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Wanaka Groundwater Model Report

Otago Regional Council

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Wanaka Groundwater Model Report

Prepared for

Otago Regional Council

December 2018

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Quality Control Sheet

TITLE	Wanaka Groundwater Model Report
CLIENT	Otago Regional Council
VERSION	Final
ISSUE DATE	14 December 2018
JOB REFERENCE	C03577502
SOURCE FILE(S)	C03577502R001_ModelRpt_September2018_v2_FINAL

DOCUMENT CONTRIBUTORS

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Executive Summary

Otago Regional Council (ORC) is moving through a process of setting tailored groundwater allocation limits for aquifers within their region. In the Wanaka Basin / Cardrona Alluvial Gravel Aquifer, groundwater is closely connected to the Cardrona River where groundwater discharge supports flows in the lowest section of the river and also Bullock Creek which flows through the centre of Wanaka township. Groundwater abstraction will affect baseflow in the river and therefore ORC intends to develop an integrated maximum groundwater allocation limit (MAL) which accounts for the effect of groundwater abstraction on surface water flows.

The Wanaka Basin / Cardrona Alluvial Aquifer ('the Wanaka Basin') is bounded by Lake Wanaka to the west, the Clutha River/Mata-Au to the north and east, and by low permeability schist strata to the south. Groundwater in the aquifer is sourced from rainfall recharge (including additional recharge due to irrigation) as well as seepage losses through the bed of the Cardrona River. Proportionally, seepage losses from the Cardrona River make up a large part (around 60%) of the aquifer water balance.

Groundwater movement in the aquifer is from the south towards the main aquifer discharge points at the Clutha River in the north and Lake Wanaka in the north-west. Groundwater also discharges into the Cardrona River downstream of the State Highway 6 Bridge, as well as into Bullock Creek.

A groundwater model has been developed to represent that system and to estimate the effect of groundwater abstraction on flows in the Cardrona River. The groundwater model was calibrated to, and accurately represents, the flows in the Cardrona River, as well as groundwater levels at the aquifer monitoring bore (F40/0014).

Scenario runs using the groundwater model indicate that if actual abstraction rates increased to a seasonal total of 5×10^6 m^3/year baseflows in the Cardrona River could reduce by around 86 L/s and by around 36 L/ in Bullock Creek. The model suggests that there is a lag between the onset of increased abstraction and effects in the river such that the effect of abstraction on the river will eventually approach the long term average annual abstraction rate after around 10 years of pumping. Peak groundwater abstraction rates (which could be greater than 86 L/s for short periods of time) are likely to impart effects on river flows which are smoothed and attenuated in time.

Analysis of the model and its predictions indicates that there is some uncertainty around those predictions, and the peak effect of abstraction on low flows falls into a 95th percentile confidence range of approximately 86 L/s ±34 L/s for the Cardrona River and 36.1 L/s ±5.7 L/s for Bullock Creek.

Model scenarios assessing the potential effect of low flow restrictions on surface water takes between the Mt Barker flow recorder and the Ballantyne Road bridge

indicates that restrictions could increase seepage to the aquifer, up to a maximum of around 1.7 x 10^6 m^3/year on average. Based on the model, the majority of the additional seepage would be expected to discharge towards Bullock Creek. The increased seepage would be reflected in increased groundwater levels and slightly increased flows in the Cardrona River (as a reduced extent of drying).

The model indicates that the area to the east of a line north of Mt Barker is poorly connected to the Cardrona River and Bullock Creek. Therefore, the most appropriate groundwater allocation approach to the Wanaka Basin is to split the area into two zones. One zone represents the areas where groundwater abstraction will affect flows in the Cardrona River and in Bullock Creek, and the recommended limit in that area should be defined on the basis of an acceptable stream depletion effect. The second part represents the area to the east of a line north of Mt Barker. If the thresholds in the Regional Plan: Water are applied in this area, the allocation limit should be set to around 0.75 × 10^6 m^3/year, representing 50% of recharge.

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1.0 Introduction

1.1 Background

Otago Regional Council (ORC) is moving through a process of setting tailored groundwater allocation limits for aquifers within their region. In the Wanaka Basin / Cardrona Alluvial Gravel Aquifer, groundwater is closely connected to the Cardrona River, where groundwater discharge supports flows in the lowest section of the river. In turn, that baseflow supports the ecology in the most downstream parts of the river. Groundwater abstraction will affect baseflow in the river and therefore ORC intends to develop an integrated maximum groundwater allocation limit (MAL) which accounts for the effect of groundwater abstraction on surface water flows.

To achieve an integrated allocation limit, ORC developed a groundwater model in 2011, which was used to estimate the effects of different levels of groundwater abstraction on flows in the Cardrona River. The model was calibrated to groundwater levels at the long-term monitoring bore in the aquifer (F40/0014). While the model simulated flows in the Cardrona River, these were not included as a calibration target. As a result of the limited calibration dataset, there was some uncertainty around the modelled effect of changes in groundwater abstraction on flows in the river. A proposed allocation limit of 5×10^6 m^3/year was determined based on the results of the model, which indicated that that abstraction rate would reduce baseflow to the lower part of the Cardrona River by around 100 L/s.

Pattle Delamore Partners Limited (PDP) have been engaged by ORC to recalibrate the groundwater model for the Wanaka Basin – Cardrona Alluvial Gravel Aquifer (the Wanaka Basin). Specific objectives of the recalibration were to include river flows as a calibration target and to quantify the uncertainty in predicted river flow impacts from groundwater abstraction. Additional data has also been collected in the Wanaka Basin. This included information on flow losses and gains in the Cardrona River and metered abstraction rates for both groundwater takes and surface water abstractions from Cardrona River within the basin. Additional aquifer properties data has also been collected as part of consent applications and a further five groundwater monitoring bores were drilled in December 2017. A surface water flow recorder was installed at Bullock Creek in March 2018. This additional information was used to assist with the model recalibration.

A map of the Wanaka Basin is presented in Figure 1a. This illustrates the outline of the Wanaka Basin / Cardrona Alluvial Aquifer Groundwater Zone (as defined by ORC) and shows the general topography in the surrounding area. Figure 1b shows a photo looking south across the Wanaka basin from the top of Mt Iron.

1.2 Purpose of the model

The purpose of the model is to estimate the effects of groundwater abstraction on baseflows in the lower part of the Cardrona River and Bullock Creek and to quantify the modelled uncertainty relating to those estimates. Further objectives include consideration of:

- The effect of additional abstraction on groundwater levels and existing groundwater users;
- The effects of irrigation on groundwater levels; and
- Potential allocation options across the Wanaka Basin.

2.0 Hydrogeology of the Wanaka Basin – Cardrona Alluvial Aquifer

2.1 Geology

A detailed report describing the hydrogeology of the Wanaka Basin is available in ORC (2011) and the purpose of this report is not to repeat the information already available in that document. A summary of the conceptual hydrogeological setting for the aquifer is provided below.

A map of the geology of the Wanaka Basin is provided in Figure 2. The basin is underlain and surrounded by lower permeability schist and basement strata, and infilled by Tertiary aged lake sediments, over which Quaternary alluvial and glacial strata have been deposited. A number of glacial periods have resulted in a complex and frequently reworked sequence of outwash and till deposits across the basin. Figure 2 shows the location of mapped 'till' deposits (defined as 'claybound gravels' in the GNS geological description) and more gravelly strata. The till deposits are extensive across the aquifer and a significant area of till occurs immediately to the east of the Cardrona River. More gravelly strata are mapped on the western side of, and along the line of, the Cardrona River, with the exception of till deposits to the east of Mt Iron. Recent alluvial deposits occur along the line of the Cardrona River.

Varied periods and extents of glaciations have also resulted in the contact between tertiary sediments and the underlying schist having a very complex structure. The elevated ground of Mt Iron, which represents a schist outlier, is an example of the effect of glaciations; a bore (F40/0005) drilled adjacent to Mt Iron extended to a depth of more than 100 m without encountering basement strata. However, generally, the schist basement appears to occur at shallower depths to the west of the area and beneath Wanaka township based on drillers logs.

2.2 Hydrology

The three main surface waterbodies within the Wanaka Basin are Lake Wanaka, the Clutha River and the Cardrona River (as shown in Figure 3). Lake Wanaka and the Clutha River form major hydrological boundaries around the western, northern and eastern edges of the Wanaka Basin and are likely to control groundwater levels in the aquifer.

The Cardrona River enters the Wanaka Basin from the south, and flows north to its confluence with the Clutha River just east of Albert Town. Flows in the Cardrona River are recorded continuously at the Mt Barker flow recorder (where the river enters the Wanaka Basin), and at its confluence with the Clutha River.

Flows rates have also been recorded where Ballantyne Road crosses the Cardrona River.

Flow patterns in the Cardrona River are discussed at length in ORC (2011) and Figure 4 shows a plot of observed flows at each of the three recorder sites between December 2016 and July 2017. The greatest flows are observed at the upstream Mt Barker Flow recorder. Flows at the downstream Ballantyne Road site are consistently lower than at Mr Barker, indicating that the river loses water to groundwater between those sites, although some reduction in flows is due to irrigation race intakes.

The observed flow losses continue from the river reach between the Ballantyne Road recorder and the State Highway 6 Bridge recorder. In general, the overall flow loss (at times of low flow) is around 700 L/s between Mt Barker and Ballantyne Road and at times, no surface flows are observed at Ballantyne Road, or between Ballantyne Road and SH6.

Between the SH6 Bridge and its confluence with the Clutha, baseflows in the Cardrona River increase by around 300 L/s, implying that the river gains from groundwater along that reach.

Springs occur around Wanaka township (Bullock Creek and other, smaller water courses). Bullock Creek is the largest of these spring-fed streams, flowing at rates up to 500 L/s at its outlet to Lake Wanaka. The springs occur at the base of a terrace, where the ground surface drops towards Wanaka township and Lake Wanaka.

2.3 Groundwater levels and flow patterns

ORC (2011) presents a contour map of groundwater levels from a piezometric survey undertaken in 1996, as well as subsequent surveys undertaken in 2010. While the results of those surveys (reproduced in Figure 5) indicate a relatively complex groundwater flow pattern, groundwater broadly flows from south-west to the north-east, towards Lake Wanaka and the Clutha River. This suggests that Lake Wanaka and the Clutha River form the main hydrogeological boundaries and discharge points from the Wanaka Basin Aquifer.

As described in Section 2.2, the Cardrona River interacts with groundwater in the aquifer, losing water to groundwater where it enters the basin and gaining water towards its confluence with the Clutha River. This effect is not particularly pronounced in the groundwater contours, although there is limited data to constrain the shape of the contours in either of those areas.

The contours, and other more recent groundwater level measurements indicate that groundwater levels are relatively deep (around 15 m below surface) below the Cardrona River reach downstream of the Mt Barker flow recorder. Groundwater levels are also relatively deep (up to 65 m below ground surface) across the eastern half of the aquifer. The depth to groundwater in bores in this area (for example around Wanaka Airport) is often only a few metres above the stage of the Clutha River, which could either imply low recharge or very high hydraulic conductivity.

2.4 Aquifer properties

Limited information on aquifer properties is available for the Wanaka Basin. Figure 6 shows the location and results of specific capacity information for bores in the aquifer. Available data is distributed across the aquifer although it is difficult to distinguish a clear pattern. Note that there are a number of bores located along roads (for example Ballantyne Road), which can encourage a false impression of linear features in the data. Much of the data is also based on low pumping rates (~100 m^3/day, or around 1 to 2 L/s) and therefore may not be representative of the permeability of the overall strata.

Accurate data based on well controlled aquifer tests is scarce. Results of two more detailed hydraulic tests are included in Appendix A. One of those tests was undertaken in bore F40/0335 (35 m deep) located towards the upper part of the Cardrona River and a few hundred metres from the river. This indicated a transmissivity[1] of around 1,500 m^2/day and a storage value of around 0.09.

Groundwater levels were monitored in three neighbouring bores located in a line towards the Cardrona River, none of which showed clear recharge boundary effects. The results of the test imply that the Cardrona River may be relatively isolated from the underlying groundwater (the depth to groundwater measured in the bores is around 15 m to 20 m), and seepage rates from the river may not be directly affected by groundwater abstraction. Instead, the seepage rates may be relatively constant and defined by the stream bed conductance[2].

A second test was undertaken in bore F40/0200 which is located 250 m from the Cardrona River and around 2 km upstream from its confluence with the Clutha River. The results from that test were difficult to accurately interpret, but suggested a high transmissivity (>1,500 m^2/day) and a very close connection to the Cardrona River (stream bed conductance (λ) of >10 m/d).

2.5 Summary

The Wanaka Basin is bounded by lower permeability schist strata that outcrops to the south of the basin and major surface water bodies to the north, east and west. Groundwater in the Wanaka Basin flows is sourced from both land surface recharge, and river seepage from the Cardrona River, in addition to some irrigation losses. Average losses from the Cardrona River are estimated at around 700 L/s at times of low river flows (ORC, 2011), or around 22×10^6 m^3/year. However, shorter term losses can vary relatively significantly above and below 700 L/s, with recorded losses ranging from 500 l/s to 1,000 L/s (ORC, 2017).

Groundwater generally flows to the north from the higher ground and predominantly discharges into Lake Wanaka and the Clutha River, with some minor discharge into Bullock Creek and the lower reaches of the Cardrona River.

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[1] Transmissivity is a measure of the ability of the aquifer to transmit groundwater throughout its entire saturated thickness. It has units of m^2/day and is It is defined as the product of the hydraulic conductivity *K* (m/day) and the saturated thickness *B*(m)..

[2] Streambed conductance refers to the ease with which water can move through the base of a stream or river. either from groundwater into the stream, or from the stream into groundwater

The geology of the area is dominated by till deposits to the east of the Cardrona River, whereas more permeable deposits occur on either side of the river. This indicates that seepage from the Cardrona River is likely to flow predominantly subparallel to the Cardrona River and to the north-west to discharge into Lake Wanaka and Bullock Creek.

3.0 Model structure and design

3.1 Model boundary

Figure 7 shows the extent of the model area, which is based on the existing ORC model. The model is bounded by the outcrop of low permeability strata (schist) to the south and by Lake Wanaka and the Clutha River to the west, north and east.

3.2 Model layering

In the original model developed by ORC only a single layer was developed. This was due to limited information around vertical discretization in the aquifer. Whilst there is likely to be some effective layering within the aquifer, there is not enough information to accurately determine where those layers occur, or whether any lower permeability intervals are spatially widespread. Therefore, this model also uses a single layer, although it is recognised that such an approach could lead to inaccuracies in some areas.

3.3 Model discretization

The model grid was based on a 100 m cell size applied across the whole model area, which resulted in 112 model rows and 161 model columns. The width of the active bed of the Cardrona River is around 100 m along much of its length within the model area and therefore a 100 m cell size is considered appropriate to simulate the groundwater/surface-water interaction along the Cardrona River. Whilst a smaller grid size may have benefits for representing some parts of the river, small grid sizes can make a model unstable, particularly with respect to predictive model runs and calibration using PEST.

The model was run using the freely available USGS MODFLOW-NWT code. MODFLOW-NWT uses the same model input files (and generates the same outputs) as other codes in the MODFLOW family, but the NWT solver is more reliable and faster than the freely available solvers used with MODFLOW 2005 or MODFLOW 2000.

3.4 Temporal settings

Timeseries inputs to the model consisted of:

- Recharge to the groundwater system
- Metered groundwater abstraction, and
- Observed surface water flows along the Cardrona River

Figure 8 shows the durations of data sets used to define the time varying inputs described above. The model was run in transient mode representing a time period from 1 July 2015 until 1 July 2018, based on the optimum overlap of these datasets.

All time series data was available at daily intervals. While it is possible to run groundwater models using daily stress periods, this is typically inefficient and results in very long model run times, without providing significant benefits. Given that the purpose of this model is to represent stream flows and simulate the effect of abstractions on stream flows, monthly stress periods are likely to be too long and are likely to mask the shorter term effects of abstraction. Seven day (i.e. week long) stress periods provide a reasonable balance between temporal resolution and model run times. Note that the first stress period in the model is a steady state 'warm up' where model inputs are set at their average rates. This allows subsequent stress periods are not affected by the starting conditions set in the model inputs.

3.5 Model recharge

Rainfall recharge to groundwater was determined based on the outputs from a spatially distributed daily soil moisture balance model, which used the same 100 m grid size as the groundwater flow model. This allowed the outputs of the recharge model to be used directly in the groundwater flow model.

The recharge model uses daily rainfall and potential evapotranspiration data from the NIWA virtual climate station network, which is based on a 5 km grid. Soils data across the model area is based on information from S-map including information around the profile available water for different soil types. A map showing the different soil types across the area is provided in Figure 9a. Soils data was not available across the Wanaka township.

Recharge was calculated based on a standard soil moisture balance approach, where drainage from the soil zone can only occur after the soil moisture demand is satisfied. No runoff was simulated across the majority of the model area, because there the area is relatively flat, and the soils are generally permeable, except for the Wanaka township where runoff is likely to occur due to impermeable surfaces. In reality, any runoff would likely be directed into the stormwater system which eventually discharges either into Lake Wanaka, into the Clutha River or into the Cardrona River. In the recharge model, the runoff component of the daily soil moisture balance was accounted for, but not included in the groundwater model.

- Irrigation was included in the model as part of the recharge within specified areas (shown in Figure 9b). Two types of irrigation occur across the area:
- spray irrigation (including centre pivots); and
- flood irrigation (including border dyke irrigation).

Each irrigation type was treated separately in the recharge model. Spray irrigation was simulated based on soil moisture triggers. Triggers were set at typical levels, where irrigation was simulated as occurring when soil moisture fell below 50 %. Simulated irrigation ceased when soil moisture exceeded 90% and this approach represents an efficient irrigation system.

Flood irrigation was simulated assuming a specified depth of water was applied to each flood irrigated area at three week (21 day) intervals. This is consistent with typical border dyke irrigation practice (Dommisse, 2005).

The depth of irrigation for both the spray irrigated and flood irrigated areas was varied during the model calibration process. Metered rates for the intakes from the Cardrona River for the Farrant (99478) and Wanaka (98370 and 97199.v1) irrigation races were available and the corresponding irrigation areas were provided by Otago Regional Council. The irrigation depths were therefore varied within reasonable bounds to be generally consistent with the metered rates, although losses through the irrigation race system were not directly accounted for. The Mt Barker Race (97129) was also included at a set rate of 42 L/s (ORC, 2017).

The recharge model was run on a daily timestep from July 2015 to July 2018. Daily results were then aggregated to provide weekly average soil drainage estimates. A plot of the spatial distribution of long term monthly average recharge is provided in Figure 10a, and a timeseries of the total modelled recharge is also shown in Figure 10b.

The long term average annual rainfall across the model area is around 600 mm/year, compared to a modelled average annual recharge between 2015 and 2018 of around 85 mm/year, which represents around 12% of rainfall. That proportion is similar to estimates of recharge derived from modelling undertaken by ORC (2011) for the Otago region. However, note that rainfall over the last two years has been below average, resulting in lower rainfall recharge.

The spatial variation in soil drainage is partly driven by differences in soil types across the model area and also differences in rainfall.

3.6 Model boundary conditions

3.6.1 Surface water boundaries

A number of boundary conditions were defined in the model to represent surface water features including Lake Wanaka, the Clutha River and the Cardrona River, as well as smaller streams such as Bullock Creek. A map showing the location and type of surface water boundaries in the model is provided in Figure 11.

Lake Wanaka and the Clutha River were both simulated in the model using the river boundary package in MODFLOW. The river boundary package allows water to move into, or out of the model depending on the relative elevation of groundwater levels compared to the stage in the river. The ease with which water can move through the boundary is controlled via the conductance of each boundary cell. In the model, the river conductance was varied as a calibration parameter, however the stage elevation of the lake and the Clutha River remained constant throughout the simulation and was set based on the 8 m digital elevation model for the area. River stage was defined in more detail where LiDAR data was available close the confluence with the Cardrona River.

The Cardrona River was simulated using the MODFLOW stream package (STR). The stream package is more complex than the river package because it accounts for stream flow volumes and allows water to be routed down a defined stream network. It also allows surface water takes to be simulated as diversions from the stream network. Losses from the stream network to groundwater are constrained by the available flow in the stream (i.e. no losses occur if there is no flow in the stream). The stream package is therefore much better suited to model the pattern of flows along the Cardrona River, which can dry out in its middle reaches.

Flows in the modelled Cardrona River were added to the most upstream reach based on observed flows at the Mt Barker recorder. Stage elevations were defined for the Cardrona River based on LiDAR data flown in March 2016 and set to remain constant throughout the simulation. The Cardrona River is generally braided from downstream of the Mt Barker flow recorder to at least the State Highway 6 Bridge. Therefore variations in stage are likely to be small and accounting for the model flow balance is more important than small changes in river stage elevations.

Bullock Creek was also simulated as a stream boundary condition in the model, but was constrained so that it could only gain water i.e. they effectively operated as routed drain boundaries.

Note that the stream bed conductance was varied during the calibration process. Different stream bed conductance values were assigned to specified reaches of the river, which are illustrated in Figure 11.

Surface water abstractions were simulated in the model as diversions from the main stem of the Cardrona River. The diversions represent intakes for the Wanaka and Farrant Races and diversion rates were set based on measured flows at those intakes.

3.6.2 Groundwater abstraction

Groundwater abstractions were included in the model at the locations shown in Figure 12. The timeseries of abstraction rates for each simulated bore were based on metered data.

4.0 Model calibration

4.1 Model parameterisation

Aquifer properties for the modelled area were defined by pilot points with the hydraulic conductivity at each pilot point adjusted during model calibration using Parameter Estimation software (PEST) (Doherty, 2010).

Aquifer properties across groundwater model were defined using pilot points, where the hydraulic conductivity at those points is varied during the model calibration process. The point estimates are then spatially interpolated to generate a hydraulic conductivity field across the model area. Such an approach was employed for the Wanaka model and a plot 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 the model.

Storage values were also varied in a similar way during the calibration process, although the final calibrated result indicated that the model was not particularly sensitive to the value of storage (Section 6).

4.2 Calibration Statistics

The model was calibrated using PEST to the following observations:

transient groundwater levels at bores F40/0014 (Envirowaste Tip bore), F40/0327 (Criffel Deer bore), F40/0386 (Bullock Creek bore), F40/0389 (Ballantyne Road bore), F40/0390 (Orchard Road bore), F40/0391 (SH6 bore);

- flow timeseries in the Cardrona River at Ballantyne Road;
- flow timeseries in the Cardrona River at the confluence with the Clutha River; and
- flow timeseries at Bullock Creek

Calibration statistics are provided in Table 1.

Table 1: Calibration statistics

	Observation Location	Root Mean Squared Error	Correlation coefficient (R^2 value)
Groundwater levels	Ballantyne Road (F40/0389)	0.65 m	0.90
	Bullock Creek (F40/0386)	0.13 m	0.18
	Criffel Deer (F40/0327)	0.58 m	0.55
	Envirowaste Tip (F40/0014)	1.03 m	0.80
	Orchard Road (F40/0390)	0.61 m	0.40
	State Highway 6 (F40/0391)	0.59 m	0.90
Surface water flows	Flows at Ballantyne Road (L/s)	329 L/s	0.95
	Flows at Bullock Creek (L/s)	12.7 L/s	0.96
	Flows at Clutha Confluence (L/s)	364.1 L/s	0.99
Overall			0.99

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The final calibrated model parameters are listed in Appendix B.

The aim of the model was to represent flows in the Cardrona River and in Bullock Creek and therefore greater weight was given to matching those observations in more detail compared to matching groundwater level observations. 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.

5.0 Model results

5.1 Mass balance

A plot showing the mass balance for the 2 year simulated model period is shown in Figure 15 and a summary table showing the average values over the 2 year model run is shown in Table 2. It shows that the majority of inflows to the model are from surface water leakage (i.e. losses from the Cardrona River), together with periodic rainfall recharge events. Rainfall recharge events do not appear to have a significant effect on surface water leakage. At times of lower stream flow, surface water leakage is reduced and this is balanced by an increase in releases from aquifer storage (i.e. a decline in groundwater levels).

Outflows from the model are dominated by discharges to the Cardrona River and Bullock Creek, with lesser discharges to Lake Wanaka and the Clutha River. Groundwater abstractions also make up part of the outflow from the model, although they represent a small proportion of the water balance. Rainfall recharge events typically result in storage capture (i.e. groundwater level increases) accompanied by slight increases in discharges to the rivers.

A summary of the mass balance components in the model and their average values (over the three year model period) is shown in Table 2. Note that storage largely balances on average.

Table 2: Mass Balance Summary (Average over 3 year model run)

	Storage	Discharge to Clutha River /Lake Wanaka	Stream leakage (Cardrona River / Bullock Creek)	Rainfall recharge	Groundwater Abstraction	Total
Inflows (m^3/day)	25,595	49	94,193	21,452	0	141,289
Outflows (m^3/day)	24,397	38,681	74,626	0	3,581	141,285
Difference (m^3/day)						4

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5.2 Groundwater levels

The location of the six calibration bores is shown on Figure 16. Figures 17a to 17f shows a plot of the observed and simulated groundwater levels at the six calibration bores within the model area and Figure 17g shows a spatial plot of groundwater levels from July 2016. Comments on the fit between the modelled data and the observed data for each bore are provided below:

Criffel Deer bore (F40/0327)

Observed data for the Criffel Deer bore is relatively limited, from late December 2017 to June 2018. In general, the modelled fit is reasonable, although the range of fluctuations is slightly underestimated in the model, however the absolute level is closely represented. The limited range of fluctuations in the simulated data may be a result of the single layer model which uses a comparatively high storage value, whereas the strata around the Criffel Deer bore may include some depth stratification and a locally lower value of storage.

Orchard Road bore (F40/0390)

Similarly, the model does not capture the full range of groundwater level fluctuations at the Orchard Road bore, which is located approximately 1 km away from true left bank of the Cardrona River, although again, the absolute level is closely matched. Both the Criffel Deer and Orchard Road bores are relatively deep and the use of a single model layer in that area may not represent the local groundwater environment around the bores in sufficient detail.

Envirowaste Tip bore (F40/0014)

Groundwater levels and fluctuations are closely matched at the Envirowaste Tip bore (located just downstream of the Ballantyne Road bridge. The absolute modelled levels are slightly high and the cause of the slightly higher levels in the simulated data is likely to be related to the fixed stage elevation used to represent the Cardrona River at that point, which may be slightly out. Whilst LiDAR provides a good estimation of ground surface elevations, errors can occur over water, which may be the case here

Ballantyne Road bore (F40/0389)

The Ballantyne road bore is located on the opposite bank of the Cardrona River to the Envirowaste Tip bore and generally, the modelled groundwater levels at the Ballantyne Road bore are a good representation of the observed data, albeit with slightly lower fluctuations in the modelled data.

State Highway 6 bore (F40/0391)

The modelled and observed groundwater levels at the State Highway 6 bore are a close match in terms of both absolute levels and fluctuations, implying that the model reasonably simulates the groundwater setting in that area, which will also be closely related to the groundwater discharge to the Cardrona River in that area.

Bullock Creek (F40/0386)

The absolute level at the Bullock Creek bore is closely matched. Whilst the fluctuations are not closely represented in the simulated data, the observed variations are very small (less than 0.2 m) and may be caused by a number of small scale features that are not represented in the model (for example short term rainfall runoff events from the hill country to the south-east). The discharge of groundwater to Bullock Creek will depend on the absolute groundwater levels in the aquifer, which are closely matched at the observed bore site.

5.3 Surface water flows

Plots of observed and modelled Cardrona River flows at Ballantyne Road and at the Clutha confluence are presented in Figure 18. The calibration focussed on low flows and the fit to these is very good at both Ballantyne Road and at the Clutha confluence. The model correctly simulates the losses in flows between point where the Cardrona River enters the Wanaka Basin and at Ballantyne Road. Downstream of Ballantyne Road, the flow gains are also accurately reproduced.

Figure 19 shows a flow duration curve for both simulated and observed flows in the Cardrona River at the Clutha confluence. The fit between the modelled and observed flow duration curve is very good, and the simulated results are very similar to the observed results at low flows.

The location of the losing reach is also correctly simulated as the reach downstream of Mt Barker and upstream of the State Highway 6 Bridge. Cumulative losses from the Cardrona River between Mt Barker and the Ballantyne Road Bridge are consistently around 700 L/s (Figure 20a and 20b), which is consistent with the average losses. Note that the groundwater model runs at weekly timesteps, and therefore is unlikely to simulate larger losses that occur for short times at higher flows.

Gauging data for Bullock Creek close to the confluence with Lake Wanaka is available from March 2018 until June 2018 and that data has been used as part of the calibration dataset. A plot showing the observed data and modelled data is shown in Figure 20c. The modelled data shows less variations compared to the observed data, although the scale is relatively small and the difference between the modelled and observed data is a few litres per second. In general, the flow is closely matched at around 400 L/s. It is useful to note that to match the modelled flow to the observed flow required a limited hydraulic connection between the strata downgradient from Bullock Creek / around Wanaka township and the lake.

6.0 Sensitivity analysis

6.1 Parameter sensitivity

Observed measurements in the model were split into different groups representing either flow (at Ballantyne Road, the Clutha confluence or Bullock Creek) or groundwater level observations (at each separate observation bore). The sensitivity of each group to model calibration parameters is presented in Figures 21a to 21i.

The simulated flows in the Cardrona River (Figures 21a and 21b) were most sensitive to the stream bed conductance parameter which controls the ease with which groundwater can move into and out of the stream boundary. Parameters 'str1' to 'str7' represents the stream bed conductance between the Mt Barker

Flow recorder and Ballantyne Road. River flows are most sensitive to stream bed conductance for this reach because it largely controls the volume of loss from the Cardrona River. The hydraulic conductivity at pilot points close to the confluence with the Clutha River (shown as parameters 'hk126', 'hk125' and 'hk120') is also an important control on the match between the modelled and observed flows. Flows at Bullock Creek (Figure 21c) are also mostly sensitive to the stream bed conductance along the Cardrona River between Mt Barker and Ballantyne Road, together with the hydraulic conductivity at intervening pilot points.

The sensitivity of simulated groundwater levels to various calibration parameters are also shown in Figure 21d to 21f. This indicates that the modelled groundwater levels at the Criffel Deer and Orchard Road bores (upstream of the Ballantyne Road bridge) are most sensitive to the stream bed conductance upstream of the Ballantyne Road bridge, together with some effect from hydraulic conductivity in nearby pilot points Modelled groundwater levels at the Envirowaste Tip bore (downstream of the Ballantyne Road bridge) are also sensitive to stream bed conductance, although the crucial factor for that bore is the hydraulic conductivity in the pilot point between the river and the bore.

Figures 21 g, 21h and 21i show the sensitivity of groundwater levels at the remaining bores further downstream and at Bullock Creek. Groundwater levels at the Ballantyne Road bore are more sensitive to hydraulic conductivity values compared to the nearby Envirowaste Tip bore, although stream bed conductance parameters are important for controlling the modelled representation of groundwater levels at that point. In contrast, groundwater levels at the most downstream monitoring bore at Stat Highway 6 are relatively insensitive to changes in stream bed conductance and are very strongly controlled by local values of hydraulic conductivity.

