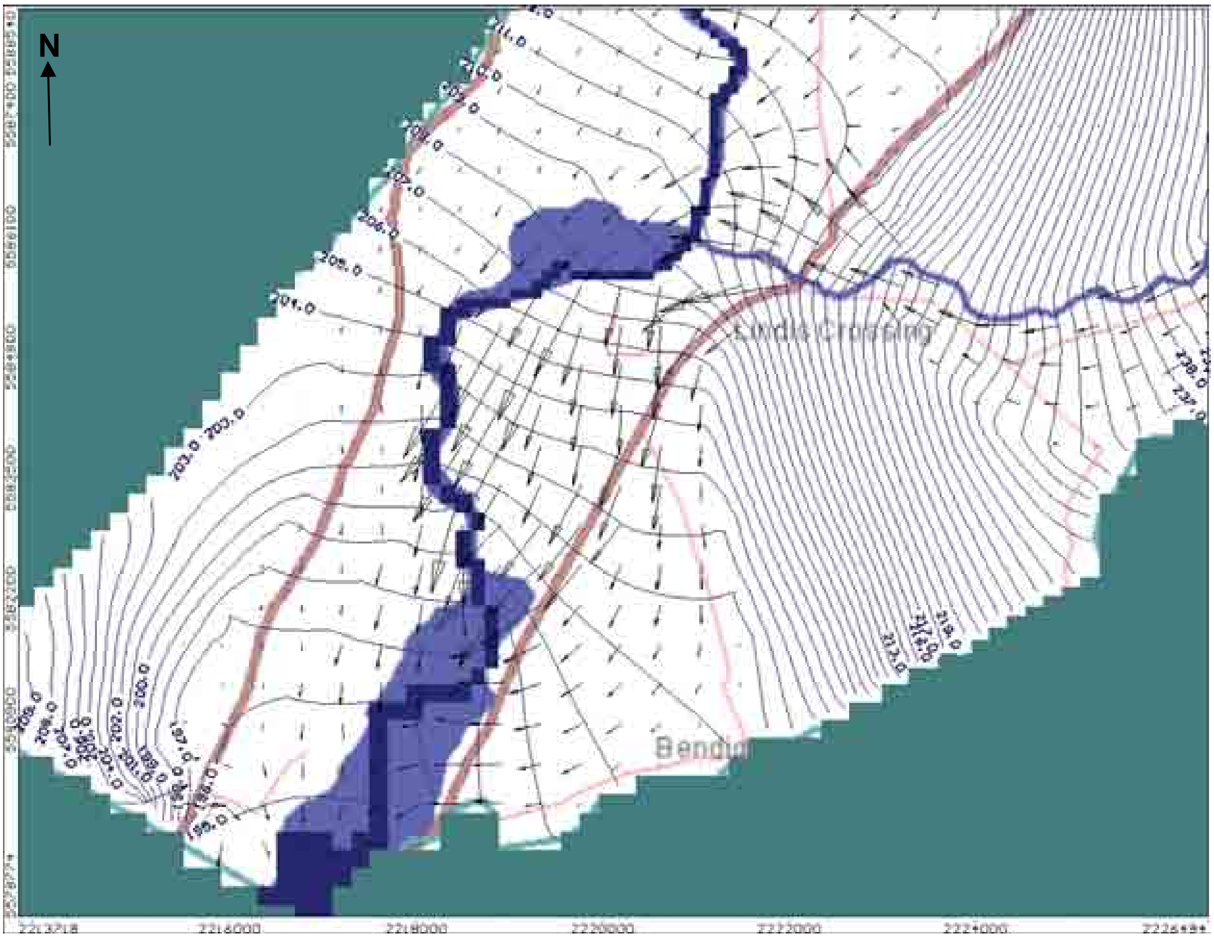

Figure 5.2 **Bendigo base scenario model contoured groundwater level (metres above mean sea level) and flow velocity vectors (arrow length is proportional to velocity and direction indicates groundwater flow direction)**

5.2 Scenario 2: Current allocation and December river flows

Scenario 2 has groundwater pumping at the maximum allowable allocation, river flows in both rivers at December levels, and the average annual rainfall recharge over the last ten years under irrigated and non-irrigated conditions.

In this scenario, the Lindis River is flowing at 403l/s at the confluence with the Clutha River/Mata-Au, which is 88l/s less than in the base scenario (Figure 5.3). This is under maximum pumping conditions as far as current allocation will allow. Actual impacts of groundwater pumping will therefore be much less, because many of the groundwater takes are not operating at rates close to the consented abstraction as yet.

It should be noted that the Lindis River flows vary greatly with surface water abstraction. These abstractions are not included in this groundwater model. The flow plots presented here (Figure 5.3, Figure 5.5 and Figure 5.6) show the impact of groundwater abstraction on river flows. The plots represent the Lindis River flow if there was no impact from surface water abstraction. The river has a continuous flow at the Ardgour Road flow site, even during summer, due to groundwater discharge to the river in this area. There are no consented surface water takes downstream of the Ardgour Road flow site, so the plots are appropriate for identifying the impact on flow downstream at this point as being solely due to groundwater abstraction.

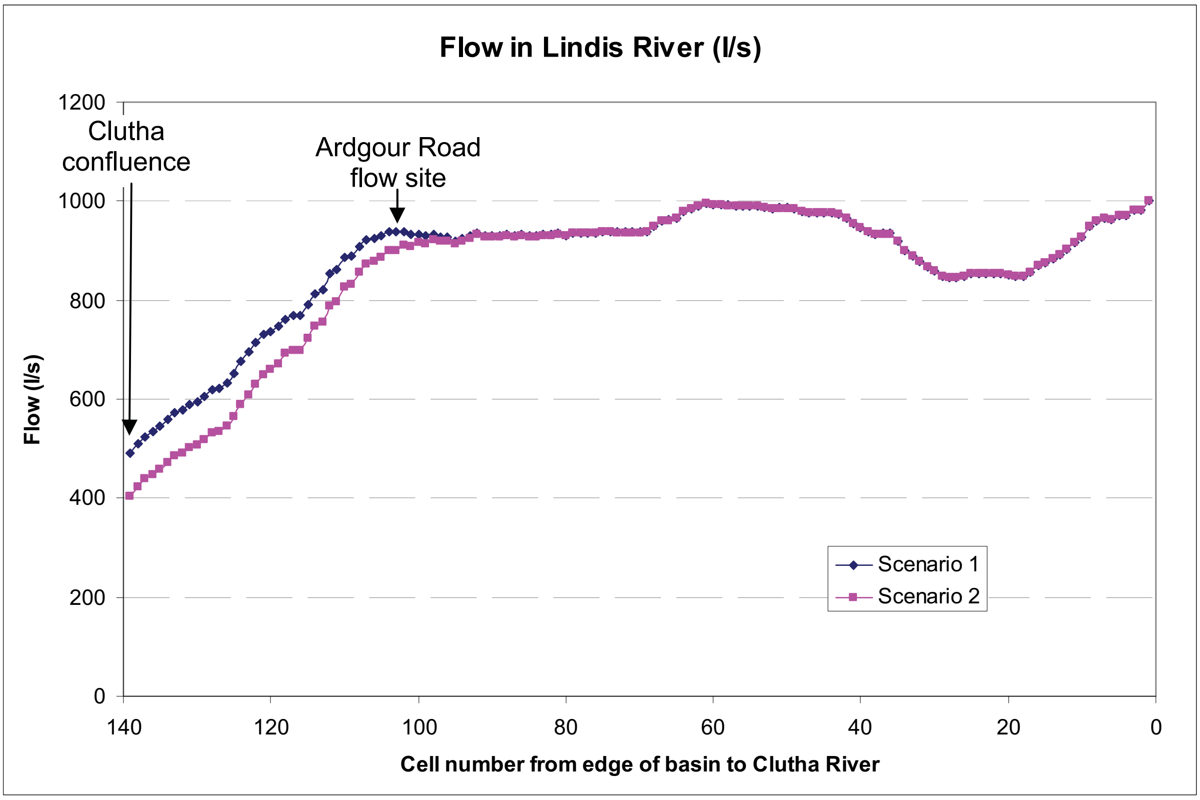

Figure 5.3 **Modelled flow in the Lindis River under Scenarios 1 and 2**

5.3 Scenario 3: Current allocation and low Lindis River flow conditions

Scenario 3 has the Lindis River at a lower flow rate (500l/s) to reflect early irrigation season flow conditions and it has current allocation pumping rates from the pumping wells. Figure 5.4 indicates that current levels of consented groundwater pumping leads to groundwater drawdown has an impact of up to 0.5m in the lower reaches of the Lindis River. Modelling also shows that the Lindis River dries out over about 500-600m before reaching the confluence with the Clutha River/Mata-Au (Figure 5.5). Scenario 3A was run by turning off the pumping bores in the lower reaches of the Lindis River. The two bores that were switched off were Davidson G41/0316 and Perriam G41/0230, located between Lindis Crossing and the Clutha River/Mata-Au confluence. The impact of turning off these two pumping wells was approximately 200m less dry stream bed occurring before the confluence and additional flow in the river of 25l/s.

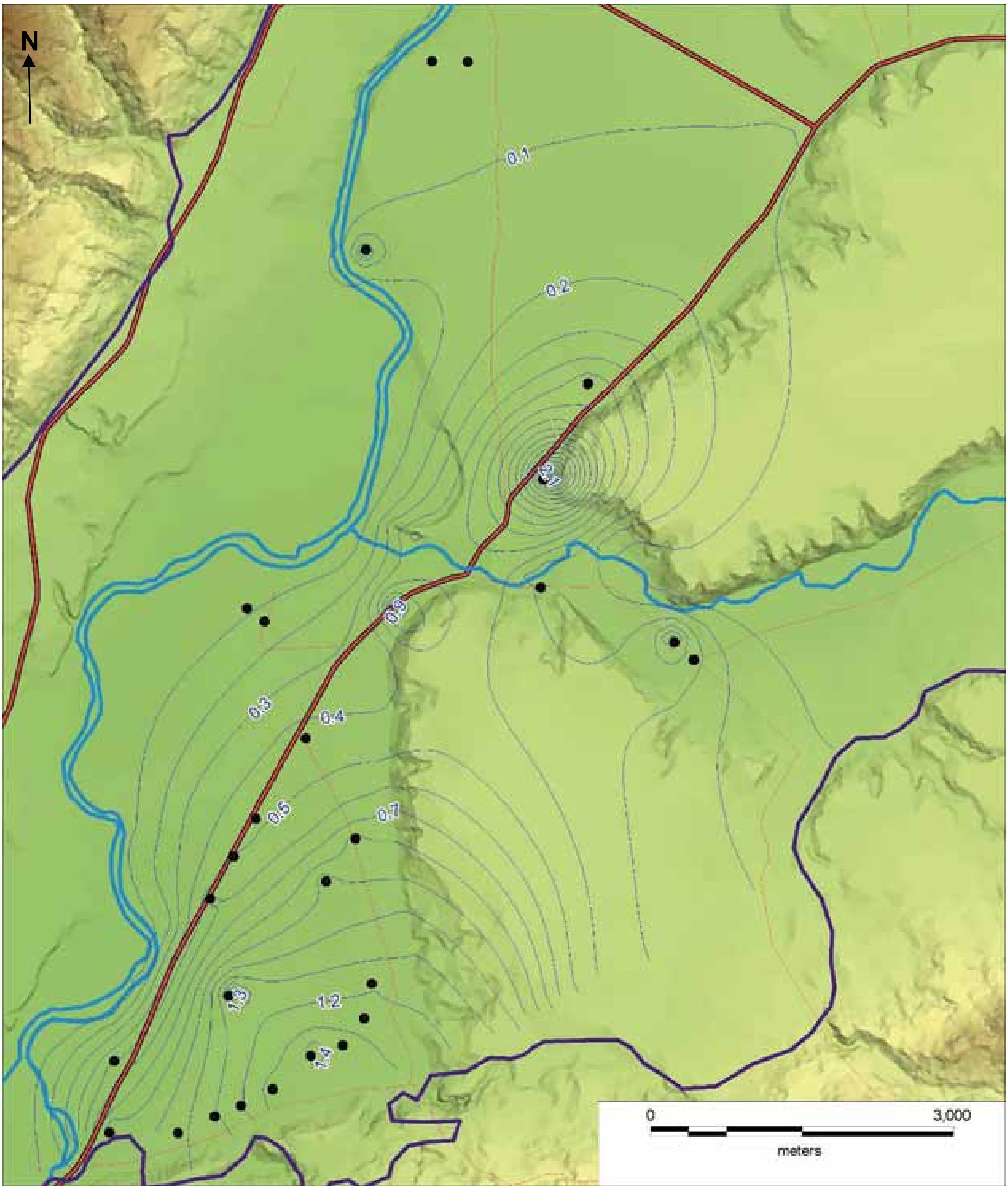

Figure 5.4 **Drawdown of water table caused by pumping at current allocation limits during low flow conditions in the Lindis River (500l/s). Position of pumping bores shown by black points**

5.4 Scenario 4: No groundwater pumping and low Lindis River flow conditions

Scenario 4 was run to show the effect of no groundwater pumping during low flows. Flow at the edge of the basin is 500l/s and by the Ardgour Road flow site the flow is 438l/s. Figure 5.5 shows that, without the impacts of groundwater pumping, the Lindis River flows nearly to the confluence with the Clutha River/Mata-Au. The impact of groundwater abstraction in this area is crucial for maintaining river flow through to the Clutha River/Mata-Au. Figure 4.9 and Figure 4.10 show monitored groundwater levels between the Lindis crossing and the confluence falling significantly once the Lindis River flow is below 450l/s at the Ardgour Rd flow site. The model also shows the groundwater levels falling by 0.5m in the lower Lindis River reach area when flow is reduced to 438l/s at Ardgour Road flow site.

