CHES Implementation for the Manuherekia River, Otago

Report for Manuherekia TAG

Prepared for Otago Regional Council

September 2019

Prepared by:
Roddy Henderson
Christian Zammit
James Griffiths

For any information regarding this report please contact:

Roddy Henderson
Hydrologist
Hydrological Processes
+64-3-343 7873
roddy.henderson@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011

Phone +64 3 348 8987

NIWA CLIENT REPORT No: 2019294CH
Report date: September 2019
NIWA Project: ORC18501

Quality Assurance Statement		
	Reviewed by:	Channa Rajanayaka
	Formatting checked by:	Rachel Wright
	Approved for release by:	Helen Rouse

Contents

Tables

Figures

Executive summary

To allow water management and water plan development for the Manuherekia catchment, Otago Regional Council (ORC) need to develop an understanding of catchment hydrology and water use so that policy options and rule scenarios can be assessed. To assist ORC with this task, NIWA is to implement the Cumulative Hydrological Effects Simulator (CHES) model for the Manuherekia catchment. This will allow ORC to test alternative scenarios for minimum flow at various points in the catchment, and potentially in future to assess the potential impact of water allocation decisions.

The project has three distinct stages: (1) determination of natural flows using recorded river flow and water meter data across the catchment; (2) simulation of natural flows everywhere in the catchment for an extended period (1972 to 2019) using TopNet (NIWA's rainfall-runoff model); and (3) development of the CHES model for the catchment to allow scenarios to be explored.

Naturalisation of river flows for the catchment was challenging. The sum of all water meters in the catchment resulted in some very unrealistic assessments of total water resource especially at low flow. To resolve this, an assessment was made by ORC staff of all meters to determine whether they were measuring water abstraction from natural water courses or water takes from storage or irrigation distribution systems that had already been measured when abstracted from rivers. Effective data for most locations required (Chatto Creek, Thomsons Creek, Lauder Creek, Dunstan Creek and Falls Dam) are now available for six low flow seasons. Two significant aspects remaining unresolved are the quality assurance (QA) procedures applied to meter data, and the degree to which main stem river flows, and consequently takes from them, are measuring water that has leaked, or is the result of return flows. The former may lead to under or over estimation of the water resource, and the latter will give rise to a positive bias for the naturalised main stem flows at Ophir and Campground.

TopNet (NIWA's rainfall runoff model) has been successfully applied to the Manuherekia, with adjustment of input data (especially rain) to allow a realistic overall catchment water balance. Falls Dam outflows have been replaced by calculated Falls Dam inflows, and inflows have also been synthesised for the Pool Burn and Manor Burn reservoirs, so that the current model is of the completely unmodified hydrology. Simulated natural flows are thus available for the period 1972 to 2018.

The application of CHES to the Manuherekia catchment has focussed on modelling of four scenarios provided by ORC, with three low flow management points: Dunstan Creek at Beattie Road, Manuherekia at Ophir and Manuherekia at Campground. All takes modelled (those identified as natural) are governed by the flows at one of these three locations (in each case, the nearest downstream management point). Results in the form of flow duration curves are provided at significant locations in the main stem of the river for scenarios with the maximum consented take rates, and the maximum measured takes rates from five years of water meter data. Results show that where a minimum flow exists, it does provide a bottom line for the river, but that this minimum may become the resulting flow in the river for a significant fraction of the time. Downstream or upstream of these minimum flow points, major takes can still result in zero flow in the river.

The possible effect of the Falls Dam has also been modelled by substituting measured dam inflows and outflows for the modelled flows in the main stem downstream of the dam for a short period (three irrigation seasons) of recent time.

Work in a second phase of this project may include:

- Consideration of the water meter data QA and verification of the natural flows;
- Further measurements in the catchment to help understand natural recession behaviour and the relationships between tributary flows;
- Possible further development of scenarios by ORC; and
- Possible extension of the exploration of effects of abstraction into tributaries, as distinct from this phase which considers only main stem effects.

1 Introduction

To allow water management and water plan development for the Manuherekia catchment, Otago Regional Council (ORC) need to develop an understanding of catchment hydrology and water use so that policy options and rule scenarios can be assessed. To assist ORC with this task, NIWA is to implement the Cumulative Hydrological Effects Simulator (CHES) model for the Manuherekia catchment. This will allow ORC to test alternative scenarios for minimum flow at various points in the catchment, and potentially in future to assess the potential impact of water allocation decisions.

The Manuherekia catchment is a very challenging one for water resource assessment. Data collection of river flows has been intermittent at many sites, and most are affected by upstream water diversions or water storage. There are approximately 600 km of water races in the catchment, and three large managed reservoirs (Falls Dam, Manor Burn/Greenland reservoir and Pool Burn reservoir). This water infrastructure services more than 20,000 ha of irrigated agriculture.

The objectives of the current work were set out by ORC initially in late 2017, and later modified at a workshop held at NIWA Christchurch in June 2018. The main requirements were to allow exploration of the effects of minimum flow setting at three locations (Campground, Ophir and Dunstan Creek at Beattie Road) and below the major irrigation take points on the main stem (Omakau, Blackstone, Manuherikia and Galloway). CHES outputs on irrigation reliability were to be supplied to economists for further assessment. Takes and their effects on river flows were to be lumped and applied at the confluence with the Manuherekia for the main north bank tributaries: Chatto Creek, Thomsons Creek, Lauder Creek and Dunstan Creek. All other takes were to be assumed to apply at the next downstream flow recorder. The major catchment divisions used are illustrated in Figure 4-7.

The work described in this report is a substantial proportion of the work to be done in what is now regarded as phase one of the project. Phase two may include:

- Consideration of the water meter data QA and verification of the natural flows;
- Further measurements in the catchment to help understand natural recession behaviour and the relationships between tributary flows;
- Possible further development of scenarios by ORC; and
- Possible extension of exploration the effects of abstraction into tributaries, as distinct from this phase which considers only main stem effects.

2 Methods

The process for implementation of a CHES model comprises three main stages: (i) flow data assembly and naturalisation to provide time series for the rainfall-runoff model; (ii) development and calibration of a TopNet rainfall-runoff model that will provide hourly flows at every point of the river network; (iii) development and implementation of the CHES model, which involves representing major water use features on the river network, by setting rules in scenarios so that the model can deliver results such as potential alterations to water supply reliability, amount of time that instream values are preserved or affected, etc.

At the start of this project, the assumption was made that simply adding water meter data back to the river flows at sites downstream of the take points would provide naturalised flow series at each flow recorder. Water meter data are available for more than 95% of the water taken by volume for the last five years (the 2014/15 irrigation season to the 2018/19 season). This provided high confidence in the flow data that would provide the necessary results. Unfortunately, when this process was completed in September 2018, the subsequent answer for Manuherekia at Campground was a mean annual 7-day low flow of 9,500 L/s. This result was clearly at odds with previous estimates (3,900 L/s ± 800) assessed from national models and published by ORC (Olsen et al. 2017). This result prompted a thorough review of water meters and takes by ORC staff the results of which are described in the next section.

The TopNet rainfall-runoff model is described in Bandaragoda et al. (2004), Clark et al. (2008) and Yang et al. (2016). It uses inputs of precipitation and temperature from the Virtual Climate Station Network (VCSN) (Tait et al., 2006)) and applies models of physical catchment processes such as interception, evaporation, infiltration, snow accumulation and melt, shallow soil water flows and in-channel routing. The model framework is based on the digital stream network of New Zealand, which provides the flow pathways for surface water movement. Only shallow groundwater interactions are provided for, and water is assumed to enter the stream network from the sub-catchment where it fell as rain or snow. A surface water/groundwater version is available but was not selected for this work as it was thought that major groundwater interactions were not significant at the catchment scale. The model parameters are pre-calculated from GIS data of New Zealand's landscape and its hydrological properties. Since these are not reliably known for the whole country, TopNet is calibrated by applying multipliers to the parameters for each catchment being calibrated until a suitable match with the recorded or simulated natural flows is achieved. The calibration focusses on aspects of the hydrology that are most important for the work at hand, in this case low flow less than the lower quartile. The calibration process is described in more detail in section 4.6. TopNet is written and compiled in Fortran and run on NIWA's high performance computing facility (HPCF). It has been developed over many years and is currently part of the New Zealand Water Model (NZWaM) development at NIWA.

The CHES model is a time series and spatial analysis package that operates as an add-on to ESRI's ArcMap GIS suite. Output from a calibrated TopNet model provides the underlying data for the application of rules and scenarios. Input data files provide descriptions of all water takes and their rules, and the effects of water abstraction are propagated down the river network. This allows assessment of the instream effects of water abstraction, and also calculation of effects on water supply reliability depending on water demands and instream rules.

3 Flow data

3.1 River flow data

River flow data has been collected at 18 locations in the Manuherekia catchment. Only one site (Ophir) has run continuously since 1971. Many are long closed, but nine others are currently in operation. Figure 3-1 shows the timelines of flow recorders. Most of those now open have several periods of significant gaps in the past. Several ran from 2007/08 but were closed around 2011 and some of these reopened in 2016.

Only Dunstan Creek at Gorge, Lauder Creek at Cattle Yards, and Thomsons Creek at Diversion Weir are completely unaffected by water abstractions or water storage. Manuherekia at Downstream of (D/S) Forks is slightly affected by water abstractions in the upper reaches for the Hawkdun-Ida Burn race.

Flow data as hourly averages were obtained from the NIWA Water Resources Archive and the ORC hydrology staff.

Gaps in the flow data occur for many different reasons apart from site closure and re-opening. These are simply treated as having no data, and the effect on various statistics to be later derived is assessed on a case by case basis. In particular, the calculation of the 7-day mean annual low flow (MALF) requires that the lowest 7-day moving mean flow of each year is recorded. These annual minima need assessing to ensure that the lowest flow of each year has in fact been captured. Where this is not the case the year is removed from the calculation of MALF.

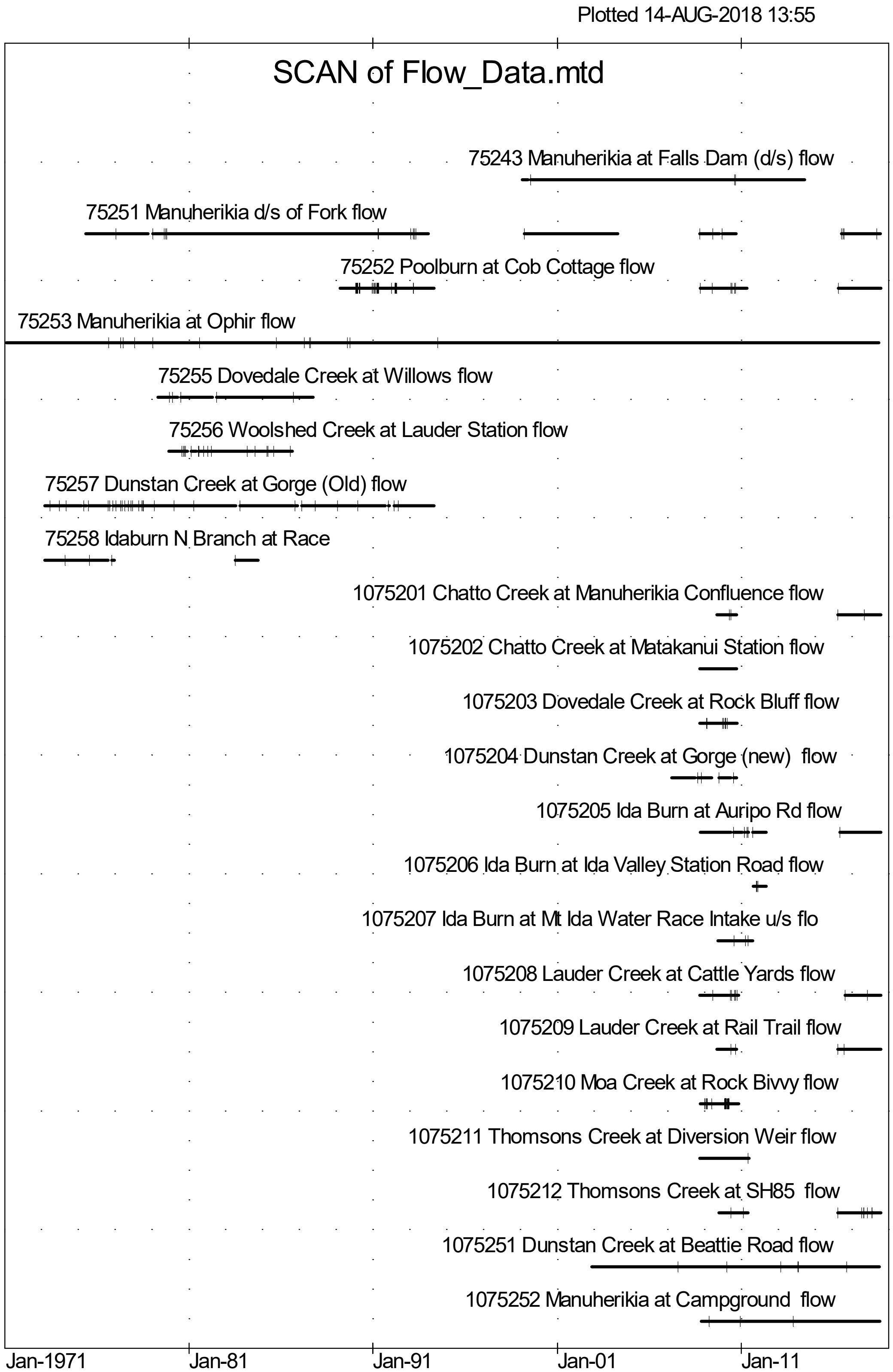


Figure 3-1: Timelines of flow records in the Manuherekia catchment. Vertical tick marks show the time of gaugings at each recorder.

3.2 Water meter data

Water meter data from ORC's database was interrogated to produce hourly flow figures from all meters in the Manuherekia catchment (138 meters). This number subsequently increased to 147. The consented maximum rate of abstraction of these meters is 25,927 L/s.

A rudimentary quality check involved removing all data that were more than two times the consented maximum rate for each meter. The number of these removals led to some speculation about the quality assurance (QA) procedures that may have been applied to the meter data. For the work described here we proceeded on the assumption that the meter data are correct.

In each sub-catchment grouping, meter data were added together to provide a time series of total abstraction from that sub-catchment. An estimate of the likely total water abstracted at each time step was calculated by dividing the total abstraction from meter data by the ratio of the total maximum allowable rate of abstraction (MaxRate) for the meters with data, divided by the total MaxRate for all meters. The general principle of this adjustment method is seen in Figure 3-2.

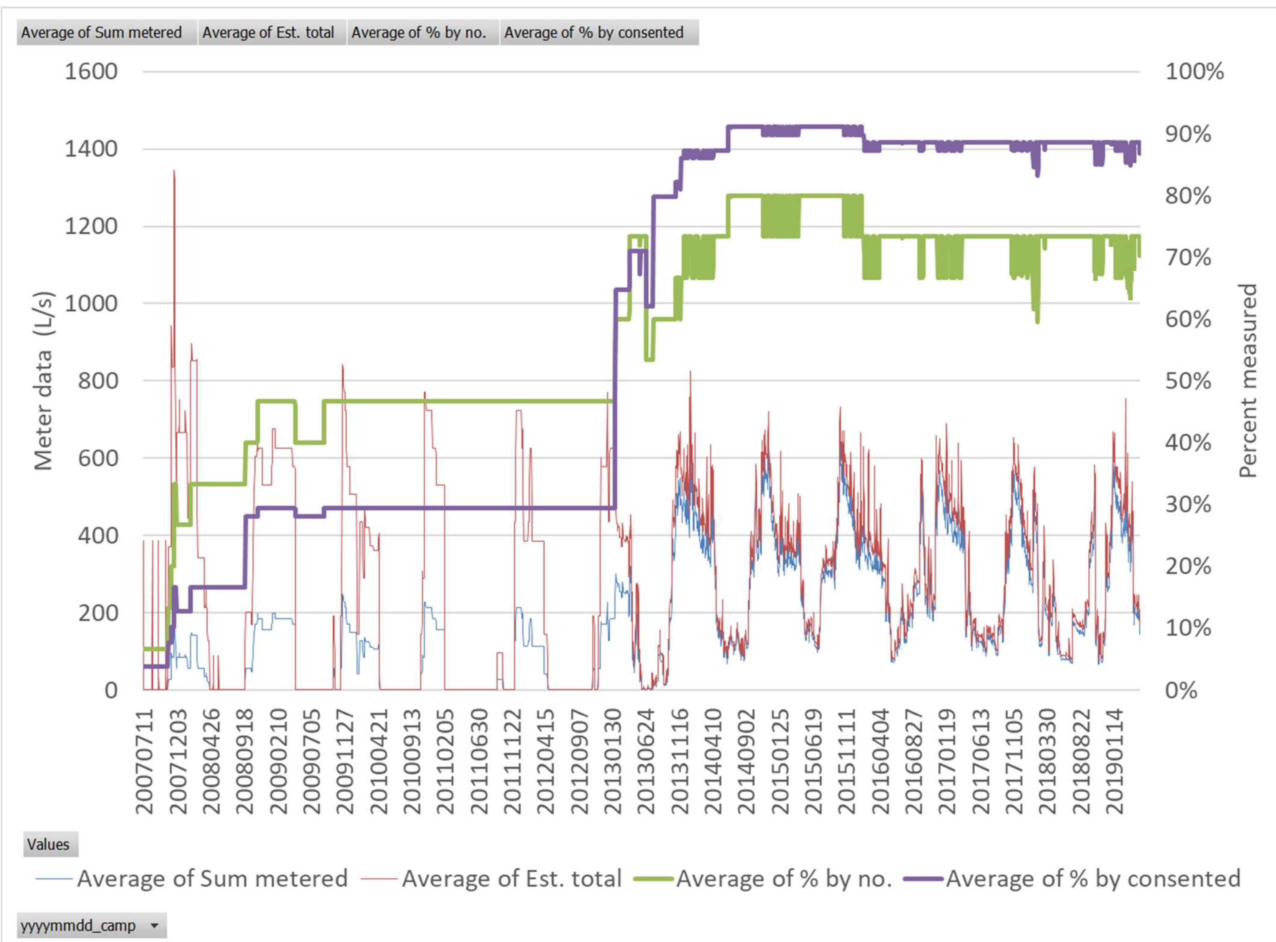


Figure 3-2: Meter data from Chatto Creek. Measured total (blue, L/s), estimated total (red, L/s), percent of used water by number of meters (green) and percent of used water by MaxRate (purple).

The first six season's data are scaled up by more than 50%. The last six seasons appear reasonable and could be used for flow naturalisation.

The net result of this initial process applied to all meters was an estimated 9,500 L/s MALF at Campground, which led to a rethink of the meter data and its applicability. Messrs Augspurger and Ravenscroft of the ORC conducted an exhaustive review of the Manuherekia water meters, visiting many locations and interviewing water users across the catchment. Their aim was to establish which meters were using water derived from an original water source, and which meters were using water delivered by a scheme that had been already measured at another location. The final meter list comprises 91 meters, most of which are assessed as measuring 100% natural water, but some (24) assessed as measuring some water that has been already measured elsewhere. Figure 3-3 shows the distribution of these meters across the entire Manuherekia. More detailed maps, graphs of the meter water use time series and lists of meters are provided in Appendix A, B and C.

Currently some significant meters do not have a complete year for the 2018/19 year. This issue affects the assessments at Lauder Creek, Dunstan Creek, Pool Burn/Ida Burn, Manor Burn and the main stem takes.

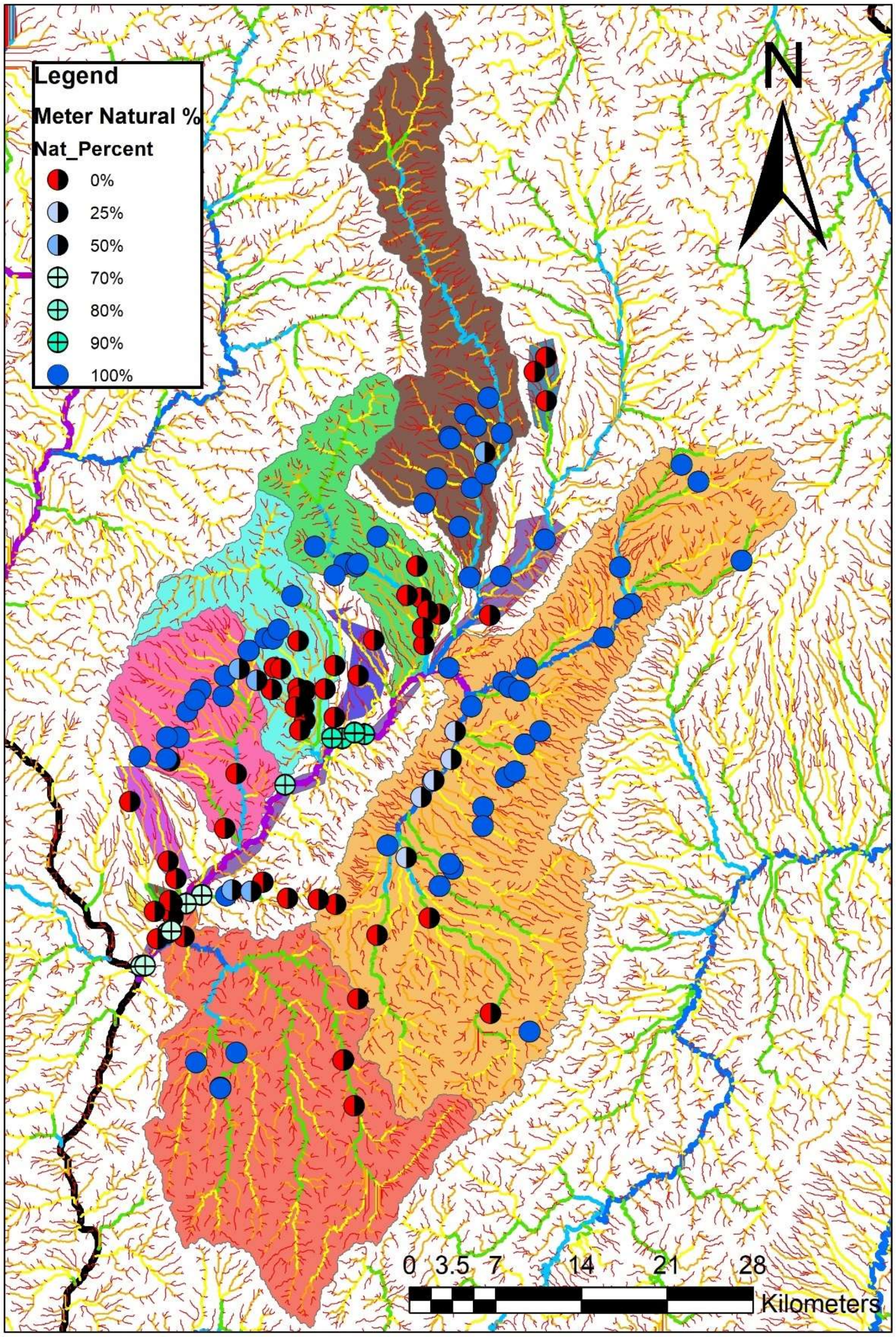


Figure 3-3: Water meters and their assessed natural fraction. Those on the main stem are marked with a different symbol and are subject to further investigation regarding water re-use. See section 3.3.8 for more details.

3.3 Naturalised river flows

River flow naturalisation is simply done by adding the sum of the takes from natural waters upstream of each flow record. Naturalised flows are needed for calibration of the TopNet model, so that longer time series of flow data can be generated with confidence.

In the simplest cases, the natural flow is calculated according to equation 1:

$$Q_{nat} = Q_{measured} + T_{natural} \tag{1}$$

where Q_{nat} is the naturalised flow, $Q_{measured}$ is the recorder flow, and $T_{natural}$ is the total takes upstream of the recorder from natural water bodies (i.e., not from storages or from other races).

If there is a storage lake in the catchment upstream this method needs extra terms. Then, natural flows are the sum of measured natural takes and recorded flows, plus natural inflows to the reservoir and measured takes from the reservoir releases, minus the reservoir releases, as per equation 2:

$$Q_{nat} = Q_{measured} + T_{natural} + \sum T_{out} - Outflow\ releases + Natural\ Inflows \tag{2}$$

Where T_{out} is water taken from reservoir releases, outflow releases are the water released from the reservoir, and natural inflows are the calculated inflows to the reservoir, based on either a model or on the measured outflows and reservoir level records.

3.3.1 Chatto Creek at Confluence

Natural flow at this site (1075201) is the sum of the recorded flow and the total take upstream. Only three irrigation seasons are available, from 2016/17 to 2018/19. The calculated 7-day MALF is 576 L/s.

3.3.2 Thomsons Creek at Diversion Weir

This recorder site (1075211) is immediately upstream of the diversion into the Matakanui main race and there are no abstractions upstream. Unfortunately, the recorder was closed in 2011. The diversion is measured by meter WM0104, and in periods where the meter flow shows natural river behaviour, it can be used as a substitute for the river flow record. This is useful for providing low flow data for TopNet calibration. The estimated 7-day MALF from the combined dataset with six annual values is 183 L/s, although the available meter data may not represent the lowest flows in each year they are used.

Because some low flow behaviour at this recorder exhibits very flat recessions, we have assumed a spring flow contribution of 100 L/s. This is subtracted from the estimated flows, the model is calibrated, and the 'spring' flow is then added back.