Groundwater levels at Bullock Creek (Figure 21i) are strongly impacted by stream bed conductance values upstream of the Ballantyne Road Bridge, emphasising the strong connection of the groundwater levels in that area to seepage losses from the Cardrona River.

Recharge values were also varied during the model calibration process, by including a multiplier for the overall recharge applied to each stress period. Figures 21a to 21i indicate that the model is relatively insensitive to variations in recharge. Storage parameters were also varied on the same pilot point basis as hydraulic conductivity and likewise, those parameters are not particularly relevant to the model calibration.

6.2 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 stream bed 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 22 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 stream bed conductance and hydraulic conductivity at pilot points around the groundwater monitoring bores and towards the confluence between the Clutha River and the Cardrona River. However, some uncertainty remains depending on which observation is fitted most closely. As noted above, groundwater levels observed at bore F40/0014 and flow both in the Cardrona River at Ballantyne Road and at the Clutha River confluence as well as Bullock Creek were sensitive to the value of stream bed conductance.

Figure 23 shows a map of the uncertainty reductions in the pilot points used to generate the hydraulic conductivity field across the model area. It indicates, as described above, that the key pilot points are those located close to the Cardrona River. There is a much greater uncertainty around pilot points located away from the Cardrona River (and away from the key calibration points), which has implications for forecast uncertainty (discussed in Section 7). Part of the uncertainty is related to the absence of observation data in that area. Whilst there are a number of groundwater take consents in the area east of the Cardrona River, the actual metered pumping rate from those takes is too low to have an a significant effect on flows in the Cardrona River. As a result, the pumping does not significantly affect the model calibration to flows in the river, and therefore the hydraulic conductivity parameters are poorly constrained in that area.

6.3 Parameter correlation

The sensitivity analysis provides an assessment of parameter correlations, which are useful to help indicate whether a model is non-unique. A large number of highly correlated parameters imply that a unique model calibration is difficult to achieve as changing one parameter can give a similar effect to changing a different parameter.

The parameter correlation matrix for the Wanaka model indicates that a total of 101,194 possible combinations were evaluated, which is too large to reproduce here. Parameter correlation values of more than 0.3 are relatively high and 4 parameters show a correlation coefficient of more than 0.3. Those parameters include the stream bed conductance along the Cardrona River and the hydraulic conductivity at pilot points to the west of the Cardrona River. For example the value of the stream bed conductance between Mr Barker and Ballantyne Road (parameter str1) is correlated to the stream bed conductance between SH6 and the Clutha River confluence (parameter str3).

To a large extent, those correlations are expected and could be reduced by using additional data (particularly groundwater level timeseries and also flow measurements) at other locations in the model domain. Non uniqueness is a characteristic of all groundwater models and has implications for model predictions and uncertainties around those predictions. Its effect discussed in Section 7.3.

7.0 Model scenarios

7.1 Abstraction Scenario

7.1.1 Description of scenario

The key purpose of the model is to determine the potential effect of abstraction on stream flows, in particular the impact of abstraction on flows in the Cardrona River downstream of the State Highway 6 Bridge as well as the effect on flows in Bullock Creek. In the 2011 ORC report the suggested maximum annual abstraction limit for the Wanaka Basin was 5×10^6 m^3/year, and a potential option presented to the community is for an allocation limit of 8×10^6 m^3/year. Therefore, to test the potential effect of that limit on flows in the Cardrona River, two abstraction scenarios were run, with the groundwater abstractions in the model scaled up to a total 5×10^6 m^3/year and a total of 8×10^6 m^3/year. On average, total current abstraction rates are around 42 L/s (equivalent to approximately 1.3×10^6 m^3/year), and under the increased abstraction scenarios, the average rates would increase to around 157 L/s for the 5×10^6 m^3/year scenario and 255 L/s for the 8×10^6 m^3/year scenario. The spatial and temporal distribution of abstraction was kept consistent with the calibrated model and all other inputs to the model remained unaltered.

The effect of abstraction on stream flows is typically assessed according to changes to the flow duration curve. The focus of these comparisons is usually on low flows because this is where groundwater abstractions will impart the greatest relative effect. Reductions in low flows are also of greatest concern when considering the ecological effects and ability for other users to access water.

The model was run four times:

- Once without any abstractions (a zero abstraction scenario);
- Once with the base case (calibrated model) scenario; and
- Twice with the increased abstraction scenarios

By comparing the modelled river flows from each of four scenarios, the impact of the additional abstraction on the resulting flow duration curve could be compared in isolation. In addition, the effects of abstraction on the average modelled flow in Bullock Creek and at Ballantyne Road were also considered.

7.1.2 Scenario results

Effects on low flows

Flow duration curves for the Cardrona River at the Clutha River confluence were evaluated as key prediction results. Figure 24 summarises the results of the model and the impacts of abstraction on the flow duration curves for the Cardrona River at the Clutha confluence and shows that, based on the calibrated model, abstraction impacts are evenly distributed across the flow duration curve indicating that abstraction effects are attenuated in time and do not occur particularly rapidly. Table 3 summarises the impacts under each abstraction scenario.

Table 3: Effects of increased abstraction on flows in the Cardrona River at the Clutha confluence and at Bullock Creek (based on a 3 year model run)

Abstraction Scenario	Average impact on flows at the Clutha Confluence (relative to the base case calibrated model) (L/s)	Average impact on flows in Bullock Creek (relative to base case calibrated model) (L/s)
Naturalised (no abstractions)	23.1	9
Calibrated model (base case)	0	0
Abstraction at 5×10^6 m^3/year	-64.4	-27
Abstraction at 8×10^6 m^3/year	-105.1	-48

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The effect of increased abstraction on flows in the Cardrona River at the Clutha Confluence over the modelled three year period is generally a relatively consistent reduction in baseflows of around 64 L/s for abstraction at 5×10^6 m^3/year and 105 L/s for abstraction at 8×10^6 m^3/year, compared to the base case abstraction scenario.

Note that the model does not indicate any increase in flow losses from the Cardrona River between Mt Barker and Ballantyne Road due to increased groundwater abstraction rates. This is because groundwater levels are naturally some depth below the river (up to 15 to 20 m) and the losses from the river are largely dependent on the stream bed conductance rather than the groundwater level.

The effect of abstraction on flows in Bullock Creek is also notable and the results indicate that Bullock Creek is potentially sensitive to abstraction from nearby bores, with average effects up to 48 L/s under the highest abstraction scenario.

Effects on the overall model mass balance

Figure 25A shows the difference in abstraction between the various scenarios, together with the relative change in discharges to surface water bodies. Note that these are presented as either flow impacts to stream boundary conditions (representing the Cardrona River and Bullock Creek) or river boundary conditions (representing Lake Wanaka and the Clutha River). The plot indicates that the full effect of abstraction on surface water bodies does not develop immediately and increases through time as storage within the groundwater system adjusts over several years. Note that some individual peaks are associated with abstractions located close to the river, which would be managed via flow restrictions. The model is based on a transient three year model run and part of the additional water taken by abstractions is absorbed by a change in aquifer storage (i.e. a decline in groundwater levels). Therefore, the results presented in Table 3 may represent a partial effect, rather than the full effect of abstraction.

Eventually, as the aquifer reaches a new steady state the additional water taken by abstractions will be equalled by a reduction in discharge to surface water bodies. However, Figure 25A illustrates that the effect is attenuated in time, i.e. the peak effect on stream flows is similar to the average abstraction rate rather than the peak abstraction rate (notwithstanding the effect of abstractions located close to the river). The effect of seasonally variable abstraction on stream flows is therefore smoothed in time (which is also shown by the consistent effect on that flow duration curve) and this is important in terms of aquifer management.

To provide an indication of the potential time required for the system to reach equilibrium (i.e. the point in time by which discharge to surface water reduces to match the increase in abstraction) the model run was extended by 9 years. This scenario used a repeating three year cycle of the existing recharge timeseries, streamflows and abstraction, resulting in a total model run of 12 years.

The model appears to reach equilibrium at the end of the 12 year run meaning that changes in storage account for around 5% of the increased abstraction rate. However, it is clear that the attenuation effect in the model is significant. After 12 years, the peak reduction in surface water flows is approximately equal to the average annual abstraction rate. Therefore, it is unlikely that the peak effects of abstraction on surface water flows across the model area would be significantly greater than the average abstraction rate.

As noted above, discharges to the river and stream boundaries will eventually reduce to match the increase in abstraction rates and the effect of that increase will be distributed between the Cardrona River, Bullock Creek, Lake Wanaka and Clutha River. Based on Figure 25A, the relative proportion of the effect on flows to Lake Wanaka and the Clutha River was relatively constant at around 22% of the total effect on all surface water bodies. The remaining 77% of effect will impact flows in the Cardrona River (55%) and Bullock Creek (23%). Figure 26 shows the long term effect of abstraction at different rates on Bullock Creek and the Cardrona River, which is also summarised in Table 4.

Table 4: Long term effects of increased abstraction on flows in the Cardrona River at the Clutha confluence and at Bullock Creek

Abstraction Scenario	Average abstraction rate (L/s)	Average impact on flows in Cardrona River (L/s)	Average impact on flows in Bullock Creek (L/s)	Average impact on discharge to Lake Wanaka and Clutha River (L/s)
Naturalised (no abstractions)	0	0	0	0
Calibrated model (base case)	42	23.1	9.7	9.2
Abstraction at 5 x 10^6 m^3/year	157	86.4	36.1	34.5
Abstraction at 8 x 10^6 m^3/year	255	140.3	58.7	56.1

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Effect of groundwater abstraction on groundwater levels

Groundwater abstraction will also have an effect on the general pattern of groundwater levels across the Wanaka Basin. Figure 27 shows the difference in simulated groundwater levels between the naturalised model (i.e. without any abstraction) and the calibrated model which includes some abstraction. The greatest predicted effect on groundwater levels occurs closest to the greatest concentration of abstraction bores to the east of the Cardrona River. In this area, groundwater levels in January 2017 (a time of large scale pumping) were around 0.5 m lower than they would have been if no abstraction took place. The drawdown effect on the east side of the Cardrona River also extends to the lower part of the Cardrona River, resulting in the loss in groundwater discharge to the river at that point as discussed above.

Figure 27 also shows the drawdown that could be expected if abstraction increased to a total of 5 × 10^6 m^3/year, compared to the no abstraction scenario. It indicates that drawdown effects would be greater, up to around 1.5 m compared to the no abstraction scenario, representing an additional drawdown effect of around 1 m.

It is important to highlight that the extent of drawdown also depends on the modelled hydraulic conductivity. The lower values of modelled hydraulic conductivity to the east of the Cardrona River result in greater drawdown due to pumping compared to the higher values of hydraulic conductivity modelled to the west of the Cardrona River.

The effects shown in Figure 27 represent a maximum at a time of greatest pumping. Effects at other times, for example during winter when less pumping occurs, would be smaller. However, as discussed above, the effect of abstraction on the flows in the Cardrona River is distributed across the flow duration curve and is attenuated in time, which indicates that eventually groundwater levels will shift downwards in response to increased abstraction. These effects represent the effects of approximately 18 months of abstraction; greater drawdowns will occur after longer periods of abstraction, although in general, these would not be significantly greater.

7.1.3 Predictive uncertainty

Assessments of predictive uncertainty are important for any groundwater modelling project. Uncertainty in any model arises from the fact that the model is a simplification of the real world system, even where the model outputs are a good match to the observed data. In addition, poorly constrained parameters can lead to uncertainties in predictions. In this model, the poorly constrained parameters are those where the uncertainty reduction is small, for example those parameters listed on the right hand side of Figure 22. Figure 23 shows the location of hydraulic conductivity pilot points across the model, and their uncertainty, to further illustrate this concept.

For example, initially the value of a parameter may have little effect on the calibration of the model, such as hydraulic conductivity in pilot points to the east of the Cardrona River. However, the value of those parameters may have a notable impact on how increased abstraction affects flows in the Cardrona River (e.g. greater values of hydraulic conductivity could result in greater effects of abstraction on low flows in the river). Parameters such as this cannot be constrained by the observed calibration data, and therefore the effect of increased abstraction in that area of the model on low flows in the river is more uncertain.

The key model predictions are the effect of abstraction on flows in the Cardrona River and in Bullock Creek. As such, the uncertainty associated with these predictions has been explored using PEST. For each of the two abstraction scenarios (i.e. abstraction at up to 5 x 10^6 m^3/year and 8 x 10^6 m^3/year), the model was run 319 times, which is the same as the number of variable parameters in the model. A single parameter was varied during each of those runs. The results of those runs were used to produce a sensitivity matrix (the Jacobian matrix), from which the uncertainty in model predictions can be derived.

The modelled error in the predicted flow impacts was calculated based on linear analysis using utilities supplied with PEST and pyEMU (White, 2014). Note that the analysis assumed a linear relationship between variations in model parameters and the effect on model predictions. In some circumstances, a linear relationship is not always valid and the predictive uncertainty can be larger than estimated. The uncertainty assessment is based on abstraction effects at the end of a three year model run and provides an indication of the uncertainty around the peak effect of abstraction after three years. The uncertainty associated with the absolute, long term effect of abstraction on surface water flows was not explored, as this is known to be equal to abstraction on average.

Table 5 summarises the predictive uncertainty based on a 95 percentile confidence interval.

Table 5: Predictive uncertainty in peak abstraction impacts on the Cardrona River and Bullock Creek

Abstraction Scenario	Average abstraction rate (L/s)	Average impact on flows in Cardrona River (L/s)	95% confidence interval	Average impact on flows in Bullock Creek (L/s)	95% confidence interval
Naturalised (no abstractions)	0	0	0	0	0
Calibrated model (base case)	42	23.1	±11	9.7	±2
Abstraction at 5 x 10^6 m^3/year	157	86.4	±34	36.1	±5.7
Abstraction at 8 x 10^6 m^3/year	255	140.3	±46	58.7	±6.9

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The predictive error shown in Table 5 effectively represents the uncertainty in the model around the peak abstraction effect. The modelled results discussed in Section 7.2.1 implied that abstraction effects are likely to be smoothed in time. However, the uncertainty analysis indicates that effects on low flows in the Cardrona River could possibly occur more rapidly and be closer to a peak abstraction rate, rather than the long term average abstraction effect. Whilst the uncertainty effect after a longer time period of abstraction has not been evaluated, it is not expected to be significantly greater than that shown in Table 5.

Figure 28 presents the information in Table 5 graphically. The purpose of Figure 28 is to illustrate how different allocation volumes for the aquifer will have different effects on flows in the Cardrona River and Bullock Creek and that there is a range of potential effects associated with an allocation volume. For example, to be reasonably confident that the depletion effect is unlikely to exceed 100 L/s in the Cardrona River, the allocation limit should be less than 4 x 10^6 m^3/year, because a 100 L/s depletion effect on the Cardrona River is at the upper 95% percentile of that allocation limit.

7.2 Effects of irrigation

7.2.1 Description of scenario

One of the primary uses of water across the Wanaka Basin is irrigation, together with other purposes including domestic, stock water and industrial uses. A potential change in land use across the Wanaka Basin includes land conversion from irrigated land to urban land, particularly on the western side of the Cardrona River. Given that irrigation is included as a component in the simulated recharge to the groundwater flow model, the effect of irrigation on groundwater levels and stream flows can be evaluated. To estimate the effects of irrigation, the groundwater model was run twice, once where simulated irrigation was included in the recharge to the model (i.e. the same as the calibrated model), and a second time where simulated irrigation was excluded from the recharge to the model. All other aspects of the model remained unchanged.

7.2.2 Scenario results

The results of the scenario are shown in Figure 29. The impact of irrigation on groundwater levels is greatest in areas where flood irrigation is present (towards the south of the model domain), because that is where the greatest effect on recharge to the model occurs. Simulated groundwater levels are up to 0.4 m higher due to irrigation than would be the case if no flood irrigation occurred in those areas. However across other parts of the model, a smaller predicted effect occurs. It is useful to point out that the greatest effect due to irrigation occurs in areas away from the main modelled discharge boundaries, such as the Clutha River, the Cardrona River, or Bullock Creek and Lake Wanaka.

Relatively minor effects are expected to occur on Bullock Creek directly, which is generally consistent with the limited changes in groundwater level that would be expected in the area around the Creek. Based on the model, the change in flows in Bullock Creek would be in the order of 2 - 3 L/s. Likewise, effects on flows in the Cardrona River at the Clutha River confluence are expected to be relatively small, because the change in groundwater levels in the reach of the Cardrona River where it gains (i.e. downstream of State Highway 6) is very small (i.e. less than 0.05 m).

7.3 Minimum flow restrictions

A further model scenario investigated the potential effect of low flow restrictions for surface water and connected groundwater takes between Mt Barker and the Ballantyne Road bridge, and downstream of the Ballantyne Road bridge. Note that the only surface water takes included in the model are the irrigation race takes for the Wanaka and Farrant races (and the Criffel race), which are located close to Mt Barker. Groundwater abstraction has very little impact on flows in the Cardrona River between Mt Barker and the Ballantyne Road Bridge because of the depth to groundwater below the river in that area. Therefore, groundwater takes were not varied as part of the scenario.

The surface water takes are included in the model as diversions from the main stem of the Cardrona River. The abstraction rates assigned to those takes were limited based on the following flow restrictions:

- 200 L/s at Ballantyne Road
- 300 L/s at Ballantyne Road
- 400 L/s at Ballantyne Road

Inputs to the MODFLOW model are fixed at the start of the model run, and therefore the abstraction rates cannot be dynamically altered based on a flow rate calculated during the model run. However, seepage losses between the Mt Barker flow recorder and Ballantyne Road are consistently 700 L/s and therefore flow at Mt Barker (minus 700 L/s) was used as a proxy for flows at Ballantyne Road to investigate the effect of flow restrictions. The abstraction rates for the Wanaka and Farrant races were reduced at the flow restriction levels listed above, allowing for some residual abstraction to ensure that flows rates in the river remained above the restriction levels.

The results of the scenarios are shown in Figures 30 and 31, which show the effect of the restrictions on the simulated flow duration curve for the Cardrona River at Ballantyne Road, and show the additional seepage to the aquifer that would occur at the different restriction levels.

Figure 30 indicates that the Cardrona River would fall dry at Ballantyne Road at times of very low flow regardless of the restriction level. However, at progressive restriction levels the amount of time when flow ceases at Ballantyne Road would reduce. Based on the calibrated model, no flow occurs at Ballantyne Road around 15% of the time (based on the three year model run from 2015 to 2018). Imposing restrictions would reduce the dry periods to around 10% of the flow record.

Additional flow at Ballantyne Road will result in additional seepage losses to the underlying aquifer and Figure 31 indicates that, on average and based on the calibrated model results, seepage losses from the Cardrona River to groundwater are around 1,090 L/s (including the reach downstream of Ballantyne Road). Setting flow restrictions would increase seepage up to a maximum of around 1,140 L/s (for a flow restriction level of 400 L/s). That additional seepage is equivalent to an average of around 1.7 x 10^6 m^3/year of additional groundwater recharge, most of which would flow towards and discharge into Bullock Creek. The modelled scenarios do not indicate an increase Cardrona River flows at the Clutha River as a result of the proposed restrictions.

8.0 Options for groundwater allocation

8.1 Current status

Groundwater allocation typically intends to achieve specific aims and outcomes, including the protection of values assigned to surface water receptors that are dependent on groundwater discharges. The key surface water receptors within the Wanaka Basin are the Cardrona River and Bullock Creek. Both surface water receptors have values assigned to them, although specific low flow limits are not yet defined. Therefore, it is not yet possible to set a groundwater allocation limit which is based on achieving the low flow limits in the key surface water receptors. The existing allocation to consented groundwater takes across the

Wanaka Basin (as the aquifer is currently defined) is approximately 8.4×10^6 m^3/year (excluding dewatering takes).

We understand that two options have been presented to the community to date:

- Option 1 is to assign a limit of 5×10^6 m^3/year across the existing aquifer boundary (as determined from the 2011 report); and
- Option 2 is to apply a limit of 8×10^6 m^3/year, but bores located on the eastern half of the aquifer (i.e. to the east of a line north of Mt Barker) would be restricted based on aquifer levels.

Comments on each of those options are provided below, together with a third option where the aquifer is formally split into two separate zones.

8.2 Option 1: 5×10^6 m^3/year limit across existing model boundary

The background to the limit of 5×10^6 m^3/year is discussed in Section 1 of this report, and represents an allocation limit that restricts surface water depletion effects in the Cardrona River downstream of the State Highway 6 Bridge to approximately 100 L/s. Generally, the model developed and described in this report provides a similar estimate of effects on the Cardrona River at that abstraction limit, although where the uncertainty in model predictions is recognised, the effect falls into a possible range from 52 L/s to 120 /s with a median value of 86 L/s. Stream depletion effects on Bullock Creek predicted by the model described in this report at an allocation limit of 5×10^6 m^3/year are around 36.1 L/s (±5.7 L/s).

The advantage of a single allocation limit across the whole aquifer is that it is relatively simple both to implement and for users of the resource to understand. A single limit based on effects on the Cardrona River should therefore protect low flows in the Cardrona River. In addition, the single limit will provide some protection to effects on other surface waterways such as Bullock Creek.

However the main disadvantage of a single groundwater allocation limit is that it effectively assumes that abstraction of groundwater from any part of the aquifer has the same peak effect on flows in the river. In the Wanaka Basin, that may not be correct, and based on the model, abstraction on the eastern side of the river is likely to have a smaller peak effect on flows in the Cardrona River or Bullock Creek compared to abstraction on the western side.

8.3 Option 2: 8×10^6 m^3/year limit and trigger level restrictions

The second option presented to the community is to apply a limit of 8×10^6 m^3/year across the existing aquifer boundary. If that limit were applied, restrictions based on groundwater levels in the eastern part of the aquifer would be imposed on abstractors in that area.

Currently, the trigger levels where restrictions may be imposed are not yet defined. Furthermore there is limited data across the easternmost part of the aquifer to derive a trigger level that could be related back to an allocation limit and the area over which those restrictions could be applied is also not yet defined.

Therefore, setting a reasonable trigger level may be difficult based on the current state of knowledge for that part of the aquifer and Option 2 may be difficult to implement.

Based on the results from this model, an allocation limit of 8 x 10^6 m^3/year across the whole aquifer would result in stream depletion effect of 140.3 L/s ±46 L/s on flows in the Cardrona River and stream depletion effects of up to 58.7 L/s ± 6.9 L/s in Bullock Creek.

8.4 Option 3: Split allocation zone

The alternative approach to setting a single allocation limit to the whole aquifer is to split the aquifer into two allocation zones. The purpose of restricting aquifer abstraction is to protect flows in Bullock Creek and the Cardrona River. Hence it would be reasonable to apply a different limit to areas of the aquifer located some distance from those receptors, and where groundwater abstraction has little effect on flows.

Figure 32 shows a map of the stream depletion effect[3] in either the Cardrona River or Bullock Creek due to abstraction from any part of the model after approximately 150 days pumping. Greater stream depletion effects (up to 80%) occur closest to Bullock Creek and the lower part of the Cardrona River, whereas pumping from the eastern part of the aquifer has limited effect on the river within this timeframe. In addition, groundwater abstraction towards the southern part of the model area, where the Cardrona River enters the Wanaka Basin, has relatively limited effect on flows in the Cardrona River. This is in keeping with the pumping test results in that area (from the Criffel Deer bore F40/0335), which indicated limited direct stream depletion effects.

As discussed in Section 7.1, there is a lag between pumping and the onset of effects in the river and Figure 30 shows the effect of pumping after around 150 days. To account for the lag effect, an assessment of the effect of pumping after a longer period (2 years) is shown in Figure 33. It indicates that after a longer time period, stream depletion effects would be greater and would occur at greater distances from the Cardrona River and Bullock Creek. However, the results continue to indicate that, based on the calibrated model, the eastern part of the aquifer is relatively disconnected from the Cardrona River, although pumping from that part of the Wanaka Basin will have an effect on flows in the Clutha River.

Based on Figures 32 and 33, a reasonable boundary along which the Wanaka Basin aquifer could be split is shown in Figure 34. The proposed boundary is conservative and approximately follows the 10% stream depletion line i.e. at a point where the model predicts 10% or less stream depletion effects on the Cardrona River after 2 years pumping. However a conservative approach is justified in this case because of the uncertainty discussed in Section 7.1, particularly in this area of the model domain.

If the aquifer were split along the boundary shown in Figure 34, the area to the west of the boundary would be allocated based on the effect of groundwater

[3] See Appendix C.

abstraction on the Cardrona River and Bullock Creek. This scale of allocation should be determined on the basis of acceptable stream flow reductions, which will be subject to a range of considerations by various stakeholders. However, the model indicates that where abstraction across the whole aquifer was scaled to 5×10^6 m^3/year, long term effects on the Cardrona River and Bullock Creek increased to around 86 L/s (± 34 L/s) and 36.1 L/s (±5.7 L/s) respectively. If this option to split the aquifer is pursued, careful consideration of the effect of abstraction within only the western zone of the aquifer will be required to ensure that the allocation limit is appropriate.

Allocation across the eastern area should be based on recharge. The average modelled land surface recharge (including irrigation between 2015 and 2017) is around 78 mm/year across an area of around 1,917 ha. This is equivalent to an average volume of 1.5×10^6 m^3/year (or around 47 L/s). If the allocation limit in the eastern area is set to 50% of mean annual recharge (as per the Regional Plan: Water), then the allocation limit would be around 0.75×10^6 m^3/year. In comparison, metered abstraction rates in the eastern area amount to approximately 0.31×10^6 m^3/year (based on 2015/2016 and 2016/2017 data), although the total annual volume on consented groundwater takes is approximately 1.9×10^6 m^3/year.

Therefore, estimates of consented volumes compared to the volume of recharge suggest that more than 50 % of recharge to groundwater has already been allocated from the eastern part of the aquifer. However, it is important to recognise that these estimates are only based on three years of data. The ultimate effect of groundwater abstraction from the eastern area of the aquifer will be a reduction in seepage to the Clutha River, although it is likely that effect will be attenuated in time.

8.5 Recommended option

In our opinion, the most appropriate option is to split the allocation zone (Option 3). This approach would ensure that users who are taking groundwater from parts of the aquifer (distant from the Cardrona River and Bullock Creek) are not unduly restricted by a single allocation limit based on stream depletion effects on those surface waterbodies. However, the analysis above may imply that no further groundwater should be allocated from the eastern zone, because the existing allocation is likely to be greater than the 50% of recharge threshold specified in the Regional Plan: Water. Consequently, it would be appropriate to review actual water use requirements and reduce consented allocation back to less than 50% of recharge. Alternatively, the actual water use of users compared to their allocation could be reviewed to ensure that water is being used efficiently.

9.0 Conclusions

The aim of this modelling exercise was to estimate the effect of increased groundwater abstraction in the Wanaka Basin / Cardrona Alluvial Gravels aquifer on flows in the Cardrona River and Bullock Creek. The groundwater model was calibrated to flows in the Cardrona River, together with groundwater levels at a number of monitoring bores.

The model results indicate a robust calibration to both river flows and groundwater levels. Scenario modelling including increased abstraction rates indicates that in the long term the reduction in low flows in the Cardrona River is currently around 23 L/s and around 9 L/s in Bullock Creek but could increase to in the order of 86 L/s if groundwater abstraction is scaled up to a total of 5×10^6 m^3/year. However, the results of the model indicate that the full effect is likely to take at least 10 years to develop.

The results of the uncertainty analysis indicate that whilst the model matches flows in the Cardrona River and groundwater levels, the effect of increased abstraction falls into a range based on model uncertainty. The uncertainty represents the potential range of peak abstraction effects on low flows in the Cardrona River and suggests that, depending on the actual value of hydraulic conductivity in the strata to the east of the Cardrona River, greater or lesser effects could occur. This reflects the uncertainty in parameters which cannot be uniquely defined by the calibration dataset, including values of hydraulic conductivity to the east of the Cardrona River.

The existing groundwater model of the aquifer (ORC, 2011) indicated impacts to outflow to the Cardrona River downstream of State Highway 6 of around 100 L/s under an abstraction scenario of 5×10^6 m^3/year. However, the existing model was not calibrated to flows in the river, therefore there is limited confidence in its ability to predict flows. This updated model is calibrated to flows and therefore there is much greater confidence in surface water flow predictions. Whilst uncertainties in those predictions remain, they are reduced relative to the original model.

The model indicates that the area to the east of the Cardrona River is poorly connected to the Cardrona River and Bullock Creek. Therefore, the most appropriate groundwater allocation approach to the Wanaka Basin is to split the area into two zones. One zone represents the areas where groundwater abstraction will affect flows in the Cardrona River and Bullock Creek. The scale of the abstraction effect on stream flows deemed acceptable should be determined and allow for model uncertainties. Figure 35 helps to explain this concept.

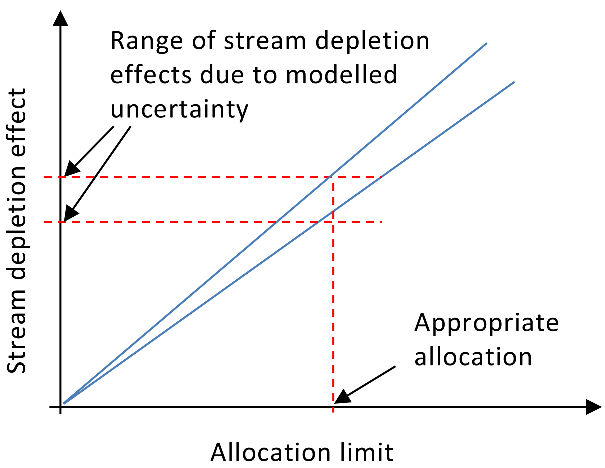

Figure 31: Stream depletion effects and allocation limits.

The second zone lies to the east of a line north of Mt Barker and if the thresholds in the Regional Plan: Water are applied in this area, the allocation limit should be set to around 0.75 × 10^6 m^3/year, i.e. 50% of recharge.

It is important to highlight that the allocation scenarios considered in this report assume that the full volume of groundwater allocated is abstracted every year. In reality, most users will only abstract a proportion of their take apart from during very dry years. Therefore, the estimated effects of abstraction on stream flows represent a conservative estimate of the potential effect of allocation of groundwater at the different volumes.