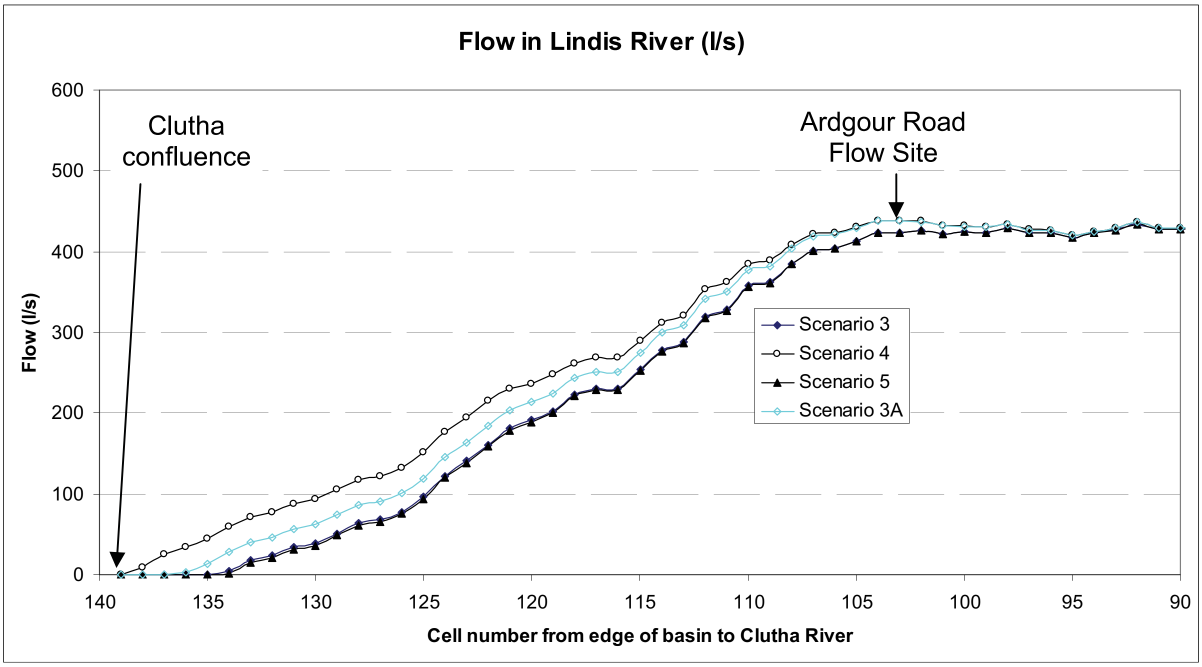

Figure 5.5 **Modelled flow in the Lindis River between the Ardgour Road flow site and the Clutha confluence under four different scenarios. Note: Scenarios 3 and 5 are overlapping**

The impact of even lower flows was further investigated during modelling. If the initial river flow was 200l/s, the flow at the Ardgour Road flow site was 130l/s and the river was dry within 1km downstream. This also reflects conditions seen in the field during most irrigation seasons.

The model was also tested at 800l/s input at the edge of the basin. The flow in the Lindis River reduces to 740l/s at Ardgour Road flow site, which resulted in continuous flow to the Clutha River/Mata-Au confluence (Figure 5.6).

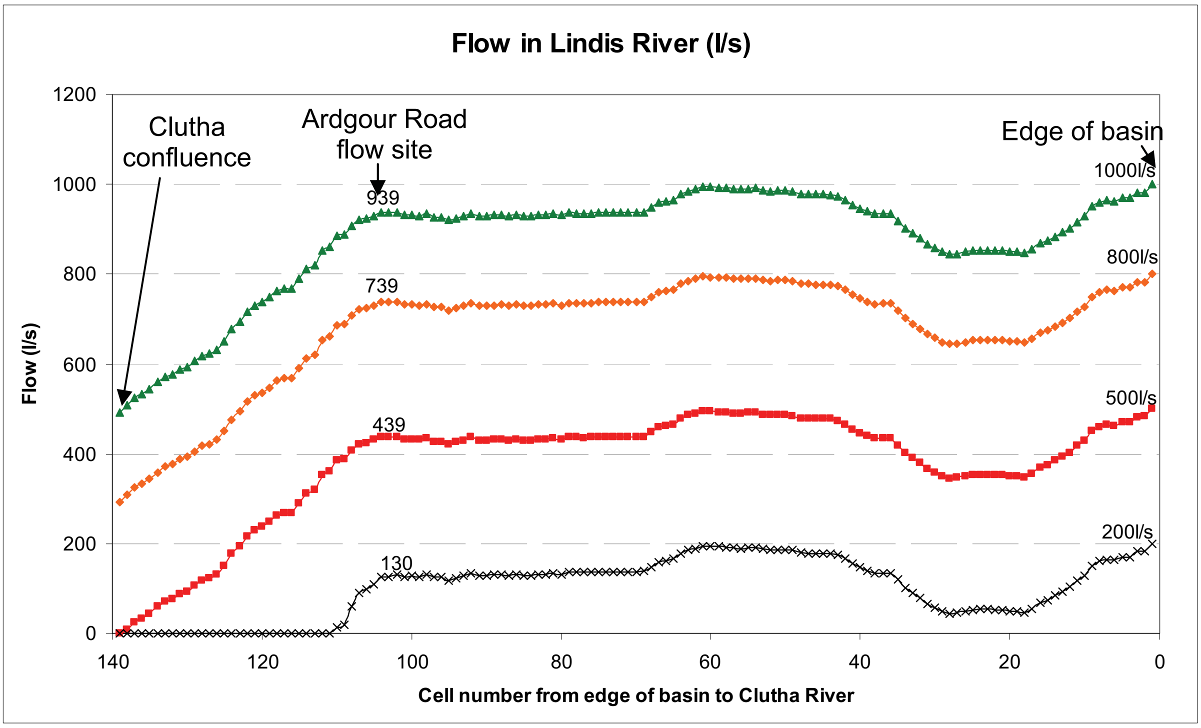

Figure 5.6 **Modelled Lindis River flows at various input flows at the edge of the groundwater basin**

5.5 Scenario 5: Double allocation and low Lindis River flow conditions

Scenario 5 had double the current groundwater pumping allocation, with the exception of those bores close to the Lindis River, which were left at current allocation, low flow conditions in the Lindis River (500l/s) and rainfall recharge conditions over the last ten years. The rainfall recharge was based on data of the past ten years, as this period was drier and therefore more conservative to use. The Clutha River/Mata-Au data were based on December flows.

The results can be looked at in terms of a water balance (Table 5.3 and Figure 5.7). The Clutha River/Mata-Au is shown to be the major recharge source to the aquifer system; whereas, rainfall recharge represents only 5% of the total inflow to the aquifer.

Table 5.3 **Water balance for Bendigo-Tarras groundwater system under Scenario 5**

Flow Component	Inflows (m^3/day)	Outflows (m^3/day)
Rivers: Lindis River and Clutha River/Mata-Au	 60,105 284,801	 16,905 208,634
Drains (spring)		6,609
Pumping bores		153,428
Constant head	26,398	6,993
Rainfall recharge	21,265	
Total	**392,569**	**392,569**

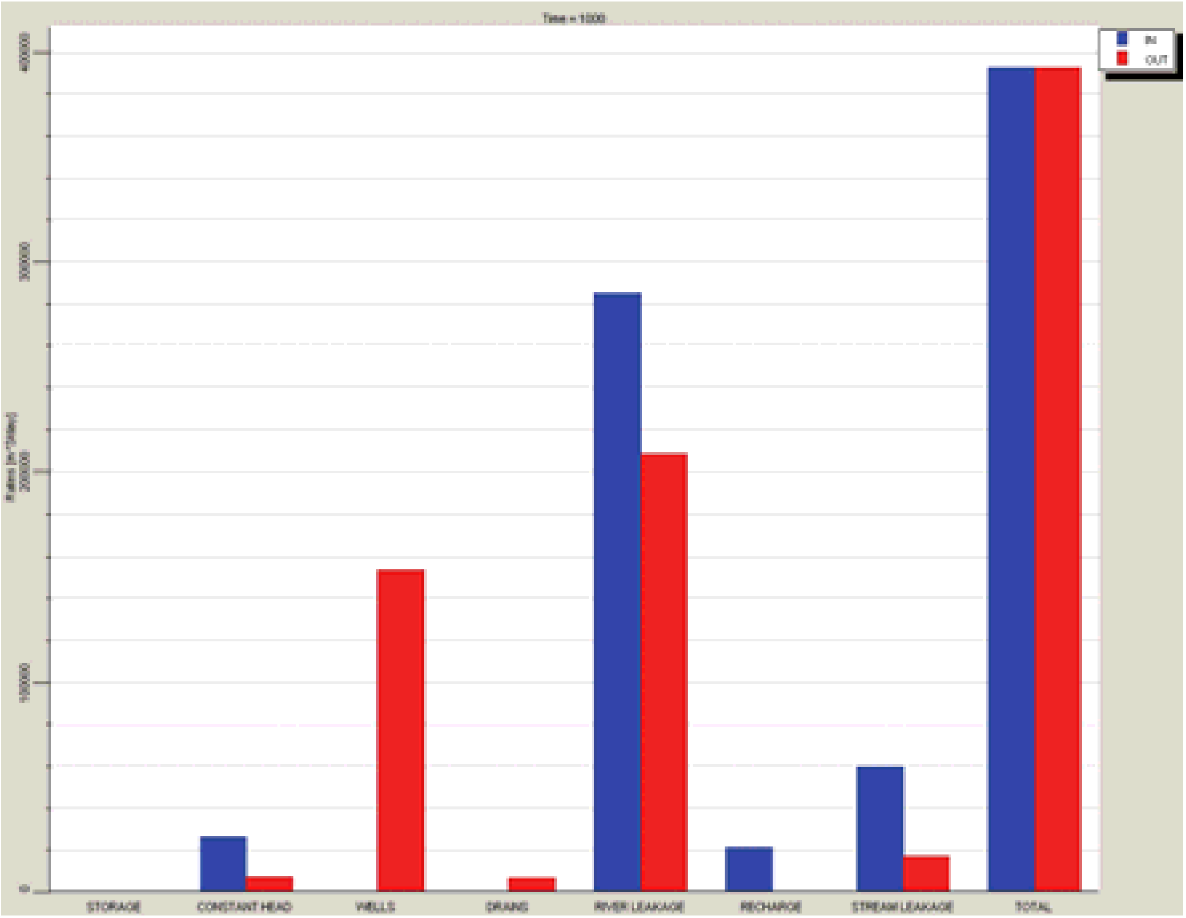

Figure 5.7 Water balance for Bendigo-Tarras groundwater basin showing inflow in blue and outflow in red

The effect of doubling the allocation outside the Ardgour Valley created some additional drawdown, particularly on the southern edge of the Bendigo allocation zone (Figure 5.7). However, the resulting drawdown was still less than 3m in total. There were no additional impacts on the Lindis River flows since pumping in the Ardgour Valley was not increased (Figure 5.4).

Traditional methods to determine groundwater allocation are based on set proportions of mean annual recharge (e.g. 50% recharge). Using this method annual allocation could be considered as 60.7Mm^3/year (365 x 166,236m^3/day). This is based on an average annual recharge of 332,471m^3/day for 365 days of the year. However, in this case, as allocation is increased, the amount of river recharge increases, which leads to even more potential allocation. There are two other limitations when using this scenario to investigate allocation limits. When doubling the current allocation, it unfairly divides the groundwater pumping between the Bendigo and Tarras allocation zones and it investigates only the current distribution of pumping bores.