3.3.3 Lauder Creek at Cattle Yards

This recorder site (1075208) is upstream of any abstractions, and provides good data for five seasons, with a nearly six-year gap from 2011 to 2016. The calculated 7-day MALF from five years is 316 L/s.

As for Thomsons Creek, recessions show evidence of spring flow, and this is assessed at 200 L/s.

3.3.4 Dunstan Creek at Beattie Road

This recorder (1072551) is downstream of several abstractions, so as for Chatto Creek, has the total abstractions added to derive a natural flow series. The analysis period is thus limited by the availability of meter data, giving six seasons from 2013/14. The calculated 7-day MALF is 887 L/s. Figure 3-4 shows the total metered water use from the applicable water meters, and the proportion of water use that is measured over time. The six most recent seasons are suitable for use although the most recent has approximately 40% missing meter data.

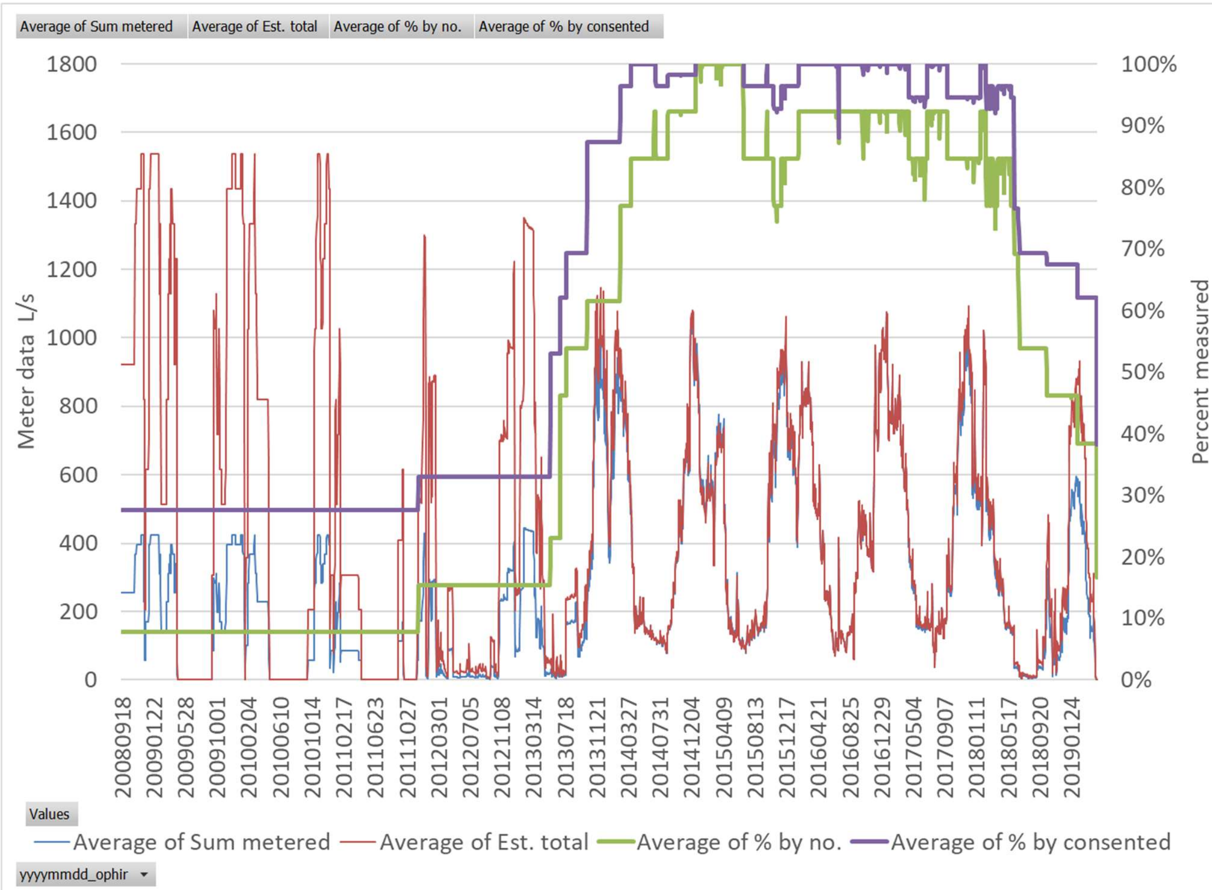


Figure 3-4: Dunstan Creek naturalisation. Left axis shows total water meter use, right axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

3.3.5 Falls Dam

Falls Dam operates in the upper reaches of the Manuherekia as a storage and release mechanism for irrigation water and is also used to provide some low flow releases to maintain a voluntary minimum flow at Campground of 900 L/s. Water that flows in to the dam is from the upper Manuherekia and includes the catchment measured by the flow recorder at Downstream of Forks (75251). Flows out of the dam have been measured in the past at Manuherekia at Falls Dam (d/s) (75243). This site closed in June 2014. There are also lake level records from Falls Dam at Dam (75244) between 1999 and 2003.

Mount Ida Race abstracts water at many points along the Hawkdun Range upstream of Falls Dam and has a water meter (WM0118) where it leaves the catchment of the upper Manuherekia and enters the Ida Burn en route to the Taieri. Data for these flows are available from 2007.

From 2014 onwards outflow data and lake levels are available from Pioneer Energy which operates the lake for power generation as well. Lake levels, machine flows, bypass flows and spill flows are available, and we have used these together with lake bathymetry to calculate an inflows series from 2014. Adding the flows from meter WM0118 gives a complete picture of the catchment above the dam.

Figure 3-5 shows the calculated inflow series to Falls Dam together with the independently measured flow record from the Manuherekia at d/s Forks. The agreement is good, and the inflow series is a suitable one for use.

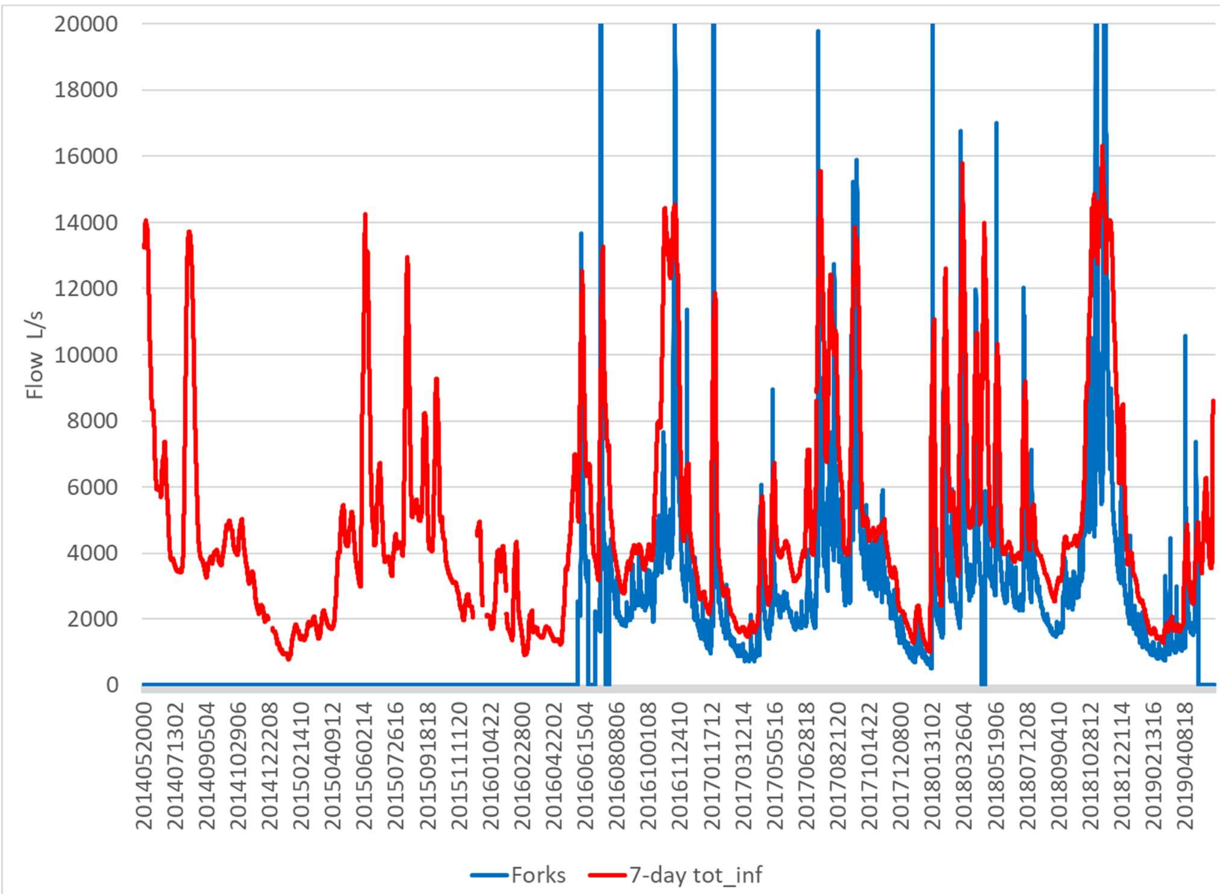


Figure 3-5: Falls dam naturalisation, 2014 - 2019. The red trace is the calculated inflows to Falls Dam with a seven-day moving mean applied. The blue trace is the flow record from the upstream site Manuherekia at d/s Forks.

An earlier inflow series (from 1975 to 2012) has also been derived (Stewart 2012), using available data and correlations with Dunstan Creek and Lindis Peak. At present use of this is not necessary as the available water meter data for the rest of the catchment flow naturalisation restricts the work to the most recent five or six seasons.

3.3.6 Pool Burn at Cob Cottage

This recorder (75252) is downstream of many abstractions, a water transfer from the Taieri and one from the upper Manuherekia (Hawkdun-Ida Burn Race), and one large water storage reservoir (Pool Burn). Thus, we use equation 2, but for this very dry catchment, we assume that water released from storage during low flow periods (outflow releases) is all used by water users (T_{out}) and there are no return flows. This means that we can simplify equation 2 by removing T_{out} and Outflow Releases, according to equation 3:

$$Q_{nat} = Q_{measured} + T_{natural} + Natural\ Inflows \tag{3}$$

Inflows to the Pool Burn reservoir are estimated by using the flow record from Taieri at Canadian Flat (site 74318) and a ratio of mean flows from a national model (Woods et al., 2006).

Calculated MALF from four years is 245 L/s.

3.3.7 Manor Burn

There are no flow recorders in the Manor Burn catchment. An inflow series to the Manor Burn reservoir has been estimated as for the Pool Burn by using a ratio of the flows from Taieri at Canadian Flat. The estimated MALF for those inflows is 100 L/s.

3.3.8 Main Stem Manuherekia

There are two flow recorders along the main stem of the Manuherekia that are of interest for the CHES modelling. These are Ophir (75253) and Campground (1075252). To naturalise the flows at these two locations, we need to add the total takes on tributaries that are upstream of the flow recorder, as described in the sections above, and any other takes that are from the main stem itself. Above Ophir, the tributaries are Thomsons Creek, Lauder Creek, Dunstan Creek and Pool Burn. At Campground, the additional tributaries are Chatto and Manor Burn. We use Equation (2) for the calculation of natural flows in the main stem, but unlike for the Pool Burn and Manor Burn, we cannot assume that all released water is used and thus simplify to Equation (3).

The amount by which the major race takes on the main stem are augmented by water already measured will most probably be not a simple ratio of any quantity that is measured, nor will it be a constant amount over time. These major takes are supplied with water from the natural catchment but also from Falls Dam flow releases in the irrigation season. It is not possible to assume that the water used in these major races (Blackstone, Omakau, Manuherikia and Galloway) is solely from natural water, as they are often provided with Falls Dam releases, but nor is it possible to be sure that the water they use is all from this source plus natural catchment inflows between the Falls Dam and their respective intakes. This is because given the extent of irrigation application in the valley, it is likely that water returns to the river from irrigation systems by leakage from irrigation races, by-wash from over application and enhanced runoff because of soil moisture enhancement, and return flows where water is deliberately released into waterways to be further abstracted downstream.

If we assume that the main stem take data are as recorded and only include dam releases and natural inflows, the estimated 7-day MALFs at Ophir and Campground are 4,400 and 5,500 L/s, respectively. If we assume that the water taken by the major races on the main stem is affected by the various forms of already measured water described above and that this could be approximated by reducing the amount diverted by some simple ratios according to Table 3-1, then the estimated 7-day MALF reduce to 3,300 and 4,400 L/s, respectively. These are not firm estimates but simply an indication of the sensitivity of the downstream estimates to assumptions about the upstream data.

Table 3-1: Trial race reduction factors for main stem takes. Arbitrary amounts were applied in succession downstream from Falls Dam.

Reduction	Consent Holder	River section	Meter	Max Rate (L/s)
100%	Blackstone	Upper	WM0021	403.4
100%	Omakau	Upper	WM0122	1981
90%	Coutts	Middle	WM0221	138.88
90%	Leask	Middle	WM0943	55.5
90%	CODC	Middle	WM0997	35
90%	Coutts	Middle	WM1003	41.65
90%	Coutts	Middle	WM1004	41.65
80%	Manuherikia	Gorge	WM0062	2830
70%	Shaky	Lower	WM1432	6.94
70%	Galloway	Lower	WM0044	212.25
70%	Galloway	Lower	WM0045	212.25
70%	CODC	Lower	WM0088	20
70%	Bruce's	Lower	WM0859	2.9
70%	Paterson	Lower	WM0276	13.9
70%	Robinson	Lower	WM0605	50

The numbers derived from the meter data and flow data as presented here are still significantly different from the estimates in Olsen at al. (2107). To help resolve this we examine the catchment water balance at MALF, which methodology is described in Section 3.4.

3.4 The water balance of the Manuherekia Catchment at MALF

When the flow naturalisation process is complete it is possible to examine the estimated flow contributions of all sections of the catchment limited only by the measurement points. This is done by taking the difference between upstream and downstream flow estimates and attributing that flow to the intervening catchment. Anomalous results indicate potential problems with the data from the contributing flow records or may lead to a revision of understanding of the overall catchment hydrology.

A general expectation from the distribution of rainfall in the Manuherekia is that the catchment headwaters should have a higher specific yield (L/s/km^2) that the lower reaches, that the north bank tributaries should have a higher yield than the south bank, and that the intervening catchment areas draining directly to the main stem will be very dry also.

Figure 3.6 shows the yield of the Manuherekia sub-catchments when the flow naturalisation process described above has been followed. Notable features that give some cause for concern are:

- Yield of D/S Forks seems disproportionally high relative to Dunstan Gorge and the area upstream of the Falls Dam;
- The area upstream of Ophir, but below all the other flow recorders, has a higher than expected yield;

- Chatto Creek above the confluence is also higher than expected given the catchment gradients of rainfall.

Some of these apparent anomalies could be related to over-correction of recorded flow series by addition of meter data that is double counting water use. Others could be related to the difficulty of deriving a temporally consistent set of data, since some flow data are not available for the same time periods as other sites. Another potential source of difficulty is the calibration and validation of the water meter data, the status of which is currently unknown.

Prudent adjustment of these sub-catchment yields with an eye to the relative quality of the underlying data could produce a more hydrologically realistic picture. This could be aided by use of the national models described in Booker and Woods (2013).

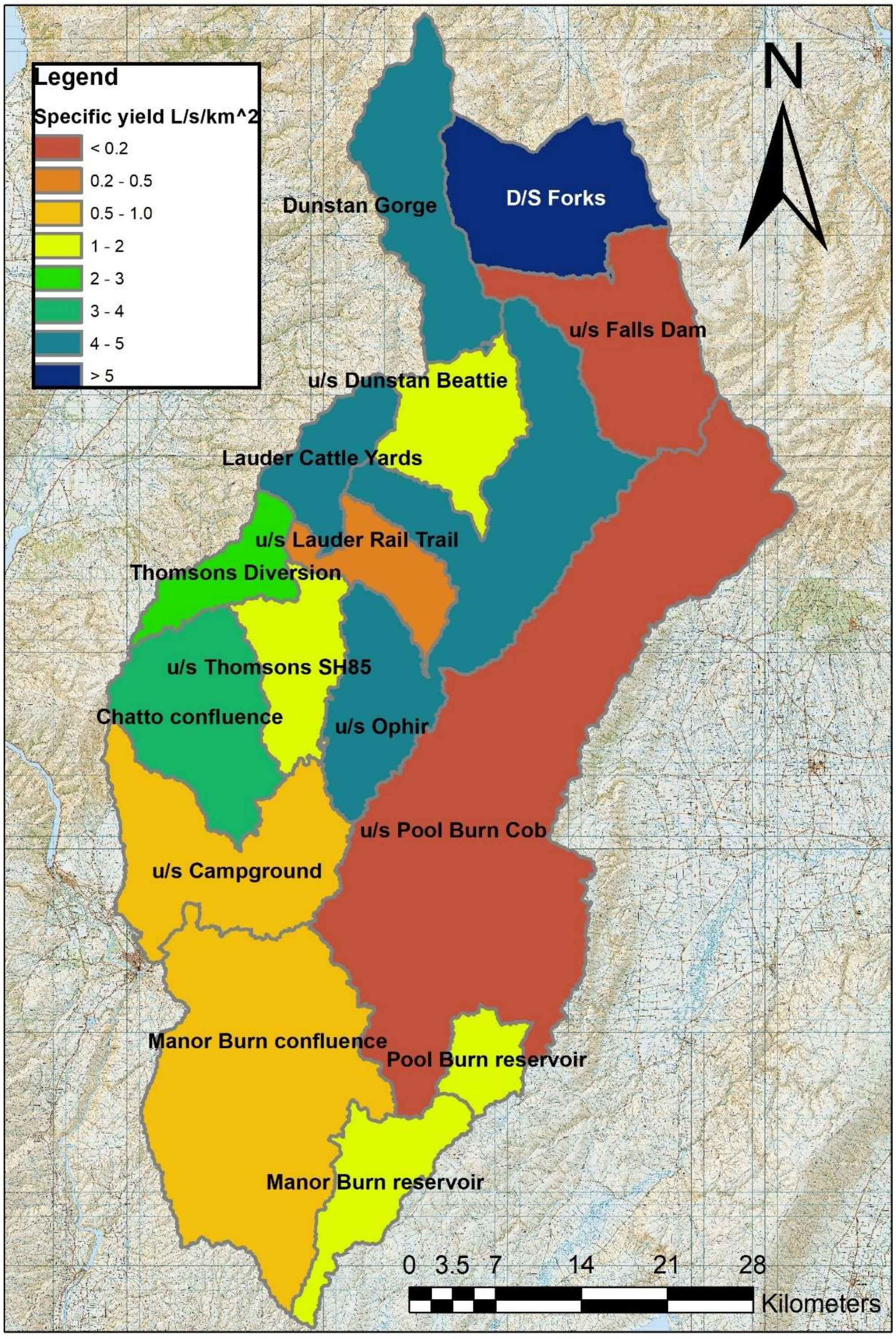


Figure 3.6: Specific yield of Manuherekia sub catchments.

3.5 Potential data issues

3.5.1 Water meter data validations

It is unclear to what extent water meter data has been validated or calibrated. All meter data have had a cursory examination and values more than twice the consented Max Rate have been removed. This does not however, constitute a rigorous QA procedure.

3.5.2 Reuse of water in the main stem takes

We do not have a satisfactory method of estimating the effects of leakage, by-wash and return flows, on the amount of double counted water in the takes from the main stem. This limitation introduces a significant potential bias to the estimation of MALF at Ophir and Campground.

3.5.3 Water meter data from 2018/19 year

There are several meters without no data for the latest year, and some of these are quite large users. This has affected the quality of the assessment of natural flows for that last year, and hence the MALF estimates.

3.5.4 Pool Burn and Manor Burn natural inflows

For the Ophir and Campground natural flow series, there are also small potential effects of the assumptions about inflows into the Pool Burn and Manor Burn reservoirs. These are currently modelled by untested ratios with data from the neighbouring Taieri at Canadian Flat.

3.5.5 Falls Dam inflows

There is a long series of derived inflows for Falls Dam (1975 - 2012) that could be of use in either calibration of the TopNet model or for validation of the model results when it is run. Permission has been given to request these, but this has not been done yet.

3.5.6 Gauging data

There are gauging data at many locations in the catchment that may provide information about intervening catchment yields during dry weather and also possibly further guidance on losses and gains between surface water and shallow groundwater systems.

4 TopNet model

The catchment hydrological model used in this study is NIWA's TopNet model (Clark et al. 2008), which is routinely used for surface water hydrological modelling applications in New Zealand. It is a spatially semi-distributed, time-stepping model of water balance. It is driven by time-series of precipitation and evaporation, derived from temperature, and additional weather elements where available. TopNet simulates water storage in the snowpack, plant canopy, rooting zone, shallow subsurface, lakes and rivers. It produces time-series of modelled river flow (without consideration of water abstraction, impoundments or discharges) throughout the modelled river network, as well as evapotranspiration (derived from weather/climate input information), but the version used in this project does not adjust river flows for effects of irrigation/water take or water redistribution between catchments. TopNet has two major components, namely a basin module and a flow routing module.

The model combines TOPMODEL hydrological model concepts (Beven et al. 1995) with a kinematic wave channel routing algorithm (Goring 1994) and a simple temperature based empirical snow model (Clark et al. 2008). As a result, TopNet can be applied across a range of temporal and spatial scales over large watersheds using smaller sub-basins as model elements (Ibbitt and Woods 2002; Bandaragoda et al. 2004). Considerable effort has been made during the development of TopNet to ensure that the model has a strong physical basis and that the dominant rainfall-runoff dynamics are adequately represented in the model. TopNet model equations and information requirements are provided by Clark et al. (2008) and McMillan et al. (2013). The version of the model used in this project does not consider water transfers from river to river or water storage, nor does it model aquifer water balances.

For the development of the TopNet model used in this study, spatial information in TopNet was provided by national datasets as follows:

- Catchment topography based on a nationally available 30 m Digital Elevation Model (DEM).
- Physiographical data based on the Land Cover Database version three (LCDB3) and Land Resource Inventory (Newsome et al. 2000).
- Soil data based on the Fundamental Soil Layer information (Newsome et al. 2000).
- Hydrological properties (based on the River Environment Classification version one (REC1) (Snelder and Biggs 2002)[1].

The method for deriving TopNet's parameters based on GIS data sources in New Zealand is given in Table 1 of Clark et al. (2008). Due to the paucity of some spatial information at national/regional scales, some soil parameters are set uniformly across New Zealand.

TopNet is currently configured to use LCDB3 (Newsome et al. 2000), reflecting 2008 land cover, rather than the latest version, version 4, which corresponds to 2011. There will be differences in land use between the two LCDB coverages, and these may have hydrological consequences if adopted in any future work.

[1] For the sake of consistency, landcover and soil information were kept consistent with the previous study (Collins and Zammit 2016)

Hydrological simulations are based on the REC 2 network aggregated up to Strahler[2] catchment order one (approximate average catchment area of 0.5 km^2) used within previous national and regional scale assessments. The simulation results comprise hourly time-series of various hydrological variables for each computational sub-catchment.

Because of TopNet assumptions, soil and land use characteristics within each computational sub-catchment are homogenised. Essentially this means that the soil characteristics and physical properties of different land uses, such as pasture and forest, will be spatially averaged, and the hydrological model outputs will be an approximation of conditions across land uses.

To carry out the simulations required for this study, a TopNet model was calibrated at each gauging station. The model was then run continuously from 1972 to 2018, with the spin-up year 1972 excluded from the analysis. The climate inputs were stochastically disaggregated from daily to hourly time steps.

4.1 TopNet model design

4.2 Physiographic characteristics

The study area is the surface water catchments discharging to the Manuherekia at Campground gauging station, as illustrated in Figure 4-1, while Figure 4-2 presents land use information. Land use in the Manuherikia catchment is predominantly pastoral.

The digital elevation model (DEM) jointly with the location of the streamflow gauging stations were used to generate a stream network and an associated set of Strahler 1 order surface water catchments. TopNet spatially distributed parameters were established for each sub-catchment using national soil information from the Fundamental Soil Layer (FSL: Newsome et al. 2000) and landuse/land cover information (LCDB3).

[2] Strahler order describes river size based on tributary hierarchy. Headwater streams with no tributaries are order 1; 2nd order streams develop at the confluence of two 1st order tributaries; stream order increases by 1 where two tributaries of the same order converge.