10.0 Bibliography

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Appendix A

Summary of pumping test results

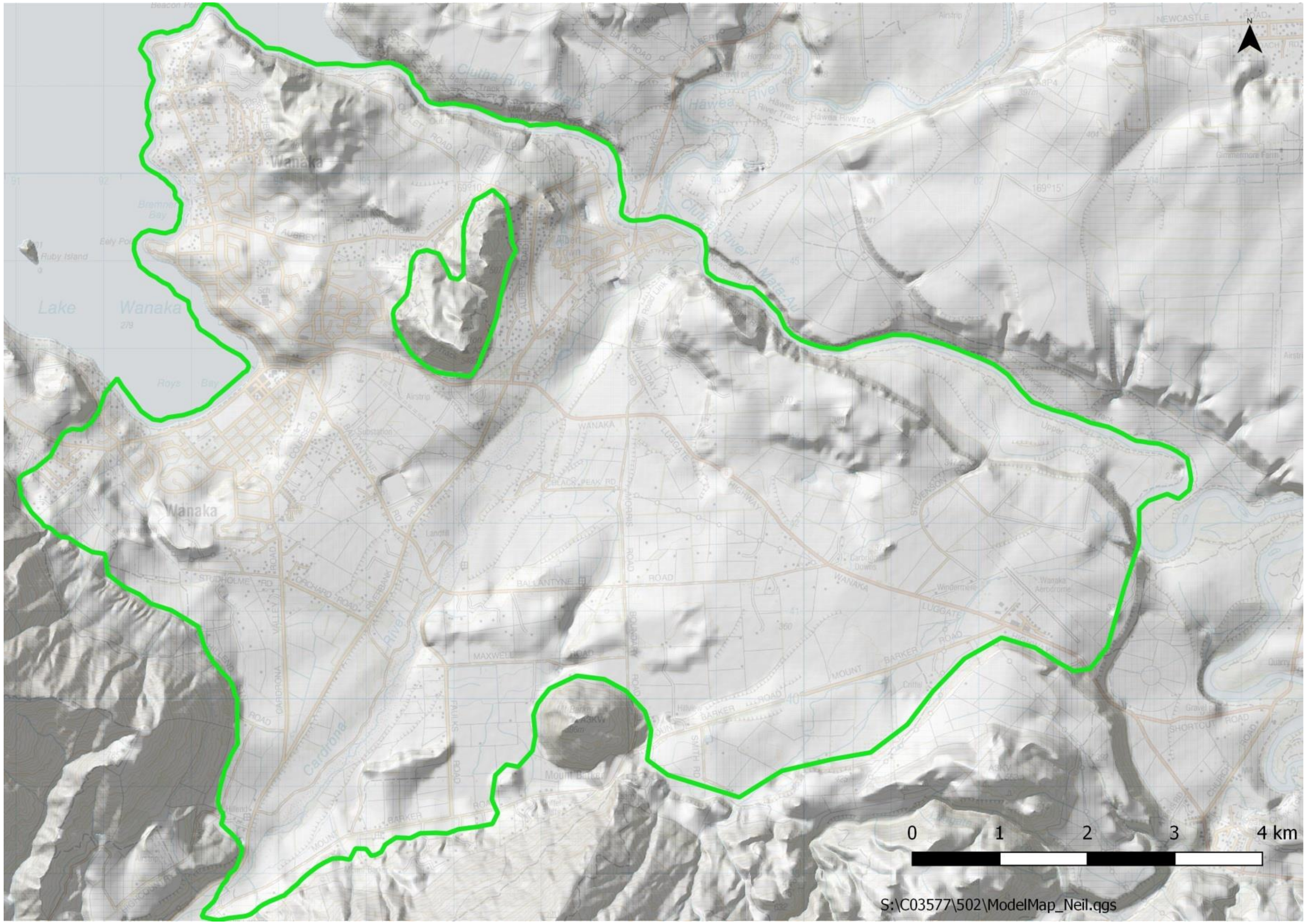


FIGURE 1A: LOCATION MAP INLCUDING TOPOGRAPHY

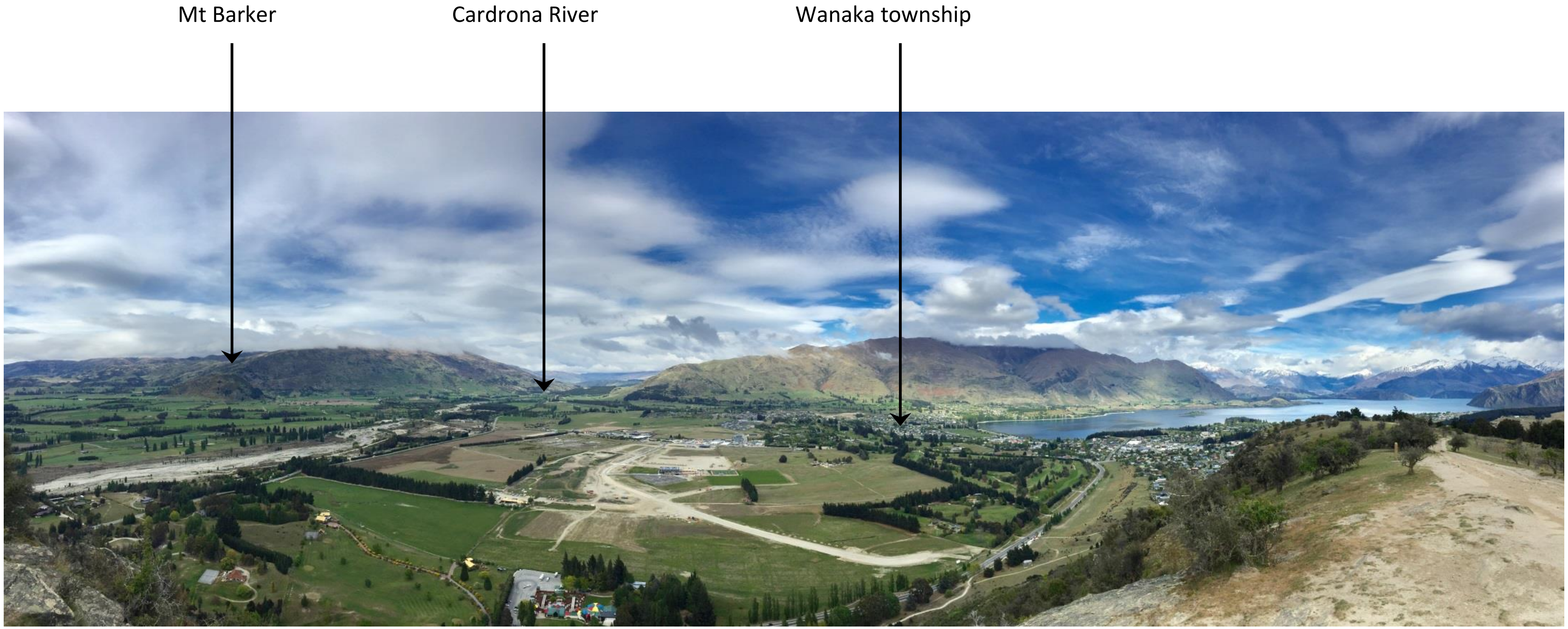


FIGURE 1B: PHOTO LOOKING SOUTH FROM THE TOP OF MT IRON ACROSS THE WANAKA BASIN

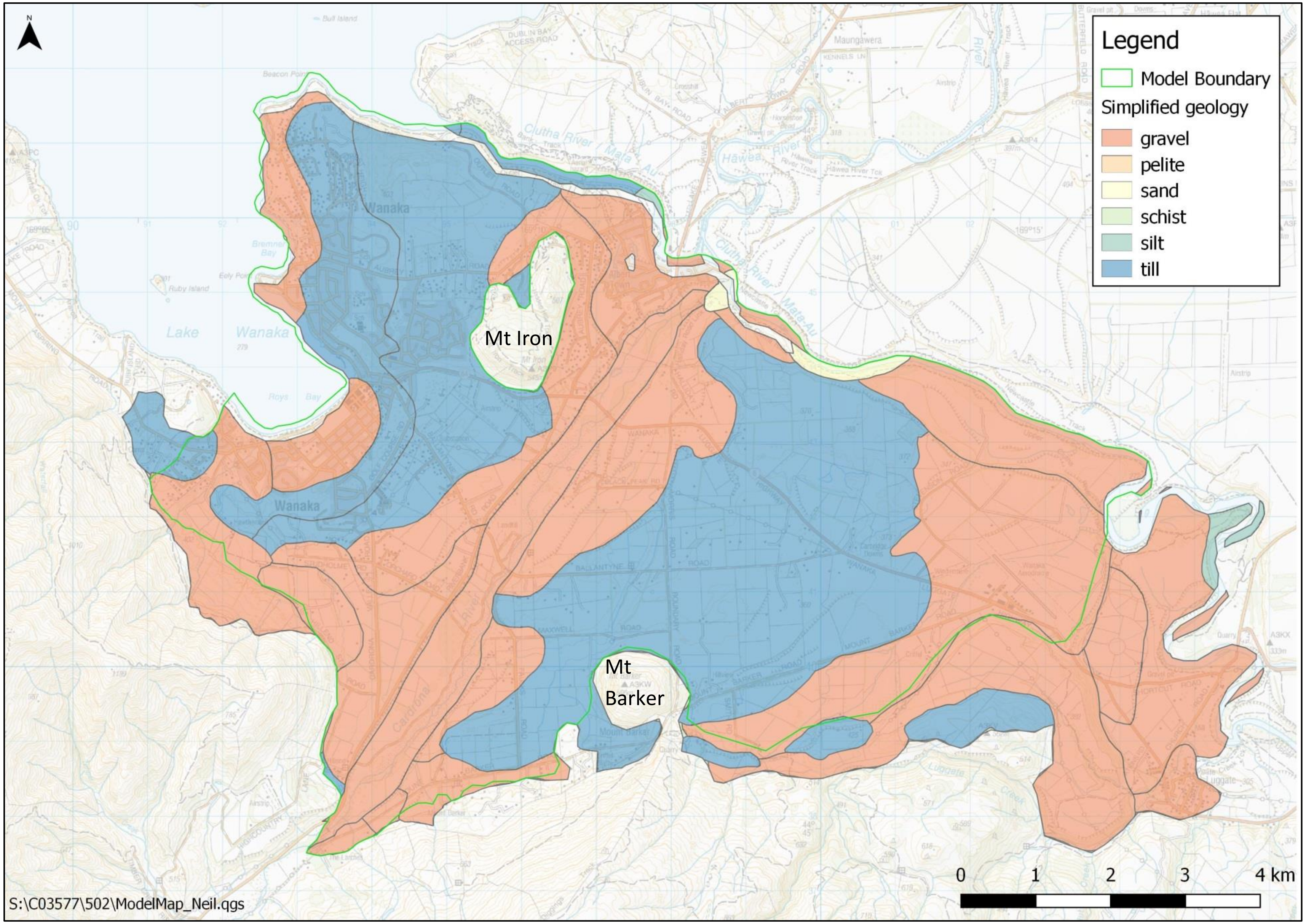


FIGURE 2: SIMPLIFIED GEOLOGY MAP

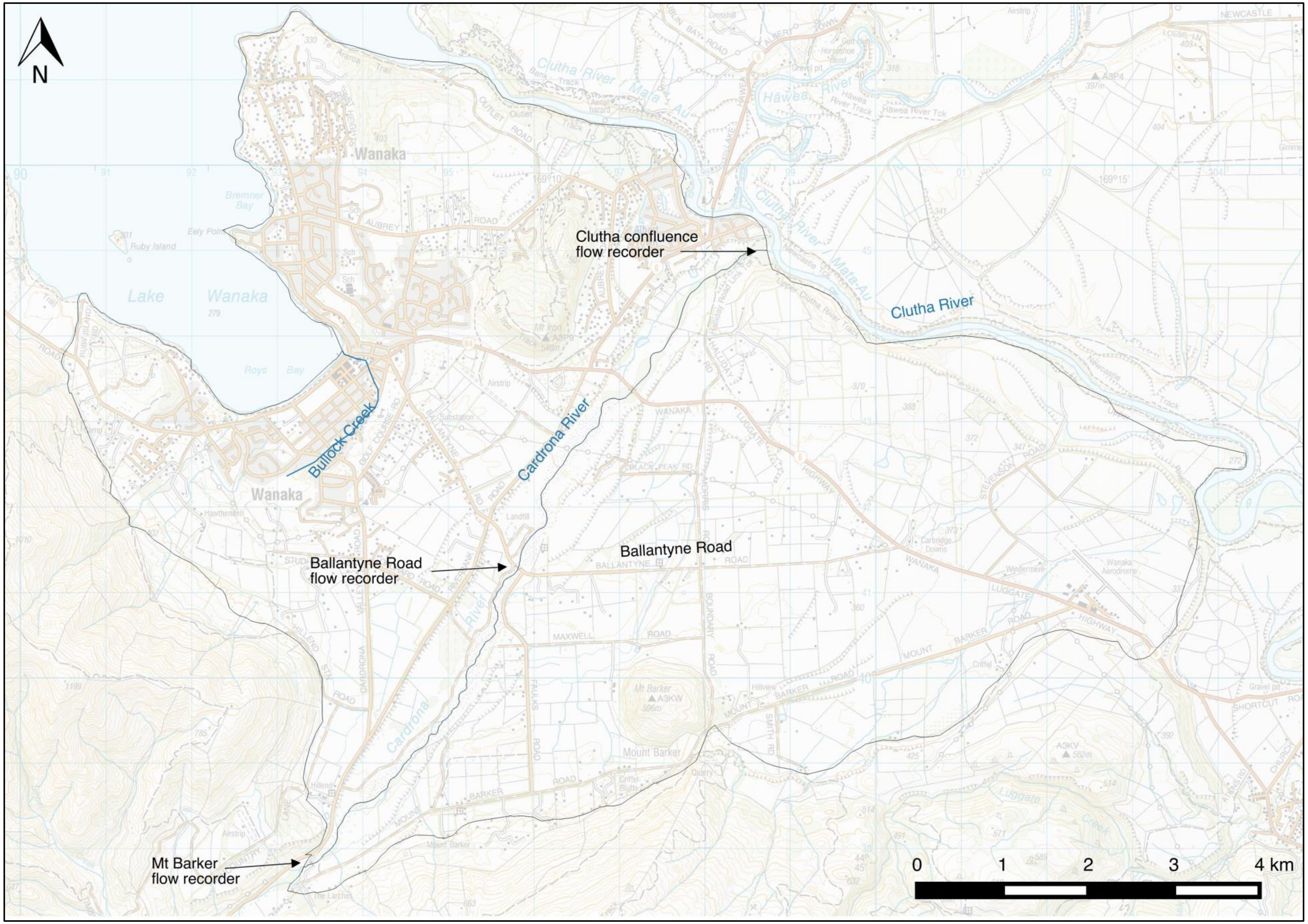


FIGURE 3: LOCATION OF SURFACE WATERWAYS WITHIN THE MODEL AREA

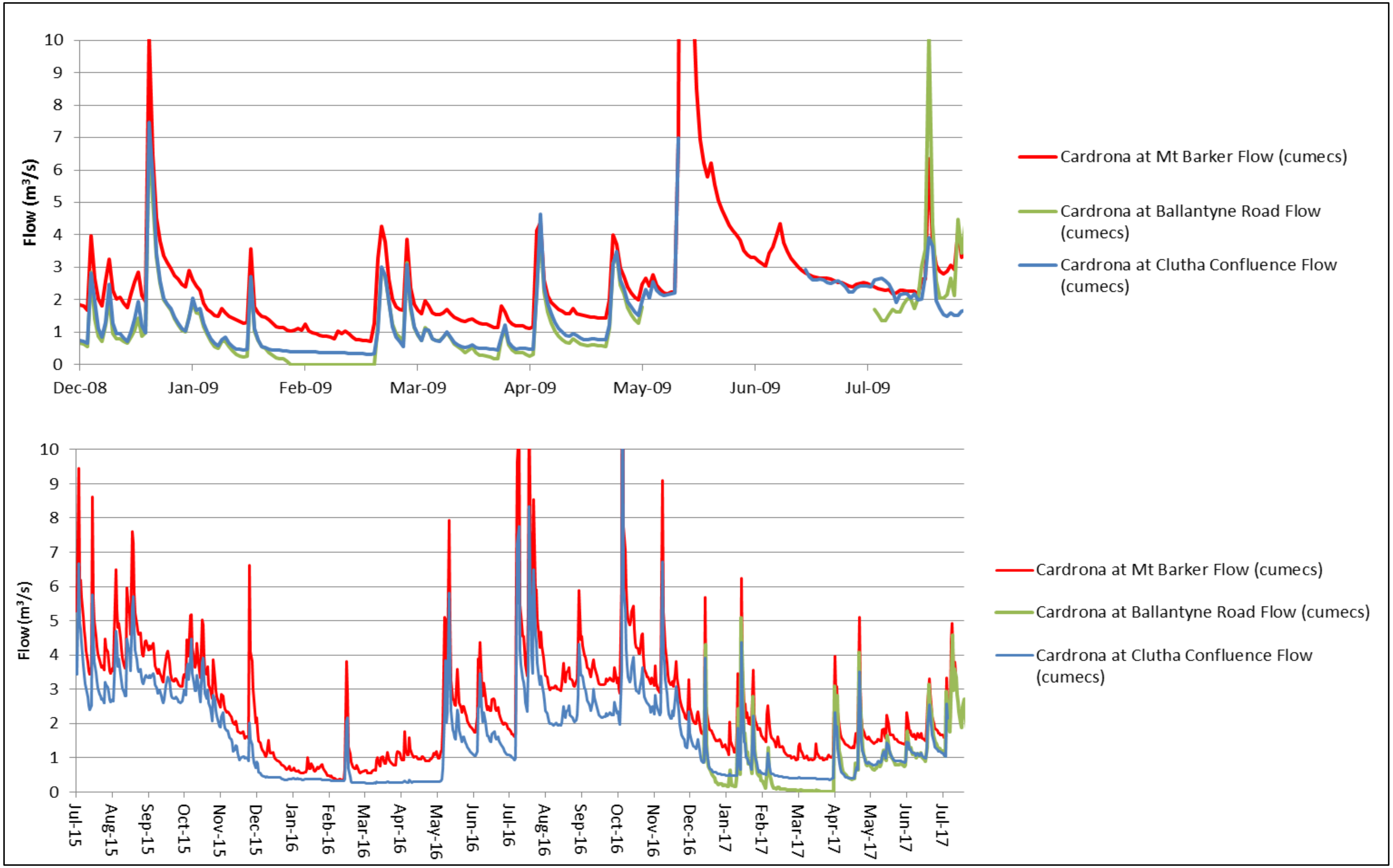


FIGURE 4: OBSERVED FLOW DATA (NOTE TWO DIFFERENT TIME PERIODS FROM DEC 2008- AUG 2009 AND JULY 2015 - JULY 2017

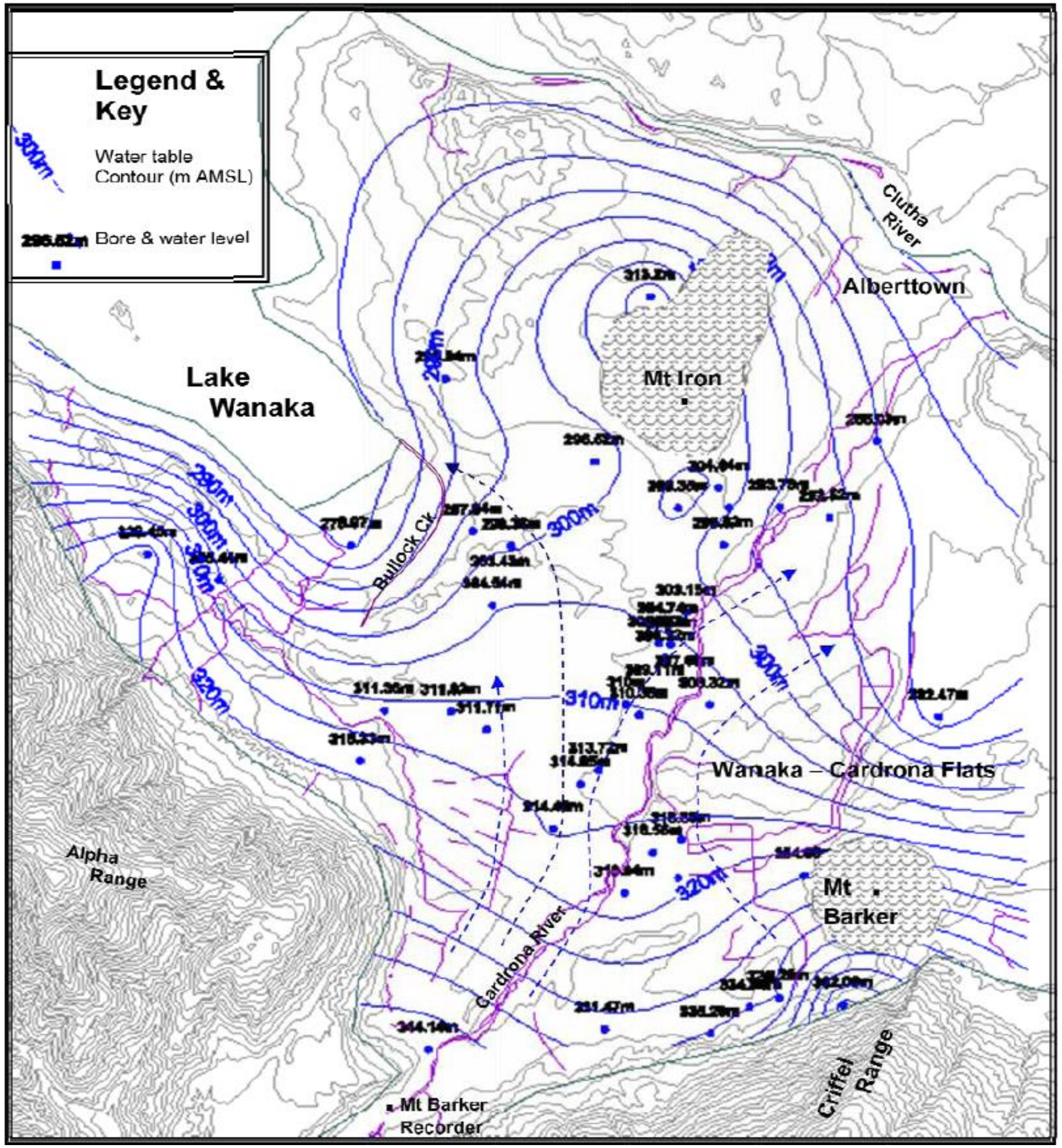


FIGURE 5: GROUNDWATER LEVEL CONTOURS (REPRODUCED FROM ORC, 2011)

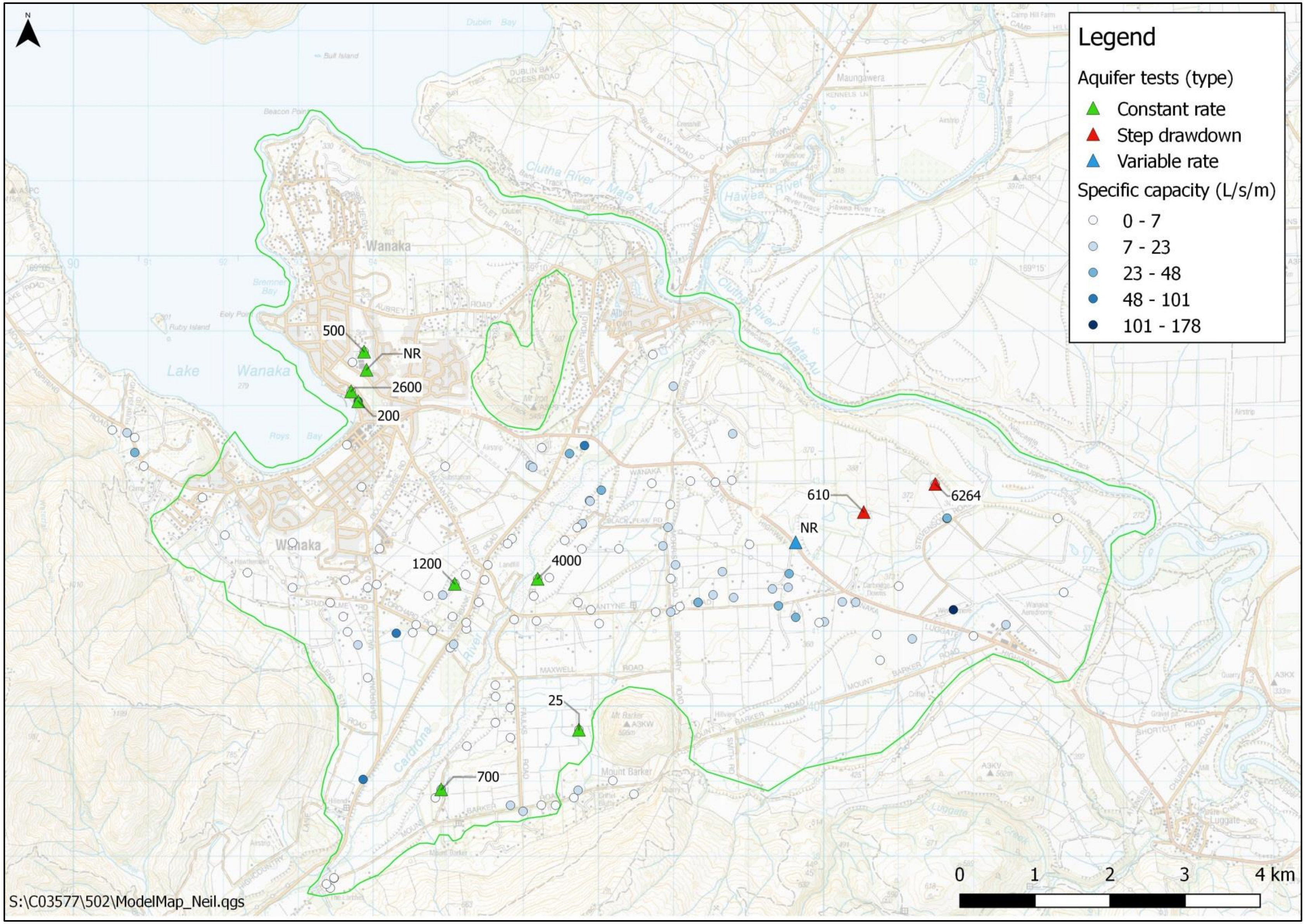


Figure 6: Location of specific capacity data and aquifer tests. Aquifer tests are labelled with transmissivity values in m^2/day. 'nr' values are 'not reported'

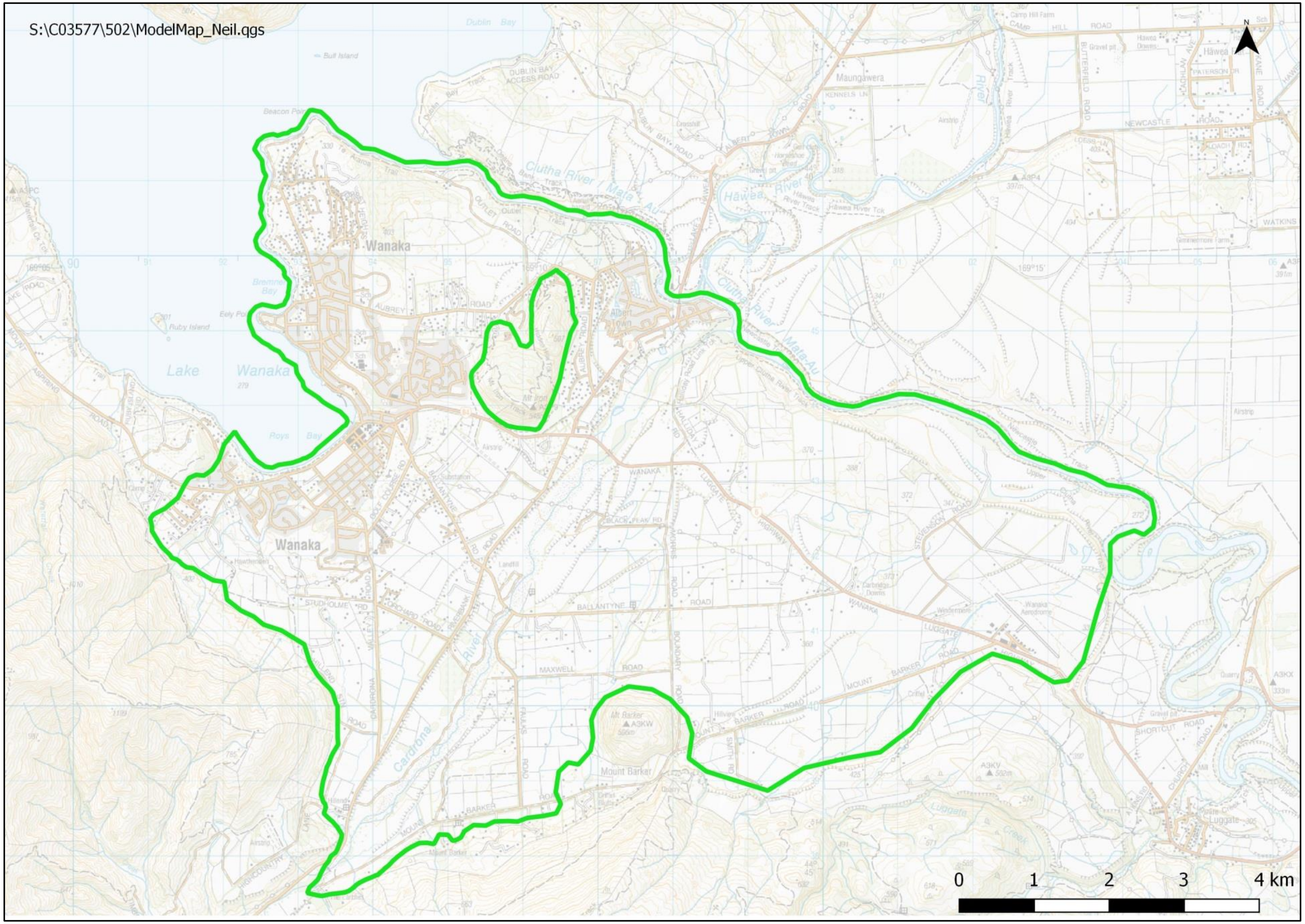


FIGURE 7: MODEL BOUNDARY

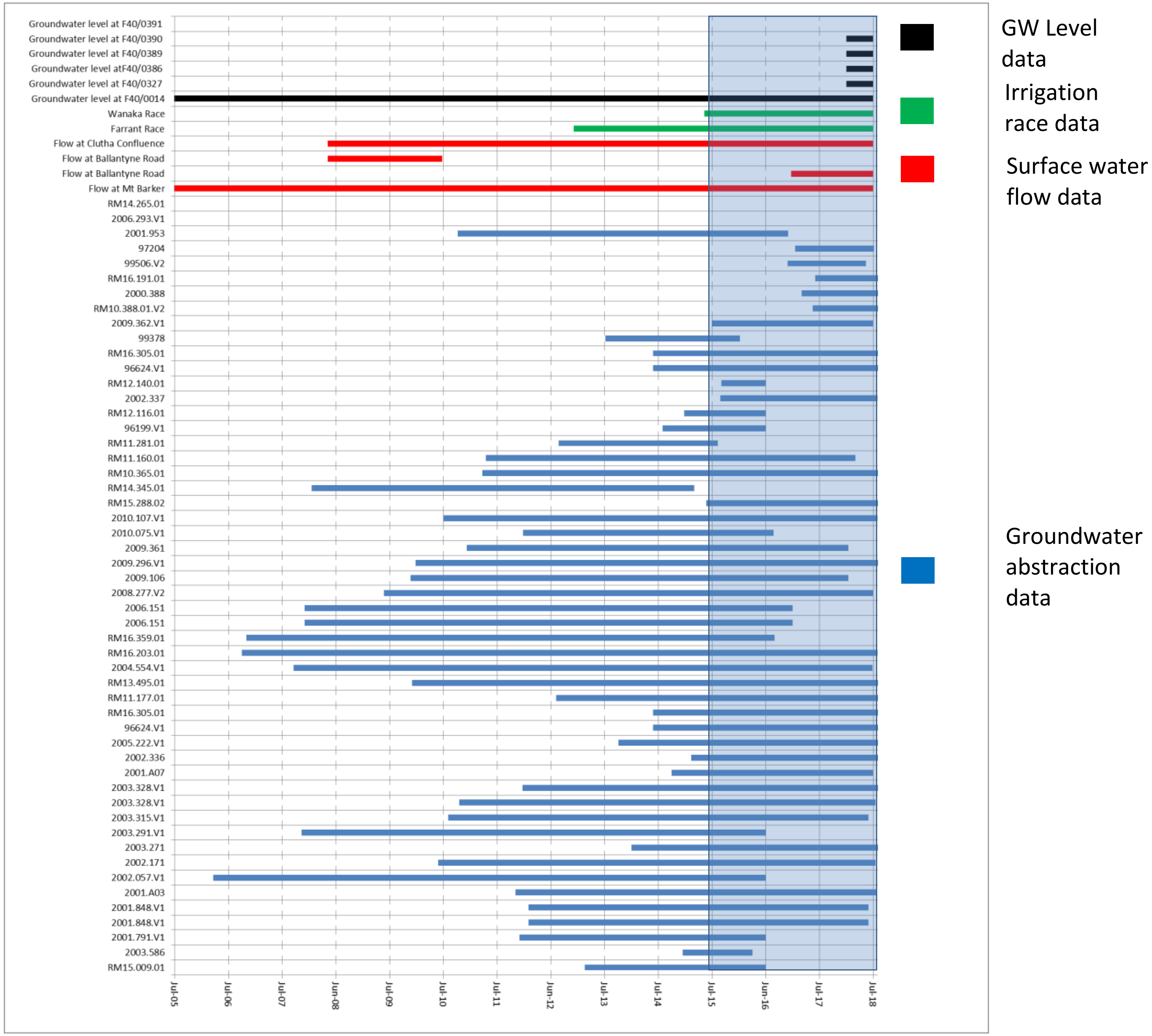


FIGURE 8: DATA AVAILABILITY IN TIME. THE BLUE BOX REPRESENTS THE MODELLED PERIOD OF TIME (JULY 2015- JULY 2018).