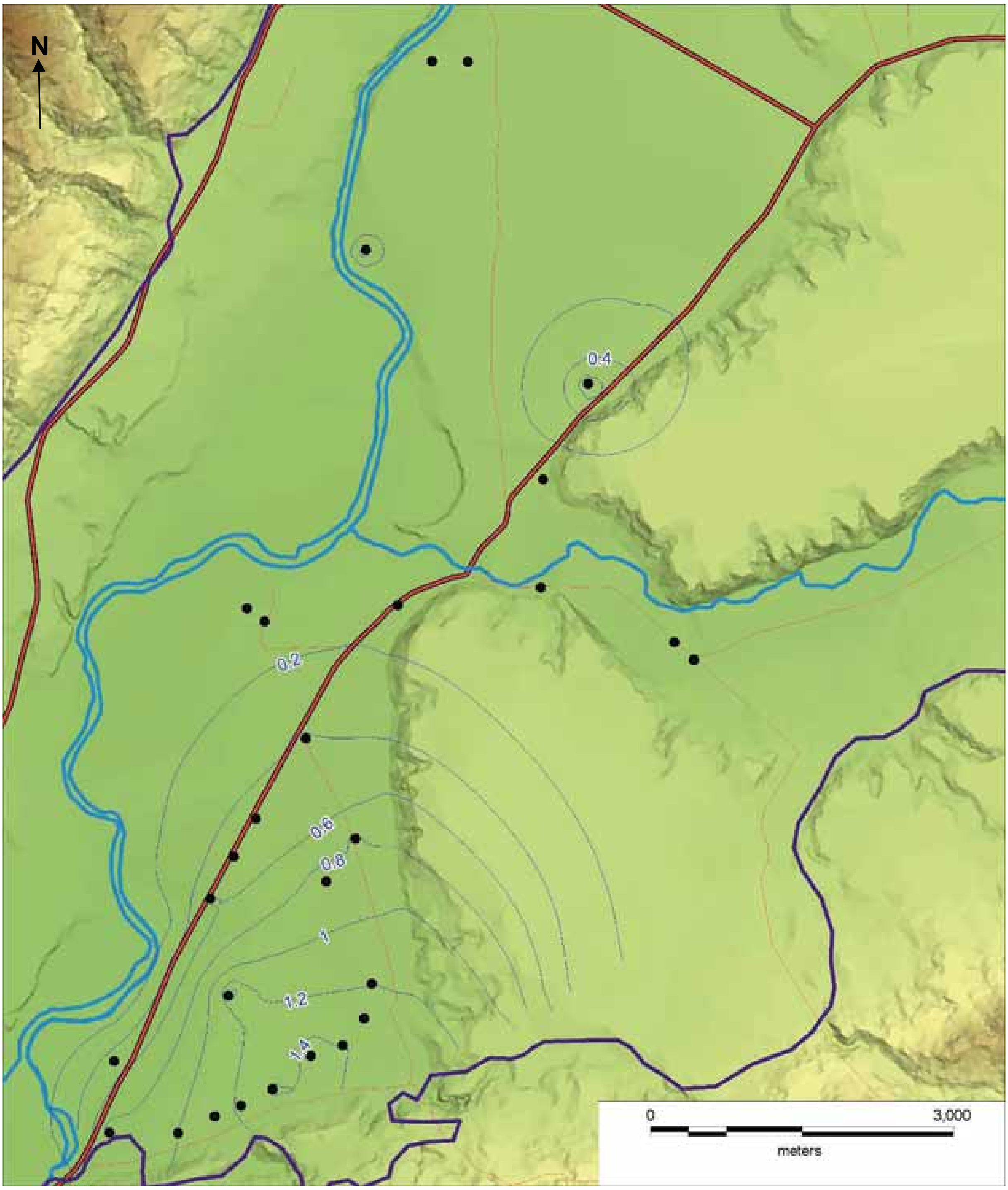

Figure 5.8 **Contours of modelled additional groundwater drawdown caused by doubling the groundwater pumping (difference between scenario 5 and 3)**

5.6 Scenario 6: Maximum pumping to drop groundwater levels by approximately 2m drawdown

In Scenario 6, the aquifer is artificially dropped to a determined level in each of the two main allocation areas. The amount of groundwater abstraction required to drop the levels is then determined. In this scenario, the Lindis River is flowing at 500l/s at the edge.

A drop in groundwater levels of approximately 2m is considered appropriate for the area, given the high hydraulic conductivity, aquifer thickness and connection with the surrounding rivers. A series of virtual pumping wells was added as "drain cells" to the model, with levels at approximately 2m below scenario 4 levels (no pumping conditions). The pumping wells were spread evenly across the allocation zones and levels reflected the gradients seen in the water table under non-pumped conditions. A buffer without wells was given to the surrounding rivers, as this reflects ORC policies in terms of restricting groundwater takes close to rivers and their effects on stream depletion.

The volume of water pumped out of the Lower Tarras allocation zone to give a 2m groundwater level drop was 102,920m^3/day, equivalent to **37.6Mm^3/year**. In this scenario the river recharge from the Clutha River/Mata-Au in the Tarras stretch is 187,694m^3/day. The volume pumped from the Bendigo allocation zone was 159,210m^3/day or **58.1Mm^3/year**. Recharge from the Clutha River/Mata-Au in the Bendigo aquifer area was 160,120m^3/day.

Cumulative groundwater abstraction created some drawdown in the vicinity of the lower Lindis River. The combined effect from pumping in both aquifers north and south of the lower Lindis River created a drawdown of up to 0.3m (Figure 5.8). The simulated effect on the flow in the Lindis River was approximately 19l/s additional flow loss and an additional drying of the stream bed close to the Clutha River/Mata-Au of up to 100m. However, this effect is at the limit of the model's accuracy.

Scenario 6 represents an extreme level of groundwater abstraction to the point at which the flow in the Lindis just starts to be affected. There are some unknowns in the groundwater system (e.g. hydraulic conductivity in areas not tested/drilled). In reality, bores are not uniformly distributed-rather distribution of groundwater abstraction is patchy, depending on land uses and property boundaries. Therefore, some caution should be taken when applying this scenario to the actual recommended limits to groundwater abstraction. This is discussed further in Section 6.

The recharge to a third allocation zone was investigated under this scenario. The allocation of most groundwater within the Ardgour Valley is controlled by the ORC Regional Plan: Water rules regarding alluvial ribbon aquifers. Groundwater takes within the Lindis alluvial ribbon aquifer are from the gravels close to the river and are treated as surface water takes with restrictions imposed during low river flows. However, there are some areas within the Ardgour Valley that contain groundwater, but are not within the alluvial ribbon aquifer. This area was classified in the model as another zone budget. The amount of land surface recharge to this area has been calculated as 1039m^3/day. This is equivalent to **379,235m^3/year**.

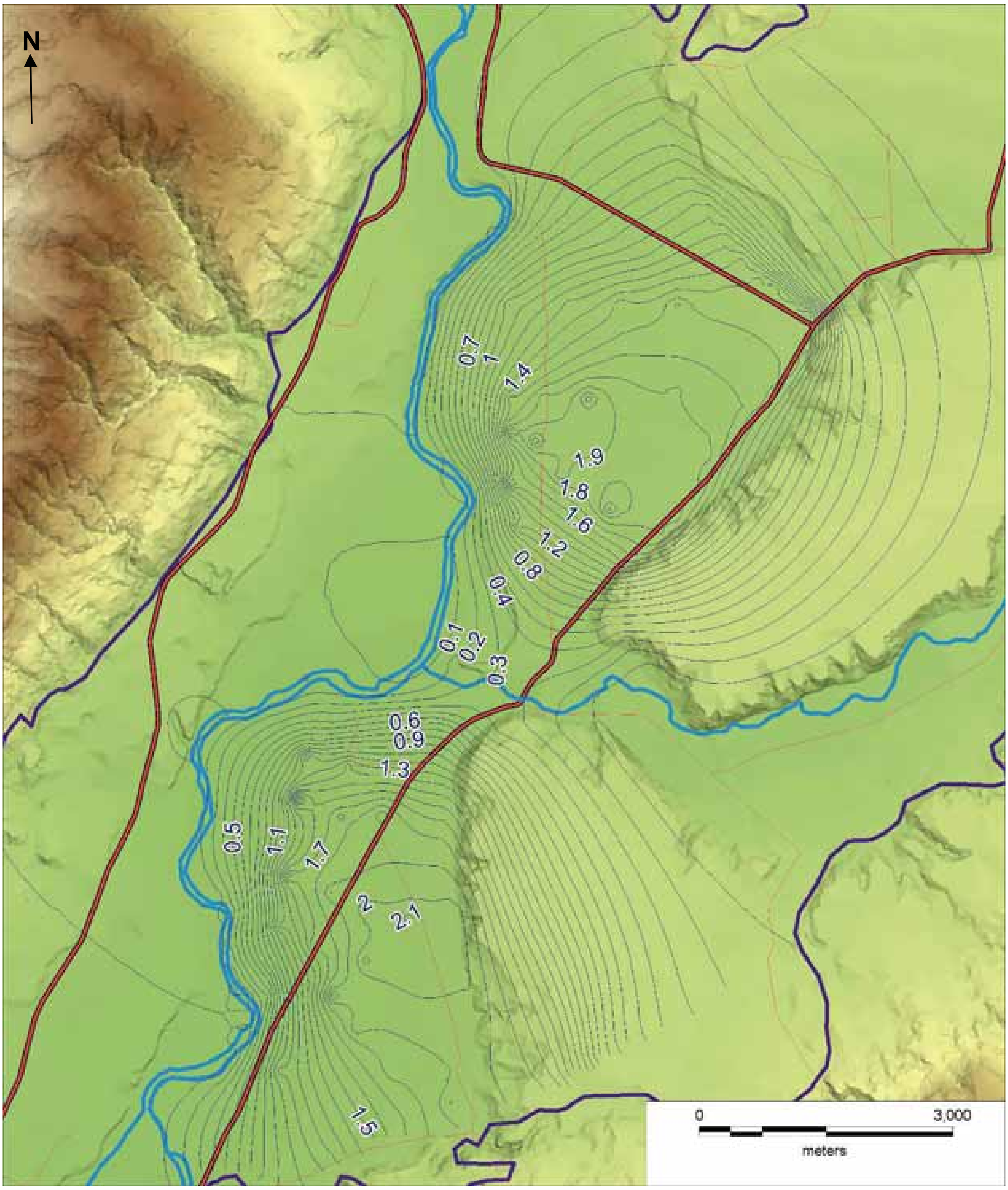

Figure 5.9 Drawdown under scenario 6, where a drawdown of approximately 2m is imposed on the model

5.7 Summary of modelling results

The dominant recharge source to the Lower Tarras and Bendigo allocation zones is the Clutha River/Mata-Au. The impact of groundwater pumping on the lower Lindis River depends on the location of the abstraction points. If the river is given a reasonable buffer, a large volume of groundwater can be pumped without affecting river flows.

6. Groundwater management recommendations

6.1 Allocation limit

The recommended allocation limit takes into account the increased knowledge of how the Bendigo-Tarras groundwater system operates; how it responds to increased pumping, flow loss contributions from the surrounding rivers; and the extent and permeability of the aquifer system from geophysical information. The previous groundwater study in the area did not take into account the large volumes of recharge water from the Clutha River/Mata-Au when recommending allocation limits. The modelling undertaken in this study has emphasised the importance of this recharge source. Therefore, allocation limits are significantly higher than the previous estimates.

As the amount of groundwater abstraction is increased, the aquifer system responds by increasing the amount of recharge from the Clutha River/Mata-Au. Therefore, traditional methods of determining allocation by a proportion of recharge were unsuitable. By limiting drawdown to a level that is considered appropriate, an annual volume of groundwater abstraction can be determined. These figures should be considered as an absolute maximum, as they do not take into account the actual distribution of pumping bores. Also, the aquifer properties are uncertain in some areas. A conservative approach is recommended by using 50% of the calculated maximum abstraction.

The recommended limit for groundwater abstraction from the Lower Tarras allocation zone is **18.8Mm^3/year** and for the Bendigo allocation zone it is **29Mm^3/year**. Current consented allocation is only 12% of the Lower Tarras allocation zone recommended limit, and only 13% of the Bendigo Allocation Zone recommended limit.

A buffer zone around the lower reach of the Lindis River should be effectively covered by recent changes to the Regional Plan: Water (Plan Change 1C). However, for more clarity on the location of the buffer, the Lindis alluvial ribbon aquifer could be extended from the Ardgour Valley right down to the Clutha River/Mata-Au confluence. This would also protect the lower reaches from any cumulative impacts of several small groundwater takes in the area.

Groundwater takes within the Lindis alluvial ribbon aquifer are from the gravels close to the river, and are treated as surface water takes with restriction imposed during low river flows. However, there are some areas still within the Ardgour Valley that contain groundwater and are not within the alluvial ribbon aquifer. This area has a land surface recharge of 379,235m^3/year. It is proposed that 50% of this recharge can potentially be allocated. The recommended allocation limit is **189,600m^3/year**.

Outside the allocation zones mentioned above, there are only a few consented groundwater takes. These are concentrated on the west side of the Clutha River/Mata-Au. Takes within this area are buffered by recharge from the Clutha River/Mata-Au. Abstraction will be balanced by induced river recharge. If there is further drilling to the western side of the basin for irrigation water, the groundwater model can be further refined to investigate allocation limits for this area. There is presently not enough information on the hydraulic properties of the aquifer on the western side of the basin to accurately define an annual limit. The Tarras settlement area has limited groundwater availability due to the local lithology, which restricts the abstraction to small quantities under the permitted volume of 25,000 litres per landholding per day.