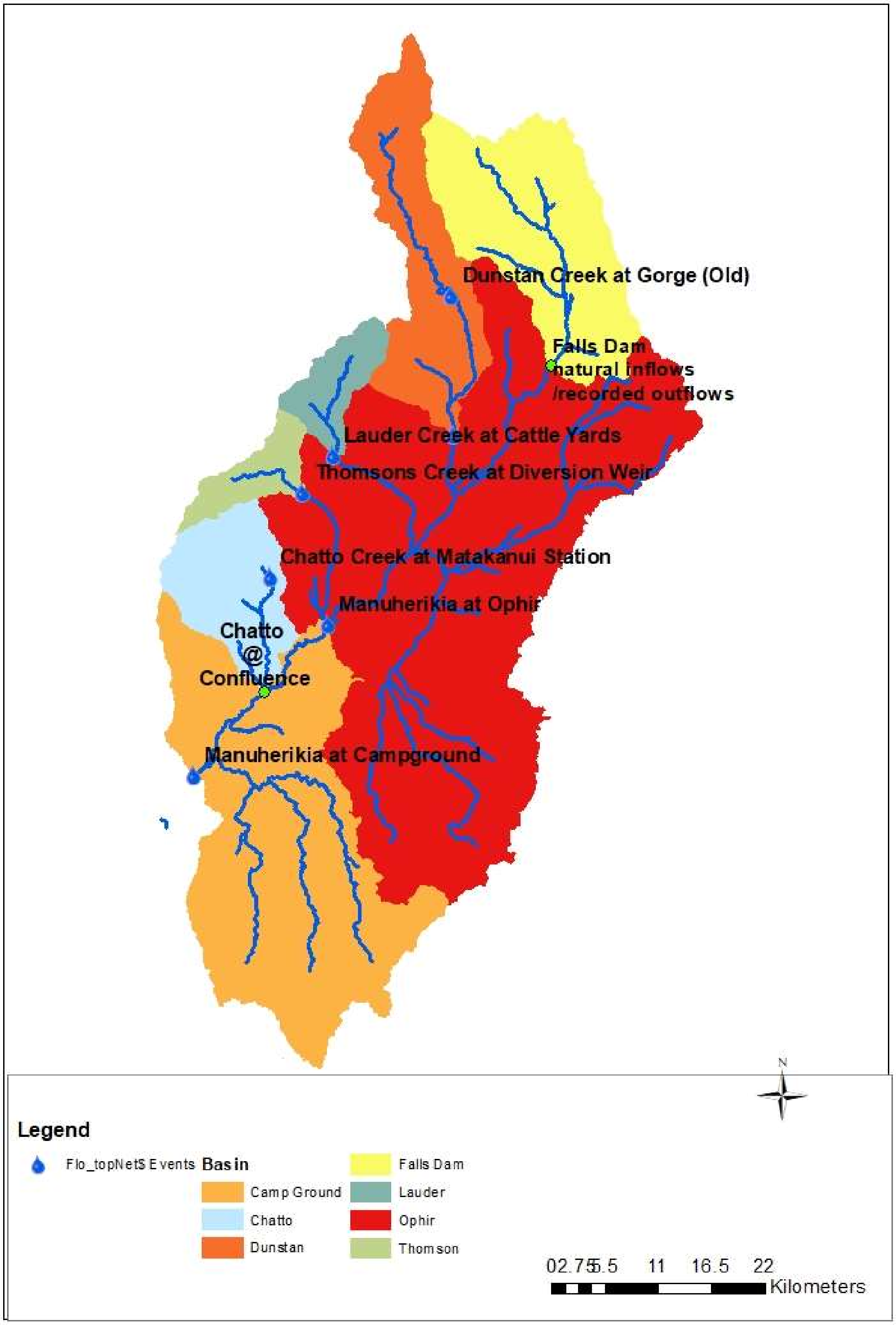


Figure 4-1: Manuherikia surface water catchments. Blue lines represent Strahler 4 streams from the REC 2 coverage.

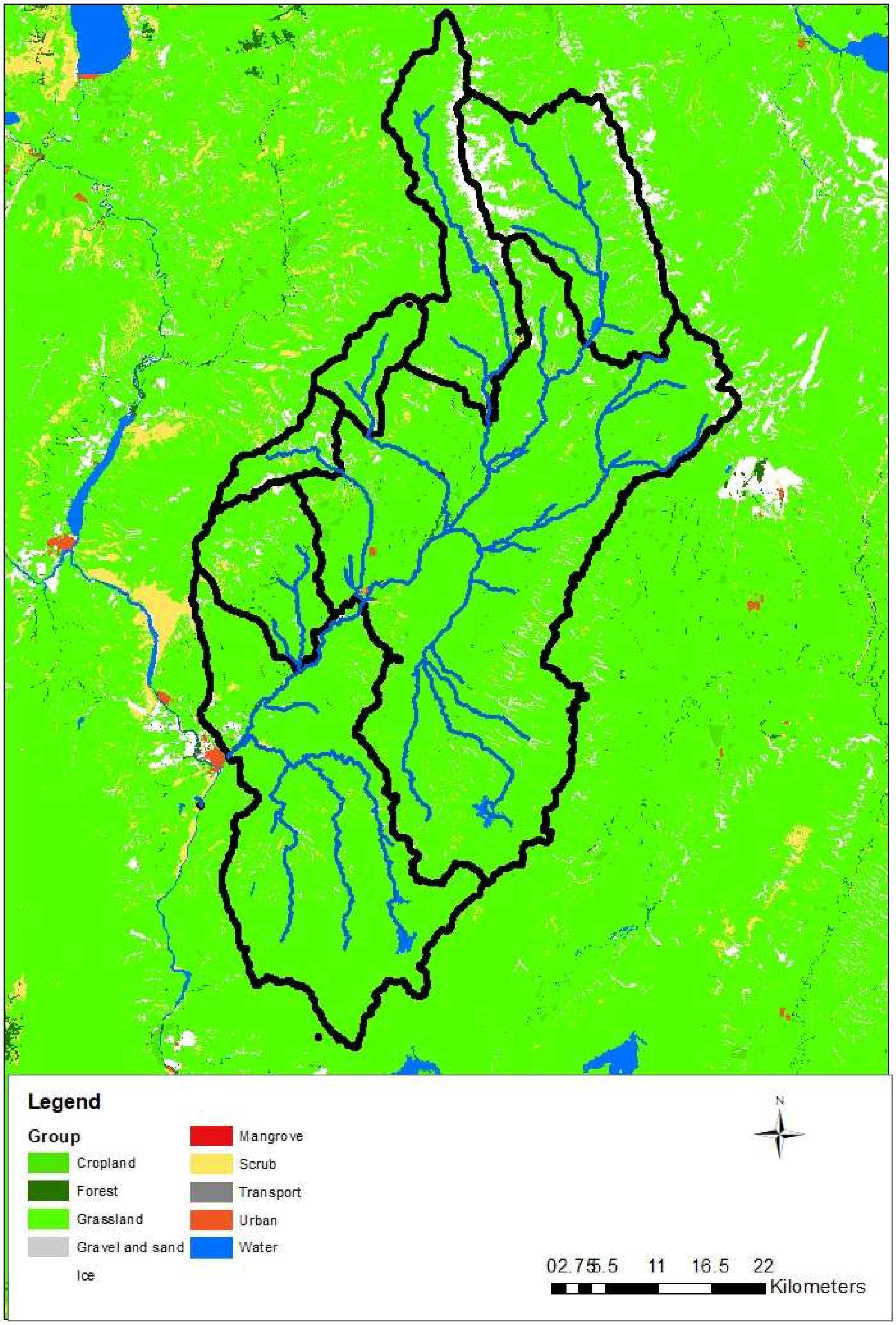


Figure 4-2: Land use in the Manuherekia surface water catchments.

4.3 Climate

Climate information, i.e., precipitation, temperature, relative humidity (rh), solar radiation (srad)-mean sea level pressure (mslp) and wind speed, is available through NIWA's Virtual Climate Station Network (VCSN) (Tait et al. 2006). The VCSN network represents daily interpolated climate information over a regular 0.05 degrees latitude/longitude grid interpolated over nearly 500 climate stations across New Zealand since 1972. Note that a precipitation station will be included in the VCSN record only if the station is included in NIWA's climate database (CliDB). Analysis of CliDB indicates that a limited number of rainfall stations located within the Manuherekia catchment are included in the VCSN "dataset". Figure 4-3 presents the location of the observed precipitation gauges used to derive the daily VCSN precipitation gridded information, while Figure 4-4 presents the location of the observed air temperature gauges used to derive the daily VCSN temperature gridded information.

Figure 4-5 and Figure 4-6 present the long term annual average precipitation and evaporation, as estimated by NIWA. The climate in the focus area is characterised by:

- Annual average rainfall is above 1,200 mm/year in the headwaters of the Falls Dam catchment, decreasing to 350 mm/year at the confluence of the Manuherikia River with the Clutha River / Mata Au.
- Annual evaporation around 700 mm/year along the catchment headwaters, decreasing to 350 mm/year at the confluence of the Manuherikia River with the Clutha River / Mata Au.

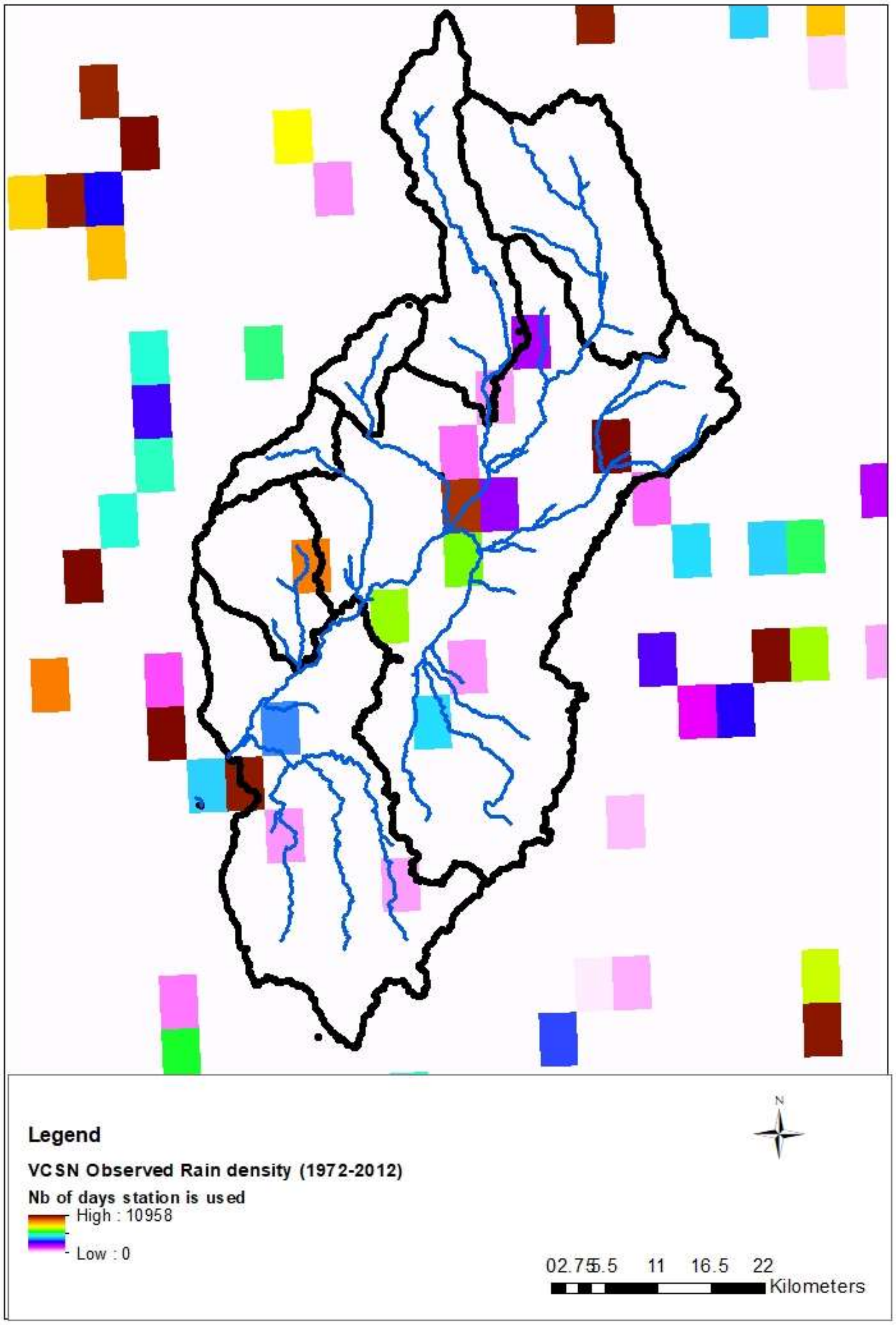


Figure 4-3: Location of the observed precipitation gauges used to derive the daily VCSN precipitation gridded information. The colour scheme represents the number of days (over a 40-year period) that a particular station is used.

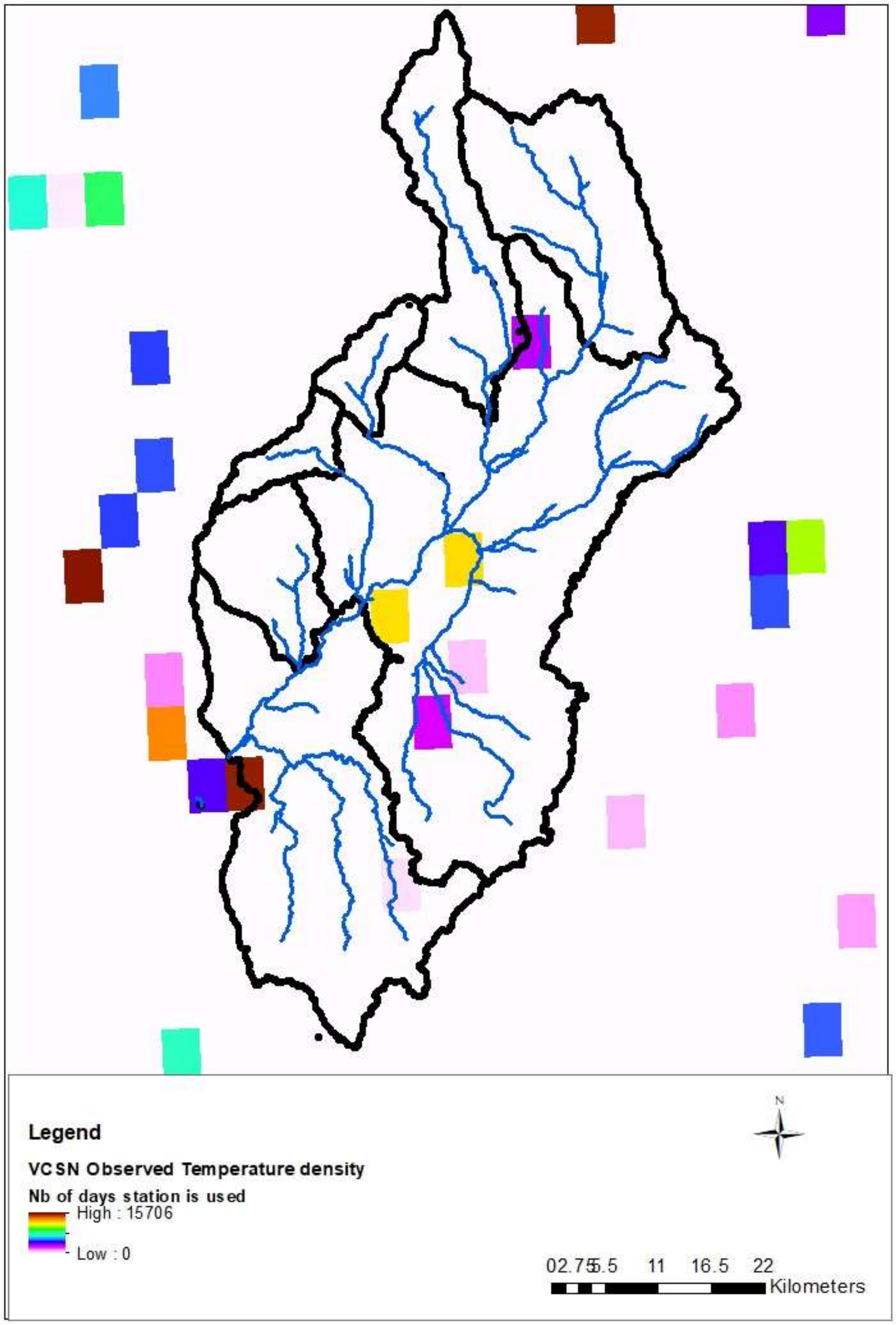


Figure 4-4: Location of the observed temperature gauges used to derive the daily VCSN minimum and maximum temperature gridded information. The colour scheme represents the number of days (over a 40-year period) that a particular station is used.

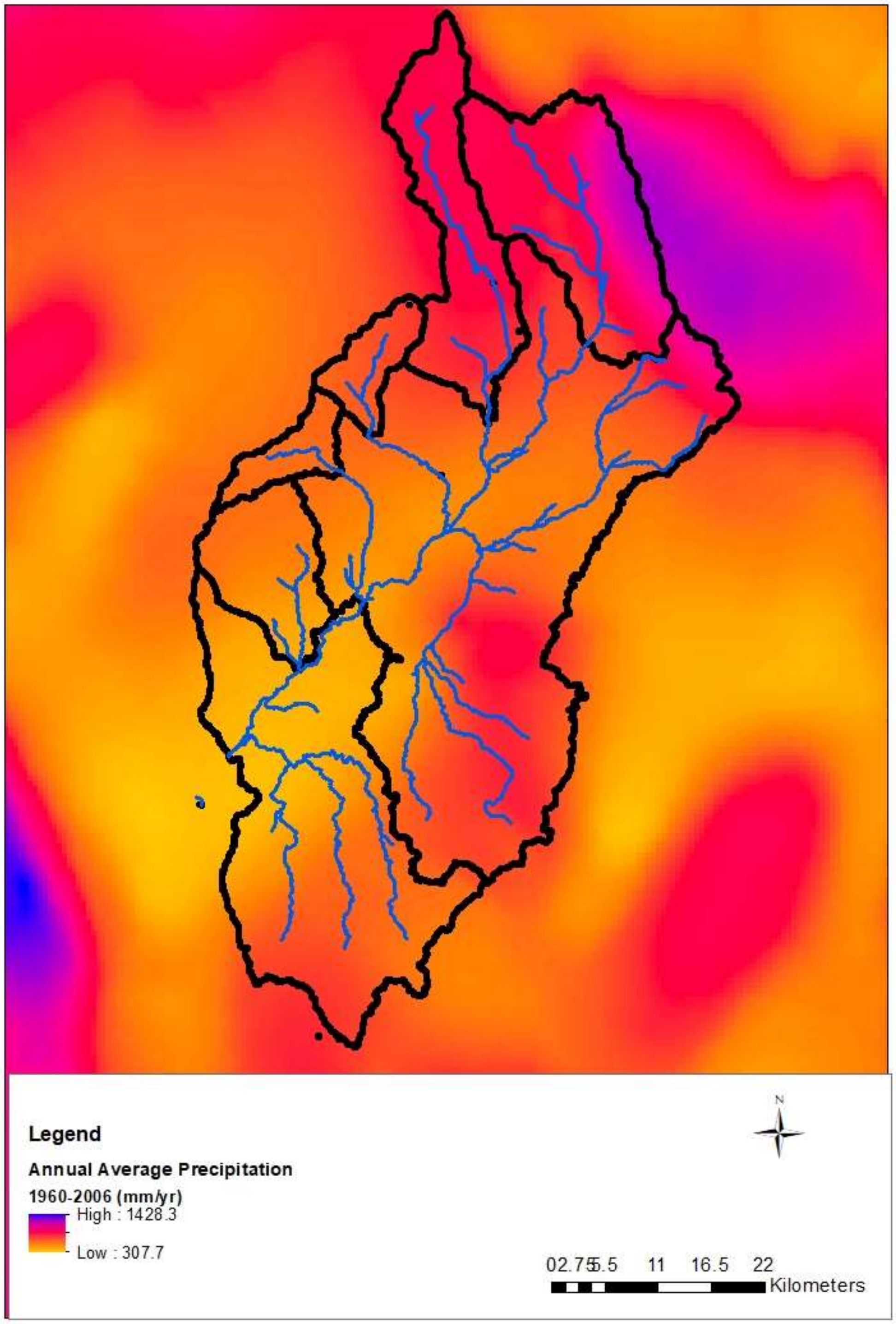


Figure 4-5: Annual precipitation across the period 1966-2006.

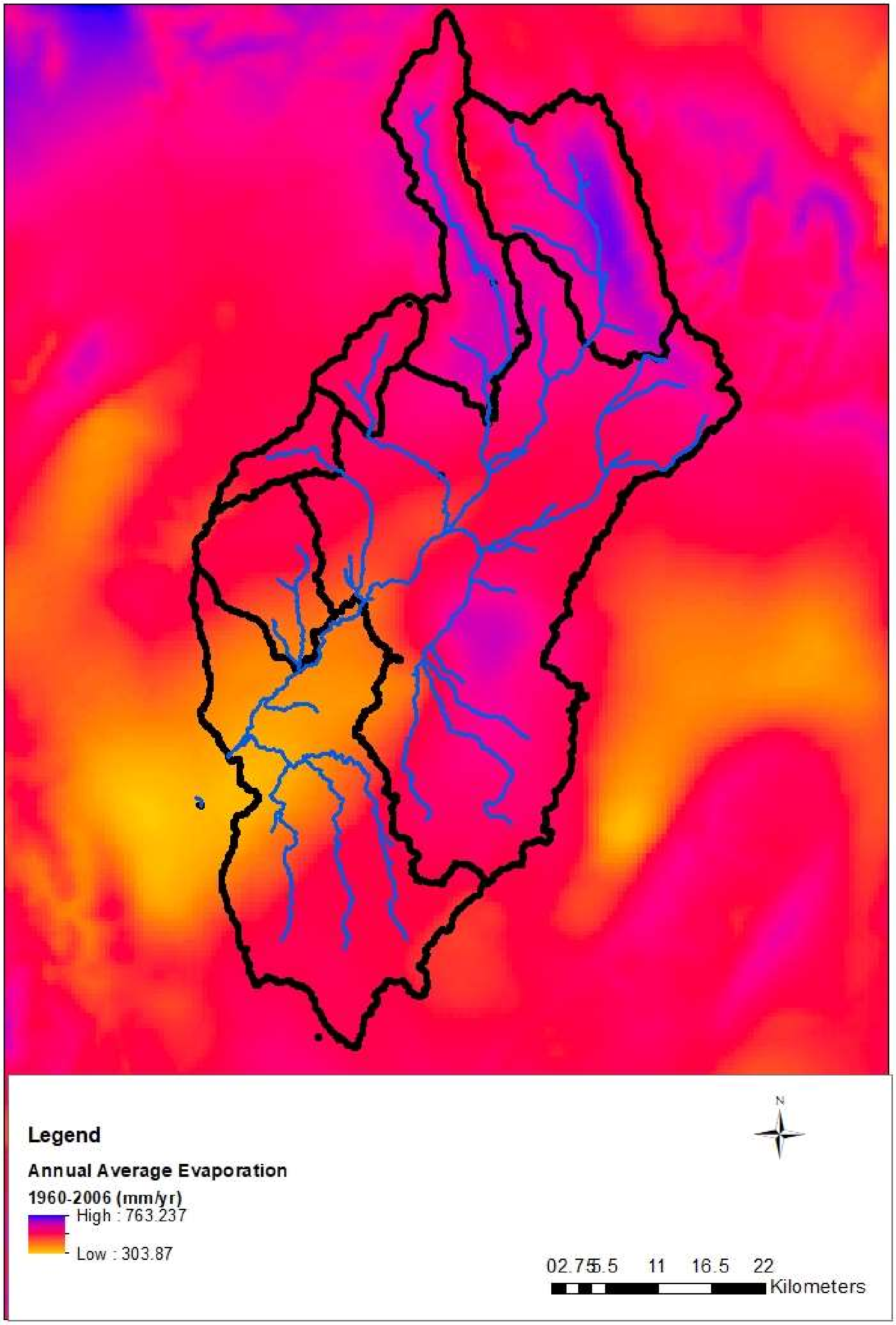


Figure 4-6: Annual evaporation across the period 1966-2006

4.4 Water consenting

In this study, all flow observations were naturalised (see section 3.3)

4.5 TopNet input data and parametrisation

For many applications of TopNet, the estimation of model parameter values requires calibration, usually using measured streamflow. The parameters requiring this type of estimation are generally associated with soil hydraulic properties (hydraulic conductivity and water holding capacity of soils). However, careful review of data quality (e.g., precipitation, temperature and streamflow) is a wise first step, before calibration.

4.5.1 Observed streamflow

For the application presented hereafter TopNet hydrological models were built for the six surface water catchments described in detail below, based on Strahler 1 catchments (typical size 0.5 km^2). The total number of TopNet catchments is 6,467 Strahler 1 catchments. See Figure 4-7 for calibrated catchment layout.

4.5.2 Precipitation

For this project application, daily precipitation was temporally disaggregated to hourly time steps, using a stochastic temporal disaggregation of the precipitation. The precipitation information was bias-corrected using a water balance approach which has been described by Woods et al. (2006).

4.5.3 TopNet parametrisation

There are 31 parameters used in a TopNet model, which represent the physical characteristics of the catchment and are generally assumed not to be subject to temporal variation. These include soil properties, topography, land cover, and channel properties. The derivation of the catchment scale TopNet parameters from nationally available datasets is described in detail in Table 1 of Clark et al. (2008). These catchment scale parameters represent the default parameter values used in the subsequent sections. However, due to the paucity of some spatial information at national scales the following parameters in TopNet are set to a unique default value across New Zealand:

- Surface hydraulic conductivity is set to 0.01 m/s;
- Soil water characteristics (i.e., Clapp and Hornberger c exponent and Green-Ampt wetting front suction) are constant across New Zealand and set to 1.0 and 0.3 respectively;
- Overland flow velocity is set to 0.1 m/s.