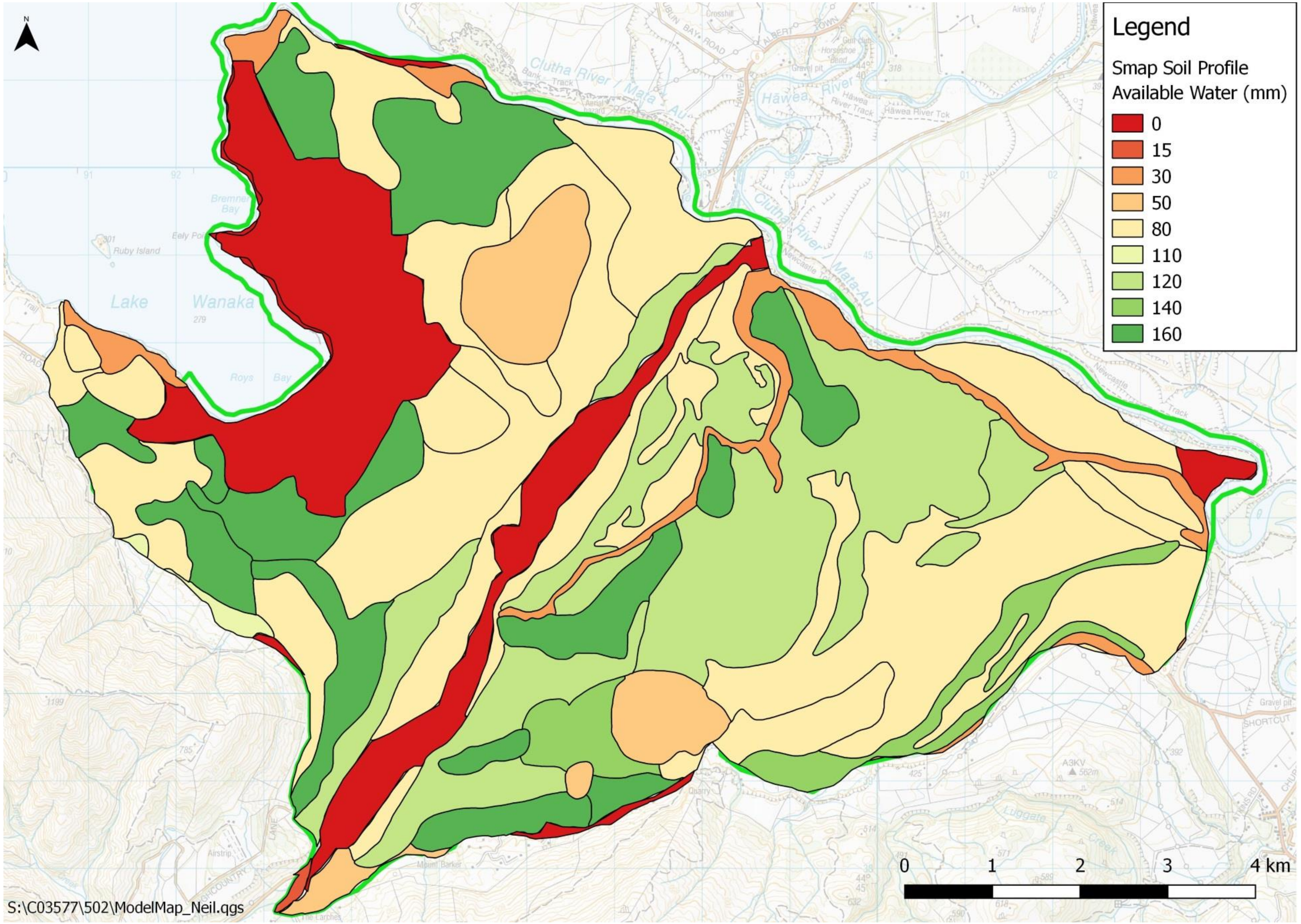


FIGURE 9A: SOILS (SHOWN AS PROFILE AVAILABLE WATER BANDS) ACROSS THE WANAKA BASIN

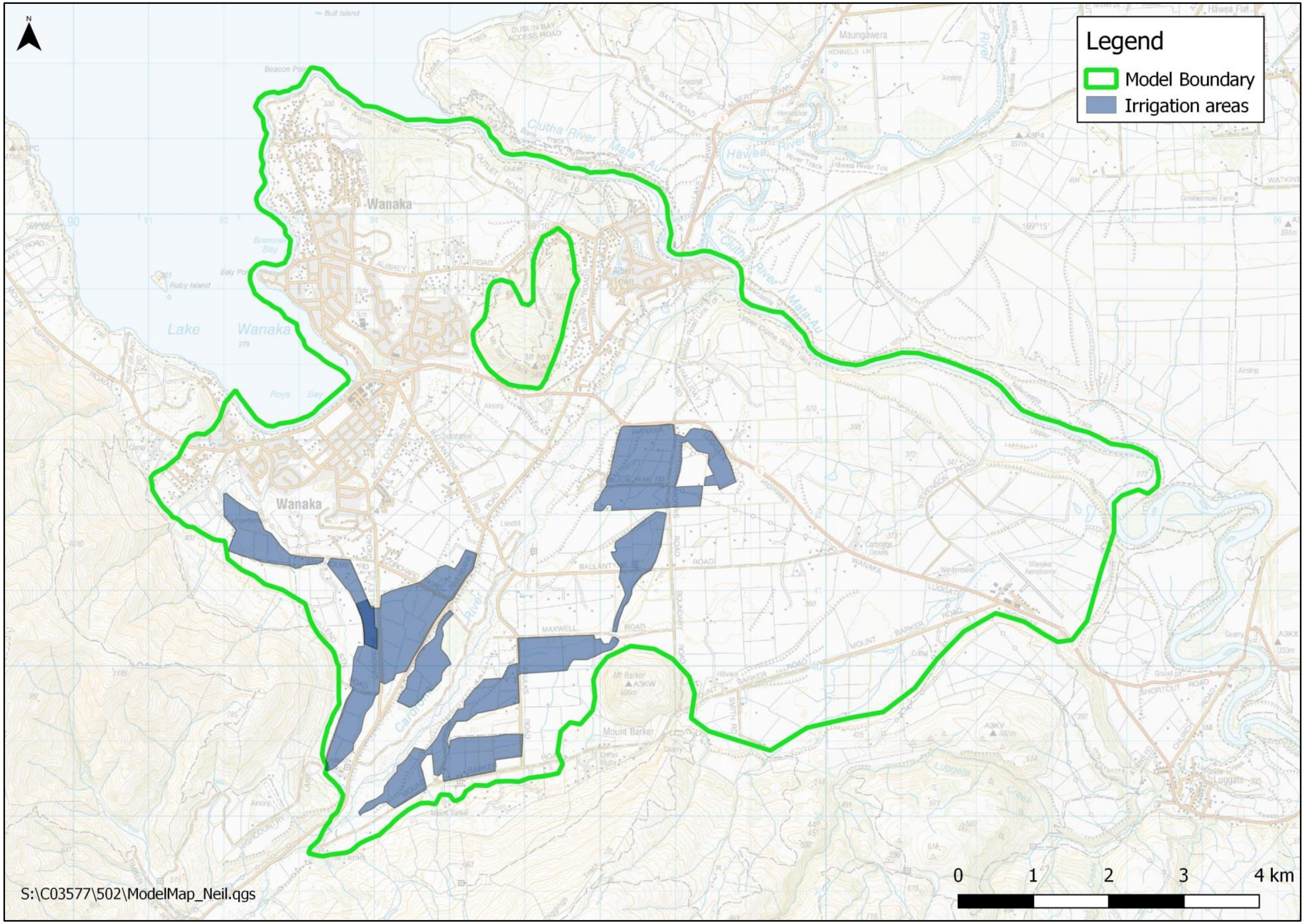


FIGURE 9B: IRRIGATION AREAS

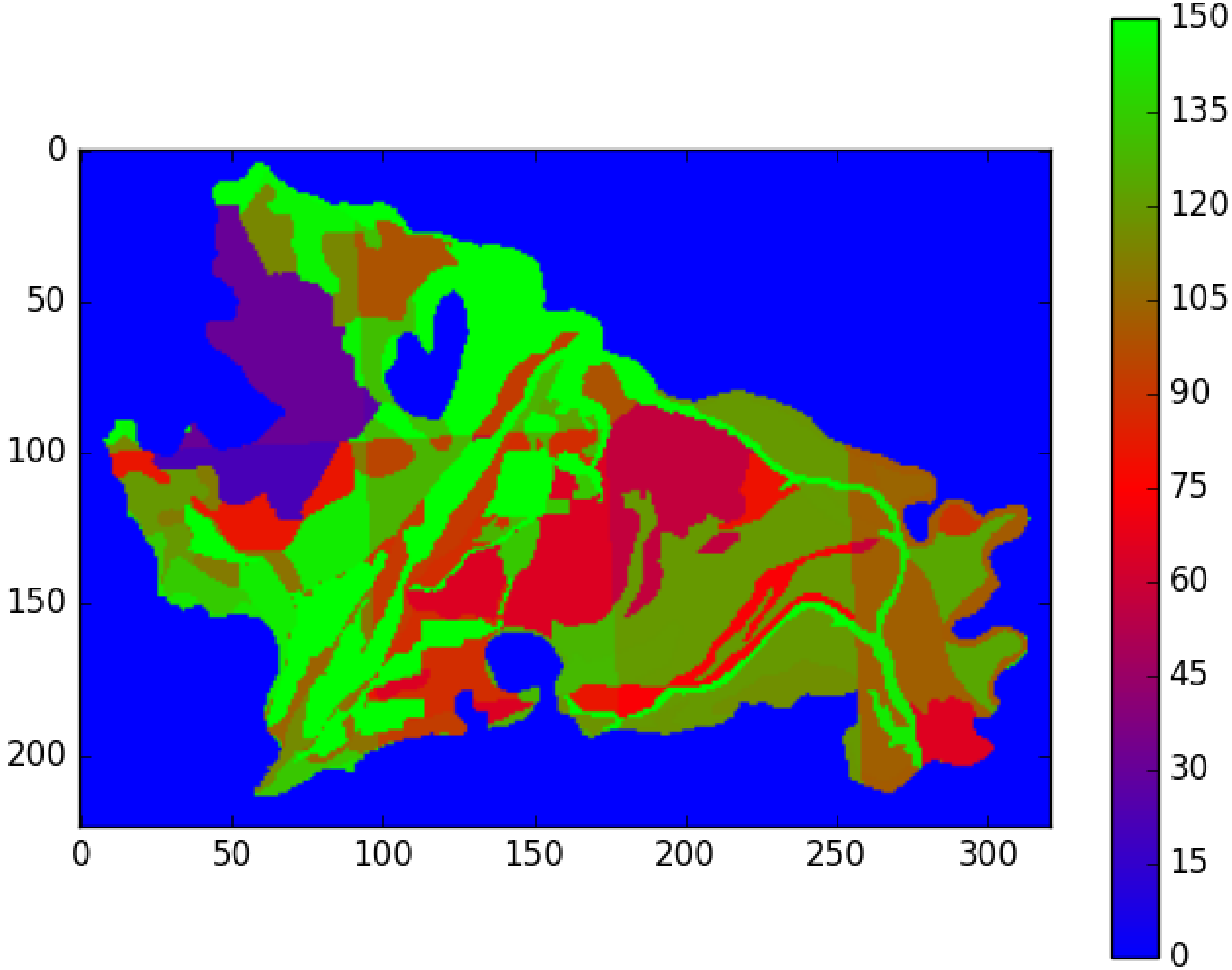


FIGURE 10A: DISTRIBUTION OF RECHARGE ACROSS THE MODEL AREA (MM/YEAR)

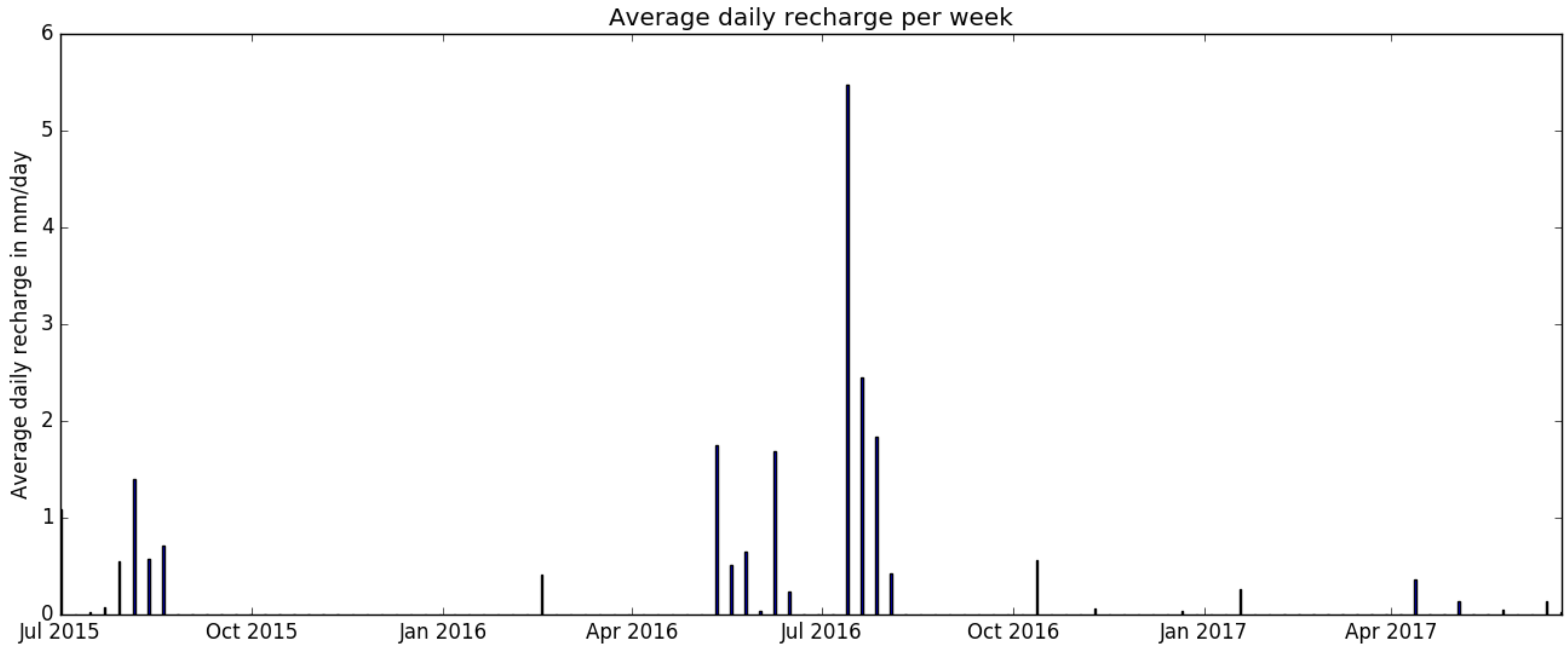


FIGURE 10B: AVERAGE DAILY RECHARGE FOR EACH WEEKLY MODELLED TIMESTEP (MM/DAY)

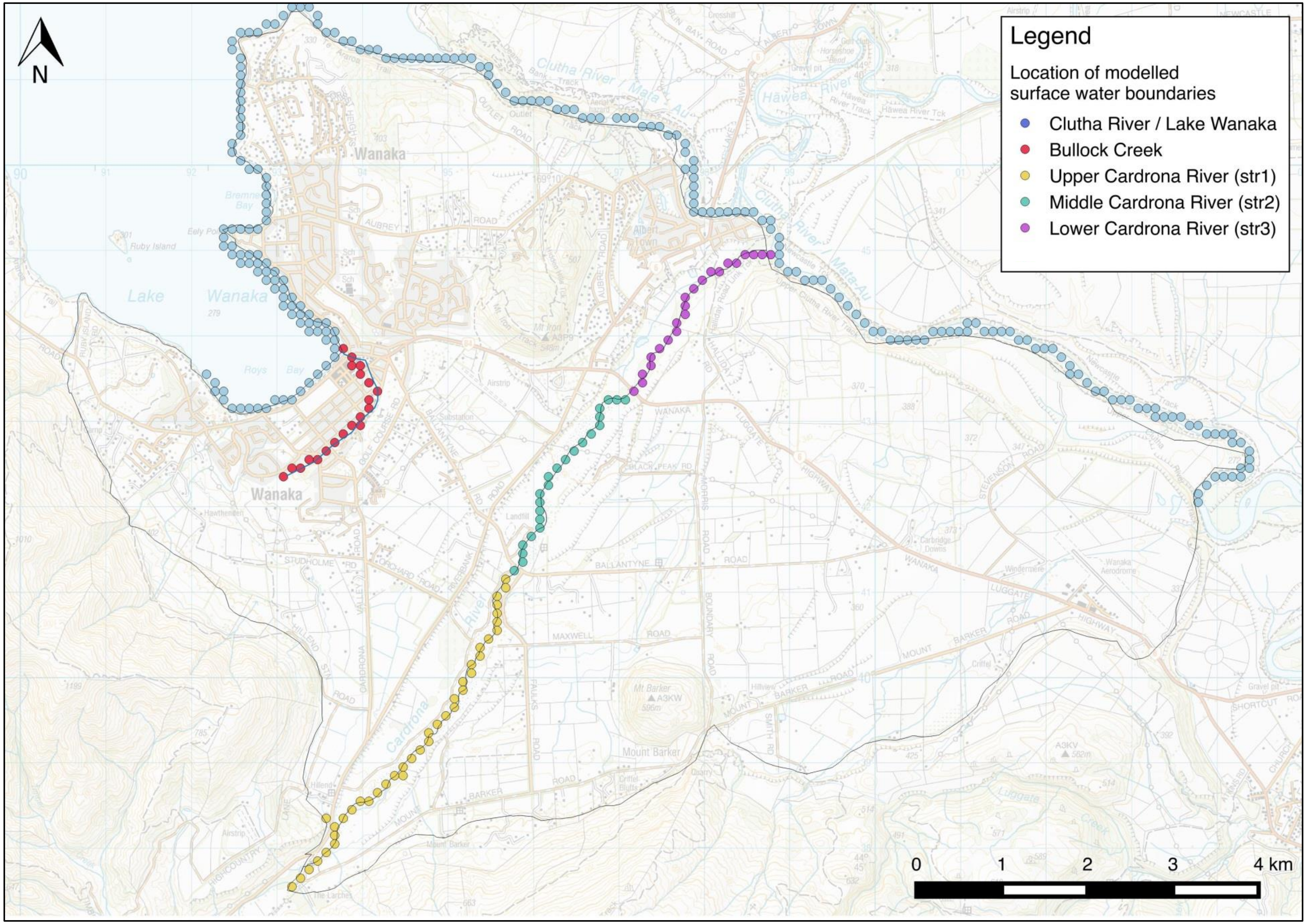


FIGURE11: MODELLED SURFACE WATER BOUNDARIES

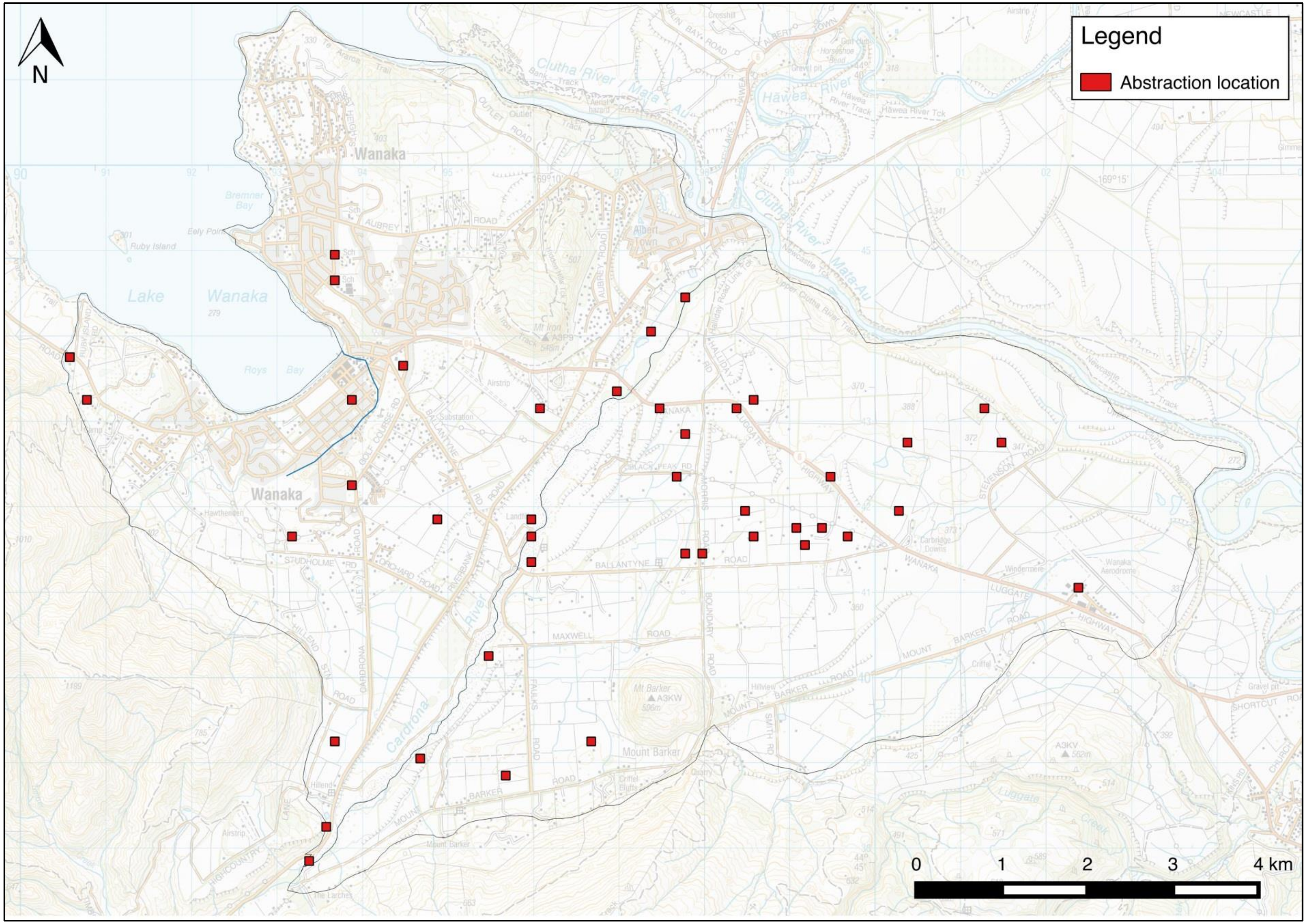


FIGURE12: MODELLED GROUNDWATER ABSTRACTIONS

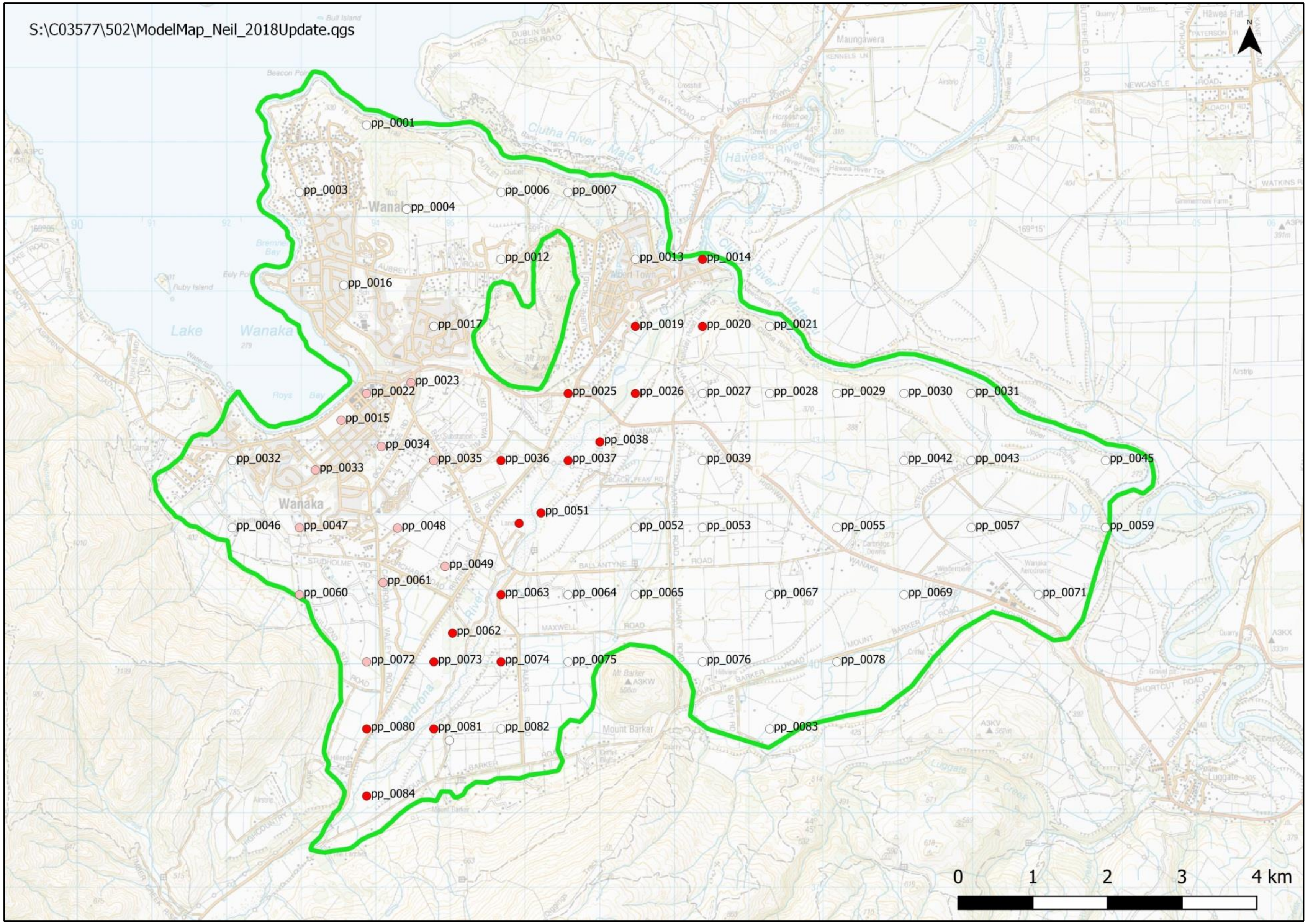


FIGURE13: LOCATION OF MODELLED PILOT POINTS (LABEL SHOWS THE NAME OF THE PILOT POINTS)