6.2 Monitoring

This study was limited by the absence of long-term groundwater monitoring data. Temporal groundwater level data can be used to study the aquifer's response to recharge and pumping. Also, more detailed groundwater modelling can be achieved. Groundwater levels fluctuate seasonally, but also show underlying long-term trends in response to pumping. If there is an imbalance between recharge and annual allocated abstraction, the groundwater levels can slowly drop by recovering each year to a slightly lower maximum level.

The study's recommendation is that investigations into locating a groundwater level monitoring site in the central Bendigo allocation zone area should be carried out.

7. References

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Appendix A Bore survey data

Thirty-five bores and nineteen river sites were used as water level monitoring sites for the study. The river levels were taken once in December 2009 and the bore water levels were monitored three times: September 2009, December 2009 and March 2010.

In late November 2009, a survey of water elevations at 19 bores and 16 river sites was carried out for elevation data for the Clutha River/Mata-Au and Lindis River and to obtain elevation data for those bores without ground elevation data (Figure A.1).

Figure A.1 Groundwater level monitoring bore sites surveyed in November 2009 shown as green points. Blue points indicate location of surveyed river levels

Water levels on the rivers and bore elevation data were collected on 30th November 2009. Bore static water levels were monitored on 1st and 2nd September, and on 8th December 2009 (Table A.1). Levels in red were recorded on 23rd December as the bores were being pumped for irrigation on 8th December.

Table A.1 Monitored water levels and GPS location data in NZMG for all points surveyed

NAME	EASTING	NORTHING	HEIGHT	September 2009		December 2009		March 2010	
				Static water level (m)	Water level amsl	Static water level (m)	Water level amsl	Static water level (m)	Water level amsl
G40/0175	2226441.95	5591277.82	277.97	-3.05	274.92	-2.85	275.12	-2.77	275.2
G40/0177	2221666.31	5590571.77	244.4	-27.36	217.04	-28.06	216.34	-28.025	216.375
G40/0251	2221851.84	5590851.9	242.5	-24.97	217.53	-25.73	216.77	-25.61	216.89
G40/0265	2221075.42	5593030.69	242.72	-20.45	222.27	-21.52	221.2	-21.68	221.04
G40/0268	2223142.18	5591276.93	249.19	-29.4	219.79				
G41/0123	2218140.83	5579585.18	197.11	-2.235	194.875	-2.57	194.54	-2.65	194.46
G41/0129	2221378.03	5585219.07	222.04	-11.01	211.03	-11.85	210.19	-12.6	209.44
G41/0174	2224618.78	5588642.02	245.5	-19.13	226.37	-19.59	225.91	-19.48	226.02
G41/0190	2219833.31	5585157.94	208.60	-1.18	207.415	-1.71	206.885	-1.84	206.755
G41/0191	2219061.24	5583326.47	202.56	-0.98	201.583	-1.33	201.233	-1.56	201.003
G41/0203	2219509.68	5580134.59	218.16	-20.61	197.552	-20.8	197.362	-20.98	197.182
G41/0206	2220775.27	5580838.35	229.43	-28.665	200.762	-30.18	199.247		
G41/0207	2219145.87	5579967.31	212.43	-15.67	196.756	-15.93	196.496		
G41/0211	2223141.8	5588813.89	243.63	-26.73	216.9	-27.01	216.62	-26.71	216.92
G41/0225	2220989.61	5581106.36	231.69	-30.5	201.19	-28.36	203.33	-30.61	201.08
G41/0228	2218468.82	5579975.29	196.45	-0.92	195.53	-1.28	195.17	-1.43	195.02
G41/0229	2220415.58	5583877.04	225.33	-21.35	203.98	-21.62	203.71	-21.78	203.55
G41/0230	2219646.14	5581327.50	211.57	-12.8	198.77	-12.9	198.67		
G41/0236	2220931.36	5585312.90	216.71	-7.41	209.3	-7.98	208.73	-8.41	208.3
G41/0262	2220462.41	5580731.16	227.38	-27.32	200.058	-27.2	200.178	-27.54	199.838
G41/0269	2219699.76	5582704.57	217.76	-16.655	201.106	-16.8	200.961	-17.025	200.736
G41/0270	2220265.31	5581750.07	221.46	-21.14	200.32	-21.16	200.3	-21.375	200.085
G41/0271	2219466.16	5582291.67	208.84	-8.98	199.856	-9.73	199.106		
G41/0282	2220615.55	5582460.14	221.7	-20.46	201.24	-20.51	201.19	-20.66	201.04
G41/0283	2220903.99	5582881.66	231.88	-29.29	202.59	-29.36	202.52	-29.5	202.38
G41/0304	2221013.37	5588708.4	220.13	-5.18	214.95	-5.85	214.28	-5.98	214.15
G41/0308	2220009.87	5585033.57	215.79	-9.47	206.32	-9.95	205.84	-10.11	205.68
G41/0313	2223204.6	5587379.02	241.11	-25.37	215.74	-25.55	215.56	-25.575	215.535
G41/0315	2219919.42	5583082.57	218.66	-16.58	202.08			-16.92	201.74
G41/0316	2222760	5586434	238.67	-20.36	218.31				
G41/0342	2222789.54	5586382.49	239.31			-22.48	216.83	-23.66	215.65
G41/0332	2221064.48	5581438.87	230.32	-28.87	201.447			-28.98	201.337
G41/0345	2220290.89	5585025.26	218.15	-11.78	206.37	-12.2	205.95	-12.38	205.77
G41/0372	2220736.46	5584583.97	223.67	-17.835	205.835	-18.24	205.43	-18.47	205.2
G41/0375	2222482.39	5588554.14	244.07	-28.96	215.11	-29.4	214.67	-29.325	214.745
LINDIS A	2220859.55	5585938.14	209.51				209.51		
LINDIS A1	2221168.05	5585806.47	212.23				212.23		
LINDIS B	2222056.34	5585557.17	217.09				217.09		
LINDIS C	2222754.73	5585474.53	219.33				219.33		
LINDIS D	2223850.55	5585227.01	226.91				226.91		
CLUTHA A	2217895.69	5579567.89	194.35				194.35		
CLUTHA B	2218833.42	5581539.24	196.69				196.69		
CLUTHA C	2218484.3	5584244.03	201.57				201.57		

NAME	EASTING	NORTHING	HEIGHT	September 2009		December 2009		March 2010	
				Static water level (m)	Water level amsl	Static water level (m)	Water level amsl	Static water level (m)	Water level amsl
CLUTHA D	2219395.07	5585599.03	206.48				206.48		
CLUTHA E	2220035.72	5585593.3	208.23				208.23		
CLUTHA F	2221265.45	5587506.2	211.67				211.67		
CLUTHA G	2220787.8	5588868.91	214.7				214.7		
CLUTHA H	2221727.76	5590934.7	218.1				218.1		
CLUTHA I	2221048.15	5593073.44	221.67				221.67		
CLUTHA J	2220515.75	5596273.93	232.27				232.27		
CLUTHA K	2219768.53	5598548.63	236.85				236.85		

Flow in Lindis River and Clutha River/Mata-Au in comparison with water level monitoring dates

The river levels in the Clutha River/Mata-Au and flow in the Lindis River are highlighted by circles in Figures A.2 – A.4 for 1st and 2nd September, 30th November, 8th December and 23rd December, when water level readings were taken on bores or rivers. It should be noted that river levels and flows were much higher for both rivers during September. However, levels and flows were similar during monitoring in November/December 2009.

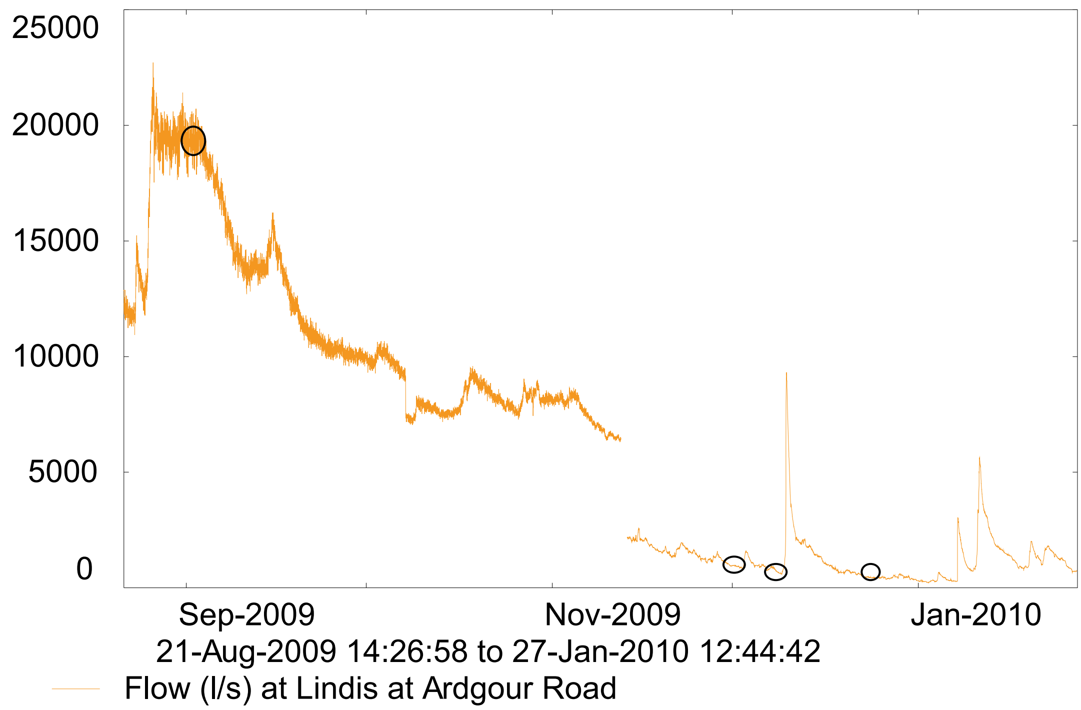


Figure A.2 River flows in the Lindis River between August 2009 and January 2010

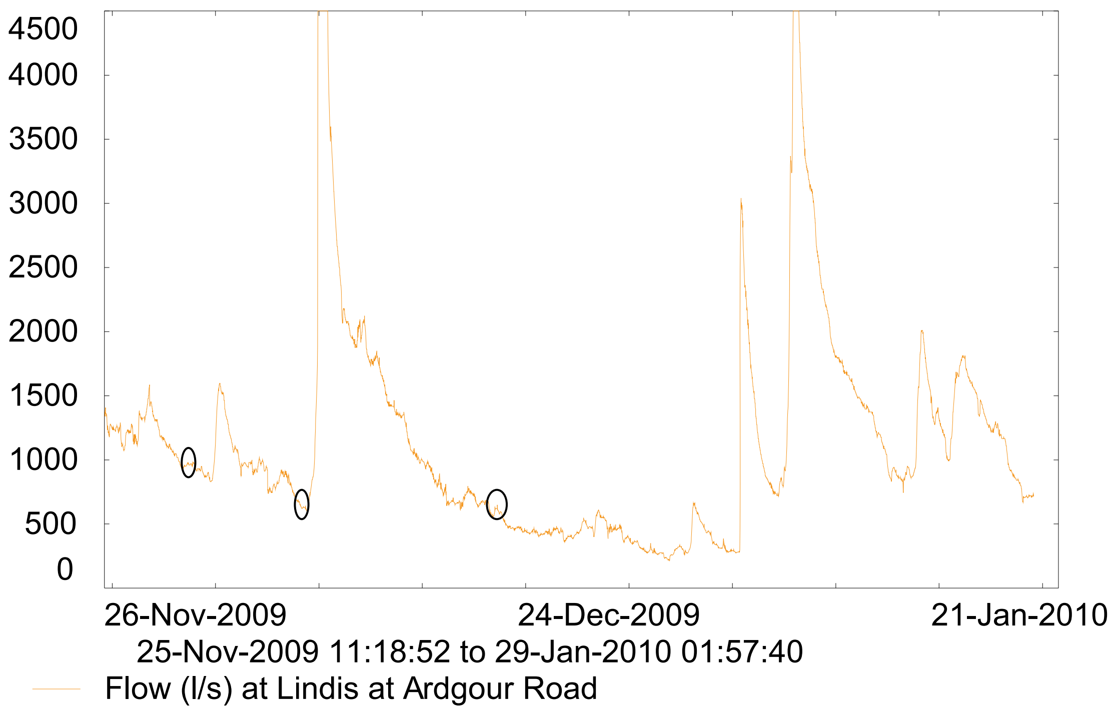


Figure A.3 **Flow in the Lindis River between November 2009 and January 2010**

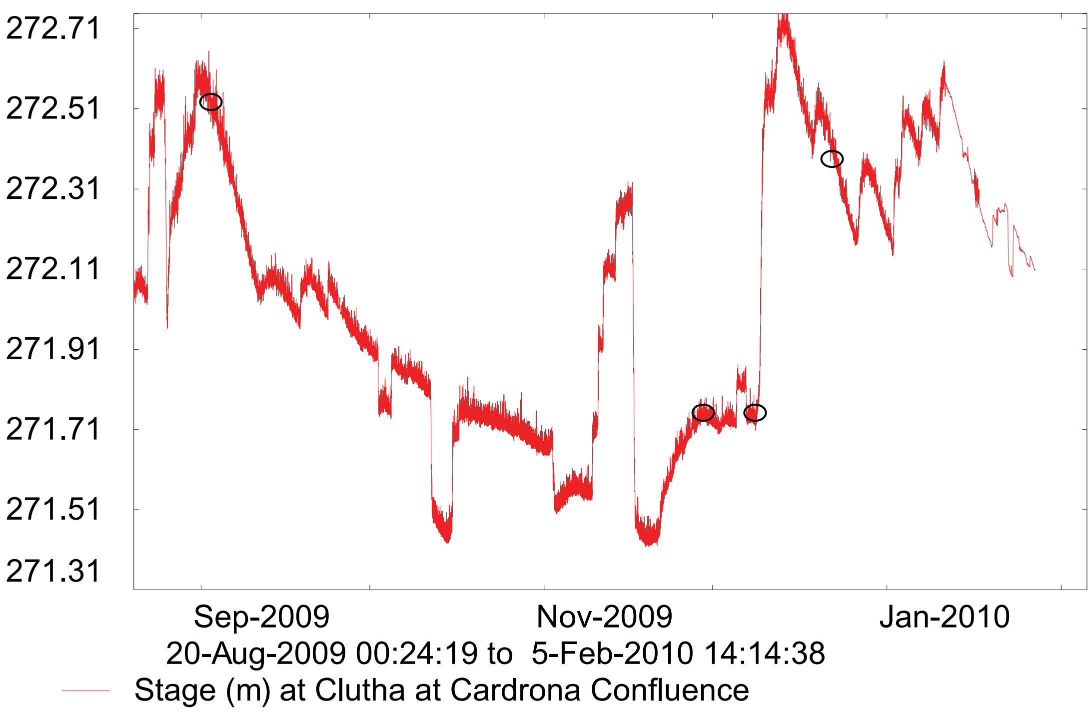


Figure A.4 **Stage height in the Clutha River/Mata-Au between August 2009 and January 2010**