The depth of hydraulically active soil and the surface hydraulic conductivity are two of the most sensitive and critical parameters in TopNet. The depth of hydraulically active soil is associated with the characterisation of the hydrograph recession, while the surface hydraulic conductivity is associated with recharge to the groundwater and subsurface flow characterisation. As a result, those parameters are generally calibrated based on streamflow information.

Figure 4-8 to Figure 4-12 present the spatial variation of the soil and vegetation related parameters in TopNet (estimated from nationally available datasets). These are presented to illustrate the spatial variability of the TopNet parameters across the Manuherekia catchment and are not further discussed in this report.

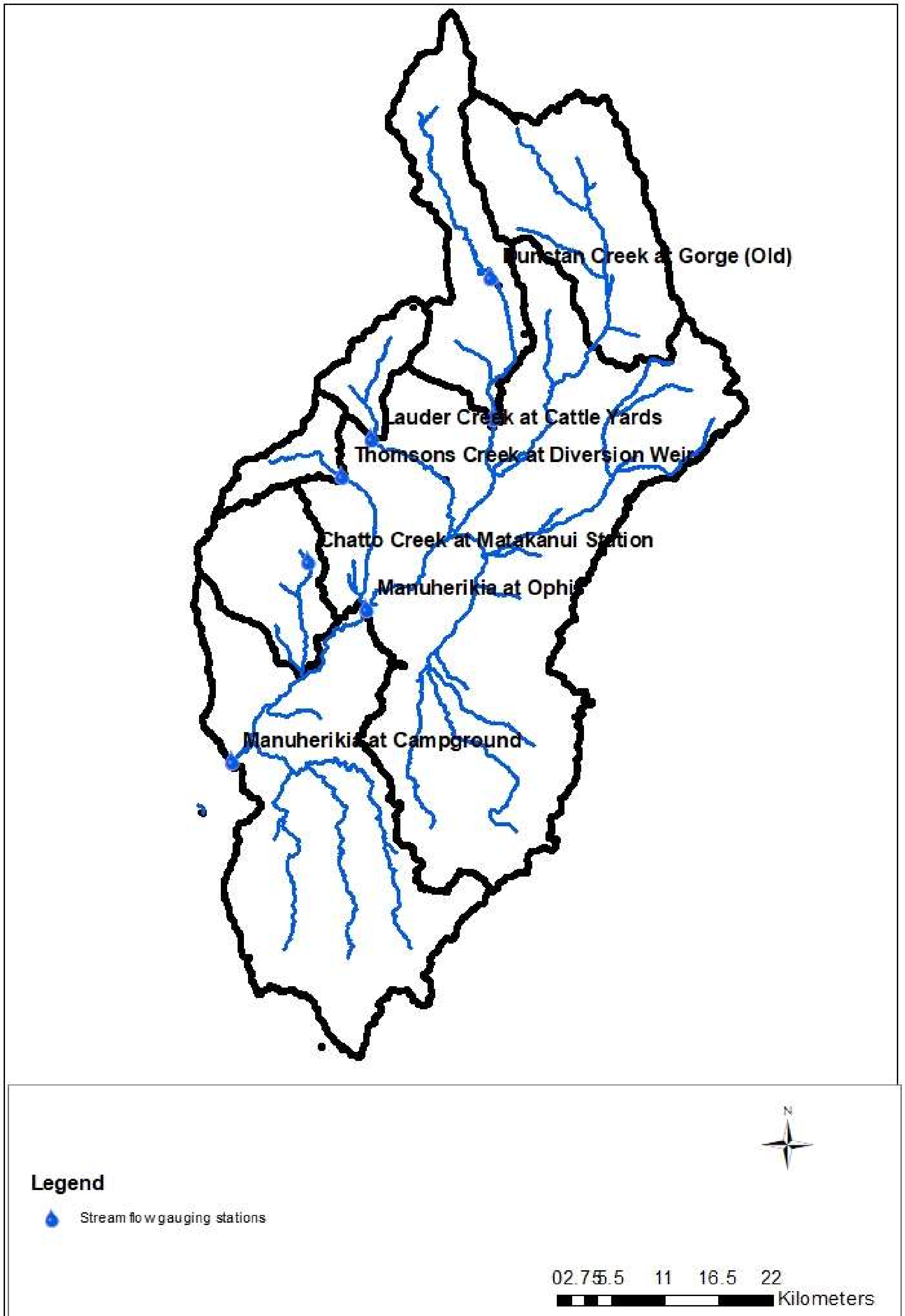


Figure 4-7: Location of the seven calibrated sub-catchments and associated flow station sites Blue drops and site names show the location of the gauging stations.

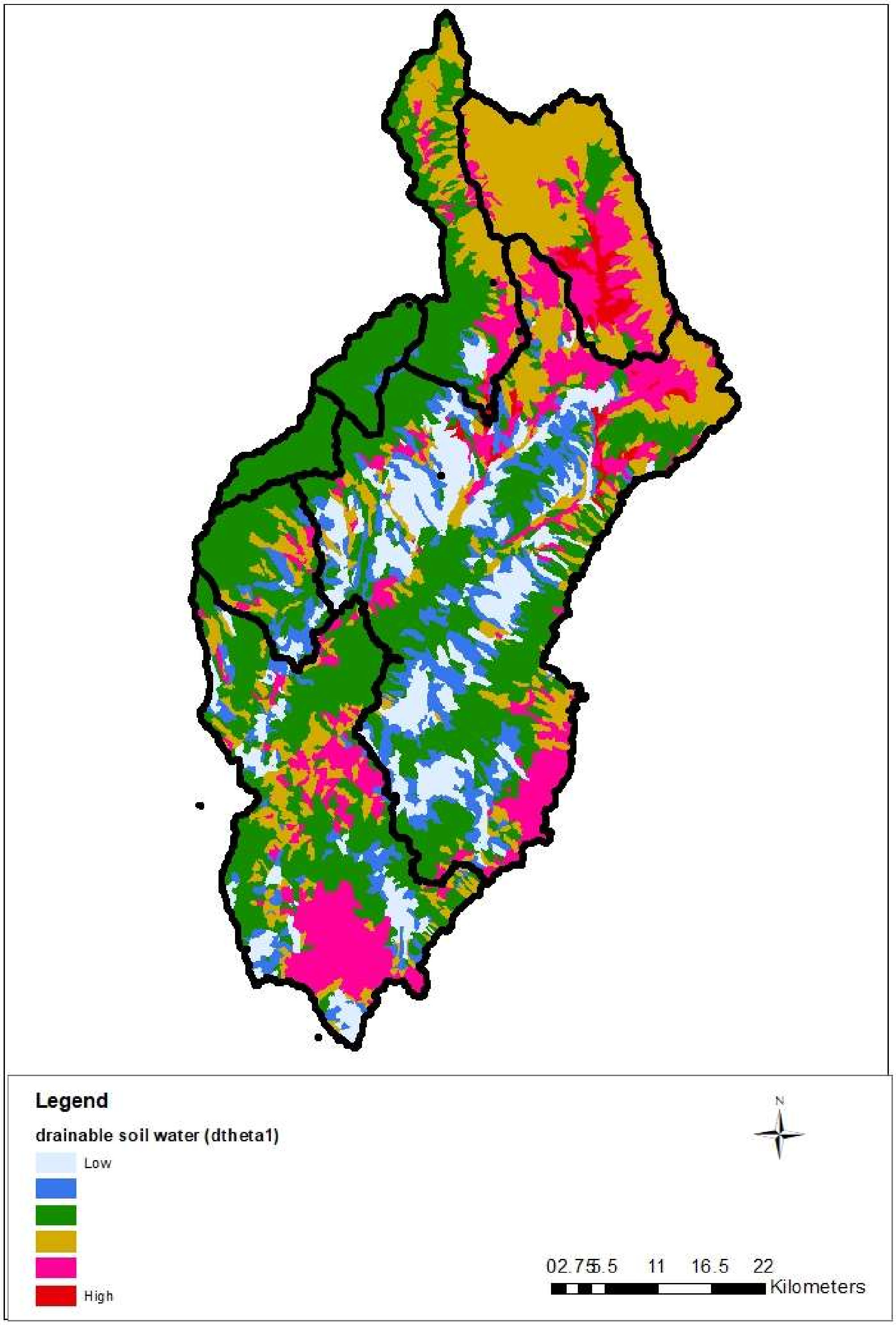


Figure 4-8: Spatial variation of the drainable water (dtheta1) TopNet parameter. Red colour represents high values of the parameter, while blue colour represents low values.

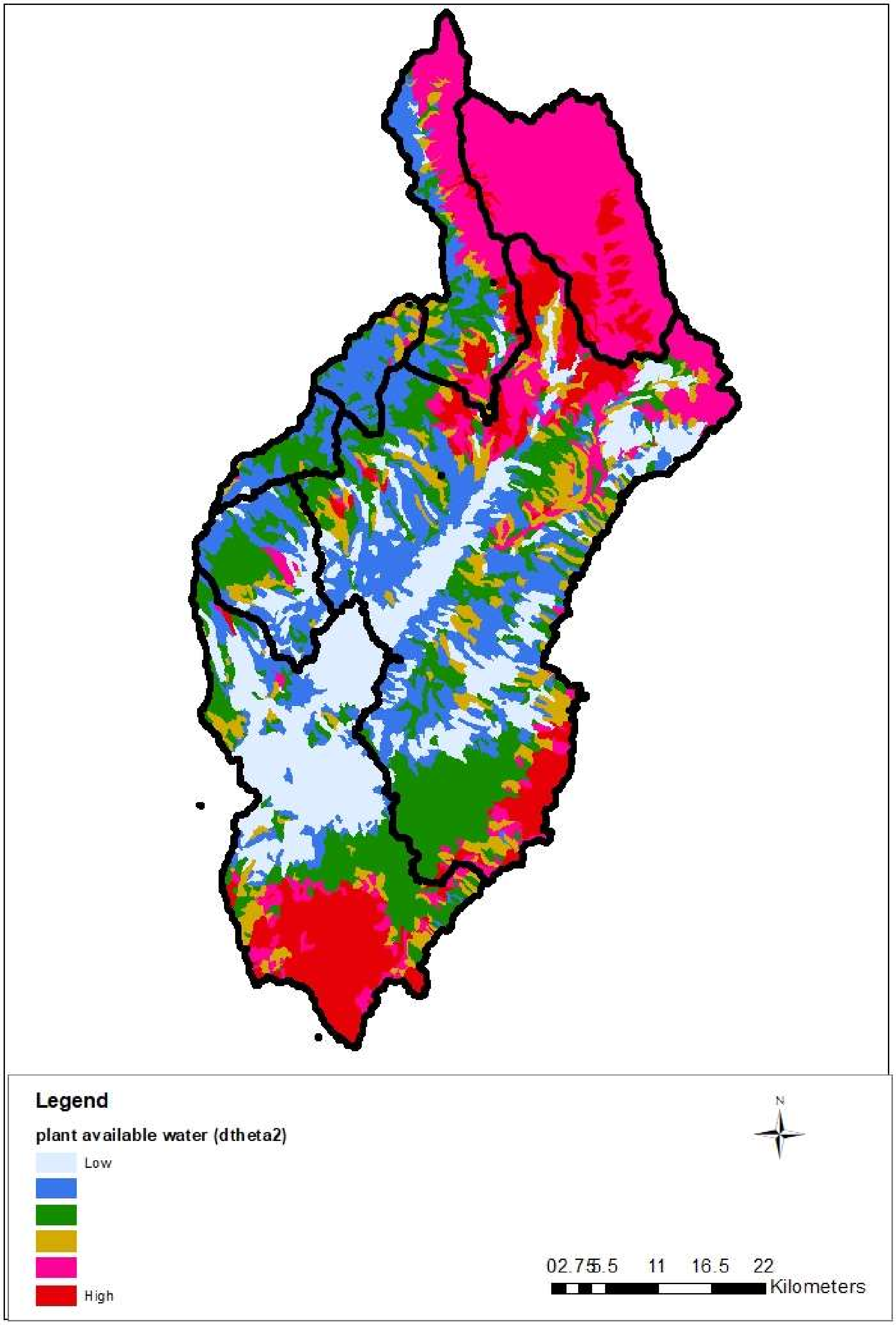


Figure 4-9: Spatial variation of the plant available water (dtheta2) TopNet parameter. Red colour represents high values of the parameter, while blue colour represents low values.

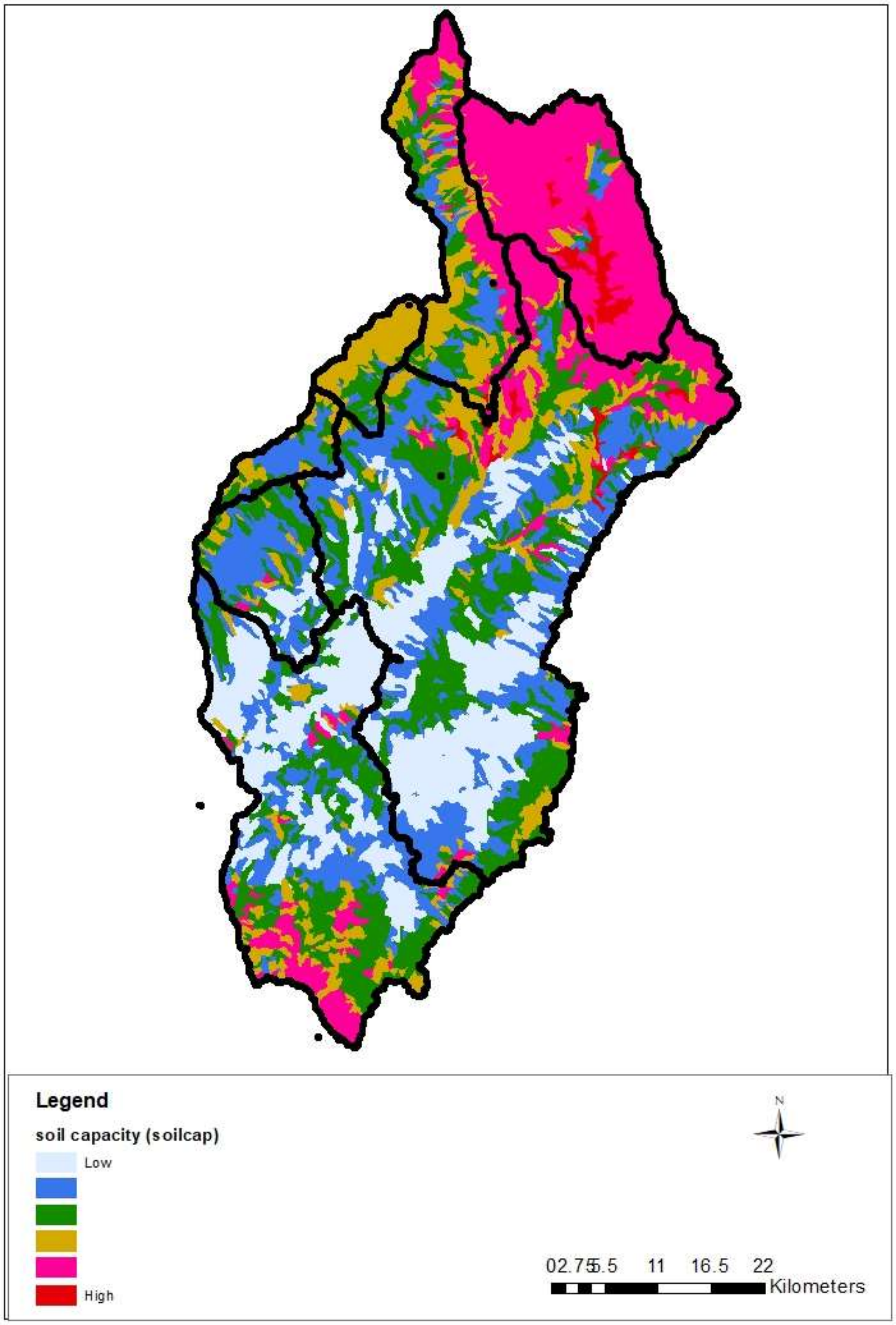


Figure 4-10: Spatial variation of the soil capacity (soilcap), used as a surrogate of the depth of hydraulically active soil in TopNet. Red colour represents high values of the parameter, while blue colour represents low values.

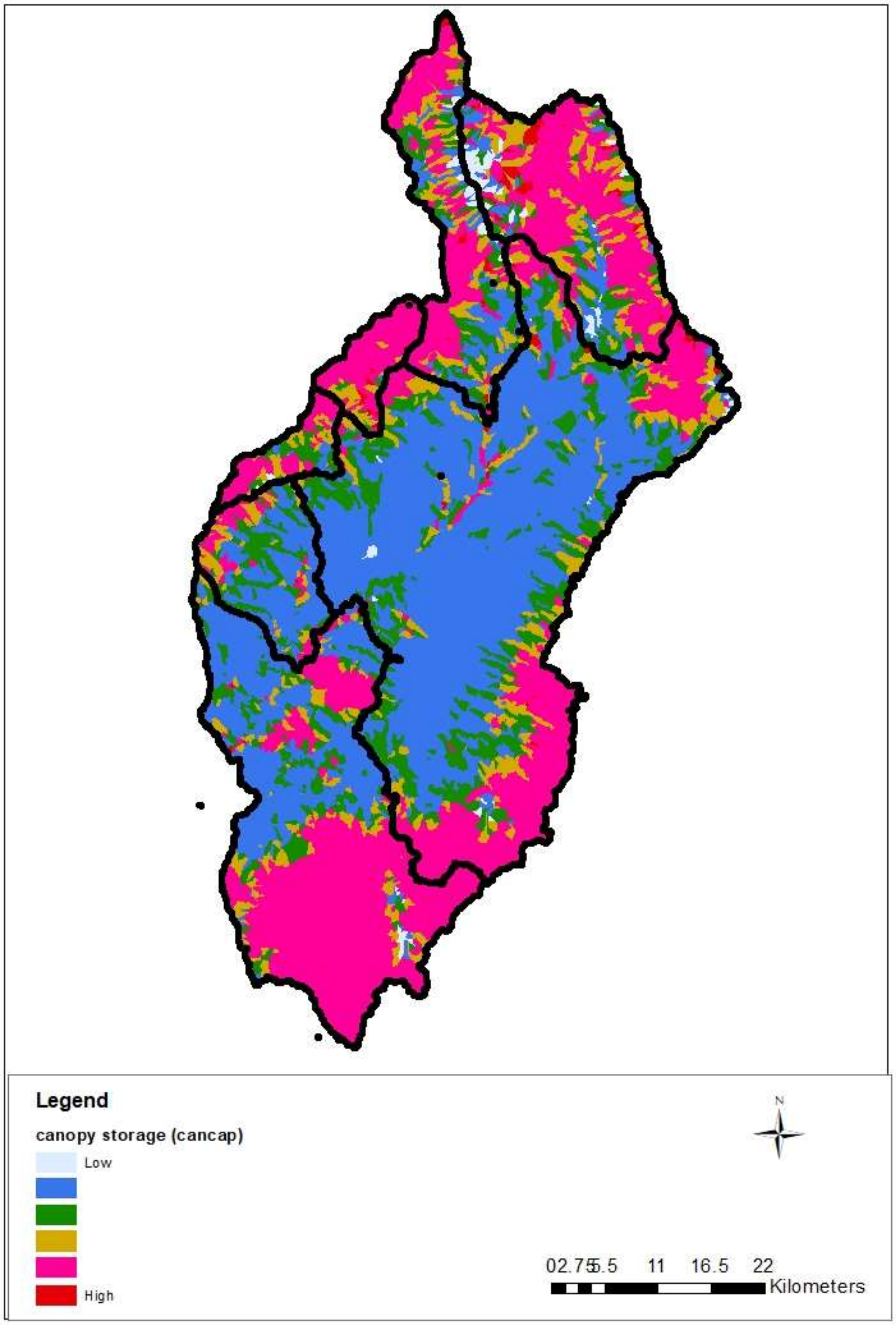


Figure 4-11: Spatial variation of the canopy storage capacity (cancap) TopNet parameter. Red colour represents high values of the parameter, while blue colour represents low values.

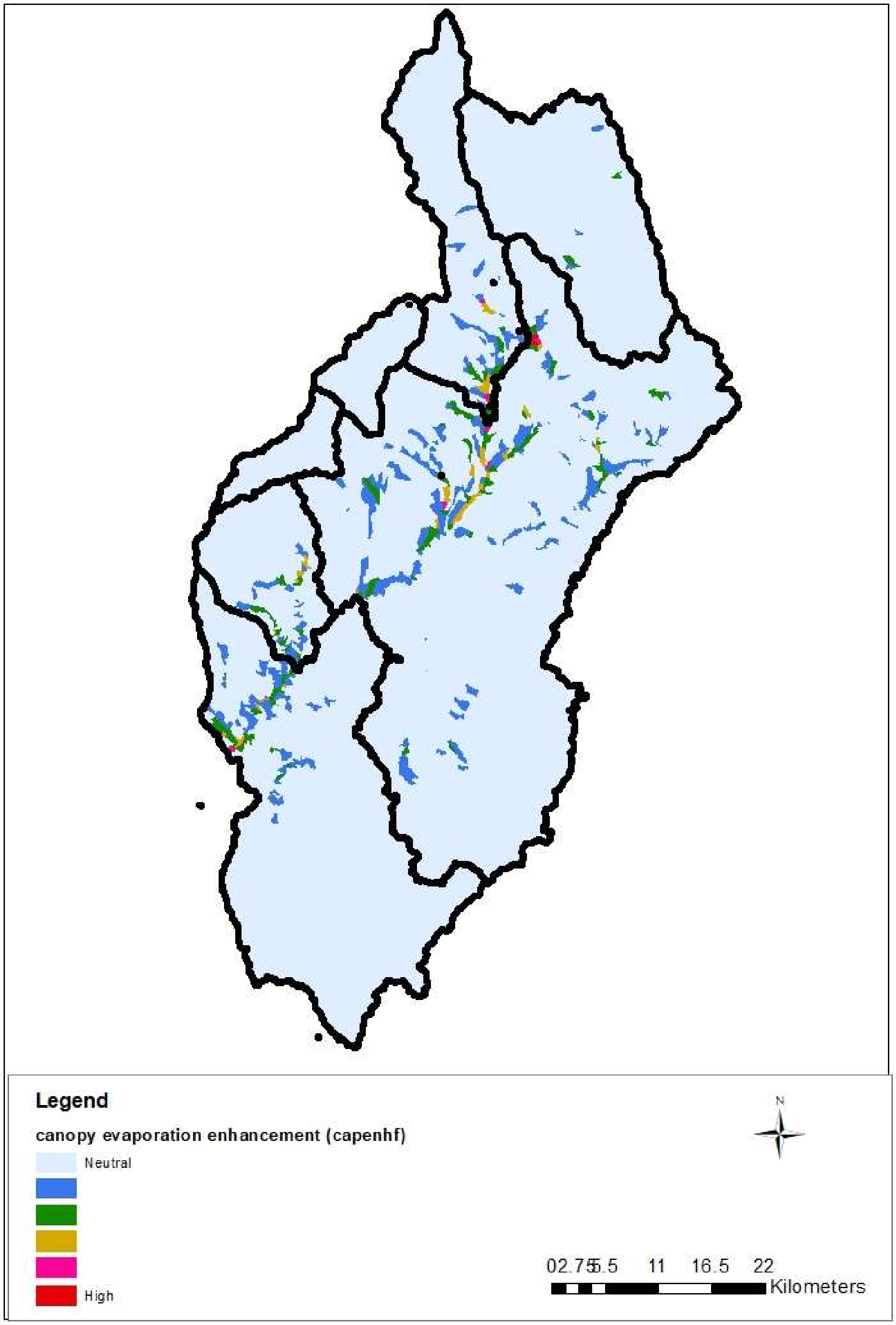


Figure 4-12: Spatial variation of the canopy evaporation enhancement factor (capenhf) TopNet parameter. Red colour represents high values of the parameter, while blue colour represents neutral values.

4.6 Model calibration

4.6.1 Calibration methodology

TopNet calibration requires the calibration of parameter multipliers, as one of the main assumptions of TopNet implementation is that the spatial distribution of the parameters is a-priori determined from catchment physiographic information from the sources described above (referred as default values in Table 4-1 hereafter). TopNet requires the calibration of seven hydrological parameter multipliers and 10 snow related parameters for each sub-catchment. The initial values of the parameter multipliers are set to a value of 1, while snow related parameters are initialised based on previous study results for the area.

Snow related parameters are calibrated separately from hydrological parameters using remote sensing snow cover area information as well as anecdotal information such as the percentage of catchment cover by glacier. Hydrological model optimization was carried out using the Shuffled Complex Evolution Algorithm (SCE-A) (Duan 1992), which is widely used in hydrologic modelling. Table 4-1 presents the usual range of the parameter multipliers used during the calibration process.

Table 4-1: Range of TopNet parameter multipliers used during calibration process.