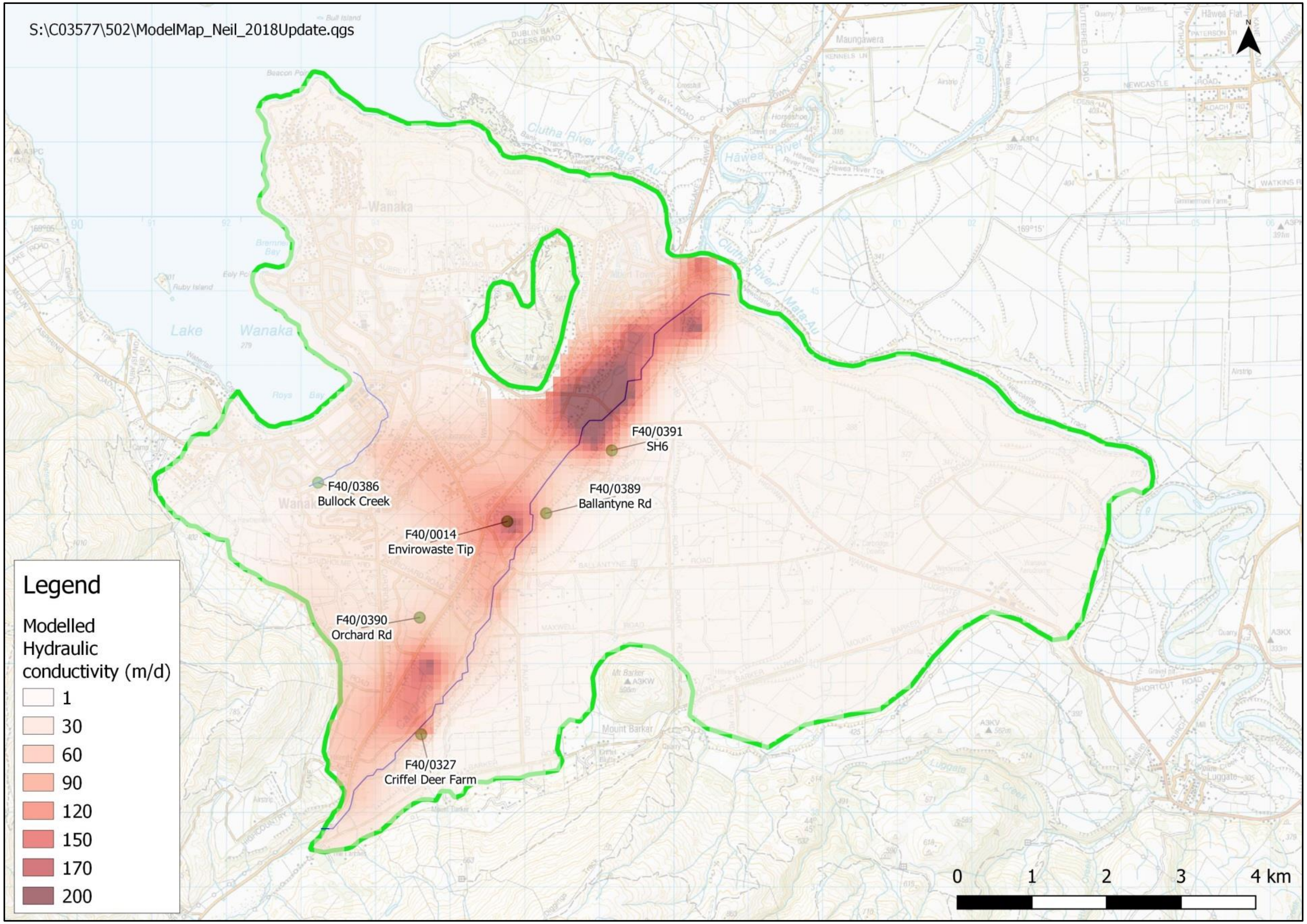


FIGURE14: CALIBRATED HYDRAULIC CONDUCTIVITY FIELD

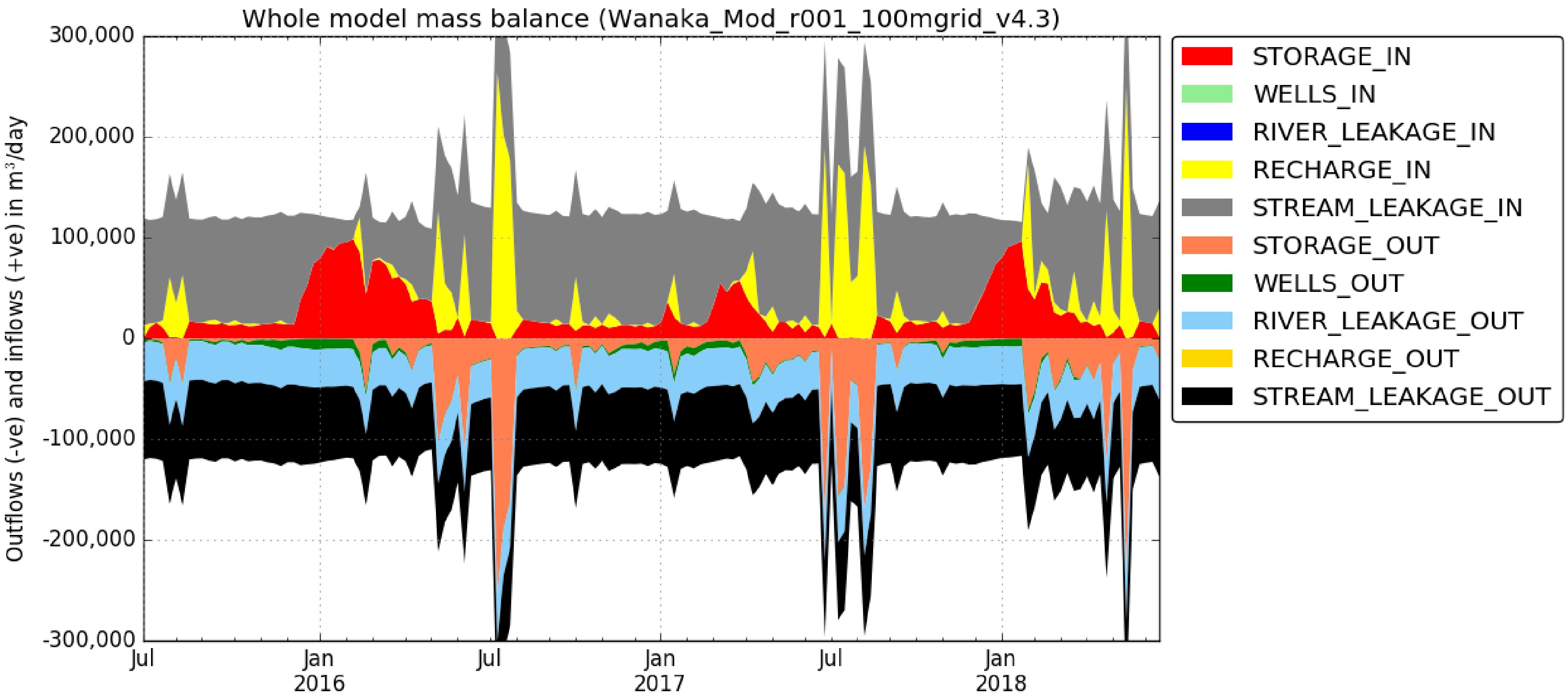


FIGURE15: MODELLED MASS BALANCE. MODELLED INFLOWS ARE IDENTIFIED IN THE KEY WITH AN '_IN' SUFFIX. MODELLED OUTFLOWS ARE IDENTIFIED IN THE KEY WITH AN '_OUT' SUFFIX.

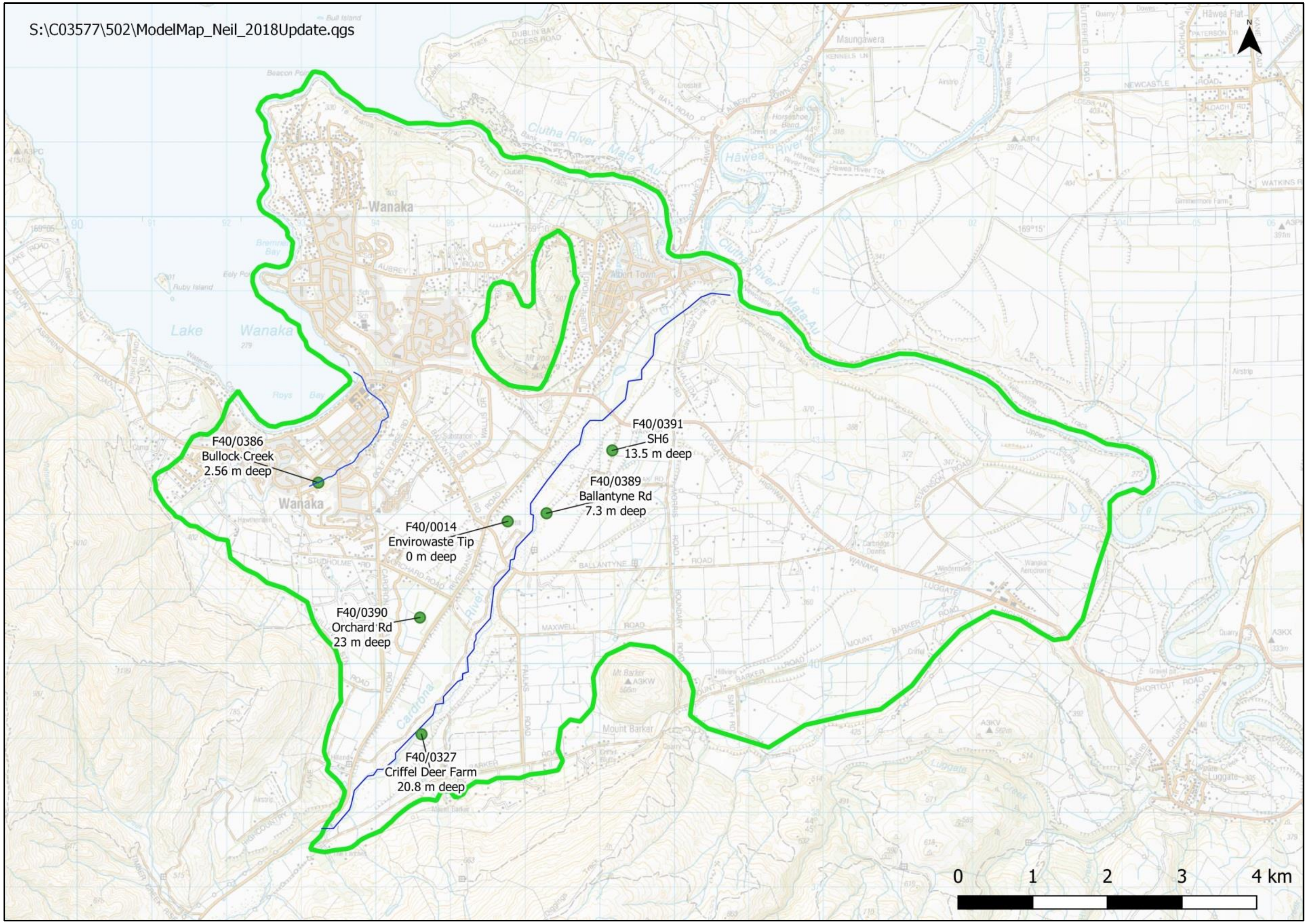


FIGURE16: LOCATION OF OBSERVATION BORES. NOTE NO DEPTH INFORMATION IS AVAILABLE FOR BORE F40/0014 (WANAKA ENVIROWASTE TIP BORE)

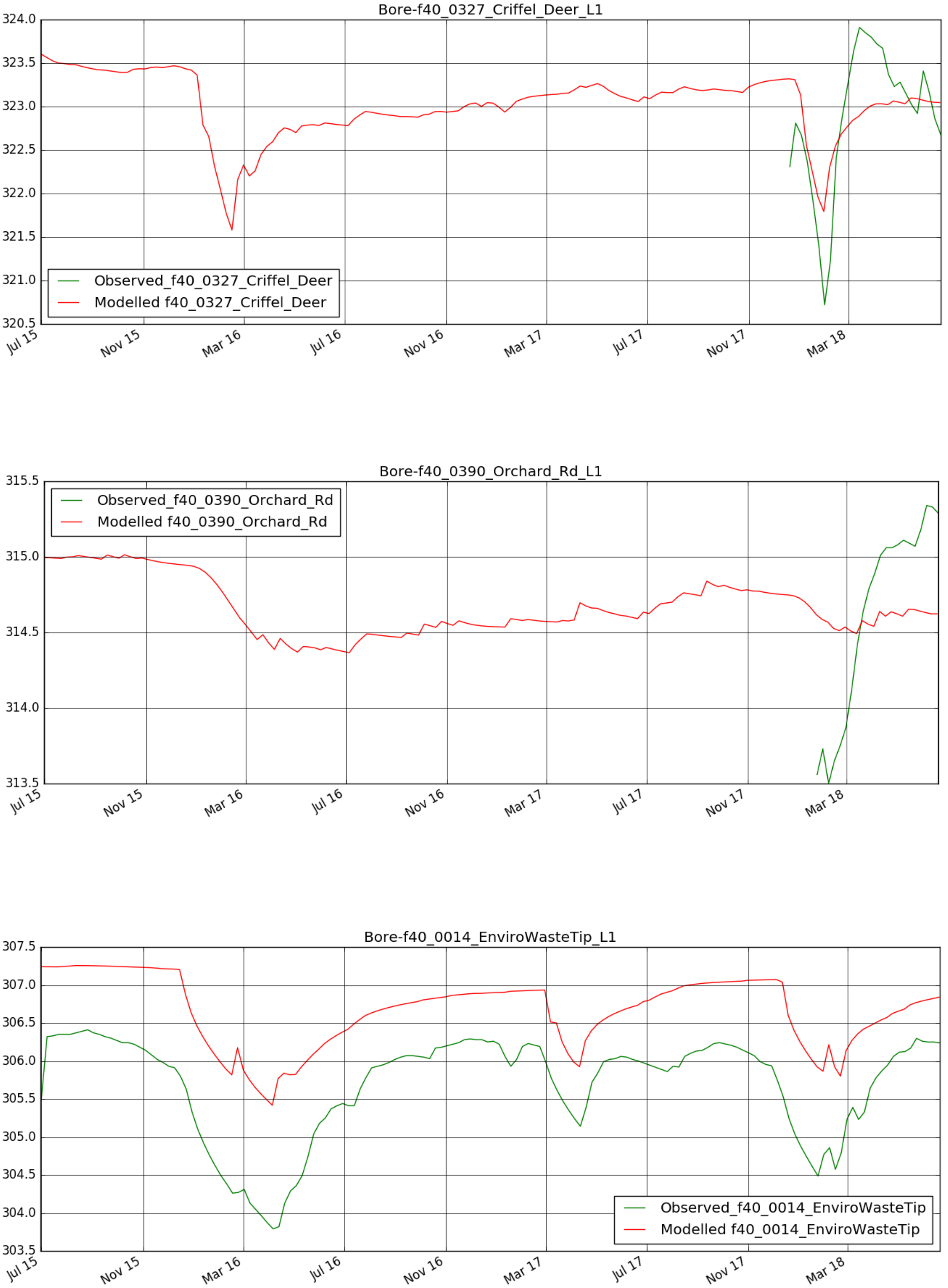
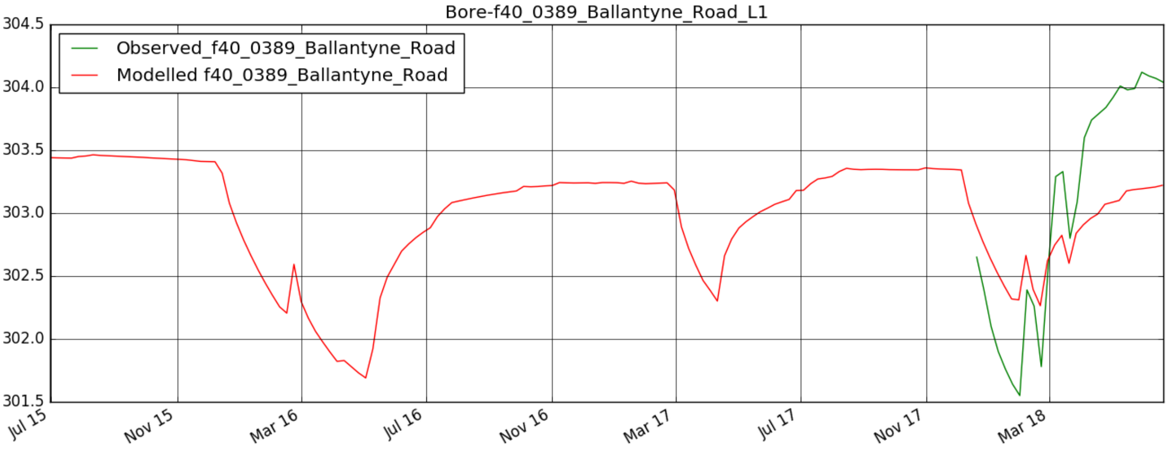
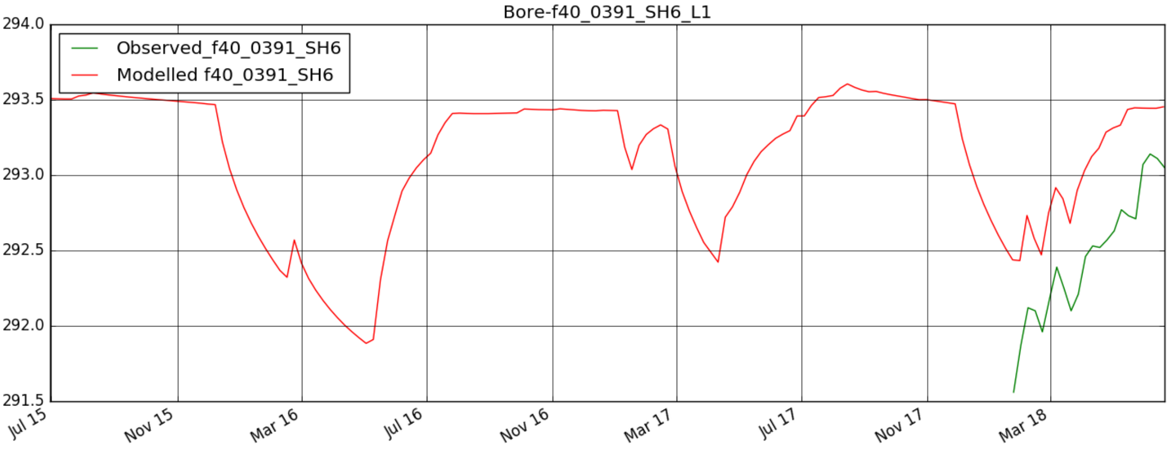


FIGURE 17A, B AND C: MODELLED AND OBSERVED GROUNDWATER LEVELS AT BORES F40/0327, F40/0390 AND F40/0014





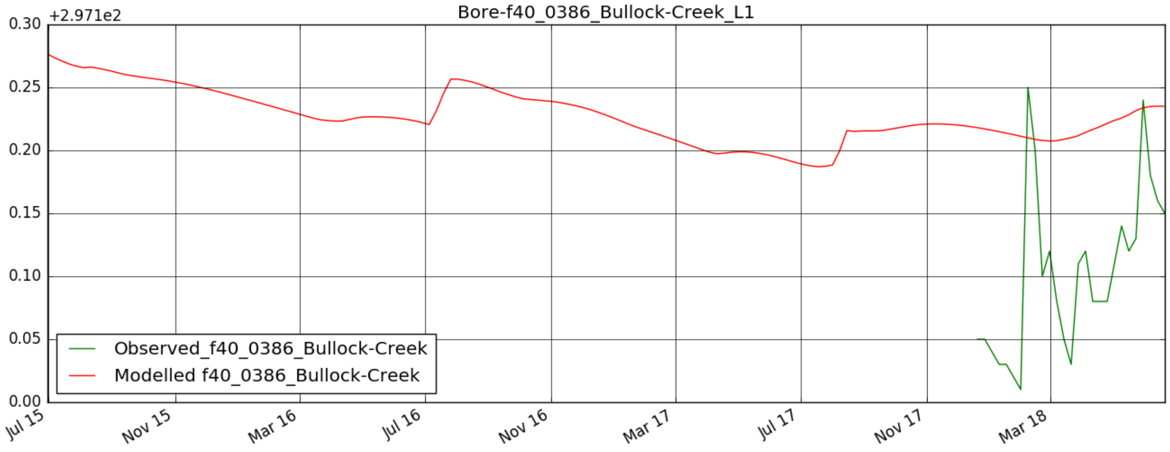


FIGURE 17D, E AND F: MODELLED AND OBSERVED GROUNDWATER LEVELS AT BORES F40/0389, F40/0391 AND F40/0386 (NOTE VERTICAL SCALE ON FINAL PLOT F40/0386, BULLOCK CREEK)

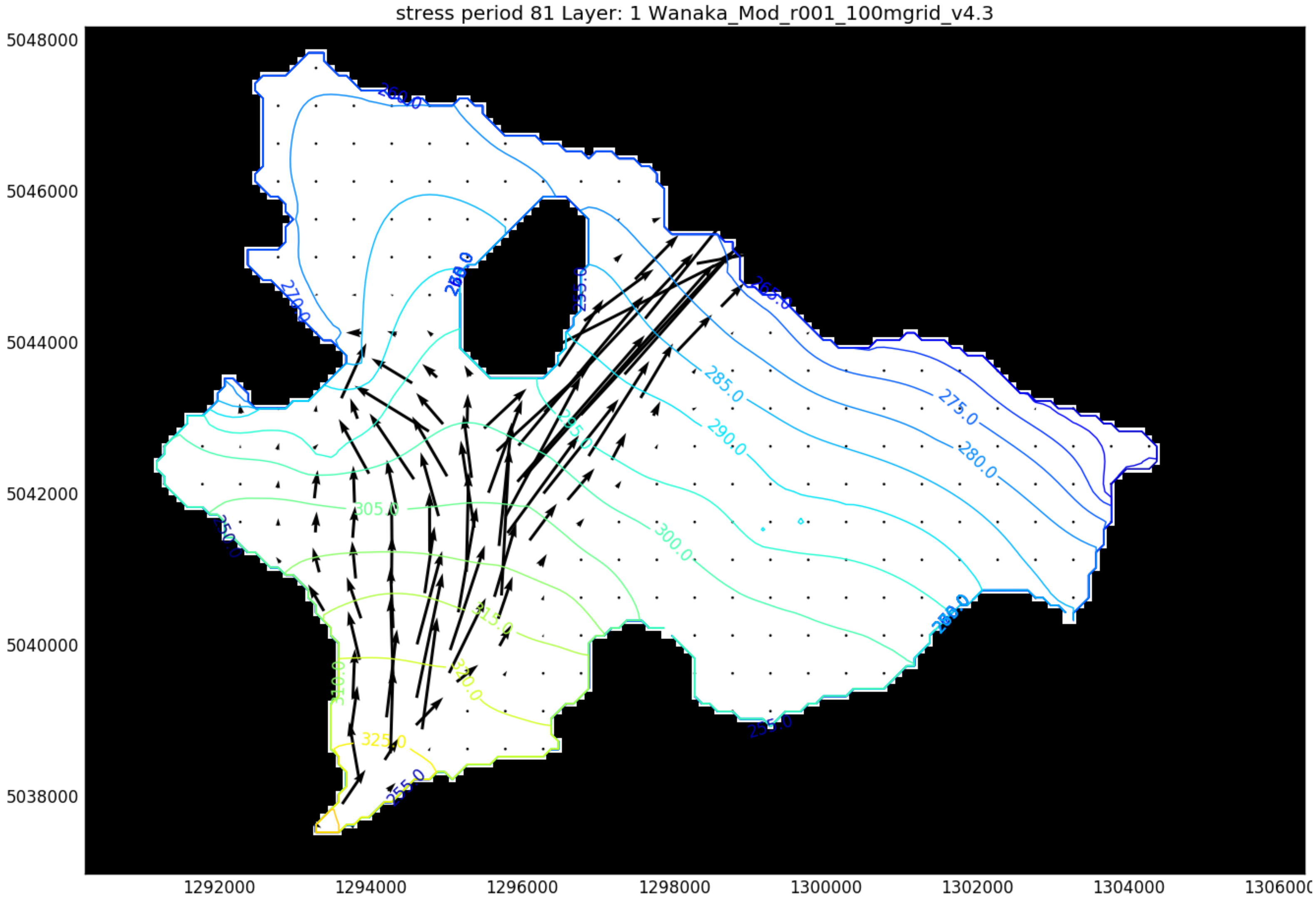


FIGURE 17G: MODELLED GROUNDWATER LEVELS (AND ARROWS SHOWING DIRECTION AND MAGNITUDE OF FLOW) FROM JANUARY 2017)

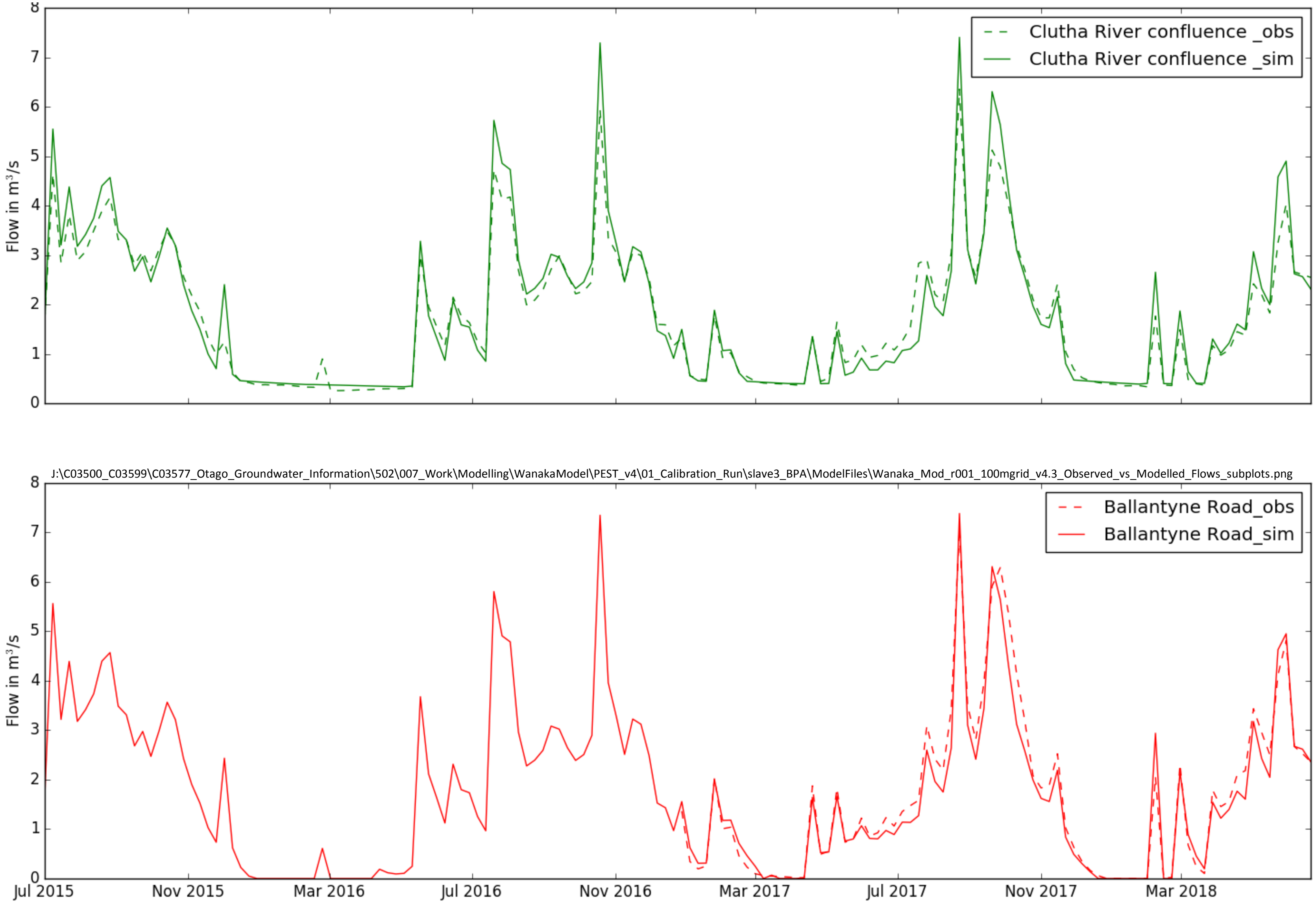


FIGURE18: OBSERVED VERSUS SIMULATED FLOWS IN THE CARDRONA RIVER AT THE CLUTHA CONFLUENCE AND AT BALLANTYNE ROAD

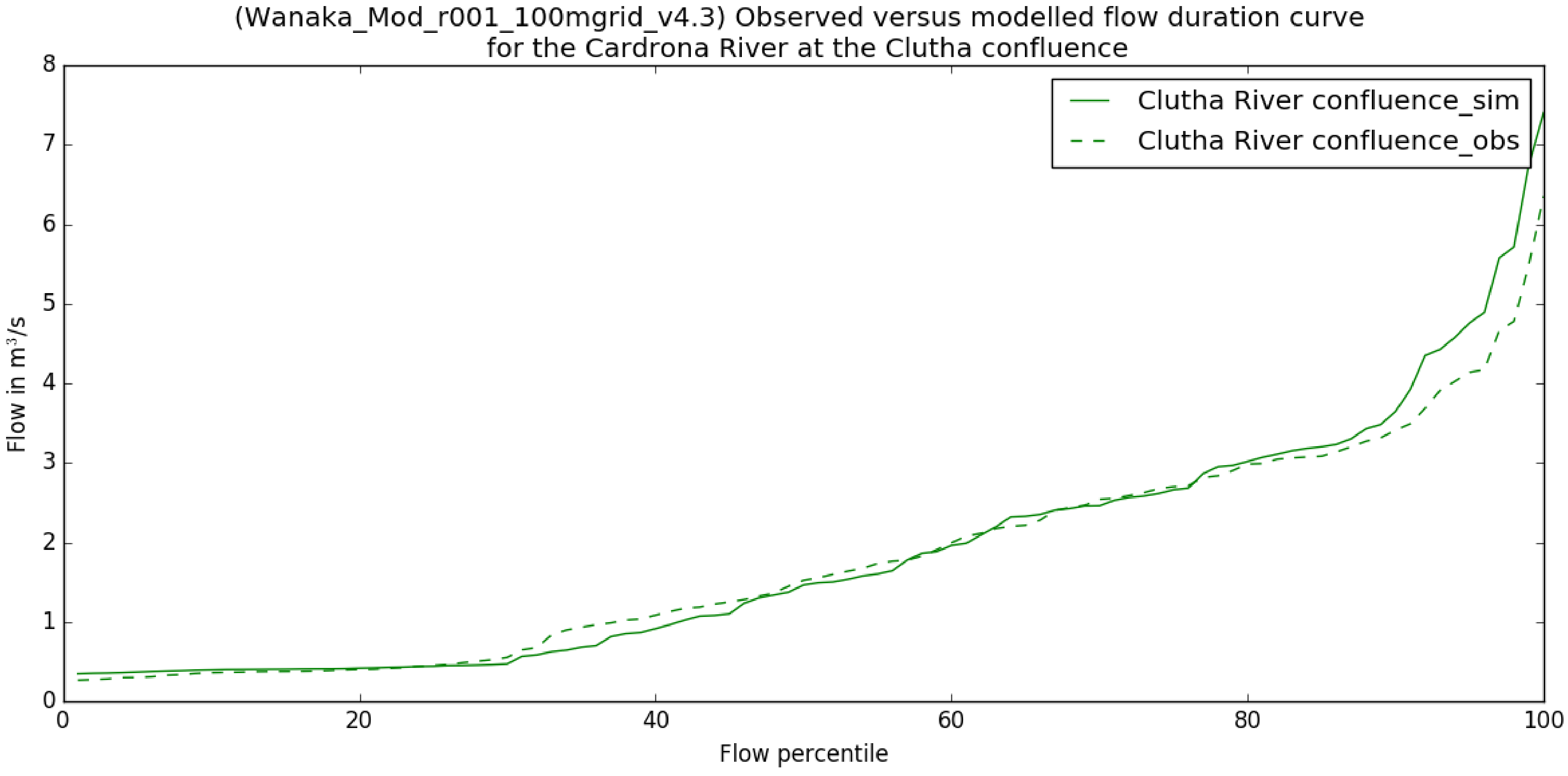


FIGURE19: OBSERVED VERSUS SIMULATED FLOW DURATION CURVE IN THE CARDRONA RIVER AT THE CLUTHA CONFLUENCE.