Appendix B Recharge modelling

To estimate the quantity of water migrating through the soil zone down to the water table, a soil moisture balance method was used. This method is based on the assumption that the soil becomes free-draining once the moisture content reaches a threshold value (field capacity). Excess water above this threshold becomes groundwater recharge. The Rushton *et al.* (2006) method was used for the study area. It estimates recharge using daily soil moisture balance based on a single soil store. Actual evapotranspiration is calculated in terms of readily and total available water. These are parameters of the soil properties and rooting depth. The model also takes into account near-surface soil storage, which allows some water to be held close to the surface to enable potential evapotranspiration on days following heavy rainfall, even when soil at depth is dry.

The base data that was required included daily climatic data (rainfall and evapotranspiration) soil properties (field capacity and wilting point) and crop rooting depth. The USDA Soil Conservation Service (SCS) runoff curve number was used to account for runoff. The hydraulic parameters for each of the soil recharge zones are given in Table B.1.

Parameters and model inputs

Rainfall

Daily rainfall values were taken from a NIWA-operated climate station in Cromwell. The Cromwell site is the closest site with a significant length of record. It has daily rainfall records beginning in 1949. However, data was used from February 1985 to January 2010 to match with evapotranspiration data. There were some small gaps in the data, which were filled with data from a NIWA Queensbury climate site.

Potential Evapotranspiration

Penman Monteith calculated potential evapotranspiration (PET) from NIWA Lauder EWS between February 1985 and January 2010. This site was chosen as it has a significant length of record. Although it is located some 33km from the study area, it has similar climate conditions (Figure B.1 and Figure B.2). The PET of Lauder and Cromwell were compared for the period from 2006 to 2009 and found to experience similar PET. Any small gaps in the data were filled with average daily values for the season over which the gap has occurred.

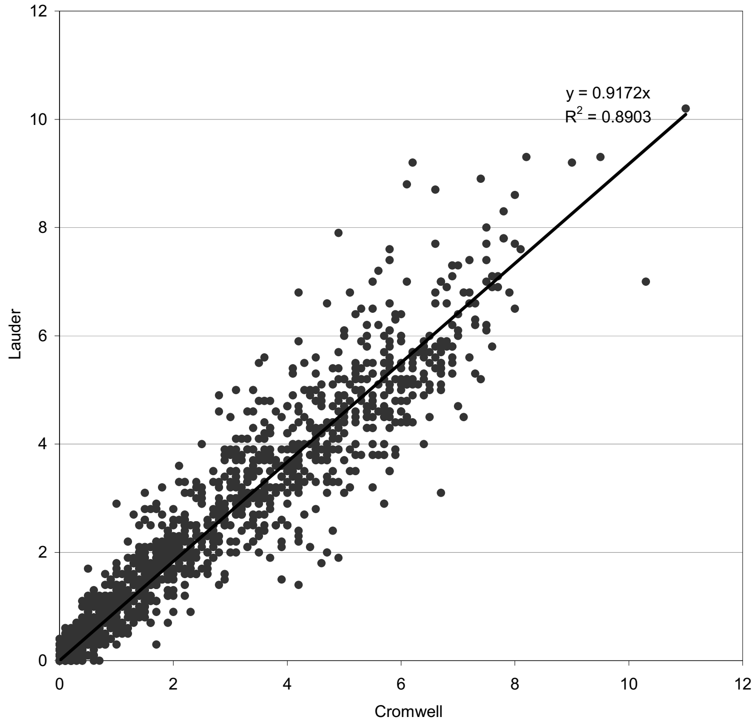


Figure B.1 **Comparison of potential evapotranspiration in Lauder and Cromwell for the three-year overlapping time period of 2006 to 2009**

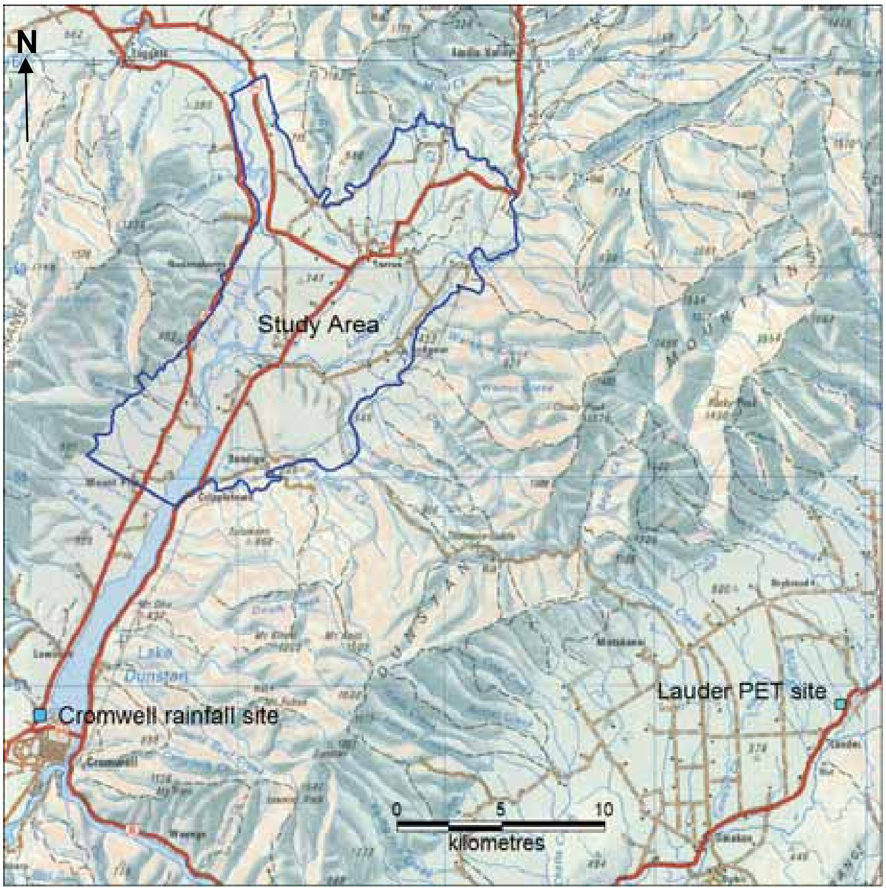


Figure B.2 **Rainfall and potential evapotranspiration sites in comparison with the study area**

SCS curve number:
A curve number needs to be estimated for each soil, which is then used to calculate maximum soil retention of runoff. Lower curve numbers result in higher soil retention thresholds, which induce less runoff. Pasture in good condition on free draining soil has a low curve number (40). Pasture in poor condition on a poorly drained soil has a high curve number (90). The Otago model assumes that slope is always less than 5 degrees, and soil moisture is not considered.

Total Available Water (TAW)
TAW is calculated from field capacity (FC), wilting point (WP) and rooting depth data.

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

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

Table B.1 Soil recharge zones and associated hydraulic parameters

Recharge zone	FC	WP	TAW	TAW_RANGE	RAW	DRAINAGE	SCS
Zone 1	25	10	15	0-50	15	W	40
Zone 2	30	10	20	0-50	14	W	40
Zone 3	40	10	30	0-80	21	W	45
Zone 4	80	30	50	30-80	30	W	45
Zone 5	90	30	60	40-80	36	W	50
Zone 6	110	40	70	50-120	42	W	70
Zone 7	110	30	80	50-150	48	W	57
Zone 8	130	40	90	60-120	54	W	50
Zone 9	160	60	100	60-180	60	W	70
Zone 10	170	60	110	60-140	50	MW	70
Zone 11	160	40	120	60-200	72	W	57.5
Zone 12	180	40	140	110-200	84	W	55
Zone 13	240	80	160	130-230	96	W	60
Zone 14	300	100	200	180-230	90	W	60
Zone 15	320	100	220	180-280	99	P	65

Recharge calculations

The rainfall recharge for each day was calculated over a 24-year period for each zone (Figure 4.2 and Figure 4.3). The average yearly rainfall recharge was then calculated and the results are given in Table 4.1. It was noted during modelling that for the last 10 years and especially the last nine years, there were low rainfall recharge rates.

Recharge under irrigation conditions

The daily recharge over the 24-year period was also calculated under irrigation conditions for those soils which are irrigated. Seven recharge zones were modelled for recharge under pasture irrigation, and four were modelled for the irrigation under grape vine irrigation (Table B.2). In the recharge modelling, irrigation water was added to the soil moisture balance on each day during the irrigation season when there was no rainfall. The application depth was based on the recommended water requirements for irrigation in Otago (Aqualinc, 2005). For example, irrigation water was added to recharge zone 11 at 3.5mm/day and to recharge zone 4 at 5.6mm/day. The type of crop to be irrigated was also taken into account and much lower daily application rates were used for modelling recharge under irrigated grape vines (Table B.2). For example, recharge zone 2 had 2.2mm added to the soil store during the irrigation season if there was no rainfall on a day.

Table B.2 Soil recharge zones and calculated recharge under non-irrigated and irrigated conditions

Zone name	Annual recharge (mm)	Recharge under irrigation (mm)	Recharge under irrigation last 10 years (mm)	Recharge under vine irrigation (mm)
Zone 1	335			
Zone 2	86.7	381	308	106
Zone 3	66.5			
Zone 4	44.1	338.2	263	59.2
Zone 5	34.2	131	73	
Zone 6	21.9			
Zone 7	19	115	58	29
Zone 8	14			
Zone 9	8.34	90	40	
Zone 10	7.1			
Zone 11	5.3	63	25	6.4
Zone 12	3.1	57.3	23.1	
Zone 13	1.7			