Parameter name (internal name)	Parameter description	Calibrated range
Hydrological parameters		
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	[0.01-2] * default
Drainable soil water (swater1)	Range between saturation and field capacity	[0.05-10] * default
Plant available soil water (swater2)	Range between field capacity and wilting point	[0.05-10] * default
Hydraulic Conductivity at saturation (hydcond0)		[0.1-10000]*default
Ch_exp	Clapp-hornberger c exponent	[0.05-10] * default
Ga-psif	green-ampt wetting front suction	[0.05-10] * default
canscap	canopy storage capacity	[0.05-10] * default
canenh	canopy evaporation enhancement factor	[0.05-10] * default
Overland flow velocity (overvel)		[0.1-10]*default
Manning n	Characterises the roughness of each reach	[0.1-10] *default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	[0.7-1.5] * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	[0.5-1.5] * default
Snow parameters		

Parameter name (internal name)	Parameter description	Calibrated range
threshold for snow accumulation (th_accm)	Temperature threshold for snow accumulation	270.15-275.15 [K]
Threshold for snow melt (th_melt)	Temperature threshold for snow melt	269.15-274.15 [K]
snowddf	degree-day factor for snow melt	1-10 [mm K-1 day-1]
Minddf	Calendar day of the minimum degree-day-factor day	1-366 [days]
Maxddf	Calendar day of the maximum degree-day-factor day	1-366 [days]
snowamp	easonal amplitude of degree-day factor for snow melt	0-5 mm K-1 day-1]
snowros	addition in melt factor caused by rain-on-snow events	0-5 mm K-1 day-1]
decmelt	decrease in melt due to higher albedo after fresh snow	0-5 mm K-1 day-1]
albdecy	time decay of snow albedo	1-5 days
cv_snow	Subgrid variability representing the distribution of the snow pack across the catchment	0-2 [-]

The calibration period (usually chosen as 2014-2016) has been chosen to represent diverse water resource hydrological conditions (e.g., annual flow below and above the observed mean annual flow/inflows at each of the gauging station) while validation was carried out at daily time steps over the 2017-2018 time period.

The evaluation of the calibration of TopNet models was completed through a combination of performance measures on hourly streamflow and log-transformed streamflow to assess overall model performance, as well as flow duration curves (observed and predicted) to assess the accuracy of the statistical distribution of streamflow throughout the time period considered. Due to the aim of the project, the TopNet models were calibrated mainly based on log-transformed streamflow with the aim of better representing low flow conditions. In addition, further care was taken to ensure that the model parameters remained between physically reasonable limits. To further represent accurately low flow conditions, calibration was carried out only during low flow periods.

The accuracy of the calibration/validation process is estimated using the following hydrological criteria and statistics:

- The accuracy of the calibration process is estimated in terms of the Nash-Sutcliffe efficiency coefficient calculated on the discharge (NS) and on the logarithm of the discharge (NS Log). The NS score represents a measure of the residual variance versus the data variance. A NS score of 1 indicates that the calibration perfectly mimics the observations in time and volume. A negative NS score indicates that the average of the observation is a better predictor than the model flow. The NS score represents the ability of the model to mimic the observations during high flow periods, while the NS Log score represents the ability of the model to mimic the observations during low flow periods. Based on the objective of the model, the main objective function was chosen to be the NS Log score. Table 4-2 provides a qualitative description of the quality of the calibration result based on the value of the Ns or NS Log score.

- Total water balance of the upstream catchment presented as annual average precipitation, evaporation and discharge at the gauging station over the period of simulation.
- Comparison of the hourly observed and predicted flow duration curve (to identify potential mismatches in the statistical distribution of the flows) and cumulative flow (to identify potential issues related to systematic bias in the calibration process).
- Validation of the model prediction carried out at daily time steps over the period 2017-2018.

The simulation results over the whole period of simulation (2014-2018) and associated analysis is presented hereafter for each catchment.

Table 4-2: Classification of Nash-Sutcliffe scores obtained using TopNet.

NS/NSLog score	Classification
NS <0.4	Poor
0.4< NS < 0.6	Adequate
0.6 < NS < 0.8	Good
NS > 0.8	Excellent

4.6.2 Dunstan Creek at Beattie Road

Calibration was done using the complete flow range. Rain inputs were adjusted to give a satisfactory water balance.

Table 4-3 shows the water balance for the Dunstan Creek at Beattie Road. Figure 4-13 shows the hydrograph, cumulative flow plot and flow duration curve for Dunstan Creek at Beattie Road.

Table 4-3: Annual average water balance for Dunstan Creek at Beattie Road. Over the simulation period (2014-2018).

Annual average precipitation (mm/yr)	Annual average evaporation (mm/yr)	Annual average runoff (mm/yr)
1,041	411	554

Analysis of the simulations indicates that:

- The calibrated model is able to reasonably represent low flow hydrological behaviour (timing and amount) across the period of simulation.
- Timing and magnitude of the absolute minimum hourly flows over the period of simulation is reasonably reproduced by the calibrated model.

- The calibrated model produces a water balance error due to an overestimation of high low peak events.

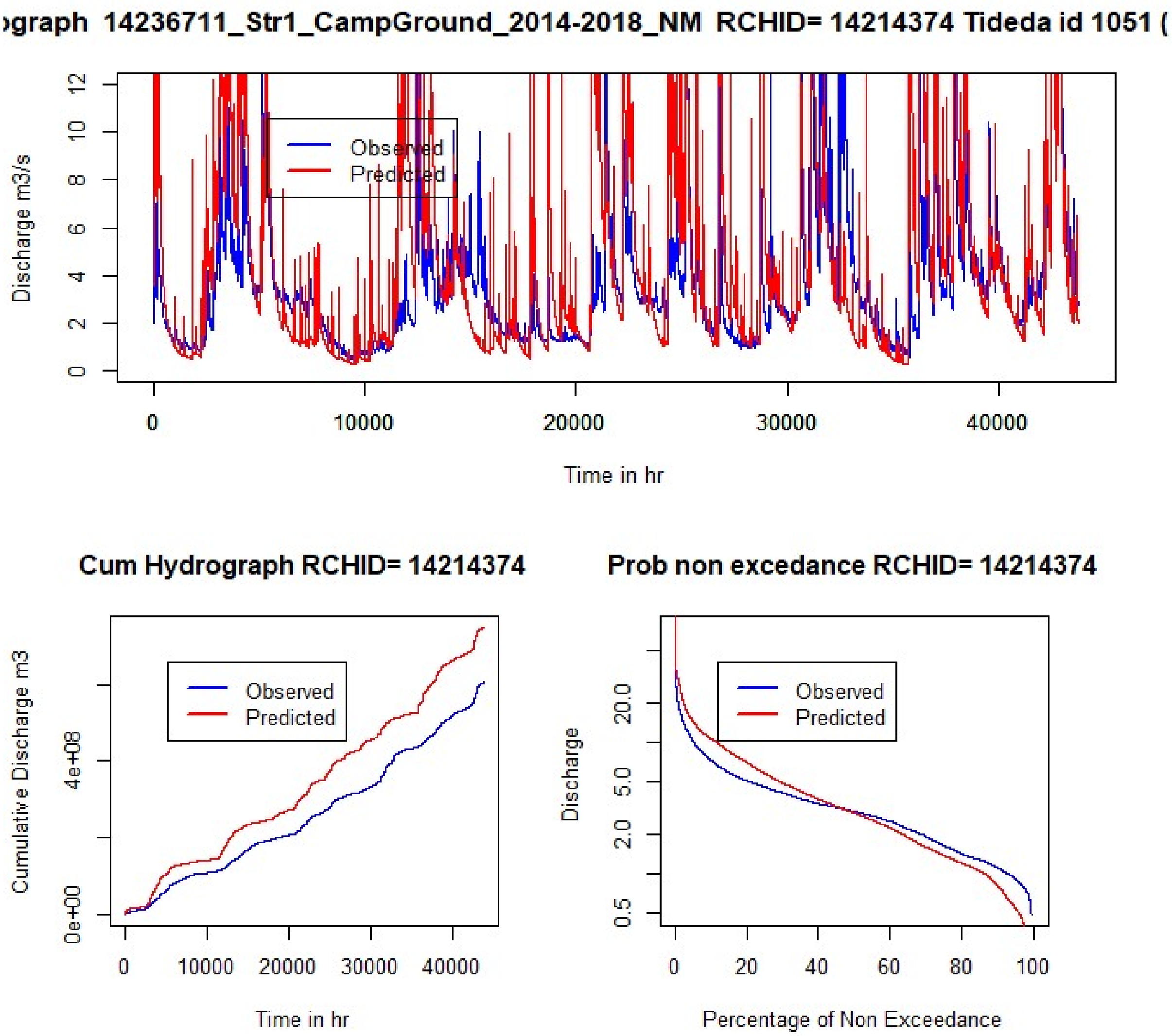


Figure 4-13: Hydrograph and flow duration for natural flow and modelled flow for Dunstan Creek at Beattie Road. Blue shows observed and red modelled.

4.6.3 Lauder Creek at Cattle Yards

Calibration was done using the flows less than 400 L/s after springs removed and an assumed spring flow of 200 L/s. Rain inputs were adjusted to give a satisfactory water balance.

Table 4-4 shows the water balance for the Lauder Creek at Cattle Yards. Figure 4-14 shows the hydrograph, cumulative flow plot and flow duration curve for Dunstan Creek at Beattie Road.

Table 4-4: Annual average water balance for Lauder Creek at Cattle Yards. Over the simulation period (2014-2018).

Annual average precipitation (mm/yr)	Annual average evaporation (mm/yr)	Annual average runoff (mm/yr)
871	350	449

Analysis of the simulation indicates that:

- The calibrated model is able to represent (timing and magnitude) two of the three low flow events available for model calibration.
- The hydrological model is largely underestimating the discharge and the shape of the recession over summer 2017-2018.

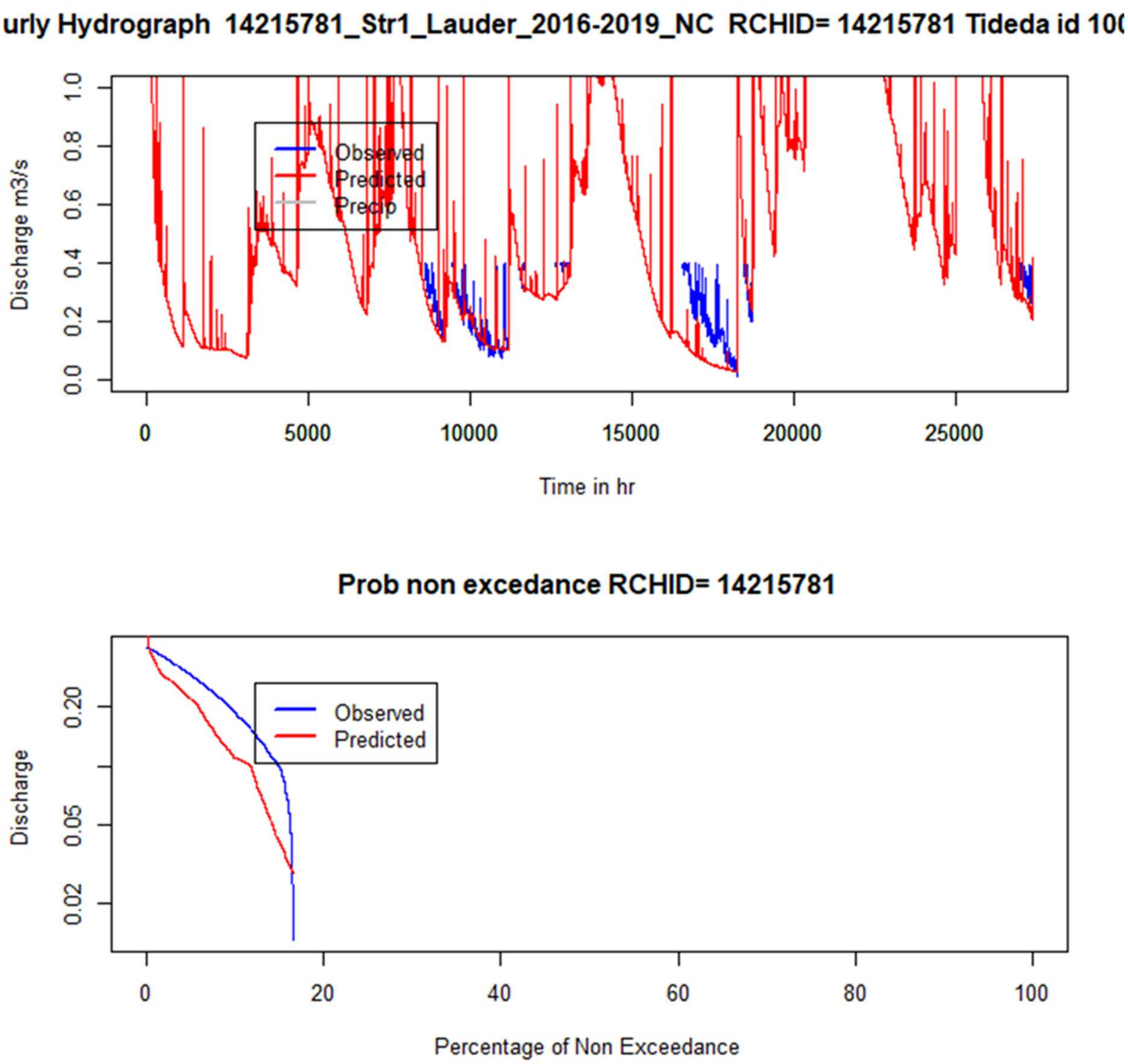


Figure 4-14: Hydrograph and flow duration for natural flow and modelled flow for Lauder Creek at Cattle Yards. Blue shows observed and red, modelled.

4.6.4 Thomsons Creek at Weir

Calibration was done using the flows less than 300 L/s after springs removed and an assumed spring flow of 100 L/s. Rain inputs were adjusted to give a satisfactory water balance.

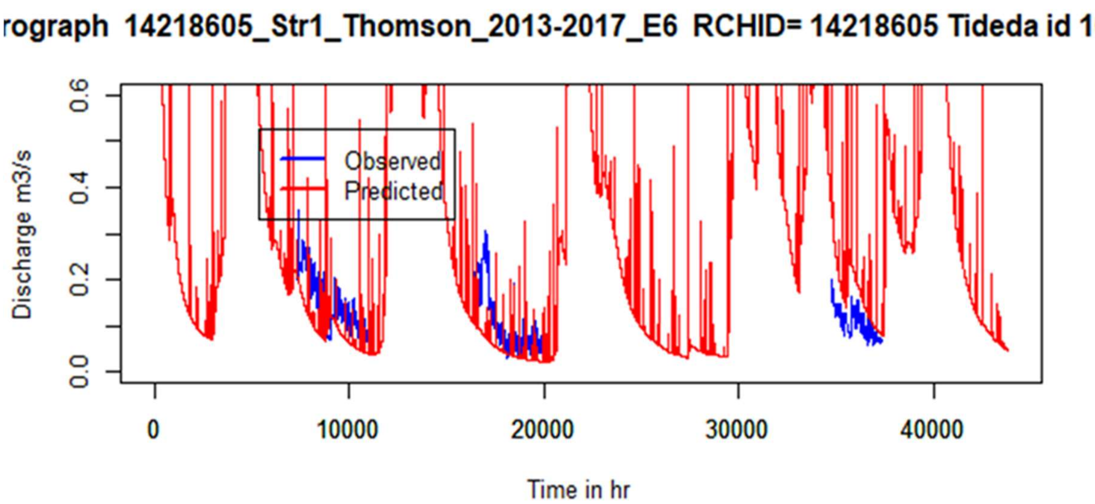
Table 4-5 shows the water balance for the Thomsons Creek catchment. Figure 4-15 shows the hydrograph, cumulative flow plot and flow duration curve for Thomson Creek at Weir.

Table 4-5: Annual average water balance for Thomsons Creek at Weir. Over the simulation period (2014 - 2018).

Annual average precipitation (mm/yr)	Annual average evaporation (mm/yr)	Annual average runoff (mm/yr)
661	303	310

Analysis of the simulation indicates that:

- The calibrated model is able to mimic the timing of the three low flow events available for calibration.
- Low flows are underestimated in quantity during summer 2013-2014 and 2014-2015 while overestimated during summer 2016-2017.



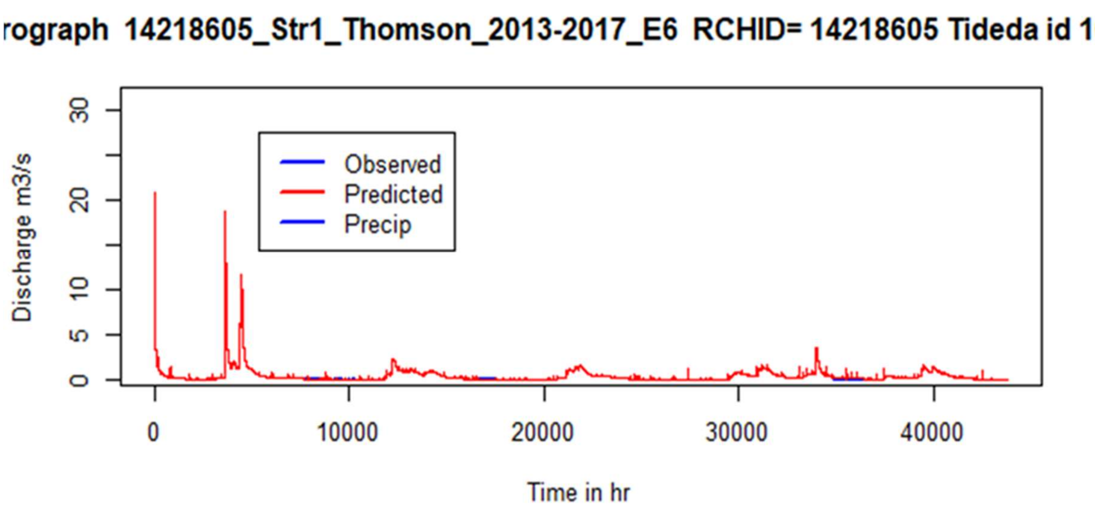


Figure 4-15: Hydrograph and flow duration for natural flow and modelled flow for Thomsons Creek at Weir. Blue shows observed and red, modelled.

4.6.5 Chatto Creek at Confluence

Calibration was done using flow less than 1,500 L/s. Rain inputs were adjusted to give a satisfactory water balance.

Table 4-6 shows the water balance for the Chatto catchment. Figure 4-16 shows the hydrograph, cumulative flow plot and flow duration curve for Chatto Creek at Confluence.

Table 4-6: Annual average water balance for Chatto Creek at Confluence. Over the simulation period (2014-2018).

Annual average precipitation (mm/yr)	Annual average evaporation (mm/yr)	Annual average runoff (mm/yr)
540	287	223

Analysis of the simulation indicates that:

- Only two summer recessions are available for model calibration.
- Timing and magnitude of the low flow events are reproduced adequately by the model, however, the hydrological model over estimates the February 2018 recession.
- Low flows were experienced by the catchment during winter 2018.

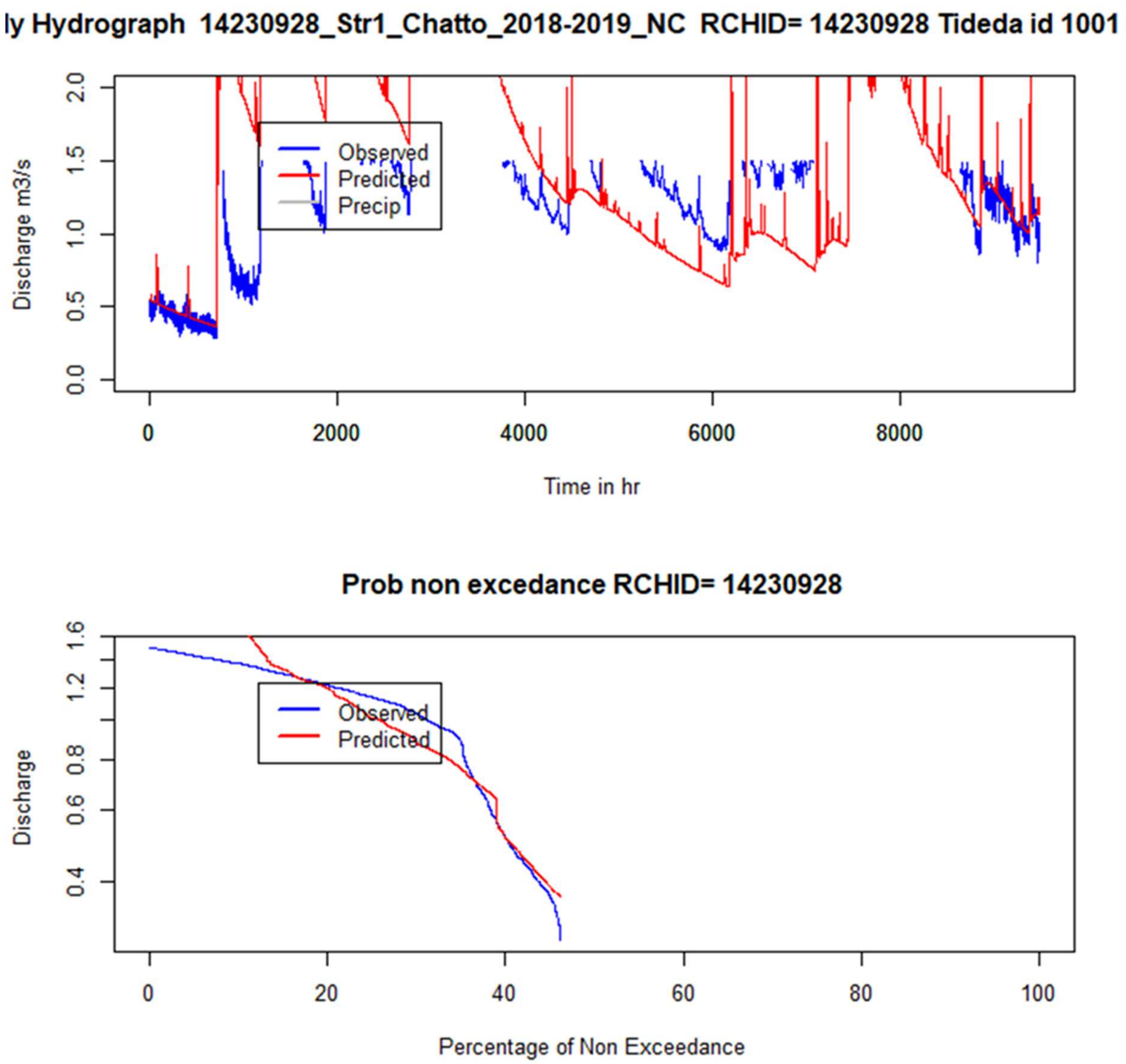


Figure 4-16: Hydrograph and flow duration for natural flow and modelled flow for Thomsons at Weir. Blue shows observed and red, modelled.

4.6.6 Manuherekia River at Ophir

The Manuherekia River at Ophir calibration did not run to a conclusion, so we have adopted the parameters of the national model and adjusted the rain inputs to enable a satisfactory water balance. This model can be revisited when the natural flow series are verified.

Table 4-7 shows the water balance for the Manuherekia at Ophir with the main stem adjustments described in Table 3-1. Figure 4-17 and Figure 4-18 show the hydrograph, cumulative flow plot and flow duration curve for Manuherekia at Ophir.

Analysis of the simulation indicates that:

- Uncalibrated model (corrected for water balance bias at Ophir) is able to represent the dynamic of low flow events.
- Timing and magnitude of the low flow events are reproduced adequately by the model, however the hydrological model over estimates the 2015-2016 and 2016-2017 recessions.
- Water balance error at Ophir is linked with the overestimation of the high flows (i.e., flows above Q50), as demonstrated by the analysis of the flow duration curve.

Table 4-7: Annual average water balance for Manuherekia River at Ophir. Over the simulation period (2014-2018).

Annual average precipitation (mm/yr)	Annual average evaporation (mm/yr)	Annual average runoff (mm/yr)
773	391	338

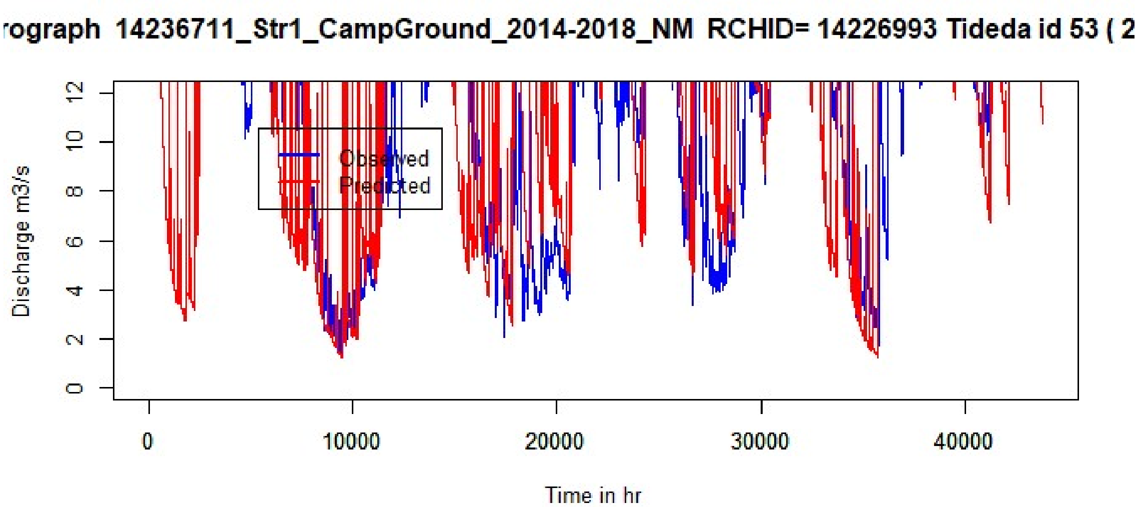


Figure 4-17: Hydrograph for Manuherekia at Ophir. Blue shows observed (adjusted simulated) flows and red, modelled.