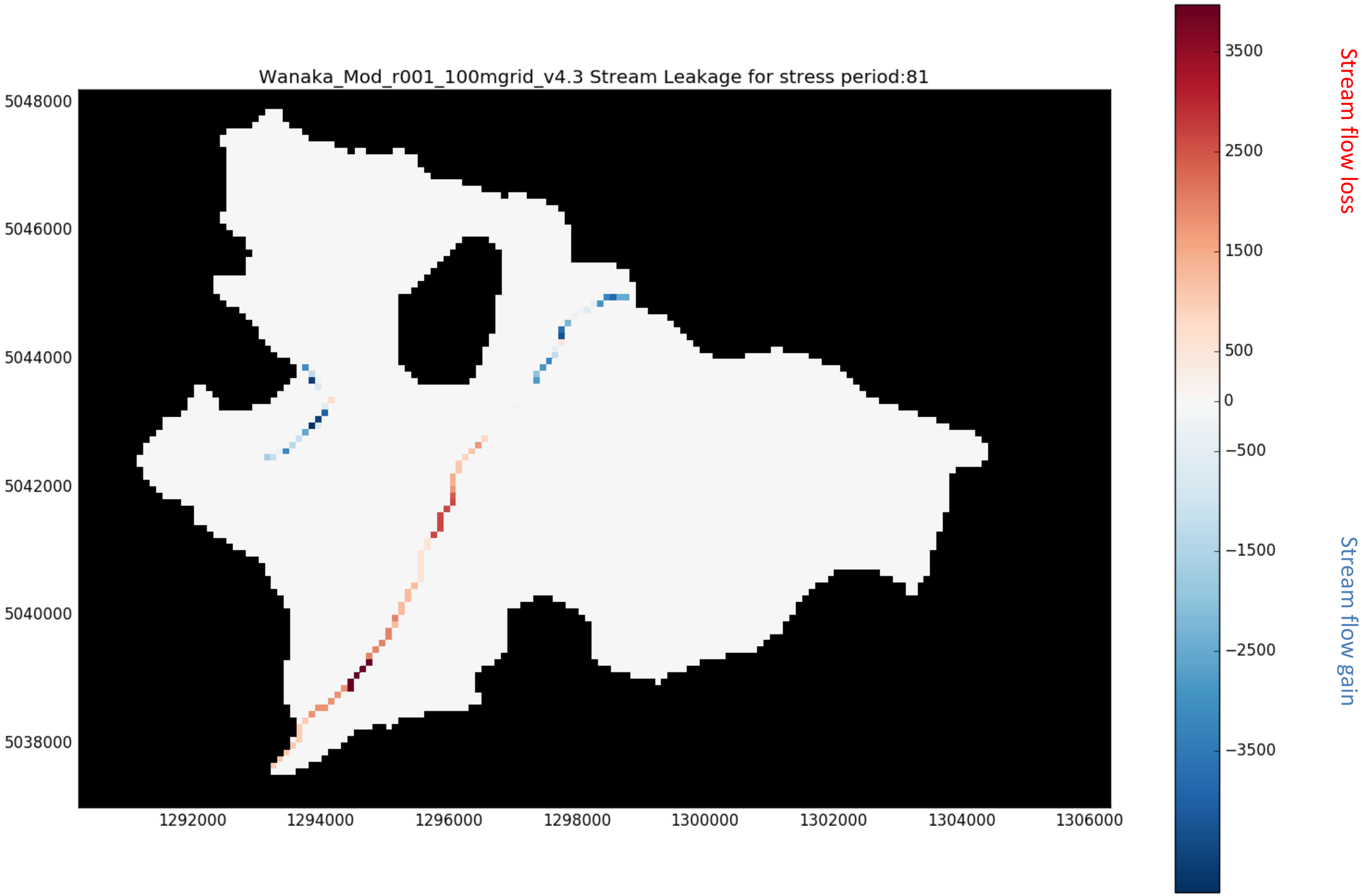


FIGURE 20A: LOCATION OF MODELLED GAINING AND LOSING REACHES IN MODELLED STREAMS IN JANUARY 2017.

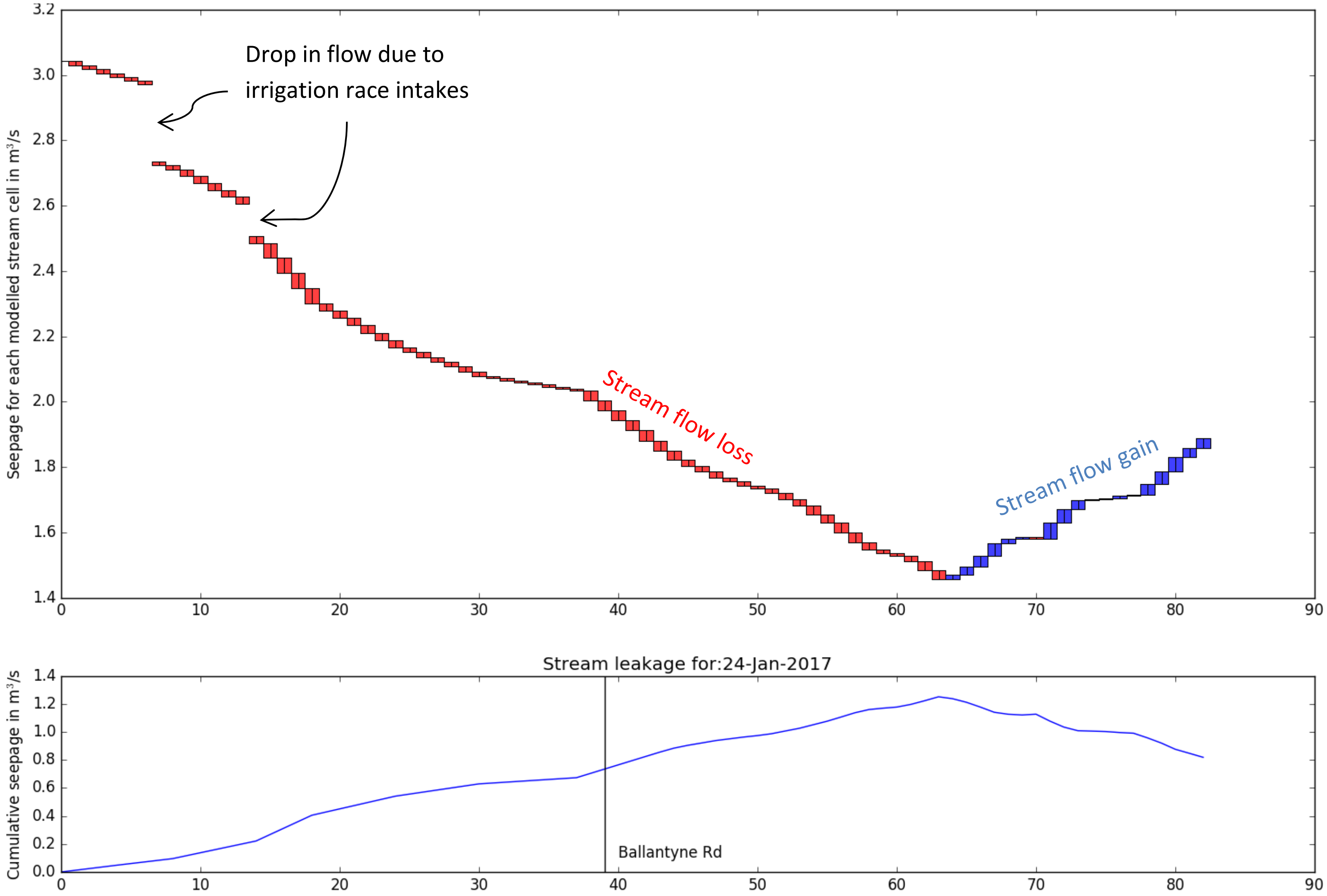
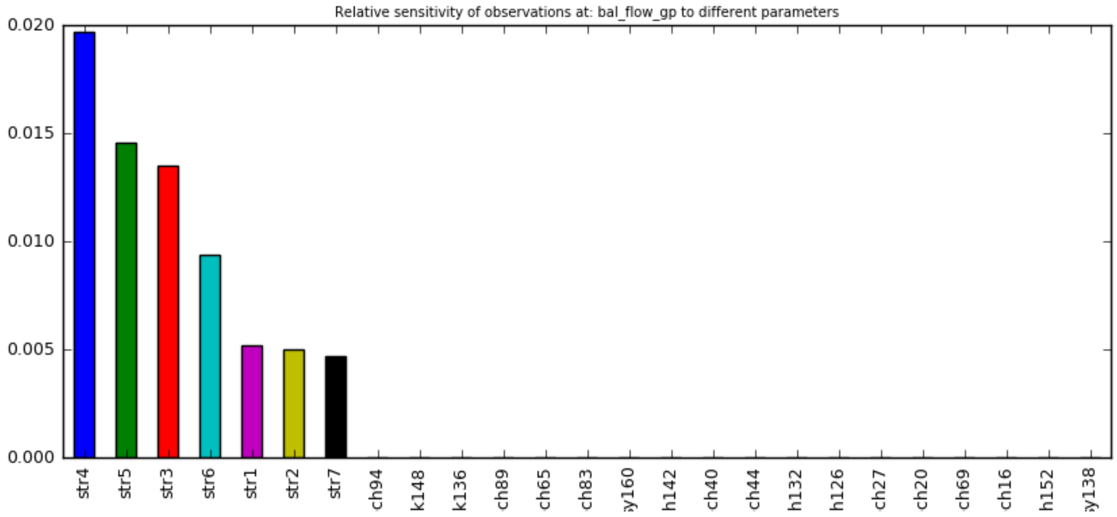
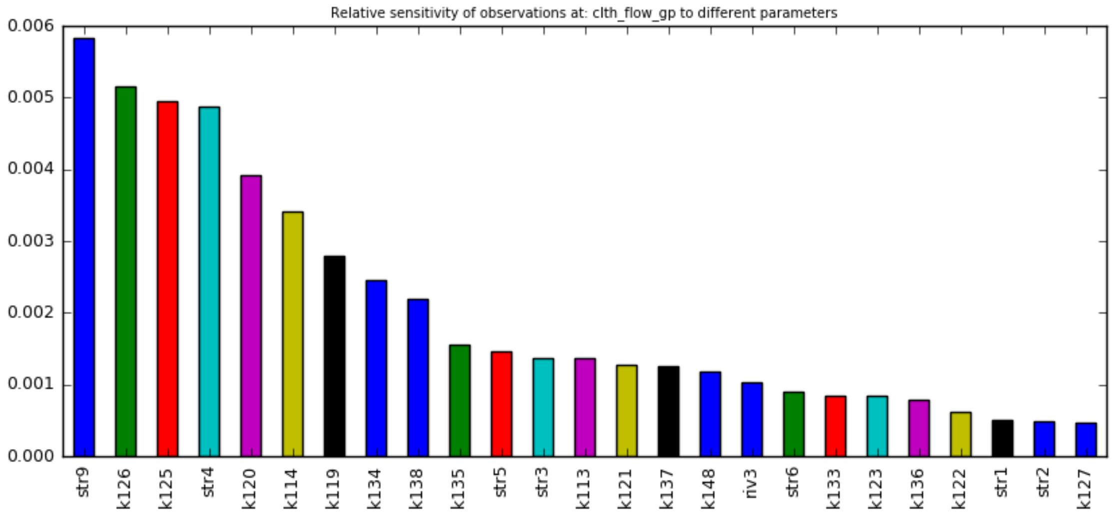


FIGURE 20B: MODELLED STREAM LOSSES AND GAINS ALONG THE CARDRONA RIVER FOR JANUARY 2017 AND CUMULATIVE GAINS AND LOSSES (LOWER PLOT).

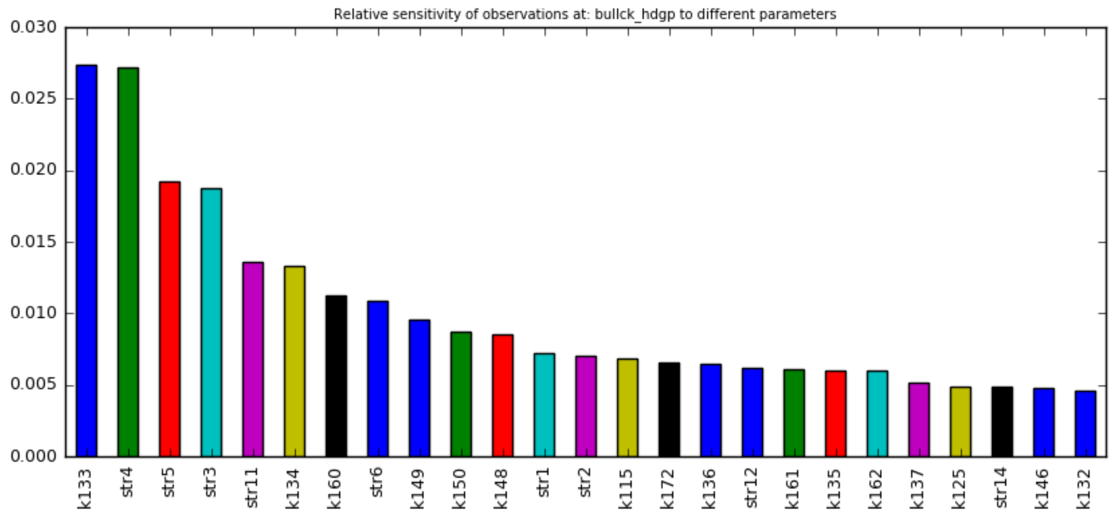
FIGURE 20C: MODELLED AND OBSERVED FLOWS IN BULLOCK CREEK



A) Ballantyne Road



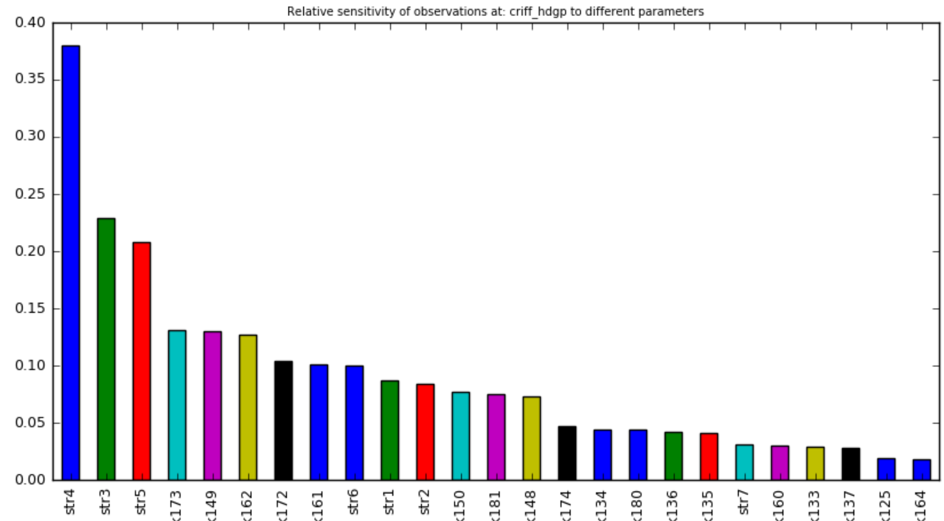
B) Cardrona at the Clutha confluence



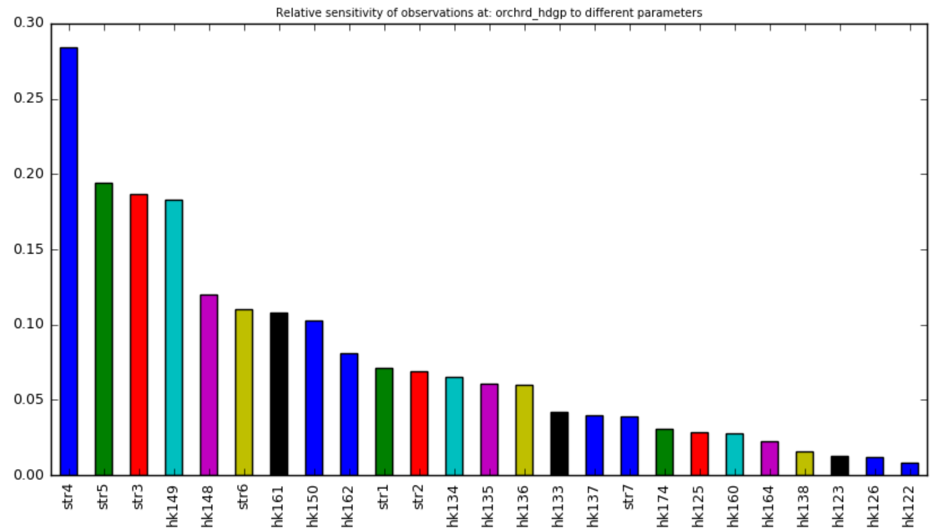
C) Bullock Creek

FIGURE 21 A TO C: RELATIVE SENSITIVITY OF FLOWS AT BALLANTYNE ROAD, CARDRONA AT THE CLUTHA CONFLUENCE AND AT BULLOCK CREEK TO MODEL PARAMETERS

D) Criffel Deer (F40/0327)



E) Orchard Road (F40/0390)



F) Envirowaste Tip (F40/0014)

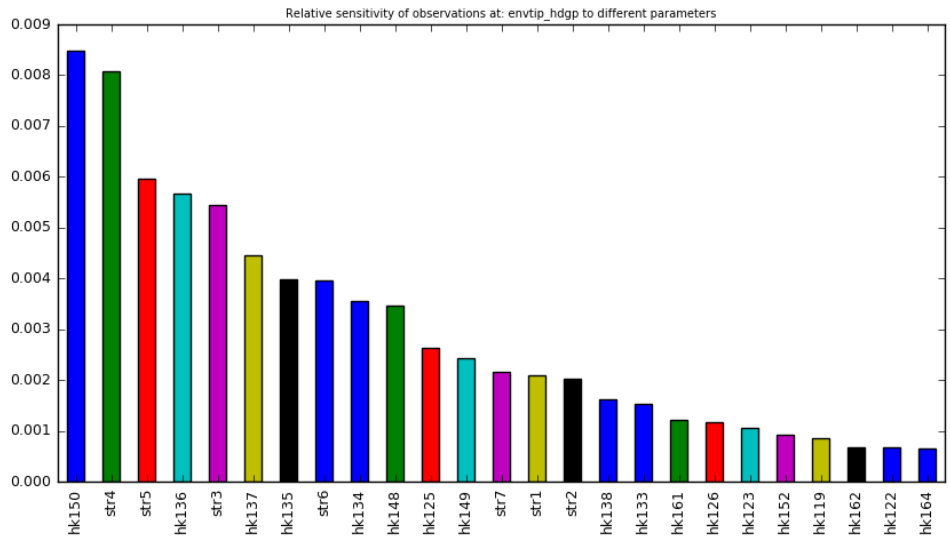
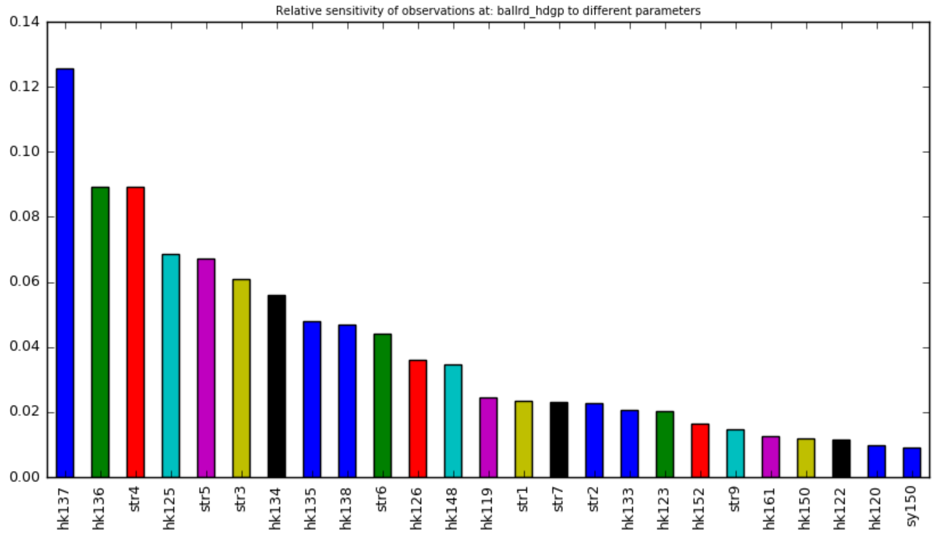
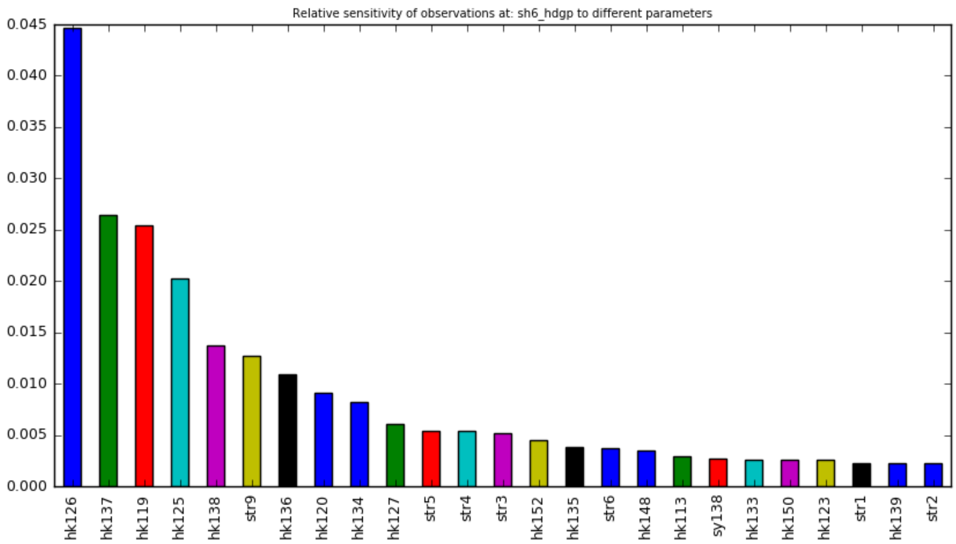


FIGURE 21 D TO F: RELATIVE SENSITIVITY OF GROUNDWATER LEVELS AT CRIFFEL DEER, ORCHARD ROAD AND ENVIROWASTE TIP BORES TO MODEL PARAMETERS

G) Ballantyne Road (F40/0389)



H) State Highway 6 (F40/0391)



I) Bullock Creek (F40/0386)

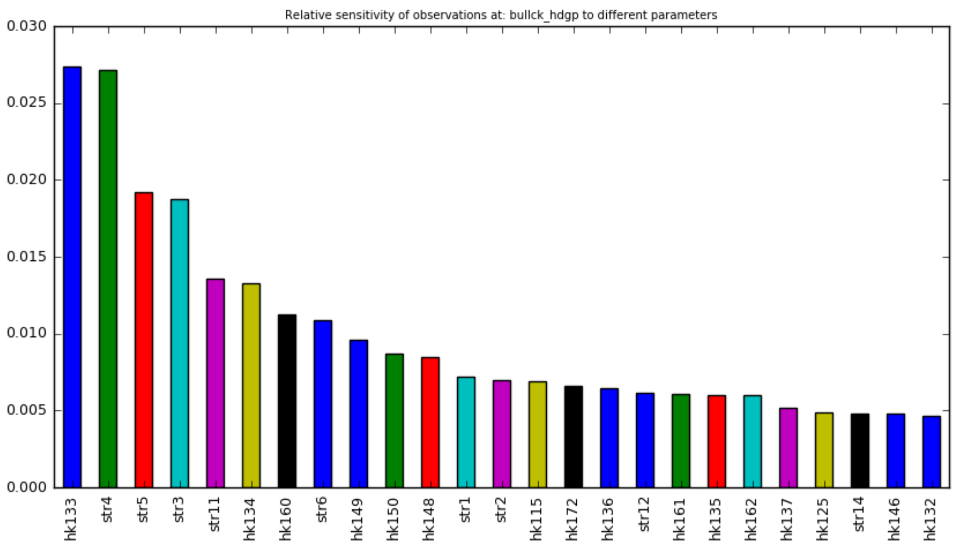


FIGURE 21 H TO I: RELATIVE SENSITIVITY OF GROUNDWATER LEVELS AT BALLANTYNE ROAD, STATE HIGHWAY 6 AND BULLOCK CREEK BORES TO MODEL PARAMETERS

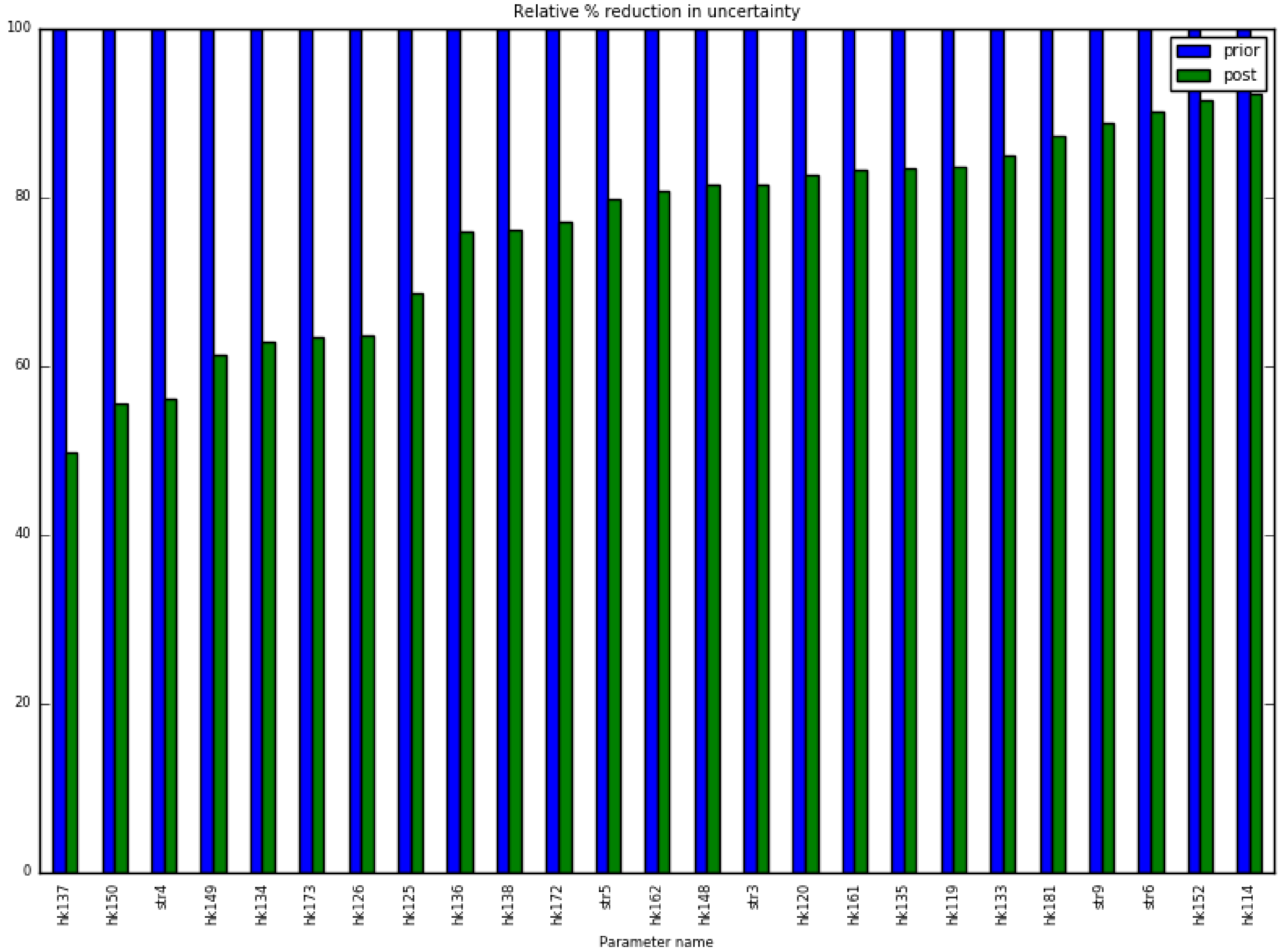


FIGURE 22: RELATIVE REDUCTION IN UNCERTAINTY FOR DIFFERENCE MODEL PARAMETERS. ONLY THE 25 GREATEST REDUCTIONS ARE SHOWN. PARAMETERS NOT SHOWN HAD VERY SMALL REDUCTIONS IN UNCERTAINTY.