Appendix C Consented groundwater takes in the Bendigo-Tarras basin

Bore number	Depth (m)	Annual take (m^3/year)	Consent number	Purpose activity	Holder
G40/0155	30.97	19440	2002.422	Single domestic irrigation	Duxson Harris
G40/0176	32.2	20160	2003.761	Communal domestic	Scarlett Water Company Ltd
G40/0177	35.05	12350	2005.144	Irrigation	Poole Lawry
G40/0192	42.55	538180	2003.789	Communal domestic irrigation	Queensberry Irrigation Ltd
G40/0207	47.93	336482	2004.975	Irrigation communal domestic	Queensbury Irrigation Scheme
G40/0212	38.2	25550	2003.963	Communal domestic	Indigo Water Company Ltd
G40/0225	42	25000	2006.269	Irrigation	Alexander
G40/0245	70.73	20800	2005.448	Irrigation and winery	Avalon Estate Ltd
G40/0262	38.17	32940	2006.272		Queensberry South Ltd
G40/0265	33.5	278380	2008.362	Irrigation	Danjube Family Trust
G41/0097	37	43008	99479	Irrigation	Gibbston Valley Wines Ltd
G41/0170	7.55	17208	2003.186	Community supply	Lindis Irrigation Ltd
G41/0181	38.44	144720	98515	Winery irrigation	Bendigo Station
G41/0190	4.3	11610	2004.508	Irrigation	Bendigo Management Ltd
G41/0198	20	73872	98579	Irrigation	Lucas
G41/0203	36.69	35640	2002.277	Irrigation	Gibbston Valley Wines Ltd
G41/0206	29.41	49050	99604	Winery single domestic irrigation	Peregrine Vineyard Ltd
G41/0214	48.7	19440	99605	Irrigation	Logantown Estate Ltd
G41/0218	24.25	11340	2000.519	Irrigation	Reinecke Degril
G41/0218	24.25	20898	2003.744	Irrigation communal domestic	Reinecke Degril
G41/0225	48.4	35640	2003.337	Single domestic irrigation	Mondillo
G41/0228	22.96	246150	2001.928	Irrigation community supply	Chinamans Terrace Services
G41/0229	40.6	262440	2002.615	Irrigation	Marlborough Development Co
G41/0230	29.7	593370	2001.A30	Irrigation	Perriam
G41/0231	25.26	563850	2007.342	Irrigation	Perriam
G41/0232	24.24	414720	2001.995	Irrigation	Perriam
G41/0252	40	38340	2002.538	Irrigation	Trophy Ridge Vineyards
G41/0257	40	34245	2002.537	Irrigation	Trophy Ridge Water Services Ltd
G41/0261	40	46845	2002.536	Irrigation	Bobsien Dellaca Ormandy & Pike
G41/0262	46.15	279900	2002.318	Irrigation	Schoolhouse Terrace Services
G41/0269	36.53	181440	2002.485	Irrigation	Zebra NZ Vineyards Ltd
G41/0271	27.32	680000	2003.058	Irrigation	Perriam
G41/0282	40.1	262440	2002.613	Irrigation	NZ Vineyard Estates Ltd
G41/0283	51.16	262440	2002.614	Irrigation	NZ Vineyard Estates Ltd
G41/0286	18.35	22000	2002.774	Irrigation	Bascorich Ltd
G41/0290	40.8	23660	2003.810	Communal domestic	Cook
G41/0304	26.2	1741824	2004.317	Frost fighting	Carlston
G41/0308	19.56	4500	2004.509	Irrigation communal domestic	Bendigo Management Ltd
G41/0312	40.78	200455	2004.180	Irrigation	Streefland
G41/0313	41.9	228375	2004.555	Single stockwater irrigation	Phoenix Trustees Ltd
G41/0315	37	72816	2004.331	Frost fighting	Zebra NZ Vineyards Ltd
G41/0316	39.3	882720	2004.382	Irrigation	Lindis Crossing Station Ltd
G41/0332	49.05	48600	2002.558	Irrigation frost fighting	Kerruish
G41/0368	41.66	41720	2009.426	Irrigation	Westbank Vineyard Ltd

Appendix D Numerical modelling

Model code selection

The USGS finite difference numerical code MODFLOW (Harbaugh et al, 2000) was used to model the Tarras-Bendigo aquifers. The 'Visual Modflow' data processing interface software was used to build the model, assist with the calibration process, including parameter optimization; and to process the output data.

Grid design

MODFLOW uses a finite difference solution method that requires the use of a rectilinear, block-centered multi-layered spatial grid. The Tarras-Bendigo model was built within a grid domain of 21 x 21.4km, with a cell size of $200m^2$ at the edges of the model and a refined cell size of $100m^2$ in the central area of the model around the confluence of the Lindis and Clutha Rivers. The cell size variation was smoothed so that cells slowly decrease in size from $200m^2$ size at the edges to $100m^2$ in the middle. The grid has not been rotated since the principal regional groundwater flow vector is to the south and the model has been constructed using one layer.

The active model domain is delineated by contact with underlying silt deposits of Tertiary/Quaternary age and schist basement. The use of geophysical data for this purpose is described in section 3.2. Figure D.1 shows the active model area and grid design.

Conceptual hydrogeology and numerical adaptation

The approach adopted in the development of the numerical model has been to assume a continuous unconfined aquifer system, with spatially variable hydraulic properties controlled by lithology.

Outer model boundaries

The active model domain is delineated by the basal contact of the Tarras-Bendigo aquifer, with underlying schist or silt layer based on geological maps of the area and geophysical data. Figure D.1 shows the location of the aquifer boundaries. All external model boundaries are assigned no-flow (impermeable) conditions.

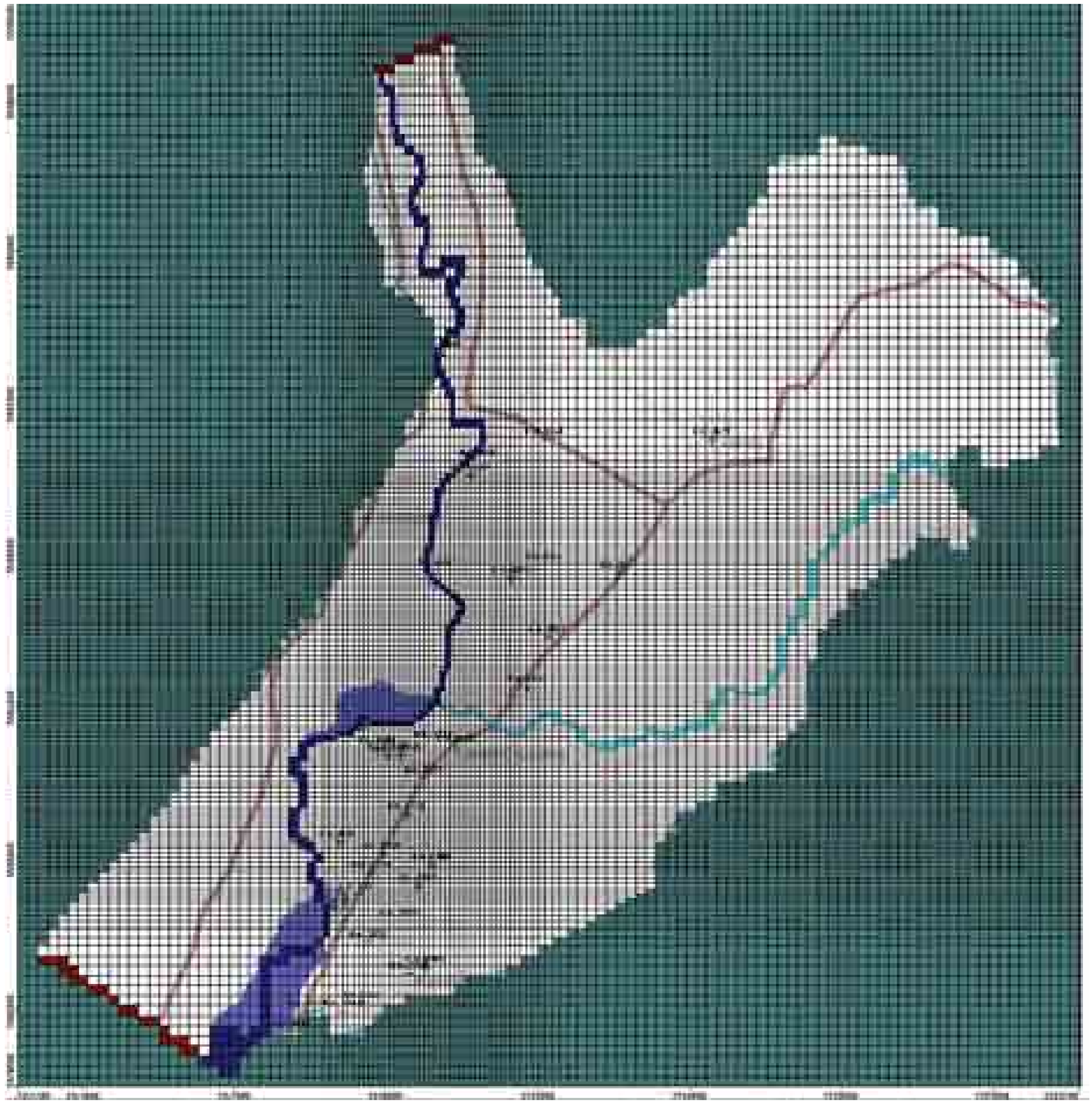


Figure D.10 **Groundwater model grid and model domain. Teal coloured cells are inactive, blue cells are river boundaries, light blue cells are stream boundary and brown cells are constant head boundaries**

Model base

Geophysical data was used to delineate the depth to low permeability silty sediments, as described in Section 3.2. The basement is considered to be deepest west of the Clutha River and Lindis River confluence (Figure D.2). Here the geophysical data showed the depth to be up to 140m down to the underlying silt layer.

Model top

The top of the model is represented by the surface topography (Figure D.3). Topographic data were derived from the 1:50,000 topographic map and levels were interpolated between the 20m contours. Additional level data from the bore survey was used in refining the typographic surface.

Layers

The model is considered as a one-layer model. This fits with the conceptual model of an unconfined sandy gravel aquifer overlying schist and silt.

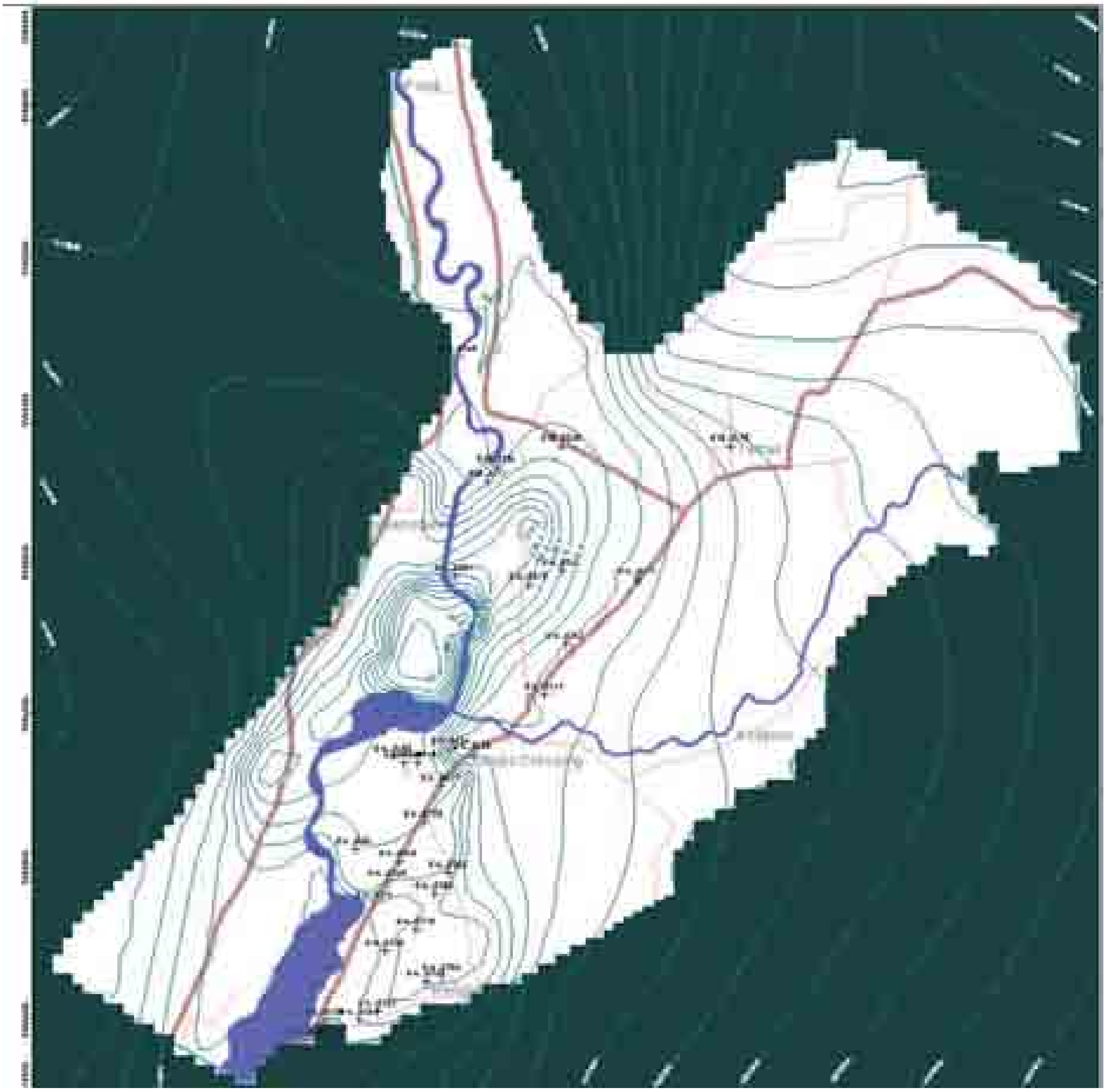


Figure D.11 **Contour map of model base representing interpreted base of Tarras-Bendigo Basin**