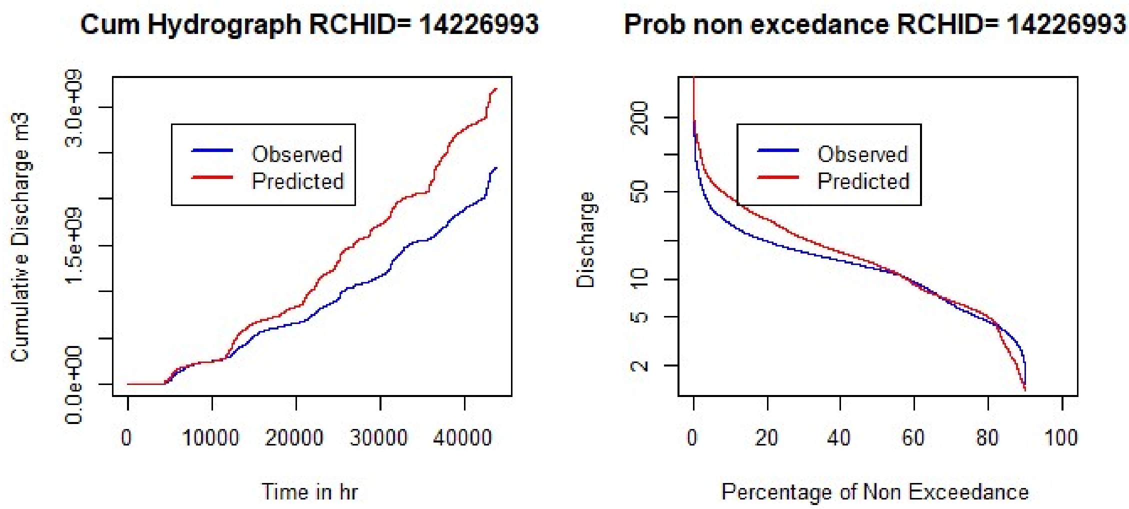


Figure 4-18: Accumulated flow and flow duration curves for Manuherekia at Ophir. Blue shows observed (adjusted simulated) flows and red, modelled.

4.6.7 Manuherekia at Campground

The Manuherekia River at Campground calibration did not run to a conclusion, so we have adopted the parameters of the national model and adjusted the rain inputs to enable a satisfactory water balance. This model can be revisited when the natural flow series are verified.

Figure 4-19 and Figure 4-20 show the fit between model and simulated natural flows both with and without the adjustments described in Table 3-1. Table 4-8 shows the catchment water balance.

Table 4-8: Annual average water balance for Manuherekia River at Campground. Over the simulation period (2014 - 2018).

Annual average precipitation (mm/yr)	Annual average evaporation (mm/yr)	Annual average runoff (mm/yr)
692	363	286

Analysis of the simulation indicates that:

- Uncalibrated model (corrected for water balance bias at Ophir and Camp Ground) is able to represent the dynamic of low flow events.
- Timing and magnitude of the low flow events are reproduced adequately by the model, however the hydrological model over estimates the 2015-2016 and 2016-2017 recessions.
- Water balance error at Campground is linked with the overestimation of the high flows (i.e., flows above Q50), as demonstrated by the analysis of the flow duration curve.

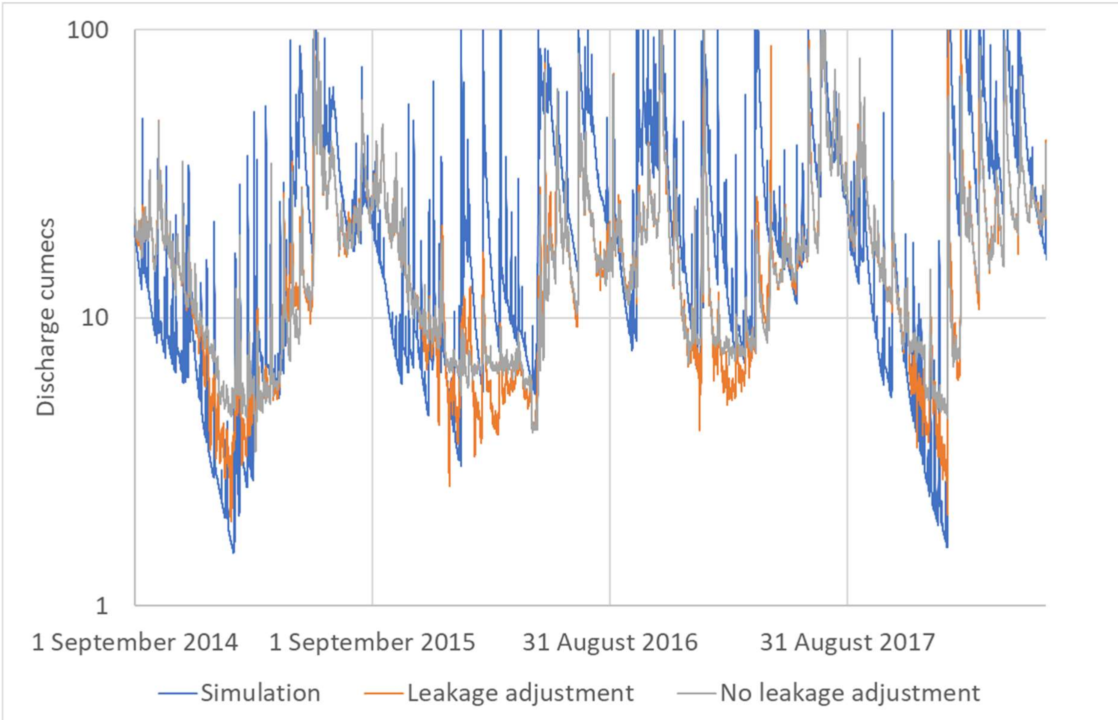


Figure 4-19: Hydrograph for Manuherekia at Campground. Blue shows modelled, and orange and grey, simulated natural with adjustments for leakage and no adjustments, respectively.

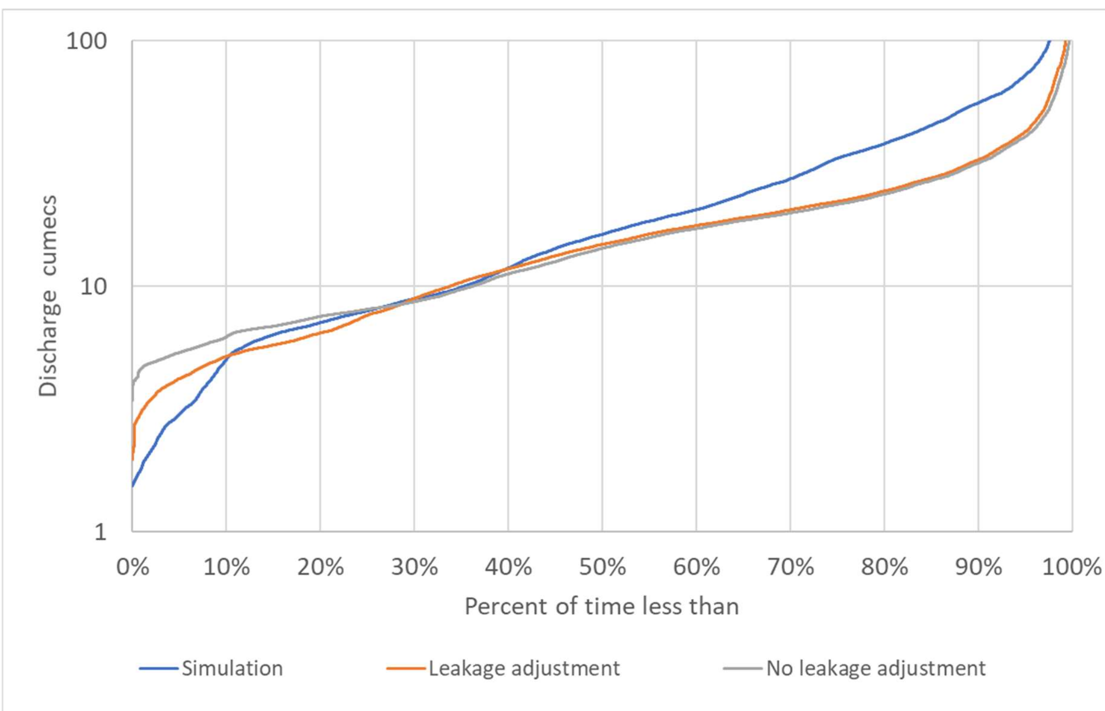


Figure 4-20: Flow duration curve for Manuherekia at Campground. Blue shows modelled, and orange and grey, simulated natural with adjustments for leakage and no adjustments, respectively.

4.7 TopNet natural flows

The final product of the TopNet calibration and running process is an hourly time series of simulated natural flow at very reach in the Manuherekia catchment from 1973 to 2018. For input to CHES, these data are aggregated to daily averages, and for the current project we only deal with reaches that are on the main stem of the river or join directly to that.

Because the calibrations have focussed on the low flow behaviour of the river, the full time series does not always represent an accurate picture of total water resource. This is evident in Table 4-9 and Figure 4-21 where the derived mean flow and 7-day MALF are compared with the measured values where possible.

Table 4-9: Mean and low flows from TopNet model and naturalised data.

	Mean Flow (m^3/s)			MALF (m^3/s)		
Site	TopNet 1974-2018	TopNet 2014-2018	Measured data	TopNet 1974-2018	TopNet 2014-2018	Measured data
Lauder Creek	1.80	1.50	1.67	0.23	0.16	0.36
Thomsons Creek	1.27	1.07	1.26	0.18	0.12	0.33
Chatto Creek	1.37	1.17	1.42	0.21	0.14	0.58
Dunstan Creek	6.09	4.88	3.85	0.85	0.59	0.89
Falls Dam	9.49	8.37	4.88	1.61	1.19	1.09
Blackstone IC	10.72	9.26		1.61	1.19	
Omakau IC	10.85	9.35		1.63	1.20	
Ophir	26.12	22.54	15.61	4.07	2.87	4.50
Manuherikia IC	26.19	22.61		4.08	2.88	
Galloway IC	27.81	24.02		4.37	3.06	
Campground	30.75	27.14	19.50	5.08	3.53	5.50

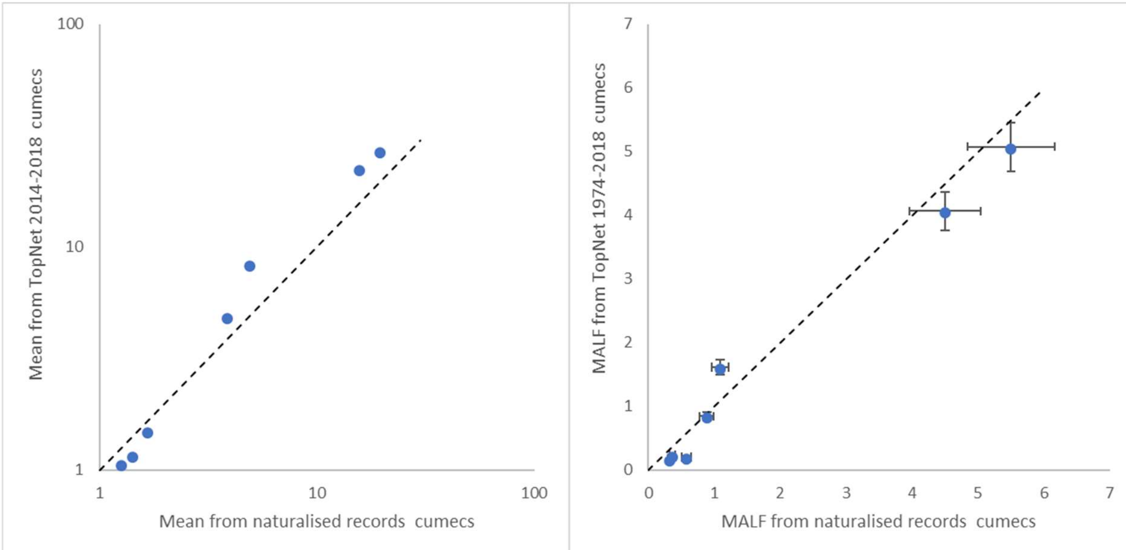


Figure 4-21: Comparison of modelled and naturalised mean and MALF flows. Mean flow axes are logged. Main stem flows above the low flow range (that is out of the calibration range) are overestimated by the TopNet model, but the fit to the estimated MALF values is very good.

Figure 4-22 shows the accumulated area downstream of the most upstream intake of the Mt Ida Race down to the confluence with the Clutha River / Mata Au, and the MALF values estimated from TopNet at various locations. The high yield of the upper catchment during low flows is evident, with a significant decline along the river. The step change after the Ida Burn confluence is evidence of the low yield of that catchment. Below that the north bank tributaries such as Lauder Creek and Thomsons Creek contribute slightly to an increased yield.

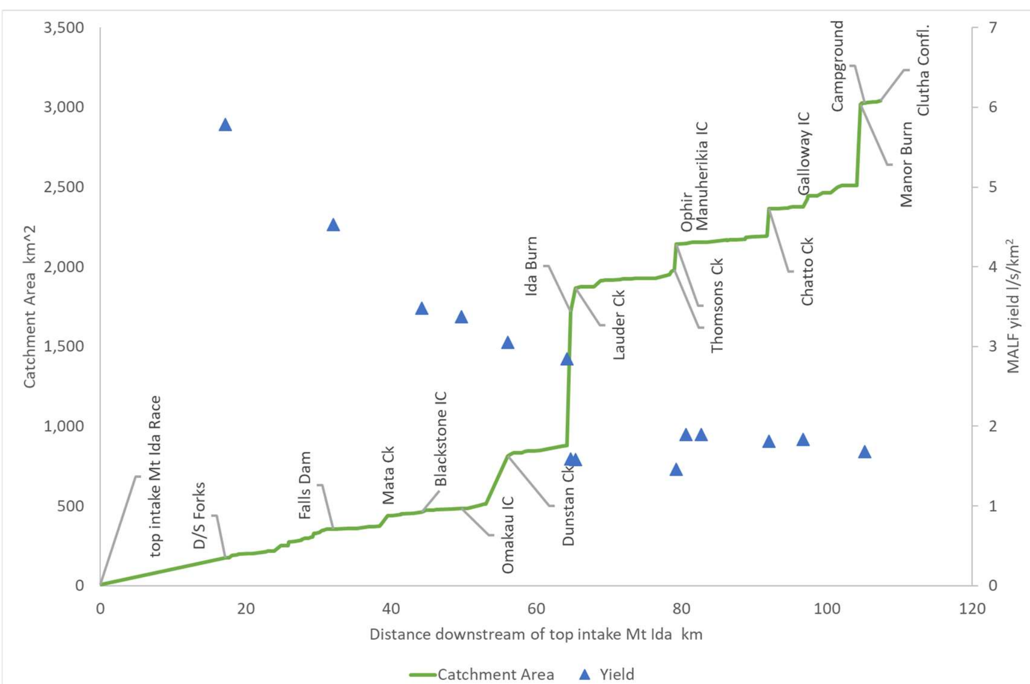


Figure 4-22: Accumulated area and low flow yield along the main stem. Step changes are evident where major tributaries join the river.

4.8 TopNet Summary

- TopNet models were calibrated for all upstream catchments with the aim of reproducing low flow timing and magnitude.
- Due to the large uncertainty in the climate information (mainly precipitation and temperature), the TopNet snow module was not calibrated. This could have resulted in some bias that will influence the representation of the summer discharge.
- The calibrated models tend to consistently underestimate the magnitude of the recession during summer 2014 and 2015, which could indicate potential mis-representation of the precipitation and temperature fields, as those catchments can be affected by snow fall which could be extremely variable.
- At Ophir and Campground, the TopNet results were able to reproduce the lowest flows of the Manuherekia River after the adjustments for leakage etc described in Table 3-1.
- Further work will be needed to complete the TopNet calibrations at Ophir and Campground with no adjustment for leakage. These runs will provide information on sensitivity to overall water balance assumptions.

5 CHES

The CHES tool has been developed to determine in-stream and out-of-stream attributes that can be related to stream flow, and to assess how these attributes are affected under different user-defined abstraction scenarios. CHES can help assess the effects of successive and cumulative groundwater and surface water takes on river flows. The tool can therefore be employed to help resource managers quantify flow losses; track the location and size of all consented catchment water abstractions; and indicate how proposed abstractions may affect existing conditions. CHES enables the analysis of simulated or measured time series of residual river flows, and water takes, for user-specified scenarios. CHES also quantifies the consequences for both the overall availability and reliability of the water resource and the residual flows that determine the in-stream environmental effects.

CHES requires mean daily natural-flow time series for each reach of the modelled catchment. CHES routes the impacts of water abstractions through the river network and determines the impacted mean daily modified flow in every reach. The resulting water-resource ‘reliability’ can then be determined.

Within each reach, CHES sums stream inflows (including natural flows and any incoming flow diversions, less accumulated abstractions from reaches upstream) and lateral inflows then subtracts any abstractions within the reach (applying any rules of the consent if defined) to give a modified outflow for the reach net of abstractions. CHES routes and accumulates the changes in stream flow in a downstream direction to create a new modified stream-flow time series for the selected catchment.

5.1 Scenarios

The concept of scenarios is fundamental to CHES. A scenario defines the data inputs (including the natural flow data) and meta-data, abstractions and calculation options that will be used to run a CHES simulation. For any analysis there should be a reference scenario – this can be the naturalised flow or a specified alternative scenario (such as current flow with existing takes). All other scenarios can then be compared to the reference scenario.

5.1.1 Minimum flow scenarios

For the Manuherikia catchment, the minimum flow scenarios listed in Table 5-1 were established by ORC:

Table 5-1: Minimum flow scenarios for the three control points in the Manuherekia catchment as specified by ORC.

	Campground (L/s)	Ophir (L/s)	Dunstan Creek (L/s)
Scenario 1: Status Quo	900	820	0
Scenario 2: Low-range	1,250	1,500	400
Scenario 3: Mid range	1,600	1,750	600
Scenario 4: Naturalised flow	2,500	2,500	750

5.1.2 Take scenarios

For scenarios that include representation of water takes, the take should be defined using several parameters including:

- **Maximum River Take**: for which the user can specify the maximum annual take volume. The number needs to be larger than zero. In addition, the user can specify the weekly maximum abstractable amount of water allowed.
- **Management Reach**: which is a specified reach that will be used to determine if the flow is above the minimum flow or not. In most cases the management reach is the reach where the water is taken from but can also be downstream of the reach where the take occurs.
- **River take rules**: are the rules to determine how much water should be taken from the river for different flow conditions. Abstraction rules can be defined for up to eight independent rule blocks, within each of which an allocation amount and conditions (relating to minimum flow and months of year) can be defined. The rules set in each block are applied sequentially from the top. Thus, rules in the first row (Block A) must be satisfied first, followed by the second row (Block B) rules, all the way down to the last row (Block H) rules. Takes can be specified as Instantaneous [L/s]; Mean Daily [m^3/day]; or Mean Monthly [m^3/month].
- **River Take**: this is the flow allocation permitted for a specified rule block. For each take, the months for which the take is valid for can also be specified.
- **Minimum flow**: which defines the minimum flow (or management flow) that must be maintained at the management flow site. (The full allocation under the rule block cannot be taken, if it would reduce the flow in the river to less than this management flow).
- **Maximum flow**: which defines a maximum (or flood) flow over which the take from the river is not permitted (to avoid dirty water being extracted).

The combined takes represented within the CHES model for the Manuherikia catchment are listed in Table 5-2. The locations of the take points are shown in Figure 5-1.

Two maximum take sets were used: the sum of the maximum rate from the consents database, and the actual maximum rate taken in the last five years according to water meter data held by ORC. Maximum paper takes are the sum of the consented maximum rate for all the water meters considered to represent takes from natural water as opposed to re-used and already measured water (see list in Appendix C). Maximum actual rates are derived from the summed water meter data of those same meters.

An important caveat is that potentially spurious data has been removed where takes exceeded two times the consented maximum rate. For the sub-catchments where many meters are summed this effect is spread across all meters and the results are generally a maximum take rate significantly less than the consented rate (on average 52%). For the major takes Manuherekia IC, Omakau IC and Blackstone IC, where only one meter is used to represent the actual behaviour, these data problems and the arbitrary cap of 2xmaximum rate mean that the maximum actual is more than the maximum consented and has thus been limited to the maximum consented for modelling purposes. These data issues need further attention.

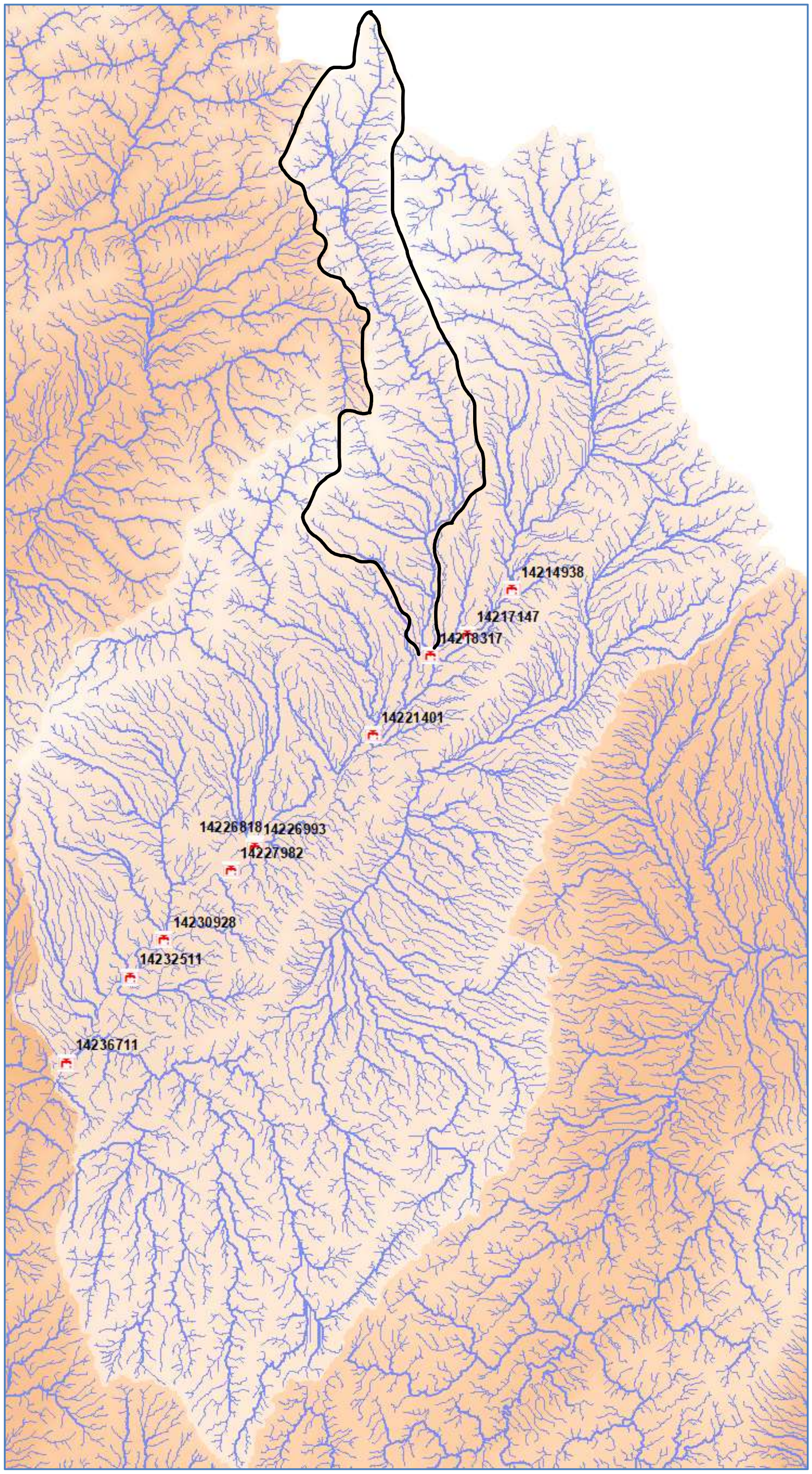


Figure 5-1: Representation of Manuherikia catchment and associated takes in the CHES software. Numbers are segment numbers from the NZ Digital Network Version2. The catchment for Dunstan Creek at Beattie Road is highlighted in black.

Table 5-2: Water takes represented in CHES for the Manuherikia catchment. MaxRate is the sum of consented instantaneous maxima; MaxActual is the maximum hourly rate over the last five years from the summed meters. For the Mt Ida Race, 30% of the flow at Falls Dam is considered available.