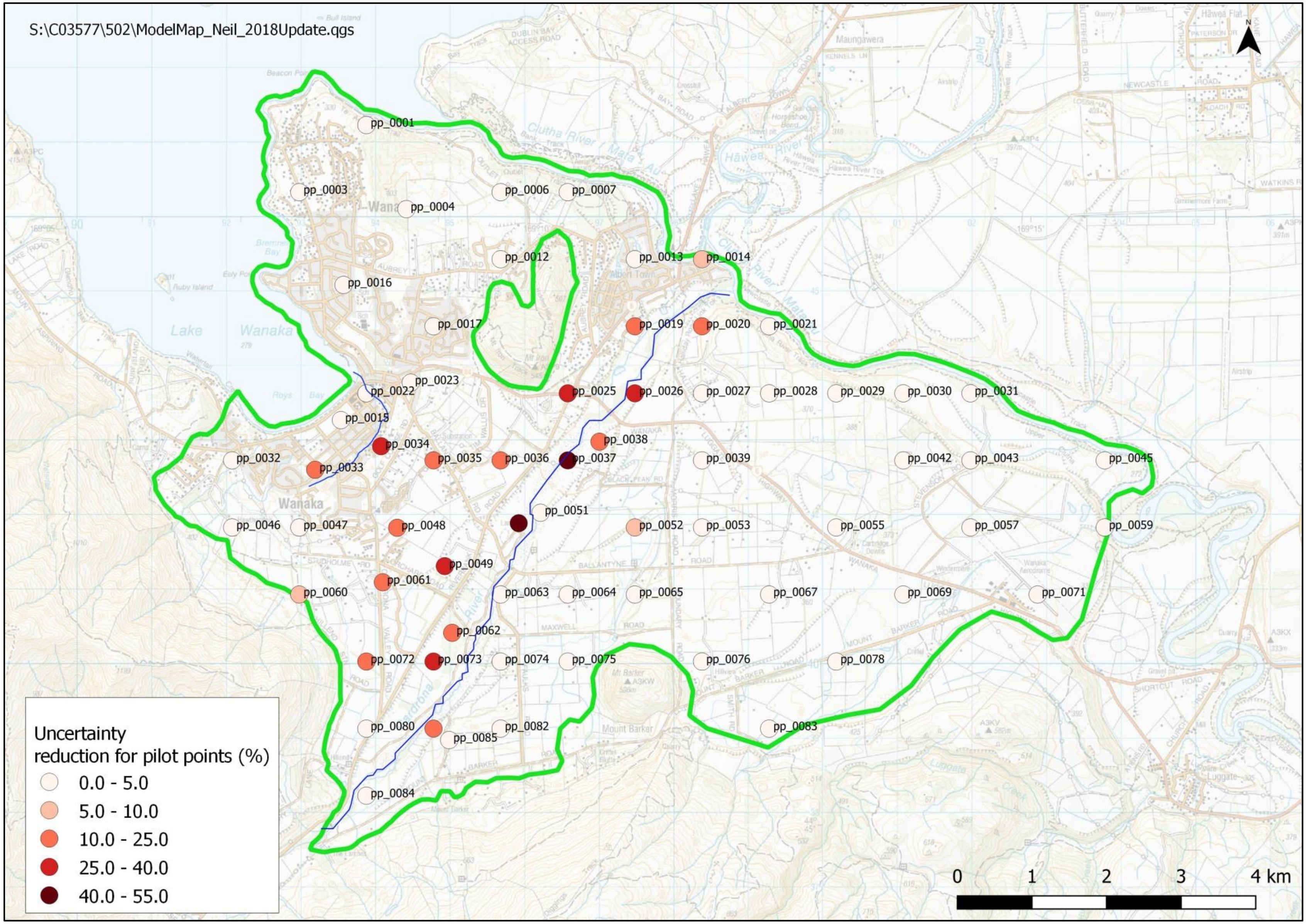
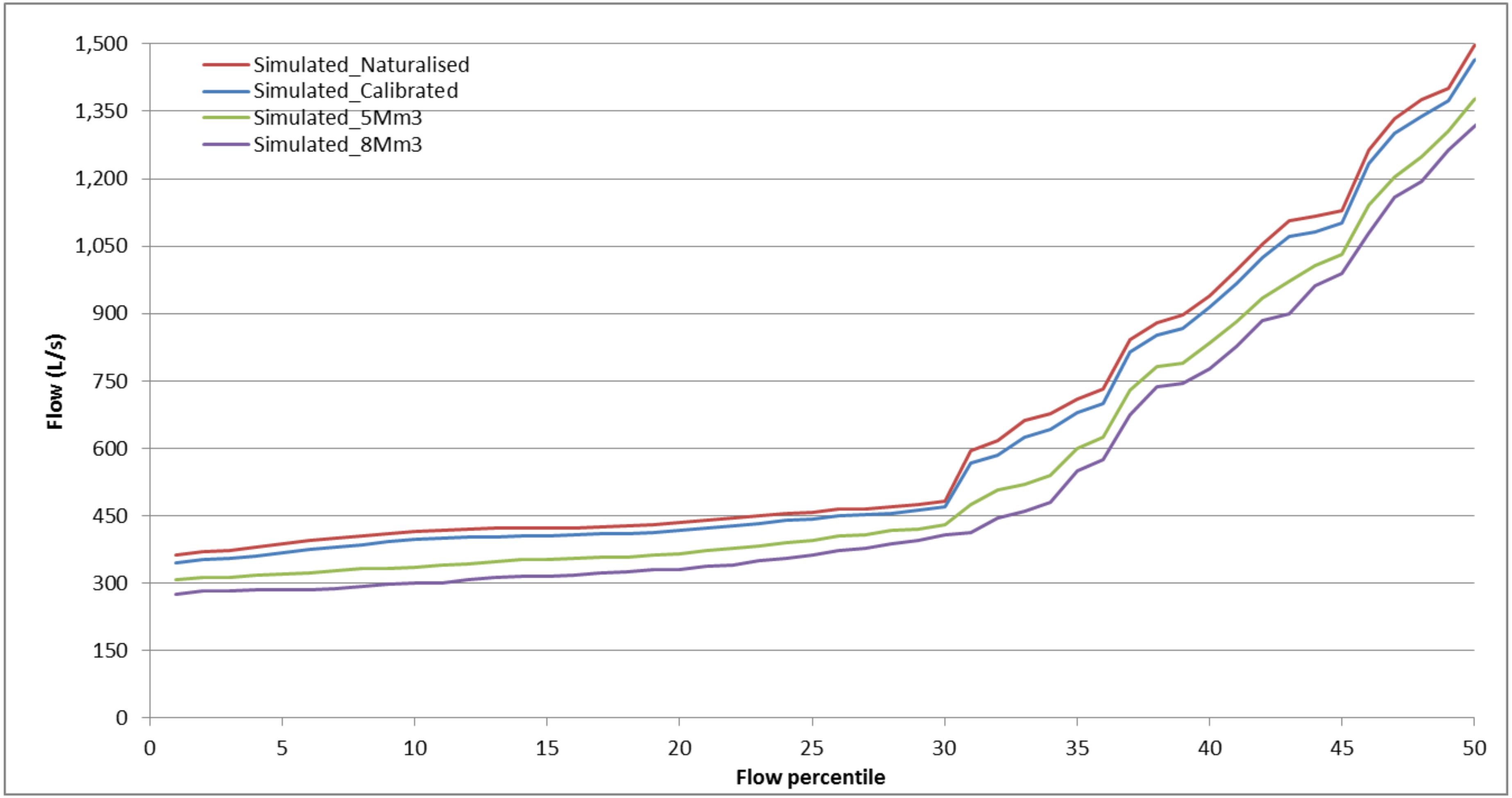


FIGURE 23: UNCERTAINTY REDUCTION IN PILOT POINTS USED TO GENERATE HYDRAULIC CONDUCTIVITY FIELD.



J:\C03500_C03599\C03577_Otago_Groundwater_Information\502\007_Work\Modelling\WanakaModel\PEST_v4\ErrVariance_AbsScenarios (2).xlsx

FIGURE 24: CHANGE IN FLOW DURATION CURVES FOR THE CARDRONA AT THE CLUTHA CONFLUENCE AT DIFFERENT ABSTRACTION RATES.

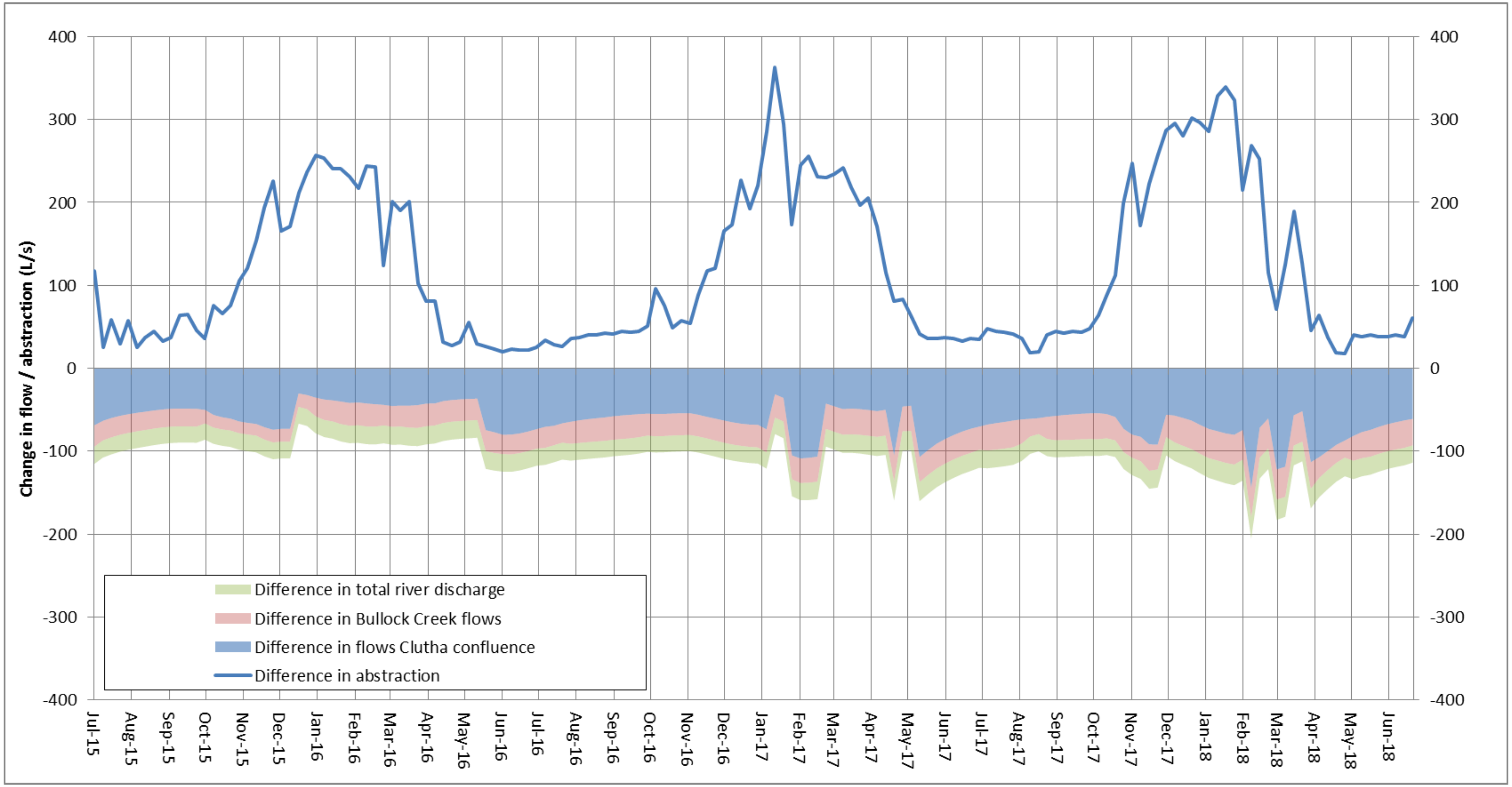


FIGURE 25A: CHANGE IN ABSTRACTION AND RESULTING DECREASE IN STREAM FLOWS BETWEEN THE CALIBRATED MODEL AND SIMULATION OF INCREASED ABSTRACTION AT 5 X 10^6 M^3/YEAR.

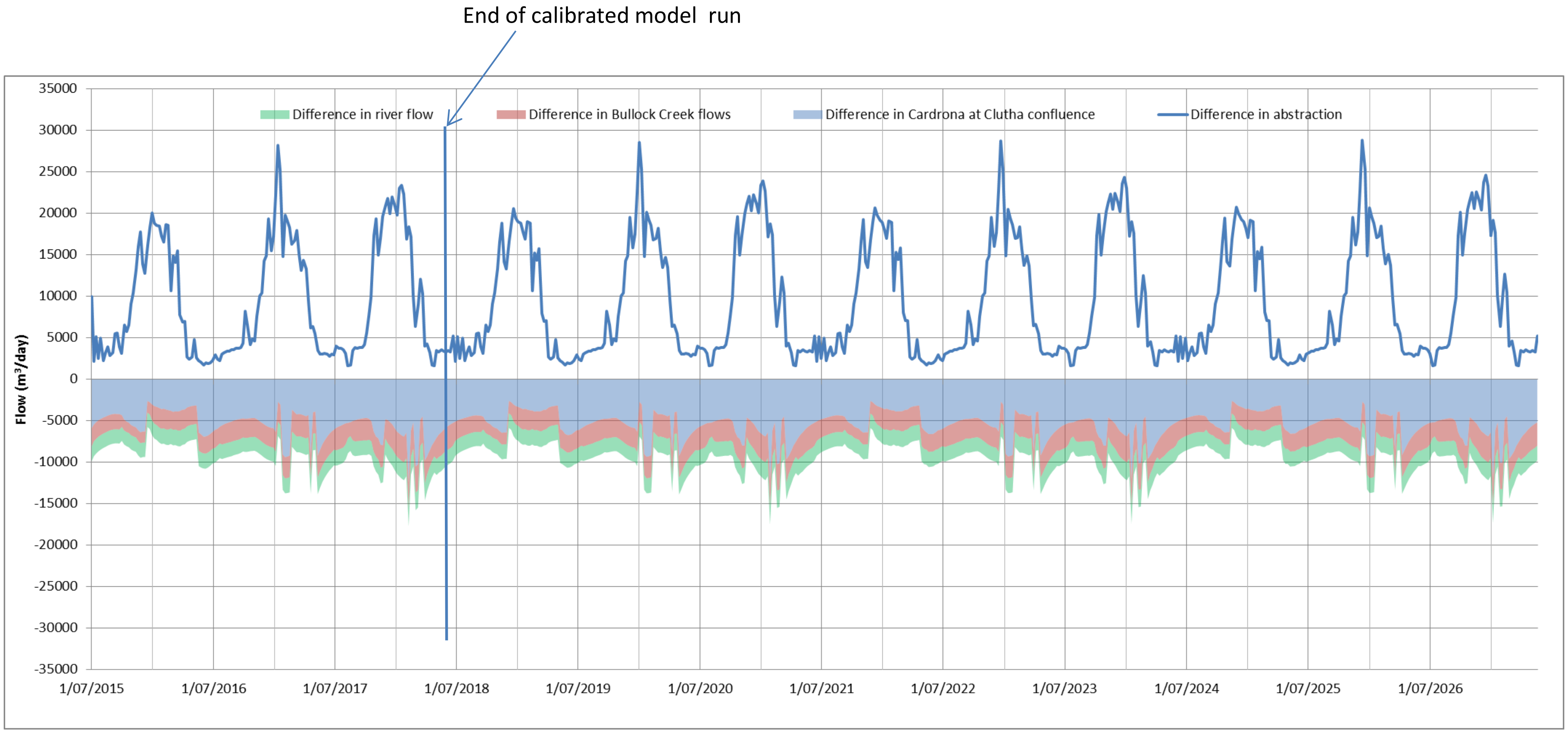


FIGURE 25B: CHANGES IN ABSTRACTION AND STREAM FLOWS BETWEEN THE CALIBRATED MODEL AND SIMULATION OF INCREASED ABSTRACTION OVER A 12 YEAR PERIOD

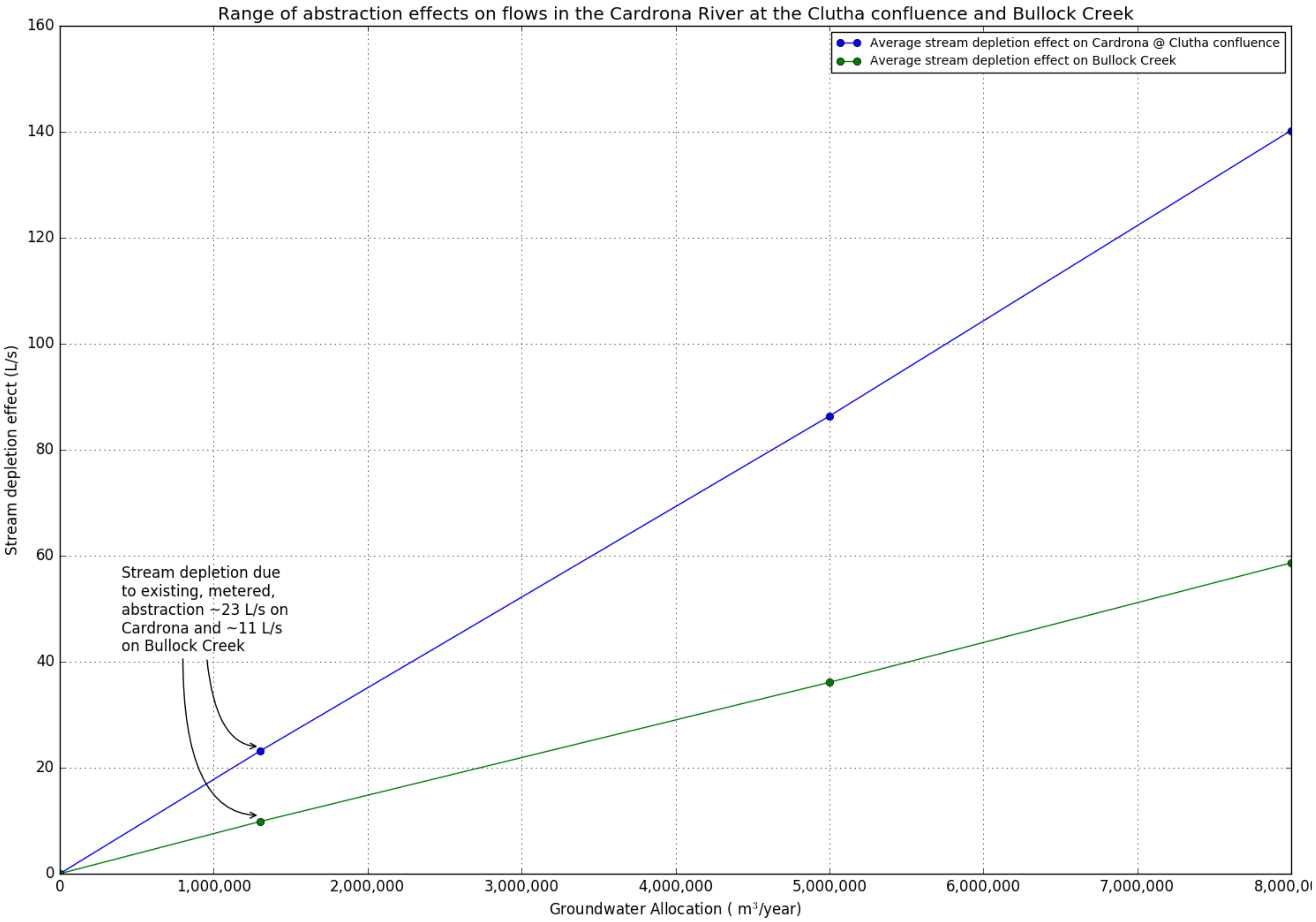
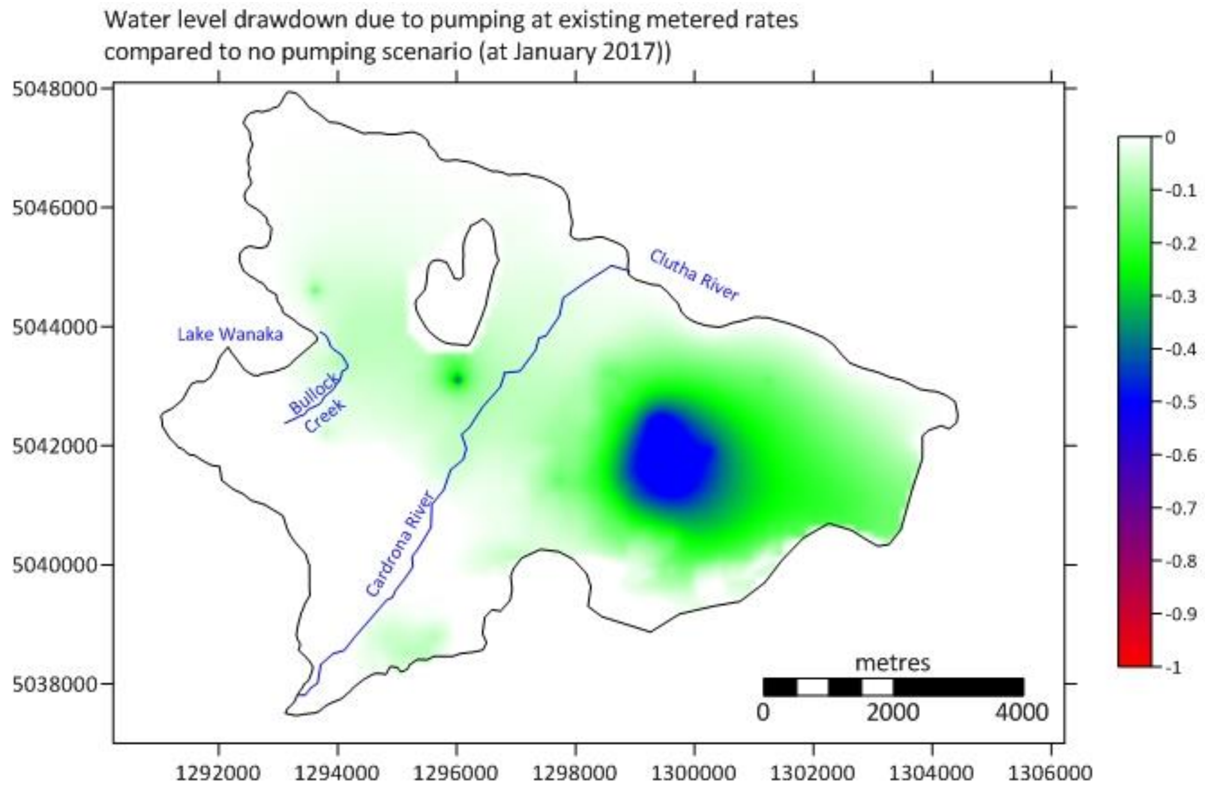


FIGURE 26: RANGE OF ABSTRACTION RATES AND MODELLED EFFECTS ON FLOWS IN THE CARDRONA RIVER AT THE CLUTHA CONFLUENCE AND ON BULLOCK CREEK



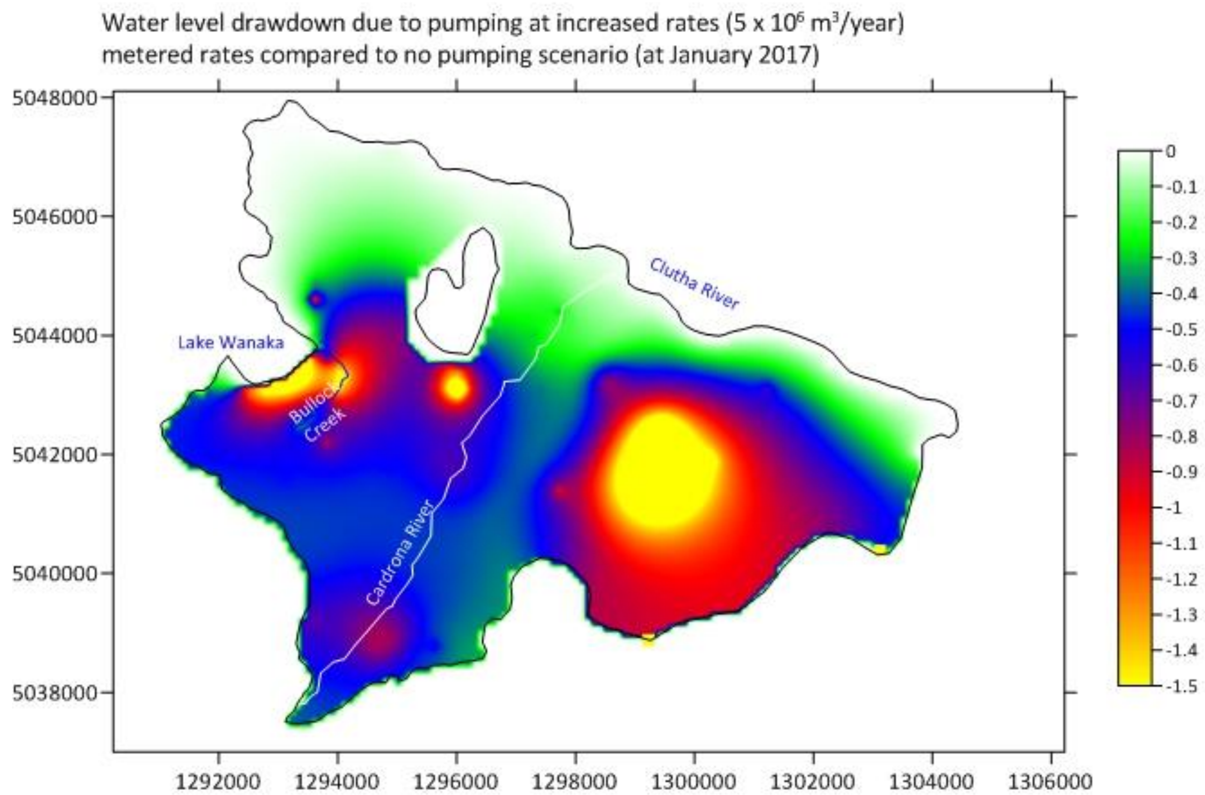


FIGURE 27: GROUNDWATER ABSTRACTION EFFECTS ON GROUNDWATER LEVELS

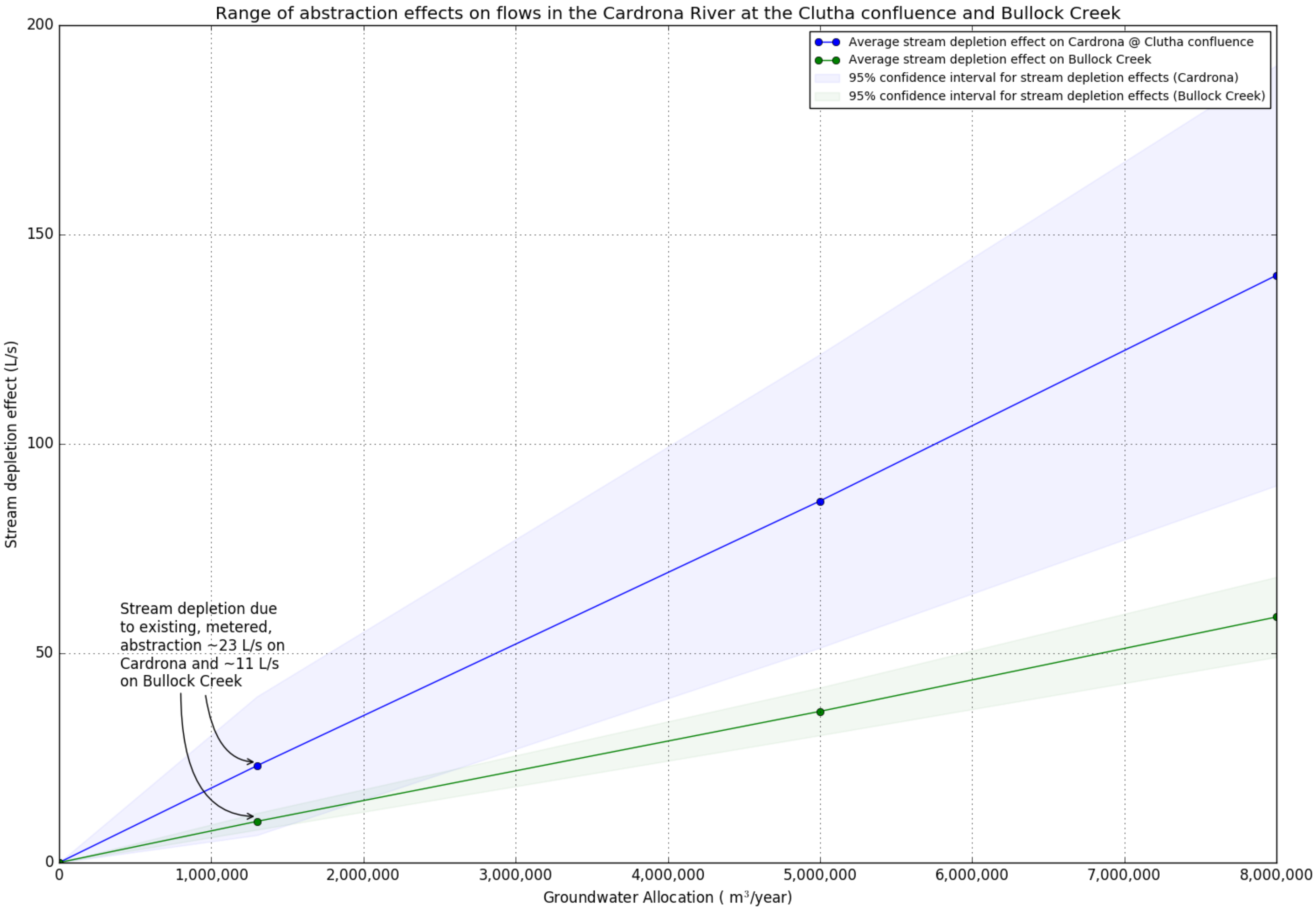


FIGURE 28: RANGE OF ABSTRACTION RATES AND MODELLED EFFECTS ON FLOWS IN THE CARDRONA RIVER AT THE CLUTHA CONFLUENCE AND ON BULLOCK CREEK AND CONFIDENCE INTERVALS

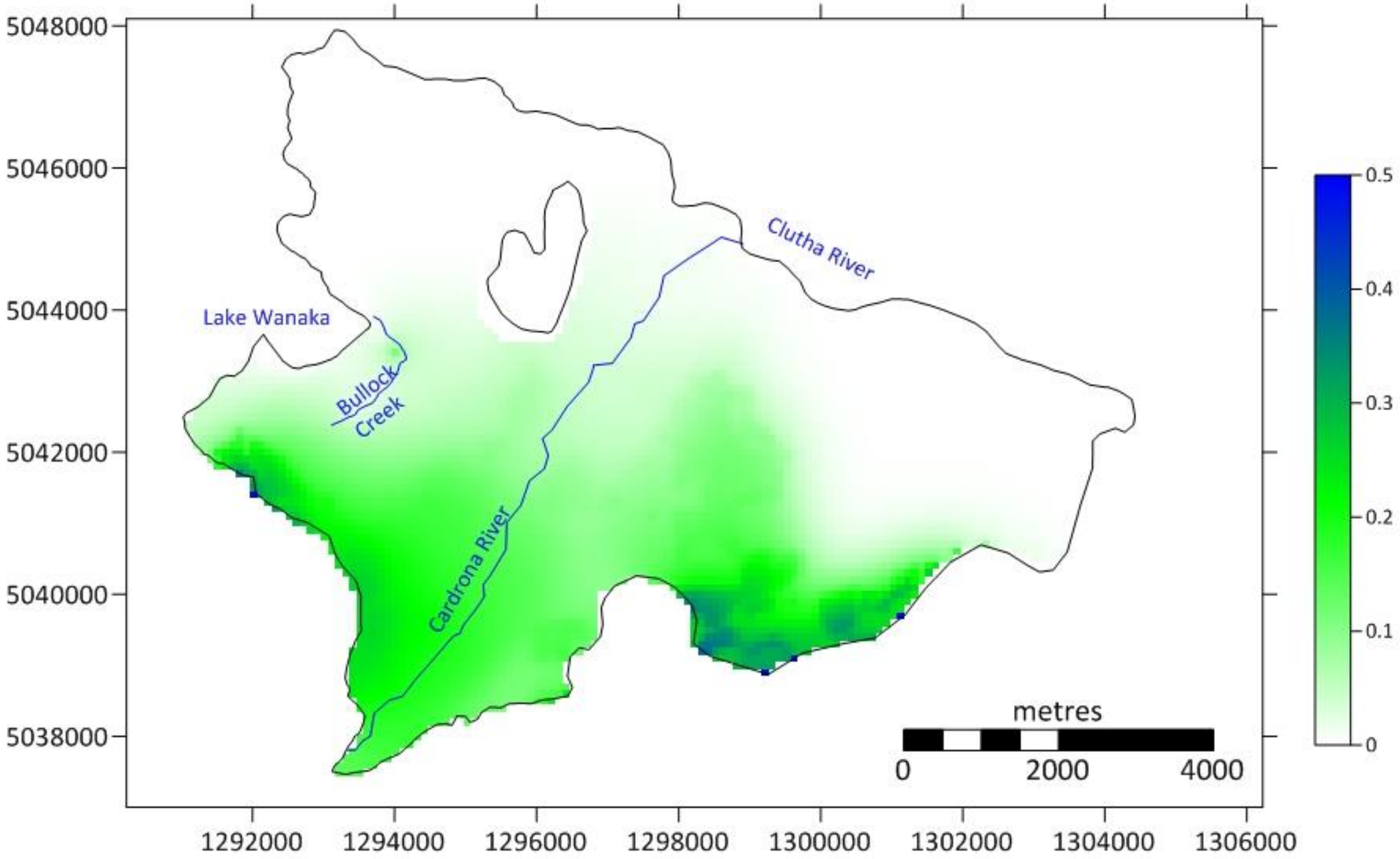


FIGURE 29: CHANGE IN GROUNDWATER LEVEL DUE TO IRRIGATION (SCALE IN METRES)