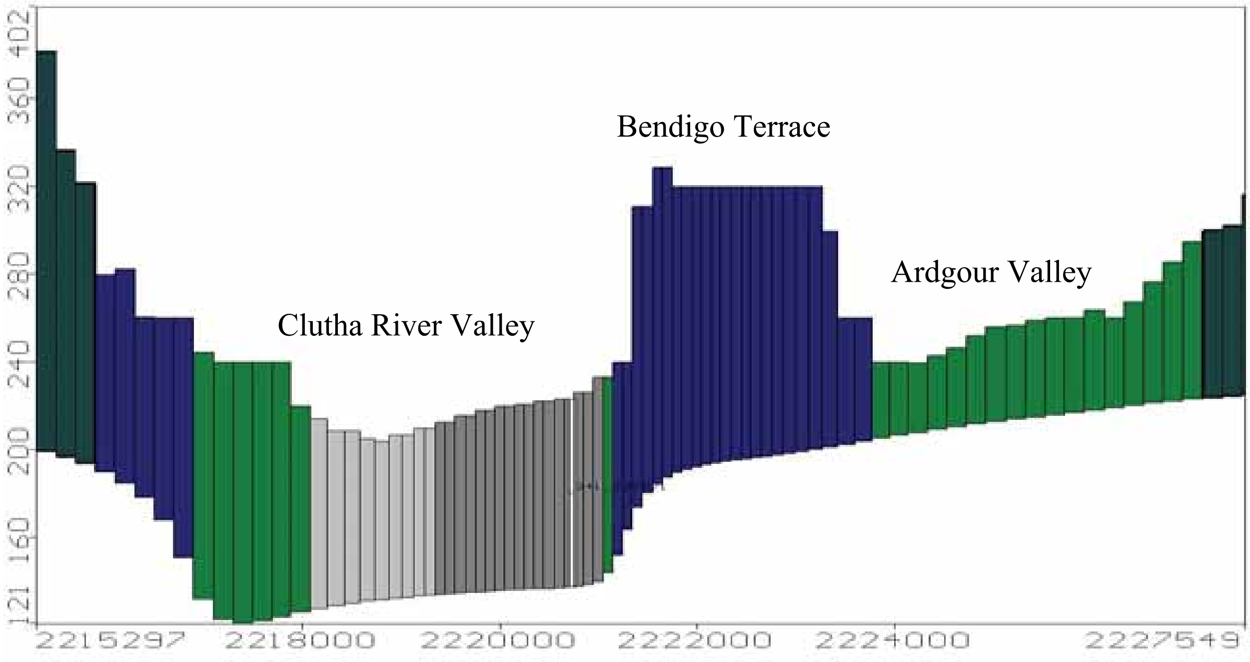


Figure D.12 **West-east cross-section through model showing base and surface topography. Colours represent hydraulic conductivity (K). Green = K 50 m/day, blue = K 1 m/day, grey = K 230 m/day and light grey K 450 m/day**

Boundary conditions

Clutha River: Modflow river boundary (RIV)

The Clutha River is a major recharge and discharge boundary to the Bendigo-Tarras aquifer. The river was simulated using the MODFLOW RIV package. The surveyed levels from December 2009 were used for stage heights. The "bed conductance" is a parameter is required by MODFLOW for the RIV and STR boundary types to control the flow transfer rates to and from the underlying aquifer. This parameter is not easily measurable and is usually derived through trial and error in the calibration process. Bed conductance is calculated using the length of the river in each river cell (L), the width of the river (W) in the cell, the thickness of the river bed (M), and the hydraulic conductivity of the river bed material (K). The stream bed conductance, C, is described as:

$C = K L W / M$

The Clutha River varies in width from 50m to 100m throughout most of its length until reaching Lake Dunstan at the southern end of the model. Vertical hydraulic conductivity was assumed to be 1 m/day. This gave a river bed conductance of 8000 to 2000m^2/day per 200 m^2 grid cell.

Lindis River: Modflow stream boundary (STR)

The Lindis River is another recharge boundary for the Bendigo-Tarras aquifer. The stream boundaries have been simulated using the MODFLOW STR package. Surveyed data carried out in December 2009 (Appendix A) were used to assign the stage heights and gradients for this system.

The Lindis River width varies between about 8m and 20m. Streambed vertical hydraulic conductivity was assumed to be about 1m/day. Subsequent calibration reduced the last segment from the Lindis Crossing to the Clutha River down to 0.5m/day to allow for the observed flow in the Lindis River. This equates to a streambed conductance of about 6000m^2/day per 200m^2 grid cell.

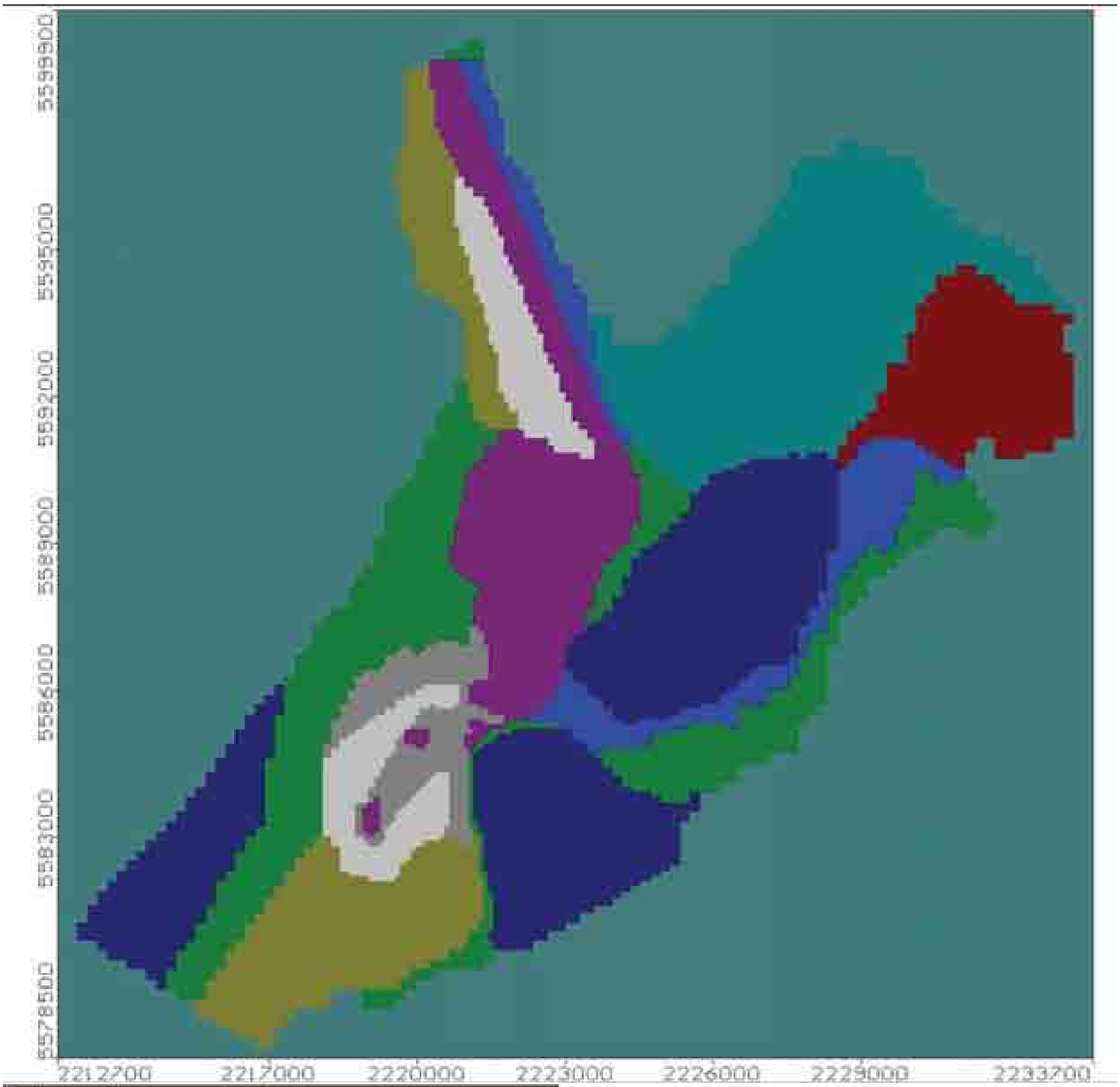
Springs: Modflow drain boundaries (DRN)

There is a spring in the Bendigo area between Tarras–Cromwell Road and the Clutha River. This is simulated in the model using the MODFLOW Drain (DRN) boundary condition. This type of boundary will only permit water to be taken out of the aquifer when the water table is modelled above the base of the drain cell (the spring elevation). When the water table drops below the base of the drain cell, flow into the spring stops. Flow from the aquifer to the drain cells (spring flow) is controlled by the value used for the drain bed conductance and the drain bed elevation. Bed conductance values were approximately 6000m^2/d for a 100m^2 cell.

Figure D.4 Location of spring in the Bendigo area

Aquifer properties

The hydraulic properties of the aquifer are discussed in detail in Section 3.4. Transmissivity values have been derived from assessment of pumping tests, specific capacity tests and geophysical data for relative permeability variations. Figure D.5 shows the hydraulic conductivity zonation developed using the conceptual model for the groundwater system, and subsequently refined during the model calibration process.



Zone	Kx [m/d]	Ky [m/d]	Kz [m/d]
2	1	1	0.1
3	50	50	0.5
4	0.12	0.12	0.012
5	5	5	0.5
6	180	180	18
7	200	200	20
8	450	450	45
9	230	230	23
10	100	100	10

Figure D.5 Calibrated hydraulic conductivity zones

Rainfall recharge modelling

There is some recharge to the Tarras-Bendigo groundwater system occurring through rainfall infiltration. This is increased significantly under irrigation conditions over a substantial proportion of the aquifer. Estimation of the quantity of water migrating through the soil zone to the water table has been modelled using a daily soil moisture balance method. Appendix B provides a description of the methodology for calculating recharge. Section 4.1 and Appendix B provide further discussion of the rainfall recharge dynamics for the catchment.

Groundwater abstraction

Less than 9Mm^3/year groundwater has been allocated from the Tarras-Bendigo aquifer system. The allocation to some 43 consent holders is almost entirely seasonal, being for irrigation use. Appendix C lists the current groundwater consents in the project area. The locations of the consented groundwater abstractions are shown in Fig 2.4.

Model calibration

Calibration approach

Calibration has the main purpose of testing the conceptual groundwater model and undertaking a parameter sensitivity analysis. It also provides a check on the boundary conditions and water balance estimation. Upon satisfactory manual steady state calibration, further calibration and parameter optimisation using the PEST algorithm was carried out.

Steady-state simulation

When an aquifer is in 'steady-state', the inputs and outputs, and therefore groundwater heads, remain constant. In reality, an aquifer is never in a truly steady-state condition. The closest they approach this condition is when heads remain stable over a relatively long period.

Concurrent groundwater level monitoring data for the model area is available for September and December 2009 and March 2010. The December datasets has been used for the base steady-state calibration. Steady-state calibration has been achieved by manually calibrating the model to head targets measured in 32 wells, and then undertaking a more detailed parameter optimisation modelling. The monitoring wells are distributed across the model domain, concentrated mostly on the Tarras and Bendigo lower terraces.

Aquifer properties developed during the steady state calibration process are shown in Figure D.5. Abstraction wells were not activated during the steady-state calibration since groundwater levels and river levels used for the base scenario were taken before the main irrigation season.

The flow in the Lindis River in the model was calibrated to observed flow during flow gauging carried out in late 2007 (Figure D.6).

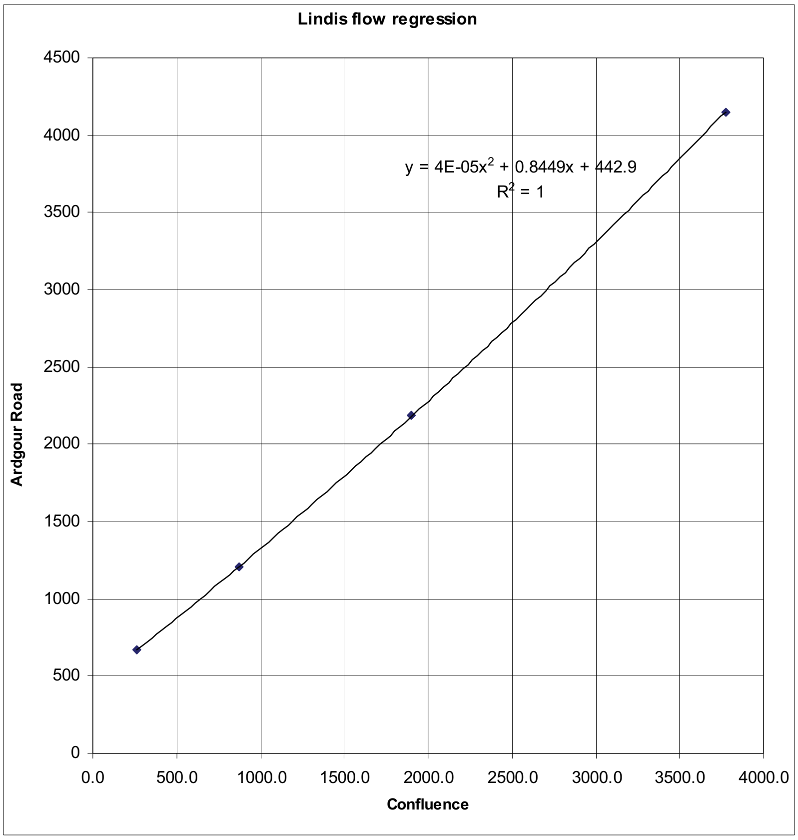


Figure D.6 **Relationship between Lindis River flow (l/s) at Ardgour Rd flow site and the confluence with the Clutha River based on flow gauging in November and December 2007.**

The results of the steady state calibration run are shown in Figure D.7, which also contains a summary of calculated heads and residuals along with the calibration statistics. The overall residual mean of the calibration is encouragingly low at -0.228m. Of the 32 calibration targets used, only one shows a residual error of greater than 5m. The highest residual is -7.45m for well G41/0174 located closely beside the bend terrace with clay layers and clay-bound gravels mentioned throughout the bore log above the water bearing sands that are screened by the bore. It is possible that this bore taps a deeper aquifer system that is partially confined in this area, which would account for the higher observed levels.