Name	Reach	Applies above:	MaxRate (L/s)	MaxActual (L/s)	Ref No.
Lauder Creek	Confluence	Ophir	952	745	14221401
Thomsons Creek	Confluence	Ophir	538	466	14226818
Chatto Creek	Confluence	Campground	2,203	716	14230928
Dunstan Creek	Confluence	Dunstan Creek	1,593	1,075	14218317
Mt Ida Race	Assumed Falls Dam	Ophir	1,926	1,057	14209801
Blackstone IC	Blackstone IC	Ophir	403	403	14214938
Omakau IC	Omakau IC	Ophir	1,981	1,981	14217147
Ophir combined	Ophir	Ophir	4,798	870	14226993
Manuherekia IC	Manuherekia IC	Campground	2,830	2,703	14227982
Galloway IC	Galloway IC	Campground	425	326	14232511
Campground combined	Campground	Campground	460	338	14236711

5.1.3 Dam scenarios

A difficulty with the current CHES software is that it does not allow the explicit modelling of in-river dams and reservoirs. To provide a view of the effect of the Falls Dam we have simulated the river downstream of the dam using the measured lake behaviour over the last five years. First, the simulated natural TopNet derived inflow to the dam is subtracted from all points downstream. Then the measured dam inflow, or measured dam outflows are added to all points downstream. The CHES simulation is then run with each of these scenarios.

5.1.4 Seasonality

The current scenarios contain only a single irrigation demand number which in the CHES implementation has been assumed to apply all year round. This is unrealistic, as generally water use in the winter months is very much lower. To avoid over-estimation of water use, and to allow presentation of more realistic and comparable reliability numbers, all statistics presented below will be for the irrigation season only (1 October to 30 April).

5.2 Outputs

Outputs in CHES can either describe catchment or reach scale.

5.2.1 Catchment scale

At the catchment-scale, CHES can be used to display the spatial variation of a selected attribute by colouring each reach based on the value of the attribute. A wide range of flow-based attributes (model results) can be mapped including:

- **Reliability** of water supply can be defined in two ways:
  Time reliability
  R1: the percent of time (total) that the user can extract all of the consented allocation.

  R2: the percent of time (total) that the user can abstract all or part of the allocated amount. The amount of time that the user cannot abstract any water is 100 – R2.

Volumetric reliability
R: Amount of water that can be taken divided by the consented maximum rate.

- **Flow**: attributes and statistical properties of the flow including:
  Min(Q): the overall minimum flow for each reach.
  Max(Q): the overall maximum flow for each reach.
  Mean(Q): the overall mean flow for each reach.
  Median(Q): the overall median flow for each reach.
  MALF: the overall 7-day MALF for each reach.
  Days less MALF: the amount of time (in percent) that a reach had a flow lower than the 7-day MALF based on the natural flow.
  FRE3: gives the flood frequency FRE3 (or 3 x median natural flow).
  Touched Reach: colour codes for whether the flow of a reach has been changed or not.
  Mean(\DeltaQ): shows by how much the mean flow changed between the natural flow condition and the active scenario.
  Max(\DeltaQ): shows by how much the maximum flow changed between the natural flow condition and the active scenario.

In addition, reliability and flow of a specified scenario can be expressed as a function of the reference scenario, for example:

- **Delta**: the change in flow or reliability between the active scenario and the reference scenario. The values are subtracted from the two different scenarios, such that for reliability R_1:

  $\Delta R_1 = R_1$ [active scenario] – R_1 [reference scenario]

- **Delta%**: the change in flow or reliability between the active scenario and the reference scenario expressed as a percentage change. For example, Delta maximum flow (ΔMax(Q)) where:

  ΔMax(Q)% = ((Max(Q) [active scenario] – Max(Q) [reference scenario])/ Max(Q) [reference scenario]) *100

5.2.2 Reach scale

At the reach-scale the following outputs can be described:

- **Flow**: reach outflow timeseries for specified scenario conditions
- **Flow (ref)**: reach outflow timeseries for reference scenario conditions
- **Flow Change**: the difference between the reach outflow for a specified scenario and the reference scenario
- **Flow Change [%]**: this plots “Flow Change” expressed as a percentage [%].

If an abstraction is defined for a reach, then the following two variables can be defined:

- **Supply [L/s]**: a time series of the amount of water that the specified abstraction is supplied with.

- **Reliability (R2) [%]**: similar to the supply time series but as a percent i.e., the percent of time that a user can abstract all or part of the allocated amount.

5.2.3 Excel spreadsheet model

During the initial CHES set-up, we also built an Excel spreadsheet model to represent the results expected at each of the eleven points in the catchment where the takes have been amalgamated for simplification (see Table 5-2).

This Excel spreadsheet provides a useful check on the full catchment CHES model, and allows the presentation of output in ways that CHES does not. As part of the spreadsheet outputs we also define **R50** as the reliability (percent of time) with which half the consented amount would be available, to indicate the sensitivity in each case.

In CHES a default order of precedence applies, that evaluates consents on the basis of the catchment area draining to the point of take. In a more fully implemented model this ensures that upstream takes are always considered first. For the Manuherekia this order results in the list in Table 5-2, where the tributary takes are considered first and then the main stem takes in order down the river. Each is none-the-less subject to its minimum flow rule at a point downstream. The spreadsheet model has been built to replicate this order. This ordering does mean that modelled results may differ significantly from real world situations, if precedence is based on other considerations such as a first-come-first-served approach to water allocation, or a catchment- or tributary-wide sharing and rostering system. For this reason, the illustrations below will focus on the flows at the control points and sites immediately downstream of them, rather than exhaustively showing results at every point.

Full explanations will be provided for the first modelled configuration, (irrigation season, no dam, maximum consented rate), and summary tables plus discussion only for the other three variations (maximum measured take rate, with and without Falls Dam).

The results below are presented for the irrigation season only (1 October to 30 April each year) from January 1973 to December 2018, the duration of the TopNet modelling runs.

5.3 Irrigation season, no dam, maximum consented rate of take

The upper limit of demand is the maximum consented instantaneous rate, especially when added up across all takes in a sub-catchment or indeed the entire Manuherekia.

Table 5-3 shows the reliabilities (as defined at section 5.2.1) at eleven sites, and four scenarios with no dam and maximum consented rates. A separate column is also provided for the catchment as a whole.

Table 5-3: Reliability for four scenarios with no dam and maximum consented rates. The right-hand column combines the results for all sections of the catchment. Maxrate consented is shown in cumecs.

Max Rate, No Dam, Irrigation Season				Dunstan				Ophir			Campground	
Scenario 1 (Status Quo)				0				0.82			0.9	
Scenario 2 (Low Range)				0.4				1.5			1.25	
Scenario 3 (Mid Range)				0.6				1.75			1.6	
Scenario 4 ('Naturalised')				0.75				2.5			2.5	
MaxRate consented	0.952	0.538	2.203	1.593	1.926	0.403	1.981	2.737	2.830	0.425	0.460	16.048
Scenario 1 (Status Quo)												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	71%	77%	41%	90%	67%	99%	86%	73%	67%	61%	66%	70%
R1	44%	53%	13%	73%	37%	98%	69%	62%	53%	54%	61%	13%
R50	69%	77%	32%	93%	64%	99%	87%	72%	60%	58%	66%	72%
R2	100%	100%	100%	100%	99%	99%	97%	92%	99%	75%	73%	100%
Scenario 2 (Low Range)												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	71%	77%	41%	82%	67%	97%	84%	69%	73%	58%	59%	69%
R1	44%	53%	13%	63%	37%	97%	69%	60%	53%	54%	56%	13%
R50	69%	77%	32%	83%	64%	98%	86%	68%	71%	57%	59%	71%
R2	99%	99%	100%	99%	99%	98%	96%	86%	99%	65%	62%	100%
Scenario 3 (Mid Range)												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	71%	77%	41%	78%	67%	97%	84%	68%	73%	55%	55%	68%
R1	44%	53%	13%	60%	37%	96%	69%	59%	53%	53%	53%	13%
R50	69%	77%	32%	78%	64%	97%	86%	67%	69%	55%	55%	69%
R2	99%	98%	99%	96%	98%	97%	95%	85%	98%	59%	56%	99%
Scenario 4 ('Naturalised')												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	71%	77%	41%	74%	66%	93%	80%	63%	70%	50%	49%	66%
R1	44%	53%	13%	57%	37%	91%	68%	55%	51%	50%	48%	13%
R50	69%	77%	32%	74%	64%	93%	81%	63%	64%	51%	49%	66%
R2	97%	96%	98%	93%	96%	94%	90%	75%	97%	51%	49%	98%

5.3.1 Lauder Creek at Manuherekia Confluence

As the first set of consents to be assessed, and a tributary without a minimum flow, Lauder is a good example of this type of situation. The consents in the catchment are amalgamated (total 952 L/s) and considered to act at the reach above the confluence with the Manuherekia.

Figure 5-2 and Figure 5-3 show flow duration curves for remaining river flow and available water respectively. In Figure 5-2 the top green line is the natural flow, and the others which generally overlap are the remaining water after each scenario's abstraction. In Figure 5-3 the maximum consented rate of take is the flat line at 952 L/s, and the scenarios differ slightly at the lowest flows. R1 reliabilities are all 44%, R50 69%, and some water can be taken 97% to 100% of the time. The river is potentially dry for 55% of the time, because there is no minimum flow modelled in Lauder Creek, and other streams and the main stem provide water to meet the downstream minimum flow at Ophir.

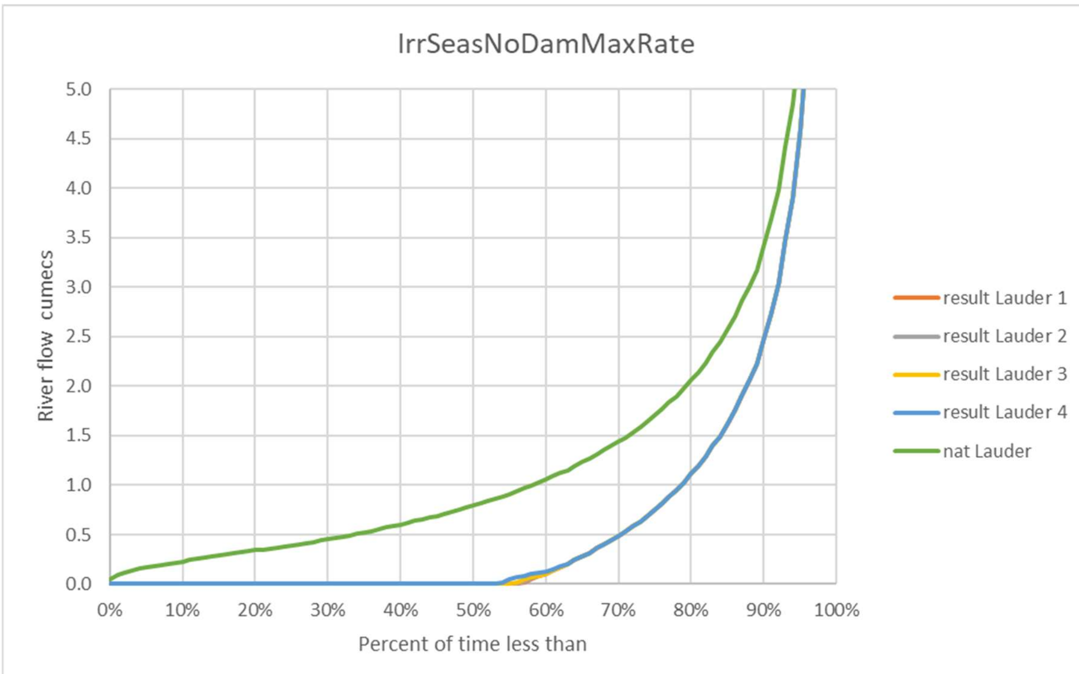


Figure 5-2: Flow duration curves for Lauder Creek at the confluence under four scenarios. Scenarios 1 to 4 as per Table 5-1. Green line shows the natural flow as simulated from TopNet.

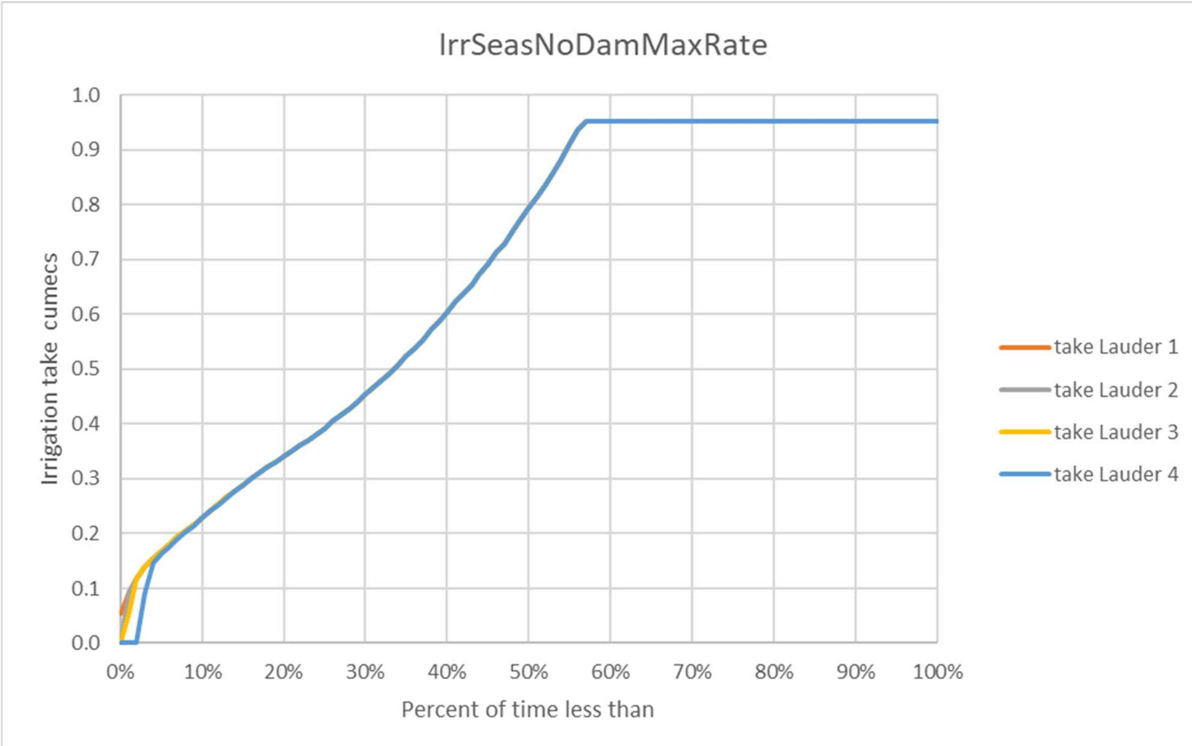


Figure 5-3: Flow durations curves for Lauder Creek water availability at the confluence under four scenarios.

5.3.2 Dunstan Creek at Manuherekia Confluence

Along with the other north bank (true right) tributaries, Dunstan Creek at Manuherekia Confluence is represented as a single amalgamated take from the reach immediately above the confluence with the Manuherekia. This take of 1,593 L/s maximum rate is the sum of takes from Dunstan Creek and its tributaries that are deemed to be takes from natural water bodies. The difference is that Dunstan Creek has its own minimum flow (see Table 5-1) that varies between scenarios and takes there are not subject to the minimum flows further down the river.

Four scenarios have been modelled for Dunstan Creek using the time series generated by TopNet at the confluence reach. Figure 5-4 shows the flow in Dunstan Creek at the confluence under these four scenarios, and Figure 5-5 shows the flow duration curves for the availability of water for out-of-stream use. The vertical separation between the natural inflows and the scenario lines represents the available water. Over most of the range this is 1,593 L/s, but at low flows it reduces, depending on the scenario and its minimum flow rule. The modelled reliabilities are presented in Table 5-3.

Reliability for the maximum rate of take varies between 57% and 73%, and the river could spend between 28% and 35% of the time at the minimum flow in irrigation seasons.

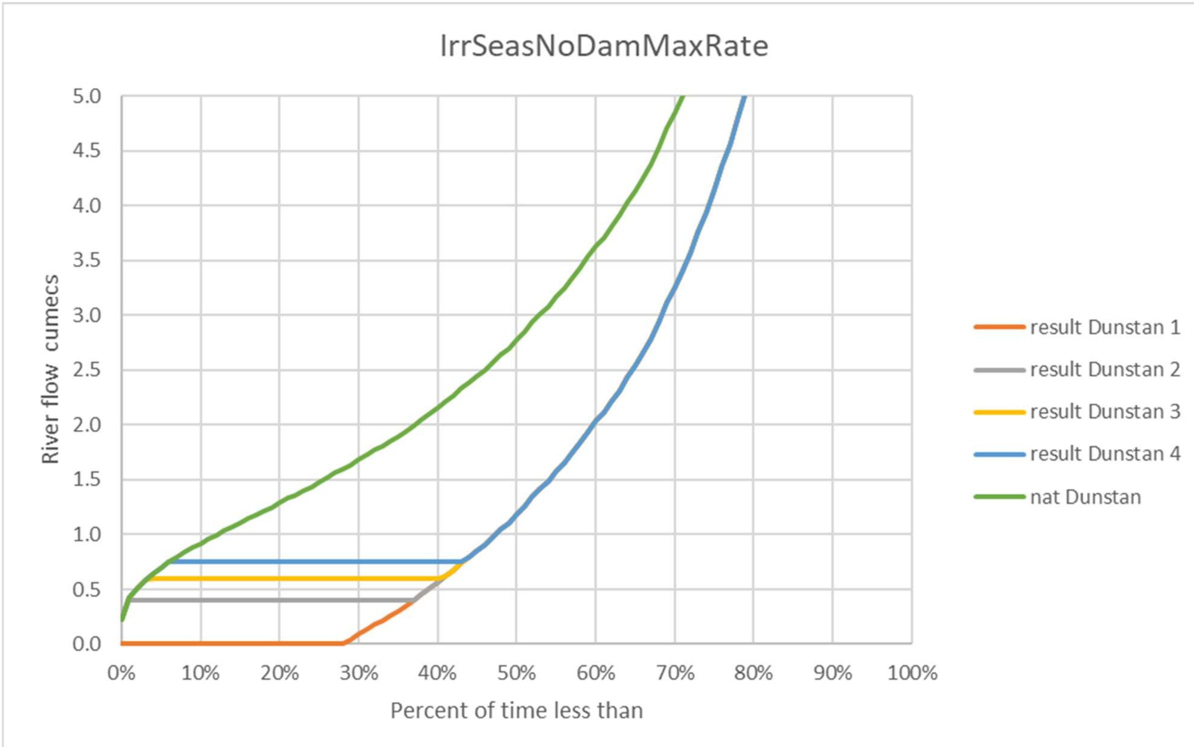


Figure 5-4: Flow duration curves for Dunstan Creek at the confluence under four scenarios. Scenarios 1 to 4 as per Table 5-1. Green line shows the natural flow as simulated from TopNet.

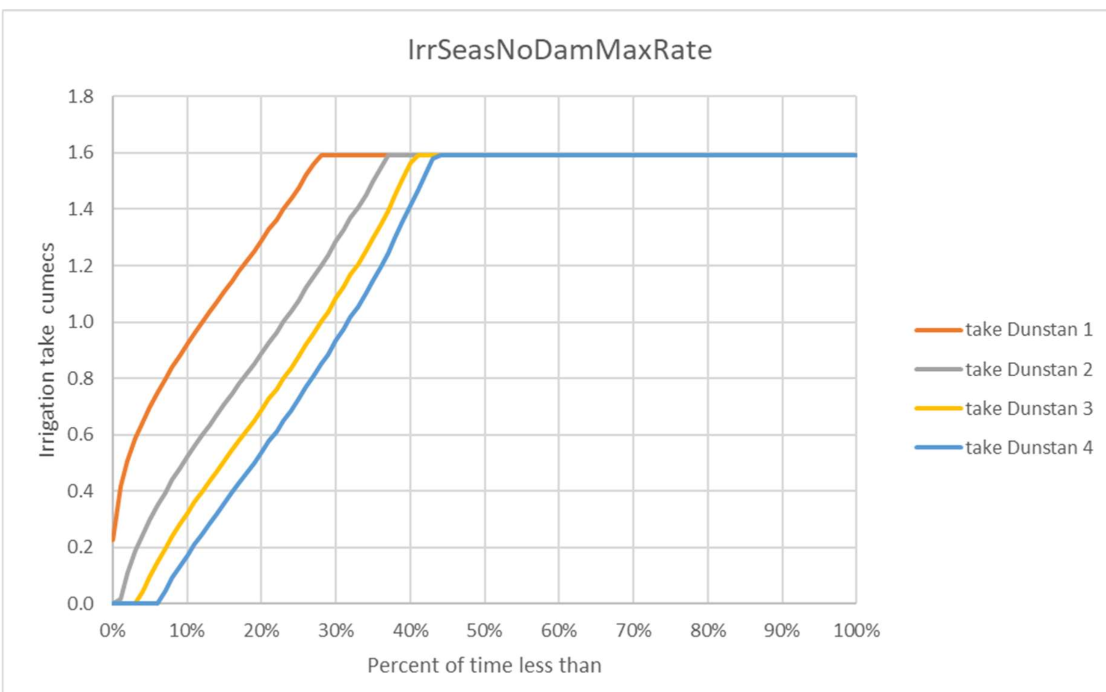


Figure 5-5: Flow duration curves for Dunstan Creek water availability under four scenarios.

Variation in these reliability values over time can be examined via plots or tables. Figure 5-6 shows the volumetric reliability over the modelling period 1972 to 2018, defined as the ratio of water take to maximum consented rate. A more detailed view of the time reliability can be provided by examining the number of days per month that water is fully or partially available. Table 5-4 shows this for the Status Quo scenario. Clustering of red months highlight historic droughts.

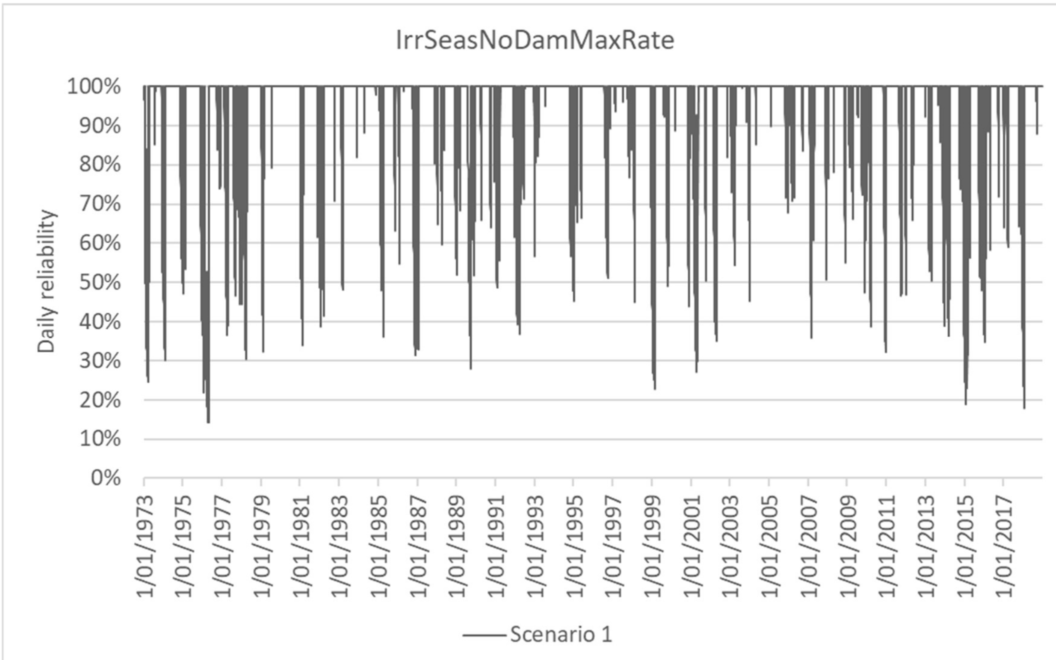


Figure 5-6: Dunstan Creek volumetric reliability under the Status Quo (scenario 1). Each day the actual take is divided by the desired take.

Table 5-4: Time reliability for Dunstan Creek at Confluence. Figures show days per month that all water would be available under the Status Quo Scenario (SC1).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	20	0	2	12	31	30	20	27	30	31	29	5
1974	1	26	31	30	31	30	31	31	30	31	21	2
1975	10	9	31	30	31	30	31	31	30	30	28	2
1976	1	5	0	2	28	30	31	31	30	22	22	29
1977	31	23	2	4	31	30	31	2	10	19	7	6
1978	8	9	1	18	31	30	31	31	30	31	30	31
1979	12	8	31	30	31	30	22	31	30	31	30	31
1980	31	29	31	30	31	30	31	31	30	31	30	31
1981	7	1	27	30	31	30	31	31	30	31	24	14
1982	2	4	4	30	30	30	31	31	30	21	30	31
1983	30	13	23	30	31	30	31	31	30	31	27	26
1984	31	29	31	26	31	30	31	31	30	31	29	31
1985	29	7	8	12	31	30	31	31	30	30	17	31
1986	23	17	31	29	31	30	31	31	30	10	7	15
1987	11	28	29	30	31	30	31	31	30	31	26	31
1988	22	29	21	22	24	30	31	31	30	31	30	11
1989	25	22	22	30	31	30	31	2	0	26	9	21
1990	31	28	31	16	31	30	31	31	19	26	30	25
1991	12	26	12	30	31	30	31	31	30	31	28	19
1992	19	13	0	10	31	17	30	31	30	31	30	26
1993	15	25	22	30	31	30	30	30	30	31	30	31
1994	30	28	30	30	31	30	31	31	30	21	26	13
1995	18	26	22	30	8	30	31	31	30	31	30	31
1996	31	29	31	30	31	30	30	5	1	26	27	31
1997	31	24	31	30	31	30	29	31	30	23	19	28
1998	31	8	31	30	31	30	31	31	30	31	30	18
1999	1	0	24	30	31	30	31	28	27	2	20	31
2000	31	29	29	30	31	29	31	31	30	31	6	24
2001	28	19	0	0	14	30	31	31	18	14	30	31
2002	31	22	1	5	31	29	31	31	30	31	25	31
2003	28	21	12	24	31	30	31	30	30	31	27	19
2004	23	29	31	25	30	30	31	31	30	31	30	30
2005	31	25	31	30	31	30	31	31	30	31	21	23
2006	31	17	22	12	31	30	31	31	23	31	30	31
2007	31	1	16	4	30	30	31	31	30	31	24	20
2008	25	29	31	22	31	30	31	31	30	31	13	28
2009	31	23	28	8	30	30	27	31	28	18	12	22
2010	26	16	10	28	31	30	31	31	30	31	10	9
2011	31	27	31	30	29	30	31	31	4	16	30	20
2012	21	29	31	17	8	30	31	31	30	31	30	29
2013	31	27	15	4	29	29	31	27	25	28	19	2
2014	30	3	3	26	31	30	31	31	26	8	14	3
2015	0	1	6	12	31	30	31	31	23	3	7	17
2016	17	18	28	20	22	30	31	31	24	23	30	31
2017	18	28	7	21	31	30	31	31	30	13	23	1
2018	1	28	31	30	31	30	31	31	26	31	30	30

5.3.3 Mt Ida Race and Blackstone IC intakes

Mt Ida Race and Blackstone IC takes are assessed next.