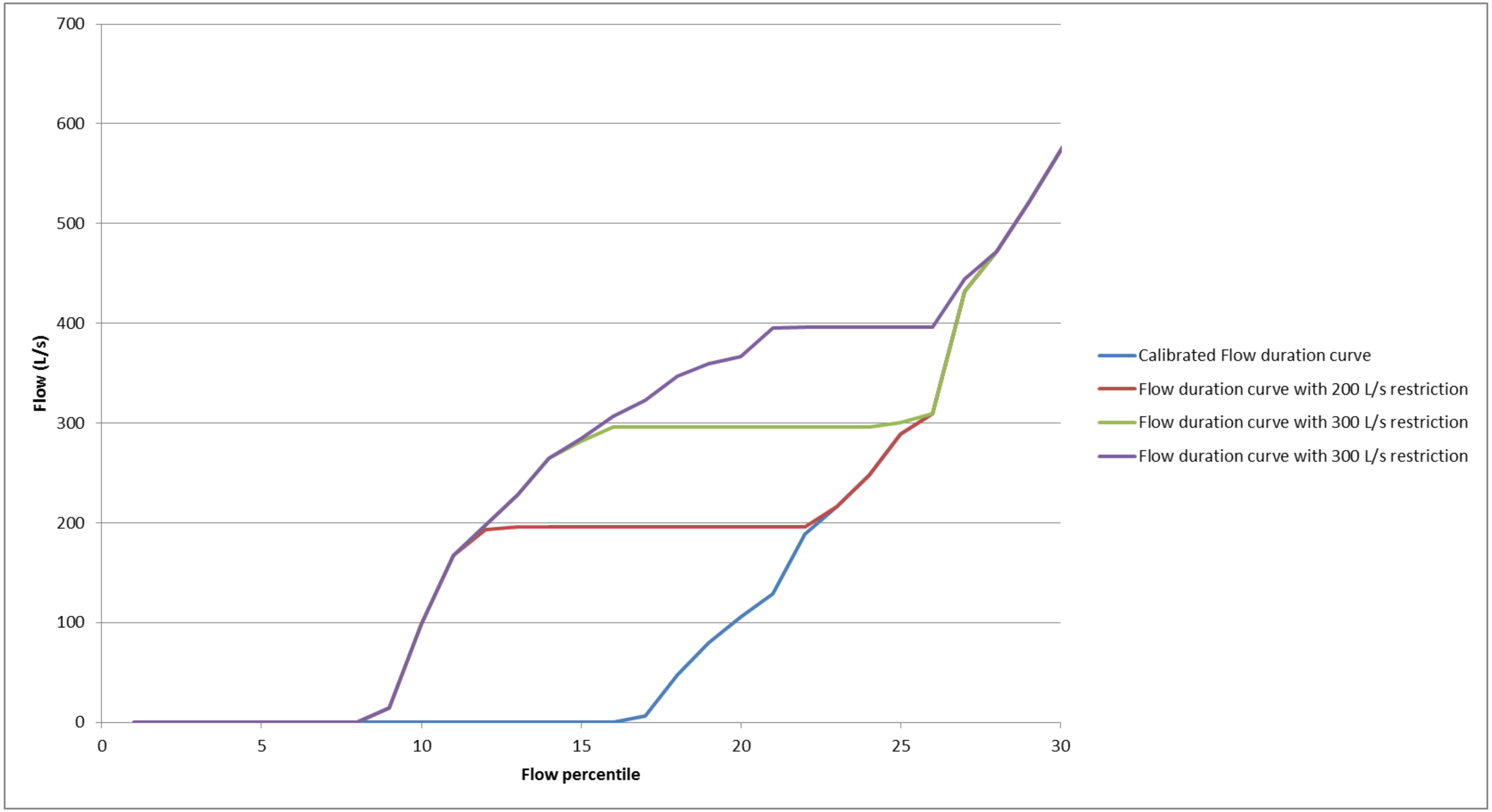


FIGURE 30: EFFECTS OF FLOW RESTRICTIONS ON THE MODELLED FLOW DURATION CURVE FOR THE CARDRONA RIVER AT BALLANTYNE ROAD

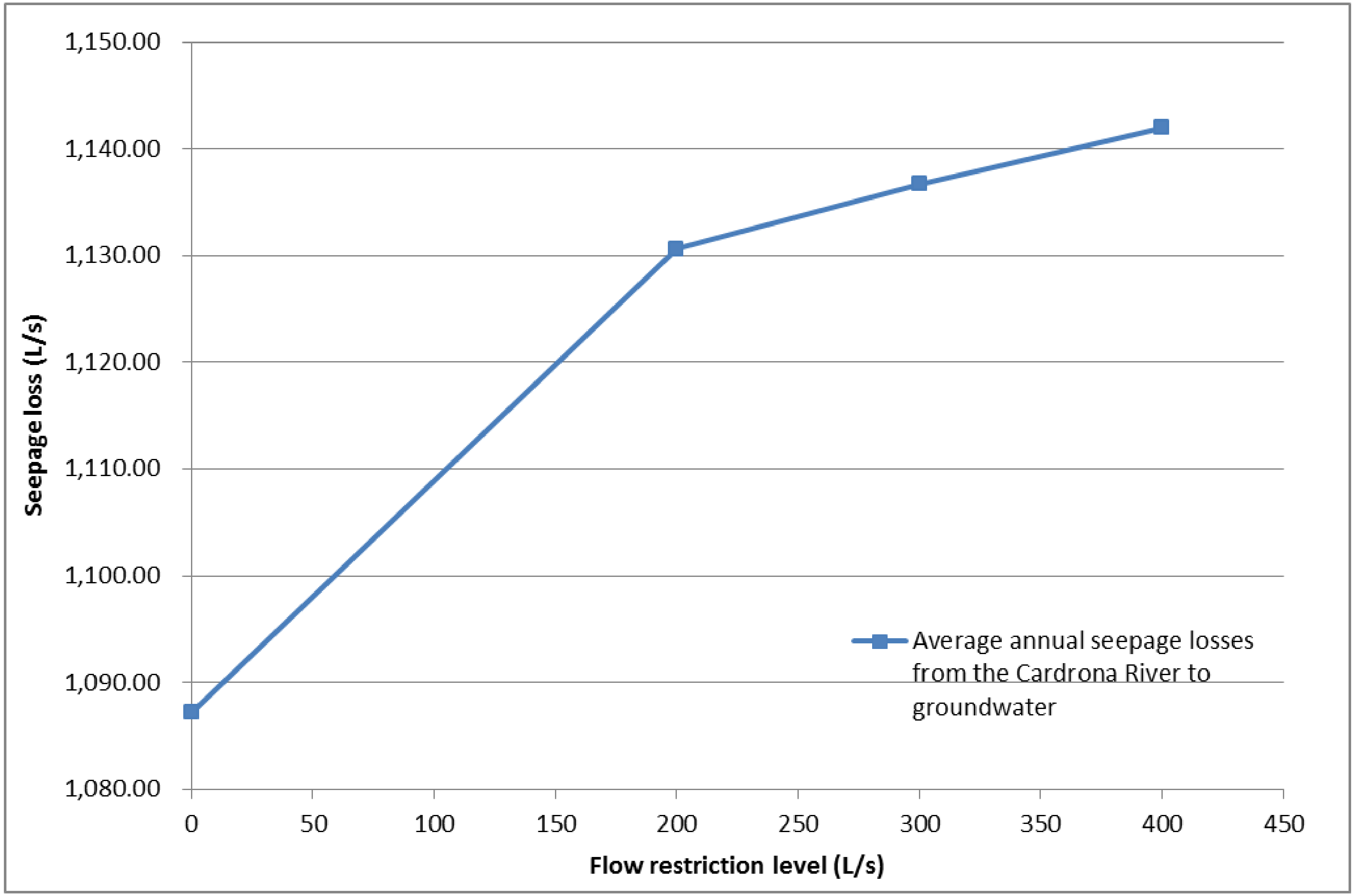
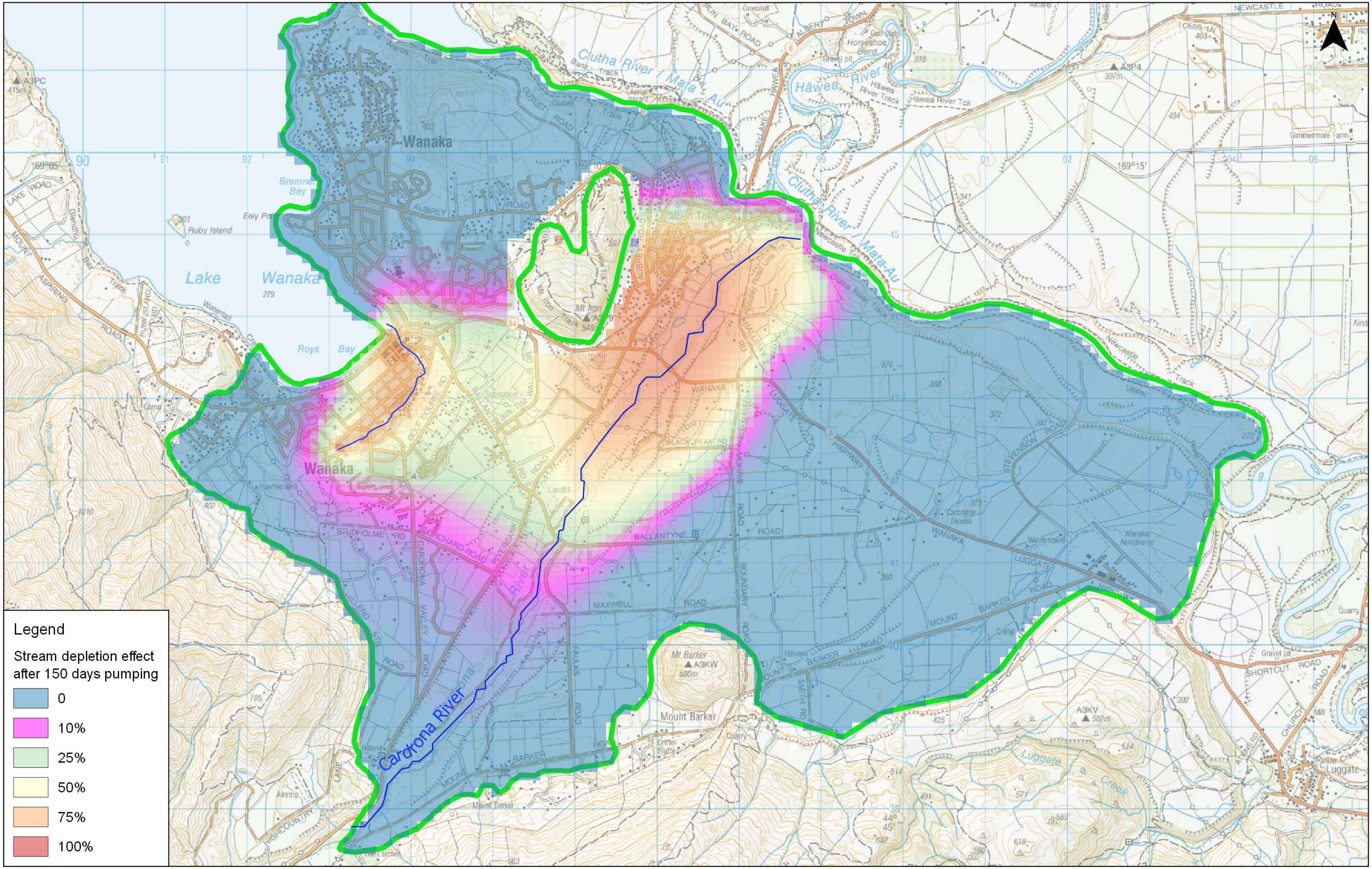
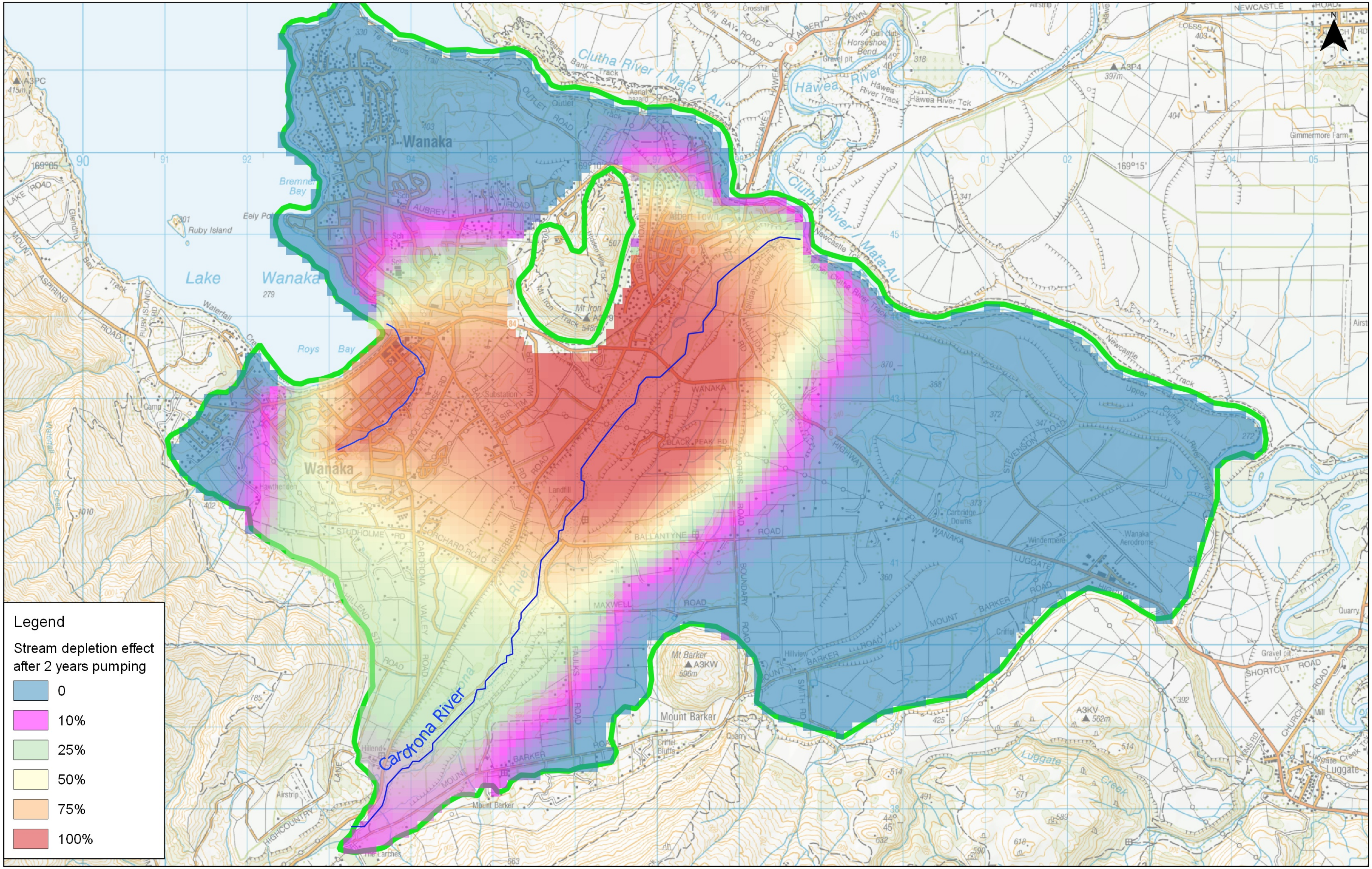


FIGURE 31: EFFECTS OF FLOW RESTRICTIONS ON SEEPAGE FROM THE CARDRONA RIVER



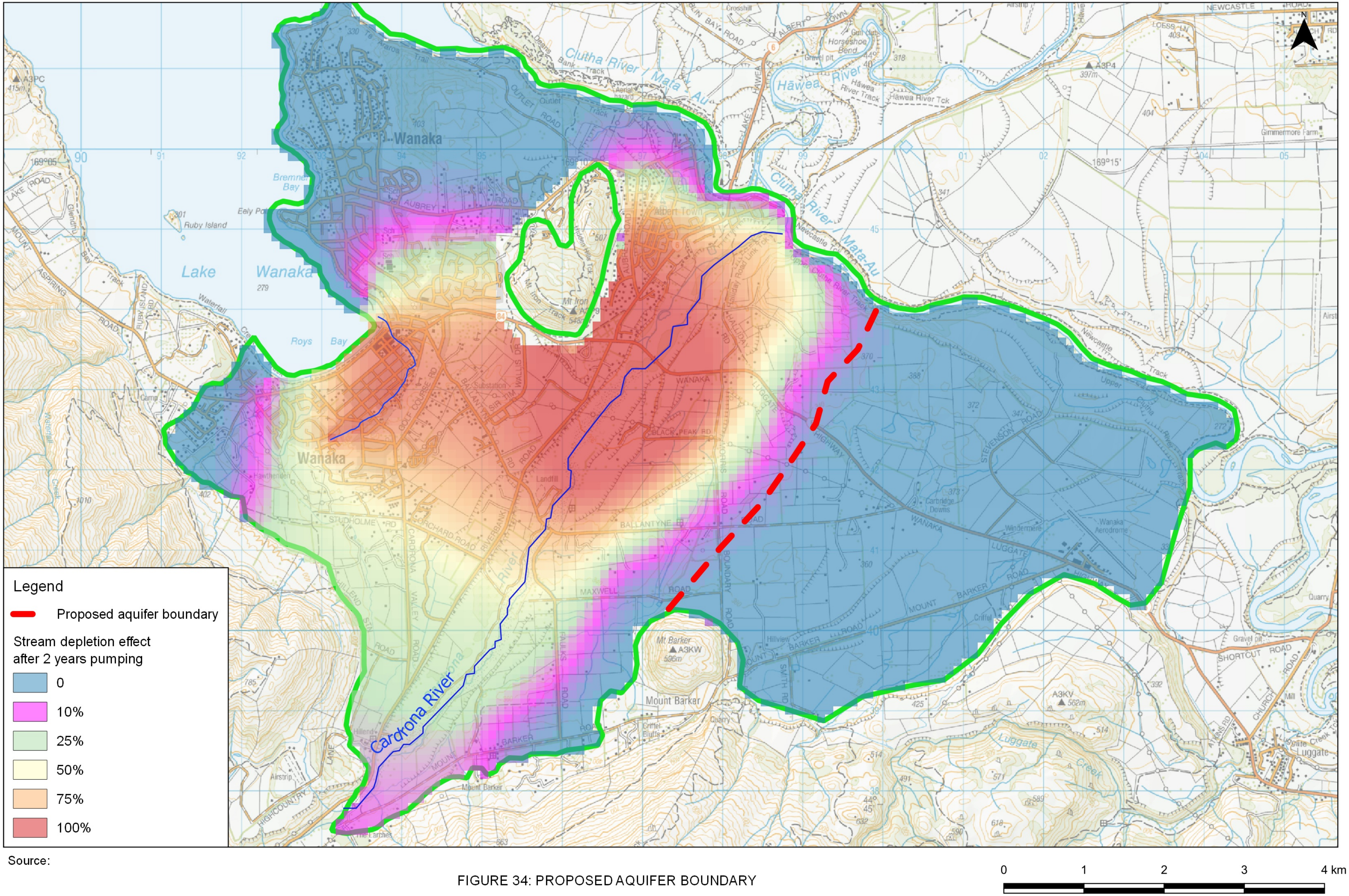
Source:

FIGURE 32: STREAM DEPLETION EFFECTS AFTER 150 DAYS PUMPING



Source:

FIGURE 33: STREAM DEPLETION EFFECTS AFTER TWO YEARS PUMPING



Source:

FIGURE 34: PROPOSED AQUIFER BOUNDARY

Appendix B

Calibrated model parameters

Table B1: Calibrated model parameters

Parameter	Value	Units
hk133	4.727665	m/d
hk134	65.20394	m/d
hk135	79.23027	m/d
hk136	64.01794	m/d
hk129	1.394649	m/d
hk130	1.000258	m/d
hk131	1.004686	m/d
hk132	1.001771	m/d
hk125	199.9237	m/d
hk126	200	m/d
hk127	1.561666	m/d
hk128	1.340332	m/d
hk120	199.3897	m/d
hk121	1.686188	m/d
hk122	19.84828	m/d
hk123	12.4855	m/d
hk115	6.512755	m/d
hk116	2.571103	m/d
hk117	3.449723	m/d
hk119	175.8056	m/d
hk107	1.849177	m/d
hk112	1.00163	m/d
hk184	60.43767	m/d
hk113	1.898862	m/d
hk185	1.332444	m/d
hk114	164.696	m/d
hk101	1	m/d
hk103	1.287405	m/d
hk104	2.131165	m/d
hk106	1.667596	m/d
hk180	83.69387	m/d
hk181	112.6773	m/d
hk182	1.670001	m/d
hk183	1.611673	m/d

Table B1: Calibrated model parameters		
Parameter	**Value**	**Units**
hk174	29.94558	m/d
hk175	1.000218	m/d
hk176	1.632708	m/d
hk178	1.000394	m/d
hk169	1.129267	m/d
hk171	1.456031	m/d
hk172	45.45861	m/d
hk173	200	m/d
hk163	99.00853	m/d
hk164	1.507867	m/d
hk165	2.200921	m/d
hk167	1.426503	m/d
hk159	1	m/d
hk160	37.48892	m/d
hk161	22.72772	m/d
hk162	52.97999	m/d
hk152	1	m/d
hk153	1.579152	m/d
hk155	1.070766	m/d
hk157	1.032526	m/d
hk148	31.63768	m/d
hk149	40.11939	m/d
hk150	200	m/d
hk151	96.83625	m/d
hk143	1.036227	m/d
hk145	1.00138	m/d
hk146	1.067447	m/d
hk147	16.4846	m/d
hk137	53.51626	m/d
hk138	200	m/d
hk139	1.639272	m/d
hk142	1.060229	m/d
sy133	0.00948	unitless
sy134	0.009521	unitless
sy135	0.005716	unitless

Table B1: Calibrated model parameters

Parameter	Value	Units
sy136	0.005	unitless
sy129	0.006674	unitless
sy130	0.006859	unitless
sy131	0.007755	unitless
sy132	0.00775	unitless
sy125	0.005	unitless
sy126	0.008589	unitless
sy127	0.007072	unitless
sy128	0.007301	unitless
sy120	0.006814	unitless
sy121	0.007246	unitless
sy122	0.008853	unitless
sy123	0.006299	unitless
sy115	0.009013	unitless
sy116	0.00725	unitless
sy117	0.006671	unitless
sy119	0.006382	unitless
sy107	0.00642	unitless
sy112	0.006892	unitless
sy184	0.012472	unitless
sy113	0.006314	unitless
sy185	0.00616	unitless
sy114	0.006696	unitless
sy101	0.007463	unitless
sy103	0.007489	unitless
sy104	0.00667	unitless
sy106	0.006304	unitless
sy180	0.007434	unitless
sy181	0.005489	unitless
sy182	0.011041	unitless
sy183	0.008728	unitless
sy174	0.022136	unitless
sy175	0.013036	unitless
sy176	0.008513	unitless
sy178	0.007581	unitless

Table B1: Calibrated model parameters

Parameter	Value	Units
sy169	0.007996	unitless
sy171	0.006585	unitless
sy172	0.010895	unitless
sy173	0.005444	unitless
sy163	0.012975	unitless
sy164	0.020326	unitless
sy165	0.008916	unitless
sy167	0.00816	unitless
sy159	0.006349	unitless
sy160	0.007827	unitless
sy161	0.013603	unitless
sy162	0.005	unitless
sy152	0.005027	unitless
sy153	0.007921	unitless
sy155	0.006985	unitless
sy157	0.006925	unitless
sy148	0.011361	unitless
sy149	0.01434	unitless
sy150	0.019893	unitless
sy151	0.005	unitless
sy143	0.00766	unitless
sy145	0.006351	unitless
sy146	0.011049	unitless
sy147	0.01229	unitless
sy137	0.005988	unitless
sy138	0.005008	unitless
sy139	0.007098	unitless
sy142	0.006954	unitless
rech2	1.248683	- (multiplier)
rech3	1	- (multiplier)
rech4	1.266993	- (multiplier)
rech5	0.703304	- (multiplier)
rech6	0.700549	- (multiplier)
rech7	0.70325	- (multiplier)
rech8	1	- (multiplier)

Table B1: Calibrated model parameters

Parameter	Value	Units
rech9	1	- (multiplier)
rech10	1.013643	- (multiplier)
rech11	0.700305	- (multiplier)
rech12	0.701769	- (multiplier)
rech13	1.000005	- (multiplier)
rech14	0.972175	- (multiplier)
rech15	1.299937	- (multiplier)
rech16	1.018974	- (multiplier)
rech17	0.988809	- (multiplier)
rech18	0.7	- (multiplier)
rech19	1	- (multiplier)
rech20	1.011112	- (multiplier)
rech21	1.012443	- (multiplier)
rech22	1.291946	- (multiplier)
rech23	1.009218	- (multiplier)
rech24	1.011197	- (multiplier)
rech25	1	- (multiplier)
rech26	1.000003	- (multiplier)
rech27	1.009809	- (multiplier)
rech28	1	- (multiplier)
rech29	0.700439	- (multiplier)
rech30	1.085883	- (multiplier)
rech31	1	- (multiplier)
rech32	1	- (multiplier)
rech33	1.011156	- (multiplier)
rech34	0.849377	- (multiplier)
rech35	0.936972	- (multiplier)
rech36	0.745654	- (multiplier)
rech37	0.700652	- (multiplier)
rech38	0.757721	- (multiplier)
rech39	1.3	- (multiplier)
rech40	0.999747	- (multiplier)
rech41	0.7	- (multiplier)
rech42	1.3	- (multiplier)
rech43	1	- (multiplier)

Table B1: Calibrated model parameters

Parameter	Value	Units
rech44	0.999992	- (multiplier)
rech45	1.0101	- (multiplier)
rech46	0.7	- (multiplier)
rech47	1.3	- (multiplier)
rech48	0.700525	- (multiplier)
rech49	1	- (multiplier)
rech50	0.7	- (multiplier)
rech51	1	- (multiplier)
rech52	1	- (multiplier)
rech53	1	- (multiplier)
rech54	0.880348	- (multiplier)
rech55	0.7	- (multiplier)
rech56	1.298654	- (multiplier)
rech57	1.299808	- (multiplier)
rech58	1.096031	- (multiplier)
rech59	1	- (multiplier)
rech60	1	- (multiplier)
rech61	1	- (multiplier)
rech62	1.012041	- (multiplier)
rech63	1	- (multiplier)
rech64	0.7	- (multiplier)
rech65	0.999029	- (multiplier)
rech66	1.011182	- (multiplier)
rech67	0.7	- (multiplier)
rech68	0.939117	- (multiplier)
rech69	1.011151	- (multiplier)
rech70	0.7002	- (multiplier)
rech71	1.011075	- (multiplier)
rech72	1.280508	- (multiplier)
rech73	0.700395	- (multiplier)
rech74	1.011168	- (multiplier)
rech75	1	- (multiplier)
rech76	1.3	- (multiplier)
rech77	1	- (multiplier)
rech78	1.008968	- (multiplier)

Table B1: Calibrated model parameters

Parameter	Value	Units
rech79	1.108998	- (multiplier)
rech80	1	- (multiplier)
rech81	1.255101	- (multiplier)
rech82	1.102651	- (multiplier)
rech83	0.998962	- (multiplier)
rech84	1	- (multiplier)
rech85	0.700514	- (multiplier)
rech86	1	- (multiplier)
rech87	1	- (multiplier)
rech88	1.135701	- (multiplier)
rech89	1.000002	- (multiplier)
rech90	1	- (multiplier)
rech91	0.700288	- (multiplier)
rech92	0.999999	- (multiplier)
rech93	1.3	- (multiplier)
rech94	0.983068	- (multiplier)
rech95	1	- (multiplier)
rech96	1.27257	- (multiplier)
rech97	1.3	- (multiplier)
rech98	1	- (multiplier)
rech99	1	- (multiplier)
rech100	0.700272	- (multiplier)
rech101	1	- (multiplier)
rech102	1.259906	- (multiplier)
rech103	1	- (multiplier)
rech104	0.71773	- (multiplier)
rech105	1.297674	- (multiplier)
rech106	1	- (multiplier)
rech107	1.3	- (multiplier)
rech108	1.3	- (multiplier)
rech109	0.7	- (multiplier)
rech110	0.943877	- (multiplier)
rech111	1.153458	- (multiplier)
rech112	0.700189	- (multiplier)
rech113	1	- (multiplier)

Table B1: Calibrated model parameters

Parameter	Value	Units
rech114	1.299895	- (multiplier)
rech115	0.877784	- (multiplier)
rech116	1.023833	- (multiplier)
rech117	0.700409	- (multiplier)
rech118	1	- (multiplier)
rech119	0.762397	- (multiplier)
rech120	1.068468	- (multiplier)
rech121	1	- (multiplier)
rech122	1.3	- (multiplier)
rech123	0.7	- (multiplier)
rech124	1	- (multiplier)
rech125	0.711743	- (multiplier)
rech126	1.003442	- (multiplier)
rech127	1	- (multiplier)
rech128	0.822856	- (multiplier)
rech129	1.272007	- (multiplier)
rech130	1	- (multiplier)
rech131	1.025549	- (multiplier)
rech132	1.002522	- (multiplier)
rech133	1	- (multiplier)
rech134	1.025451	- (multiplier)
rech135	1.189653	- (multiplier)
rech136	0.764932	- (multiplier)
rech137	0.817322	- (multiplier)
rech138	1.3	- (multiplier)
rech139	1.3	- (multiplier)
rech140	0.791567	- (multiplier)
rech141	1.3	- (multiplier)
rech142	1.000003	- (multiplier)
rech143	1.13469	- (multiplier)
rech144	1.299343	- (multiplier)
rech145	0.711184	- (multiplier)
rech146	1.3	- (multiplier)
rech147	0.761032	- (multiplier)
rech148	0.943242	- (multiplier)

Table B1: Calibrated model parameters		
Parameter	**Value**	**Units**
rech149	1.196338	- (multiplier)
rech150	1.3	- (multiplier)
rech151	0.7	- (multiplier)
rech152	1.288868	- (multiplier)
rech153	1	- (multiplier)
rech154	1	- (multiplier)
rech155	1	- (multiplier)
rech156	0.893183	- (multiplier)
riv3	4329.615	m/d
riv2	5	m/d
str1	524.0485	m/d
str2	507.0908	m/d
str3	908.749	m/d
str4	1984.097	m/d
str5	981.4516	m/d
str6	632.683	m/d
str7	272.5802	m/d
str8	1317.717	m/d
str9	2000	m/d
str10	900	m/d
str11	2000	m/d
str12	448.0564	m/d
str13	101.6524	m/d
str14	1999.358	m/d
str15	448.0998	m/d
str16	280.8009	m/d
str17	757.6627	m/d
str18	1581.985	m/d
str19	805.9608	m/d
str20	2000	m/d
str21	1999.285	m/d
str22	270.5164	m/d
str23	1545.329	m/d
str24	180.9863	m/d
str25	1712.593	m/d

Table B1: Calibrated model parameters

Parameter	Value	Units
str26	100	m/d
str27	1172.3	m/d
str28	232.3442	m/d
str29	1120.998	m/d

Appendix C

Stream depletion plot

This plot and a similar plot in Figure 33 were generated by running the groundwater model once without any abstractions (the baseline model). A simulated abstraction was then added to a model cell and the model was rerun. The results were then compared to the baseline model to determine the mass balance difference in stream flows (representing the Cardrona River and Bullock Creek), which shows the stream depletion effect for abstraction from that cell.

That procedure was repeated for every active cell in the model, which allowed the map of stream depletion effects to be generated. In total the model was run around 6,600 times. This was accomplished using a custom built parallel algorithm utilising a networked cluster of high throughput computers simultaneously to generate the map. The approach builds on an approach presented in Bakker et. al. (2016) and uses FloPy (2018).