The standard deviation/range statistic show how the errors relate to the overall gradient across the model. The average error of 1.9% is also indicative of an apparent good calibration fit.
If the observation point G41/0174 is removed, the normalized RMS drops to 0.96% and the highest residual is then 1.42 meters at G41/0228 (Figure D.8)

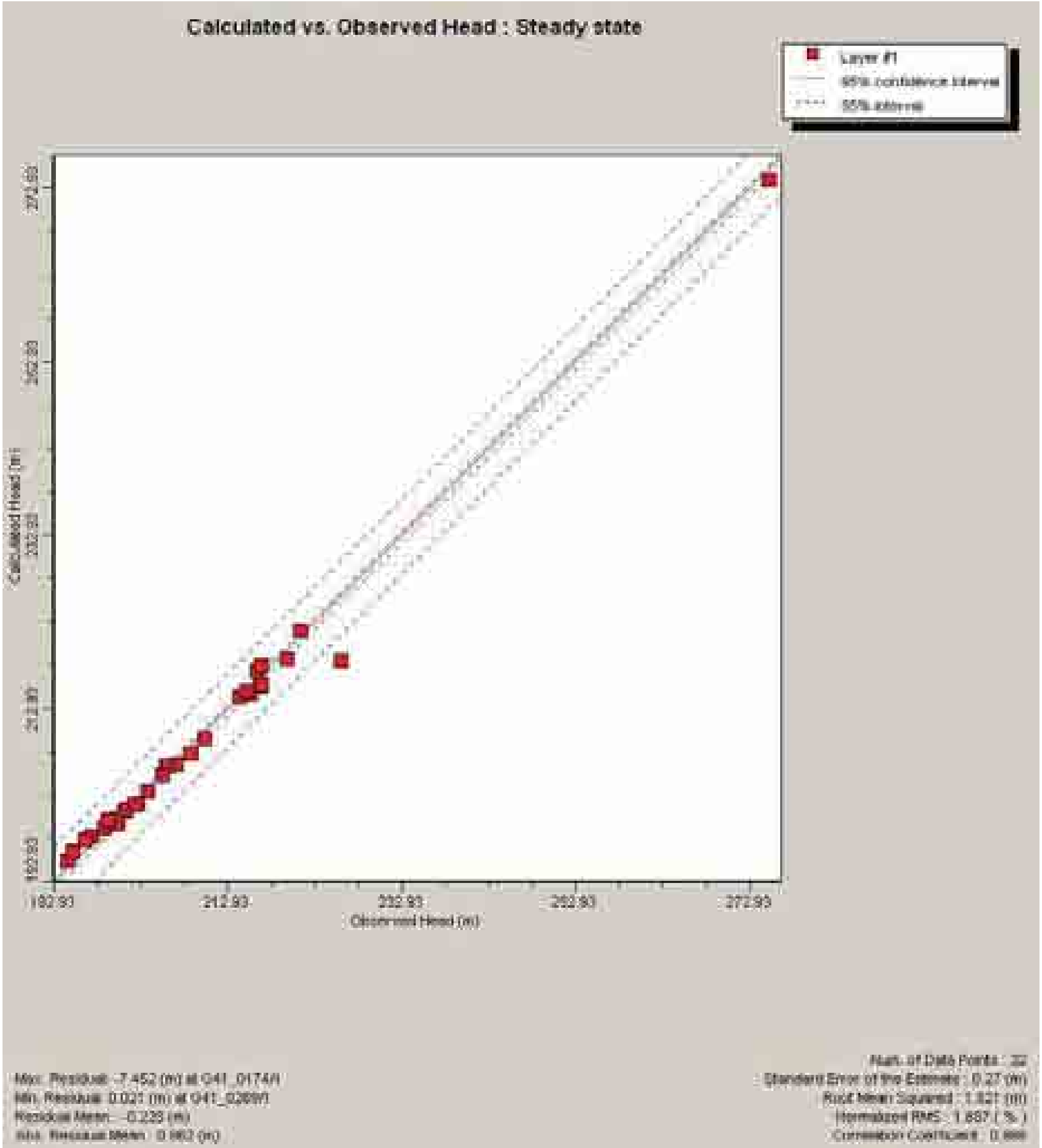


Figure D.7 Steady state calibration results

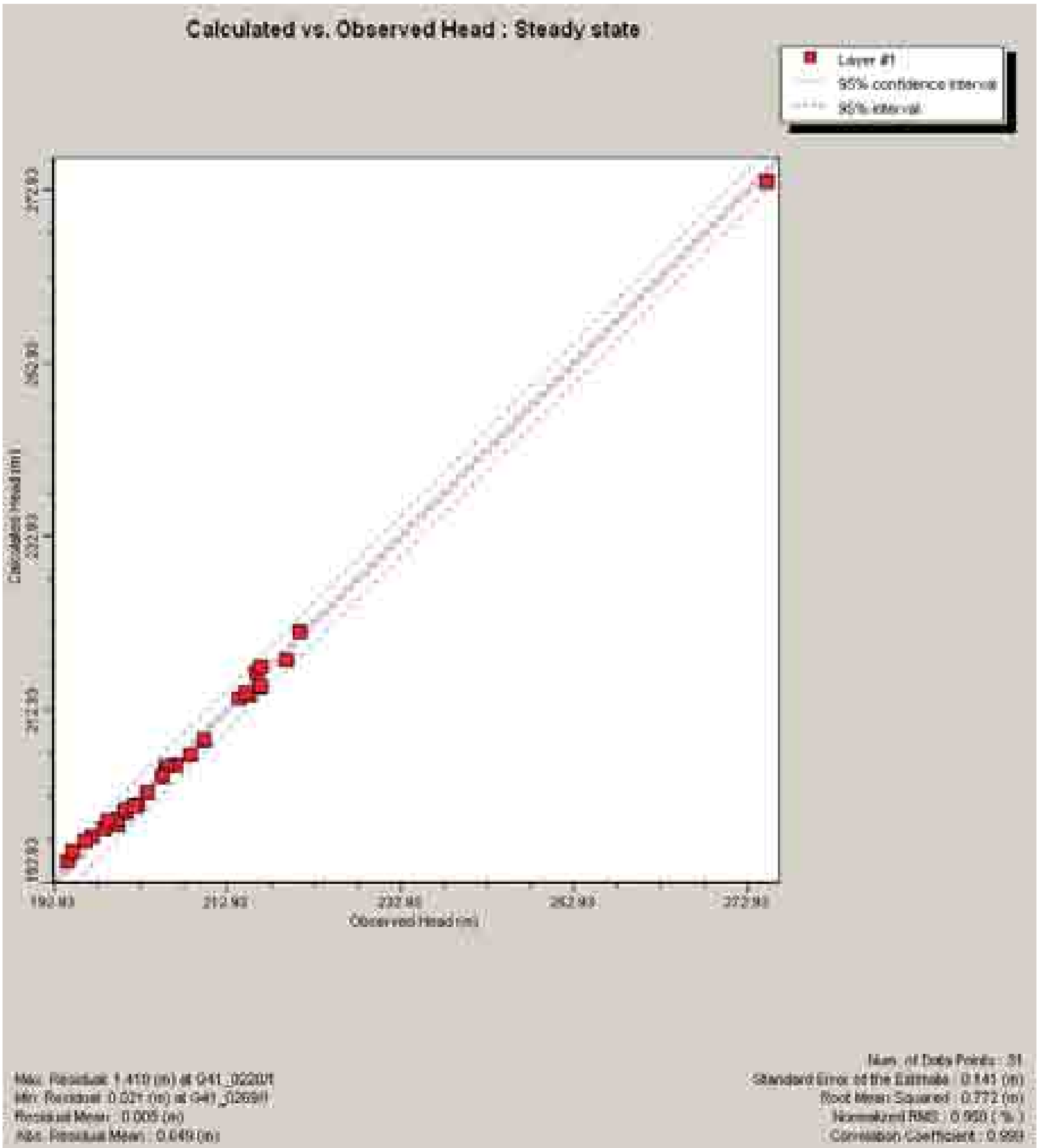


Figure D.8 Steady-state calibration results with calibration point G41/0174 removed.

Figure D.9 shows the modeled head distribution over the model domain. Comparison to Figure 3.6, constructed using observed data, shows a good agreement with the simulated regional flow pattern.

At a regional scale, in a heterogeneous aquifer system, the calibration is regarded as a good initial simulation. It provides confidence in the conceptualization of the flow system, and the assumptions that have been adopted.

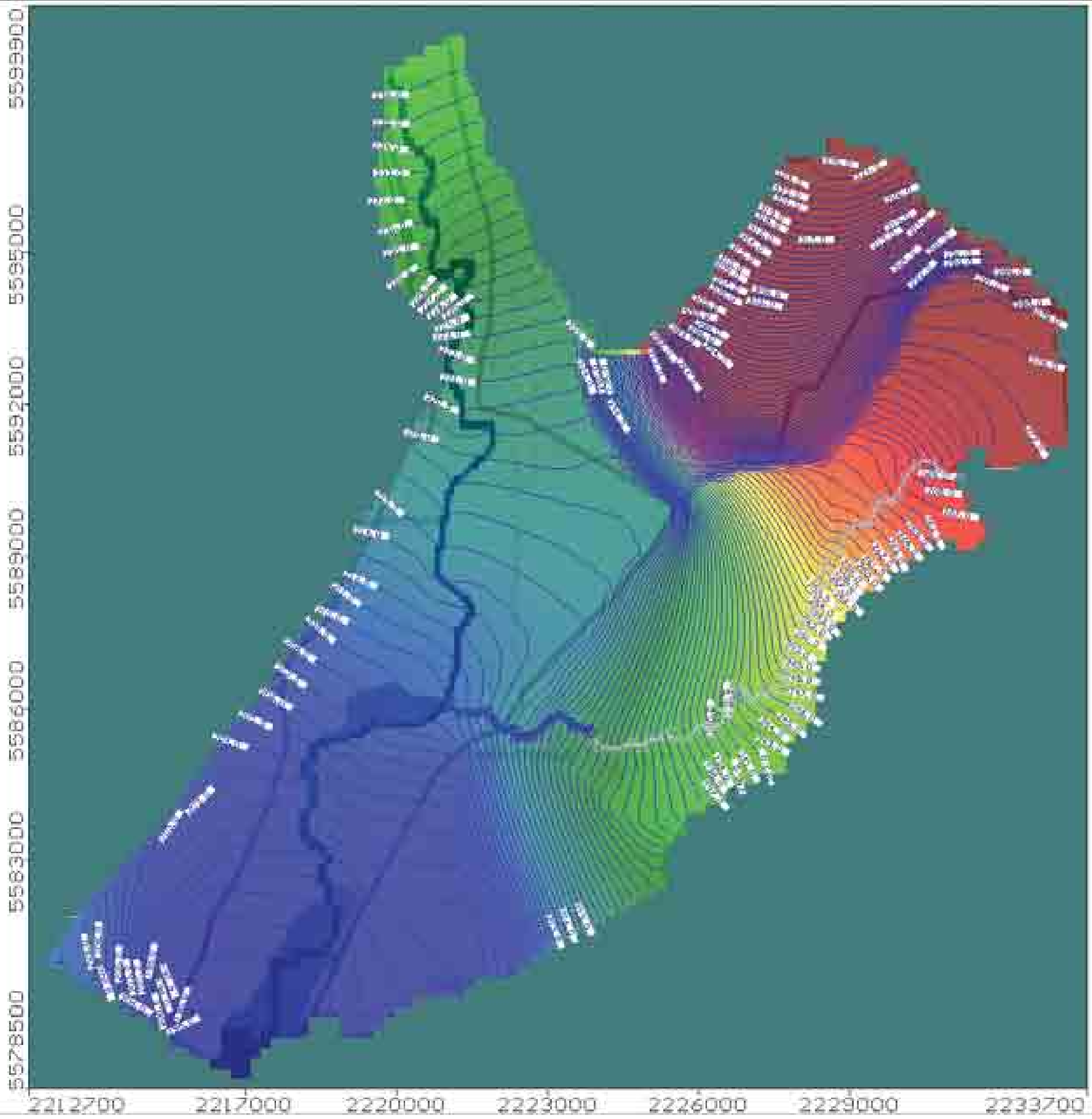


Figure D.9 Steady-state base scenario modelled head distribution

Steady-state scenarios

Different scenarios were run using the steady-state model to test the long-term response in terms of groundwater levels of reduced recharge, higher pumping rates, and low flow in the Lindis River. These scenarios are discussed in Section 5.

References

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