Mt Ida is assumed to have access to 30% of the inflow to Falls Dam. This is estimated by considering the approximate catchment area of the Mt Ida takes compared with the catchment area at Falls Dam and making some allowance for the higher yielding nature of the higher elevation catchment that drains to the race. Mt Ida reliabilities are relatively low with R1 = 37% (see Table 5-3 for details).

Blackstone IC intake is downstream of the Falls Dam, but above Dunstan Creek confluence. Its maximum rate is relatively small compared with other main stem takes (403 L/s) and its reliability is high (R1 91% to 98%), with small differences due to meeting the minimum flow at Ophir.

5.3.4 Omakau IC intake

The Omakau IC take maximum rate is larger (1,981 L/s), and the flows have been reduced by the upstream takes at Mt Ida and Blackstone. Often the flow at Ophir is still well above its minimum flow, and thus the Omakau take can remove all the remaining water from the river at that point, for up to 24% of the time in an irrigation season (see Figure 5-7).

Minimum flow rules at Ophir have some impact on this and the R2 reliability for Omakau IC varies from 90% to 97%. R1 reliability is constant at 69% (see Figure 5-8).

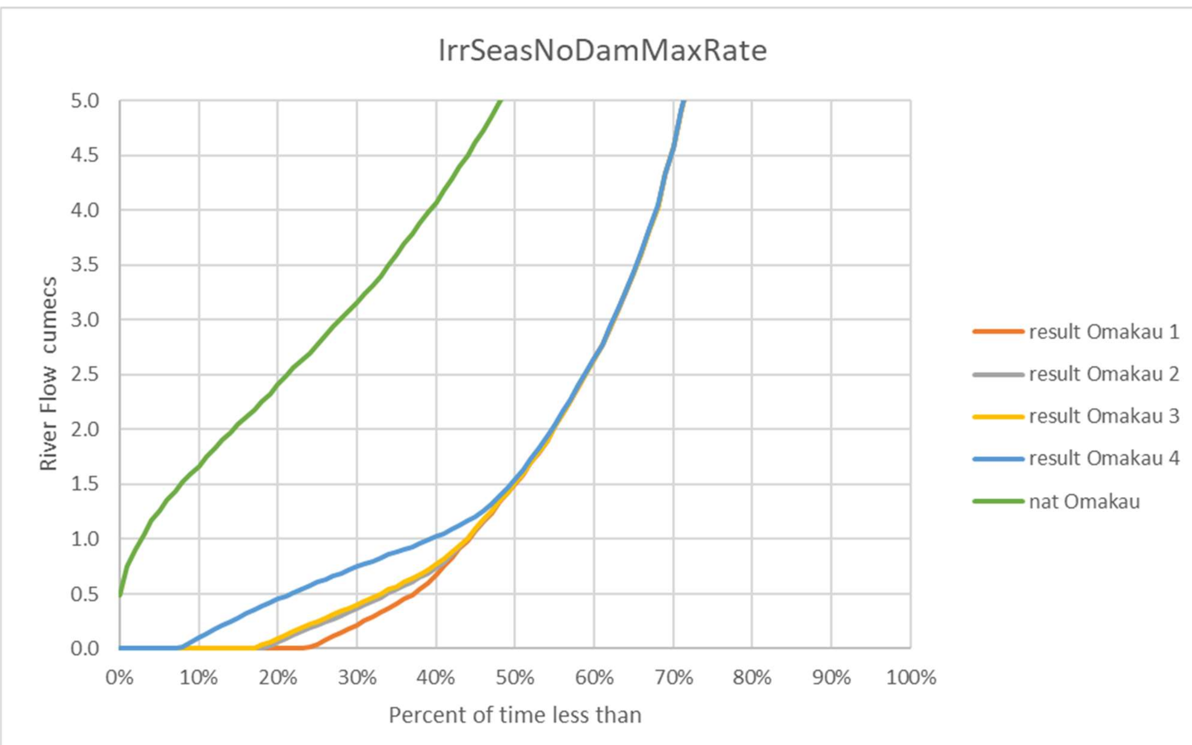


Figure 5-7: Flow duration curves for Manuherekia at Omakau IC under four scenarios. Scenarios 1 to 4 as per Table 5-1. Green line shows the natural flow as simulated from TopNet.

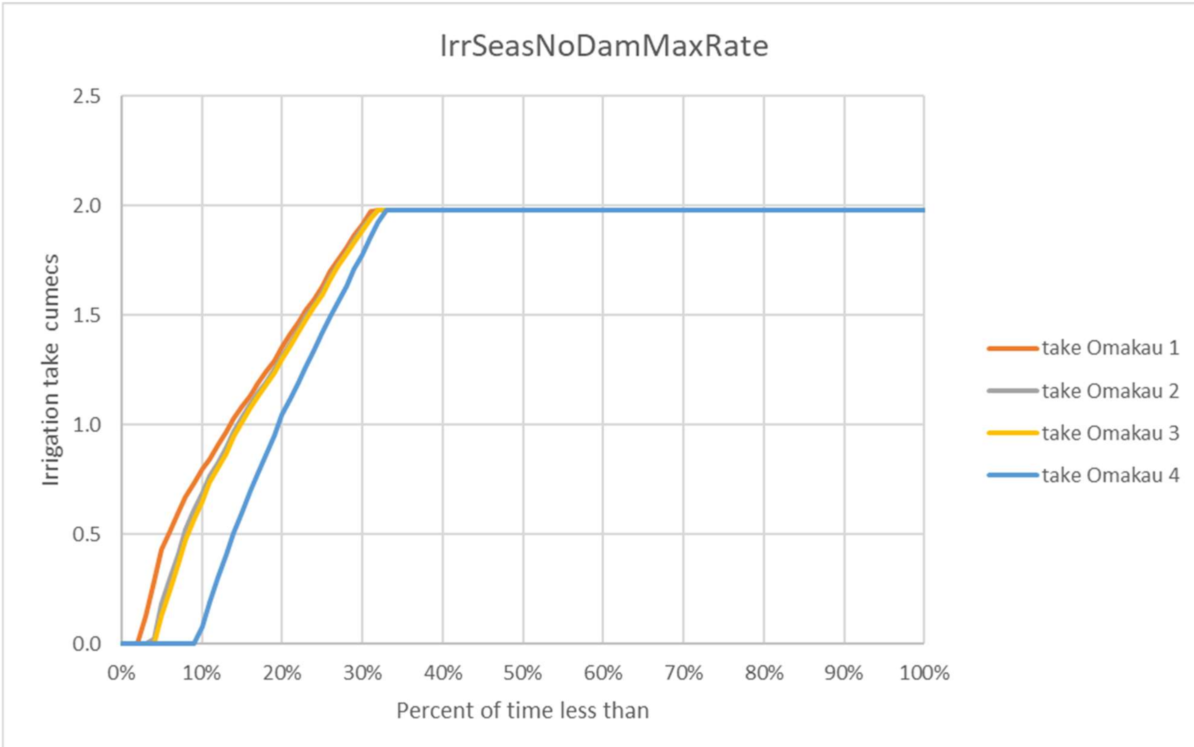


Figure 5-8: Flow duration curves for Omakau IC water availability under four scenarios.

5.3.5 Manuherekia at Ophir

A further 2,737 L/s of take occur upstream of Ophir (313 L/s near the river and 2,424 L/s from the Ida Burn/Pool Burn) and are directly affected by the minimum flow there as well as by the previously assessed takes upstream.

Figure 5-9 shows the effects in the river at Ophir of these and the upstream takes. The overall result is similar to that at Dunstan Creek; each different minimum flow occurs in the river during the irrigation season for 40% of the time on average. R1 reliability varies from 55% to 62%, and no water would be available between 8% and 25% of the time.

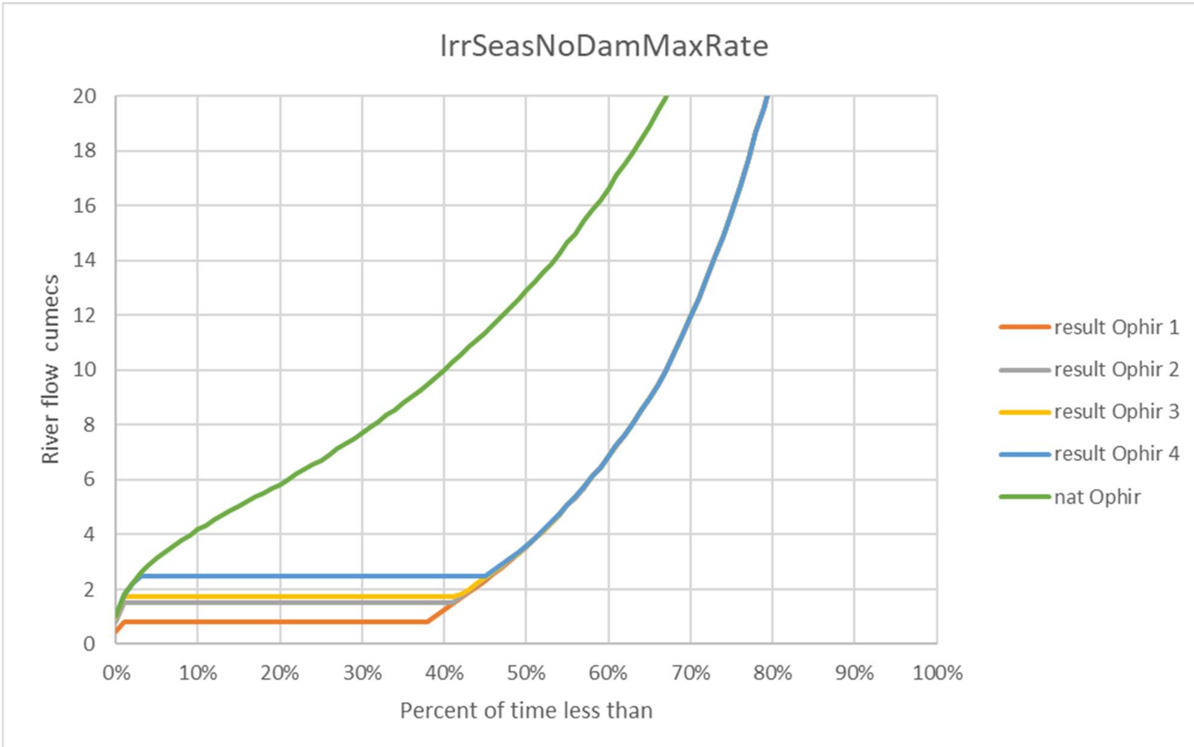


Figure 5-9: Flow duration curves for Manuherekia at Ophir under four scenarios. Scenarios 1 to 4 as per Table 5-1. Green line shows the natural flow as simulated from TopNet.

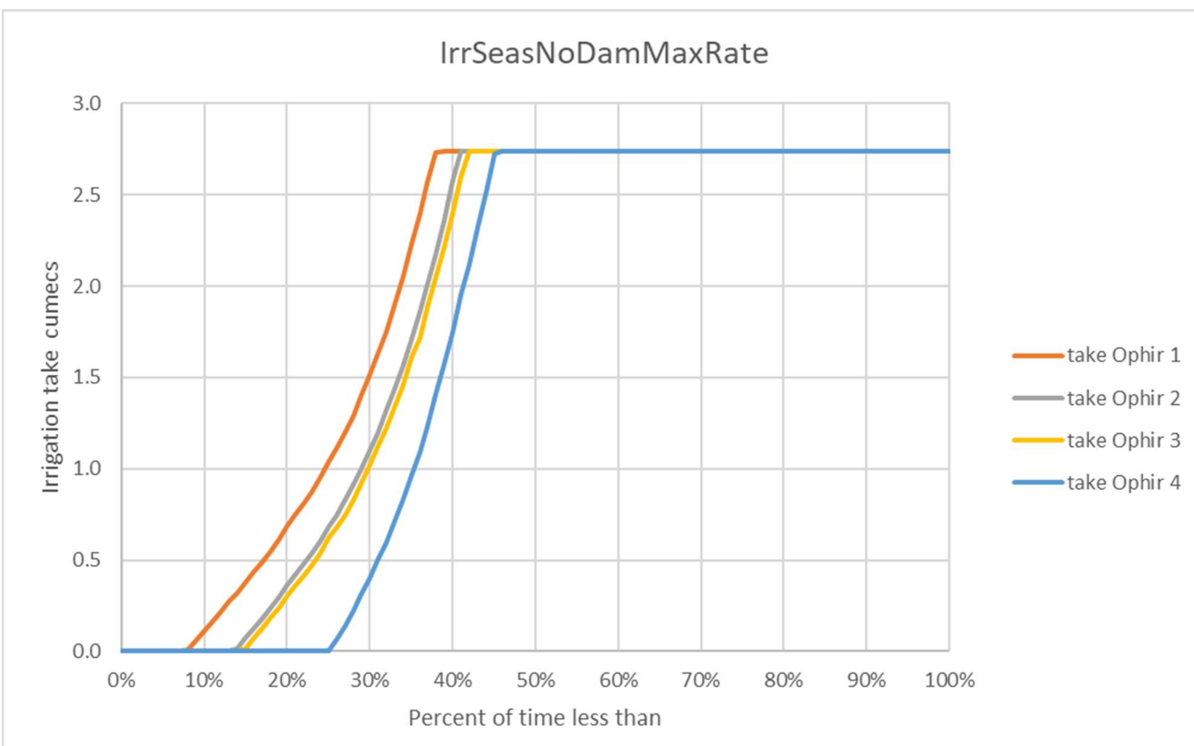


Figure 5-10: Flow duration curves for Manuherekia at Ophir water availability under four scenarios.

5.3.6 Manuherekia at WM0062 (Manuherikia IC intake)

This large take (2,830 L/s) is very close to Ophir but downstream and thus subject to the minimum flow at Campground rather than the minimum flow at Ophir. The situation is similar to that at the Omakau IC intake; because other tributaries add water to Campground below this point there is often sufficient water there to allow this take to extract to its potential, and the consequence is that the river may be dried up. Figure 5-11 shows the flow duration curves for the irrigation season. Flows in the river here can be below the minimum flow set at Ophir for more than 50% of the time.

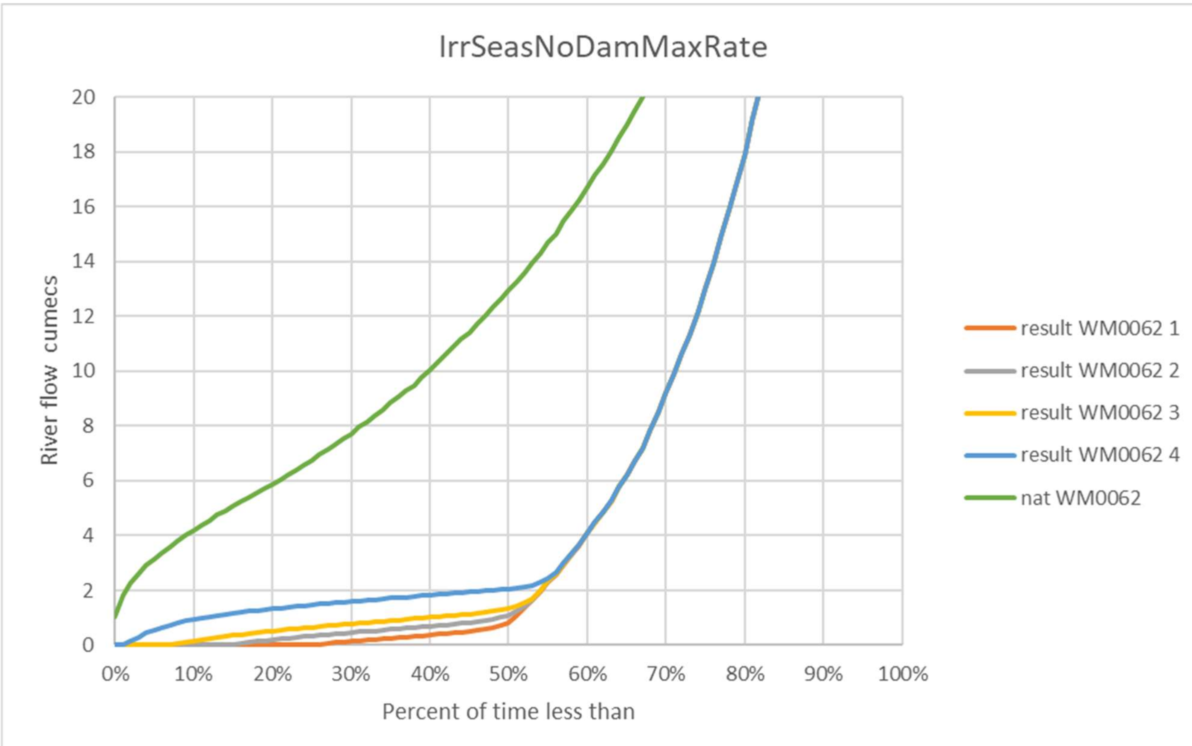


Figure 5-11: Flow duration curves for Manuherekia at Manuherikia IC intake (WM0062) under four scenarios. Scenarios 1 to 4 as per Table 5-1. Green line shows the natural flow as simulated from TopNet.

Figure 5-12 shows the distribution of available water. Full reliability is low at just over 50%. Behaviour below full reliability is not uniform between scenarios, since higher minima at Ophir mean there is potentially more water available to be taken. If the effect of a greater minimum at Campground is smaller than this then the take can be larger than for a lower minimum flow. This feature can be seen in Table 5-3 in the WM0062 column, where those reliabilities that increase with increasing minimum flow are highlighted.

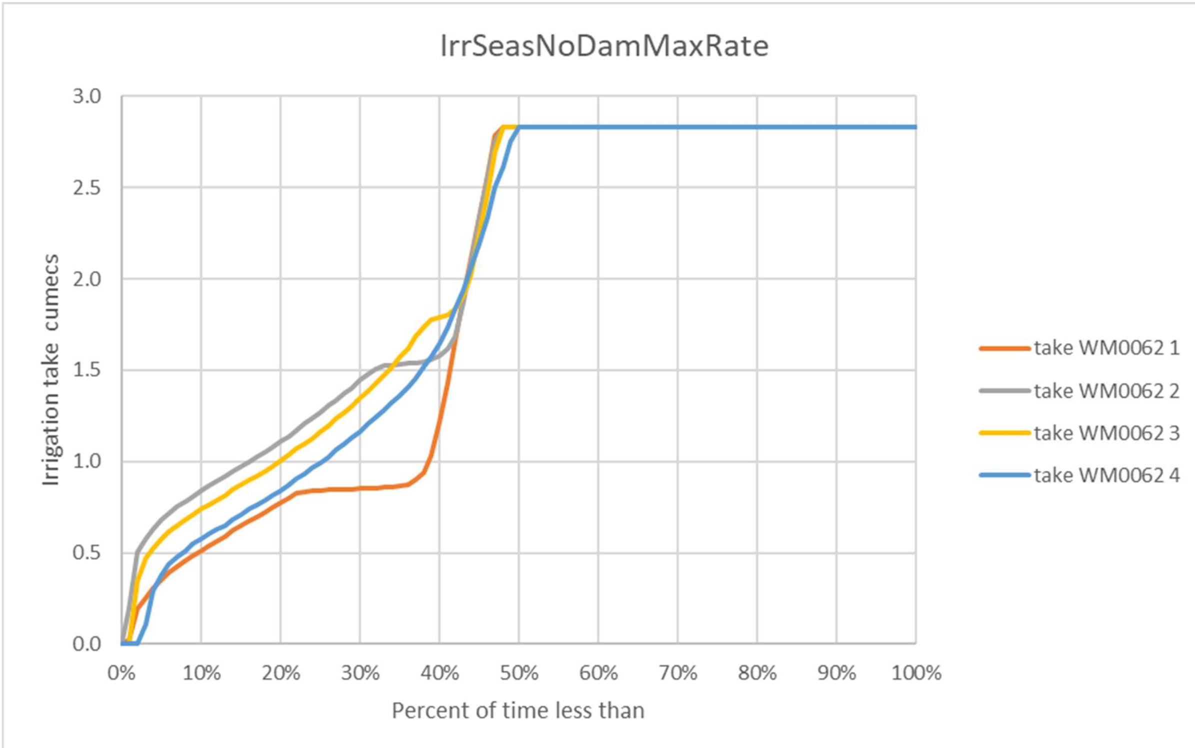


Figure 5-12: Flow duration curves for Manuherekia IC (WM0062) water availability under four scenarios.

5.3.7 Manuherekia at Campground

There are a small number of consents that take from the river near and immediately upstream of the Campground site (95 L/s) and the Manor Burn consents (366 L/s) are added to these for a total of 460 L/s. The reliability for these takes, being last in the catchment to be evaluated (since they are from the largest catchment area at Campground), is also low (48% to 61%) as shown in Figure 5-13.

The minimum flows set at Campground for the four scenarios are generally met in a similar way to those at Ophir and Dunstan Creek. The river would be at the minimum flow between 39% and 50% of the time in irrigation seasons (see Figure 5-14).

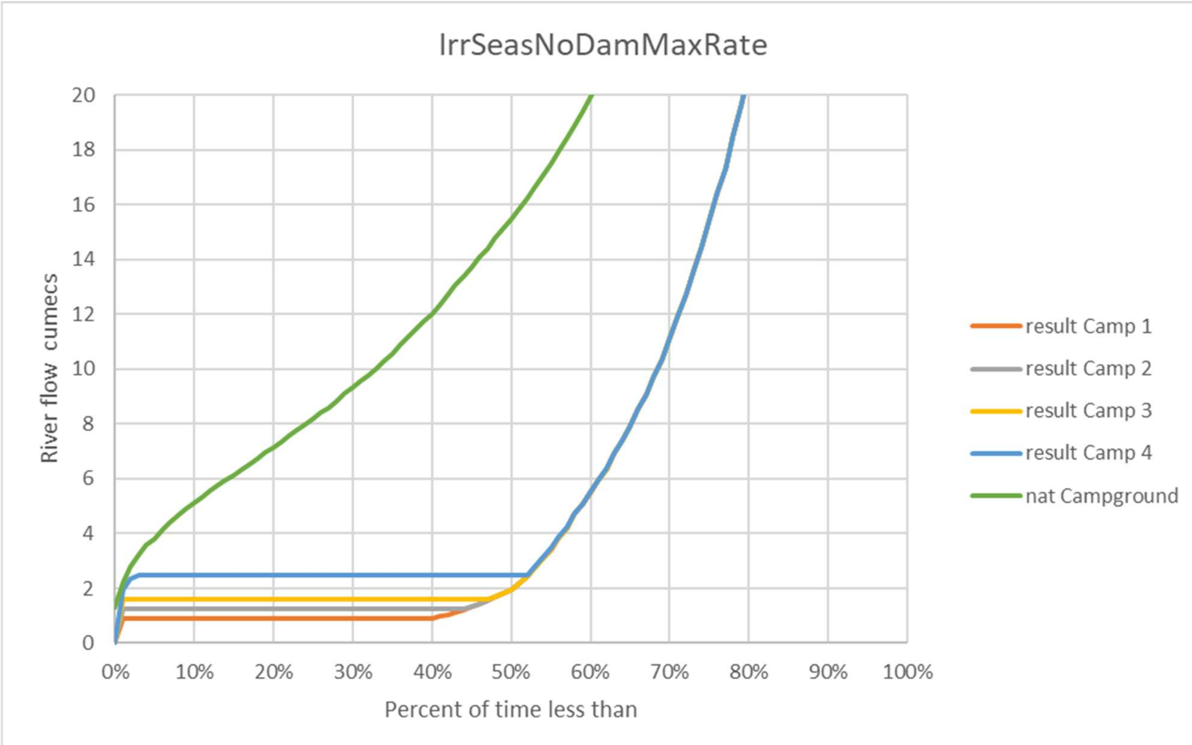


Figure 5-13: Flow duration curves for Campground and Manor Burn water availability under four scenarios. Green line shows the natural flow as simulated from TopNet.

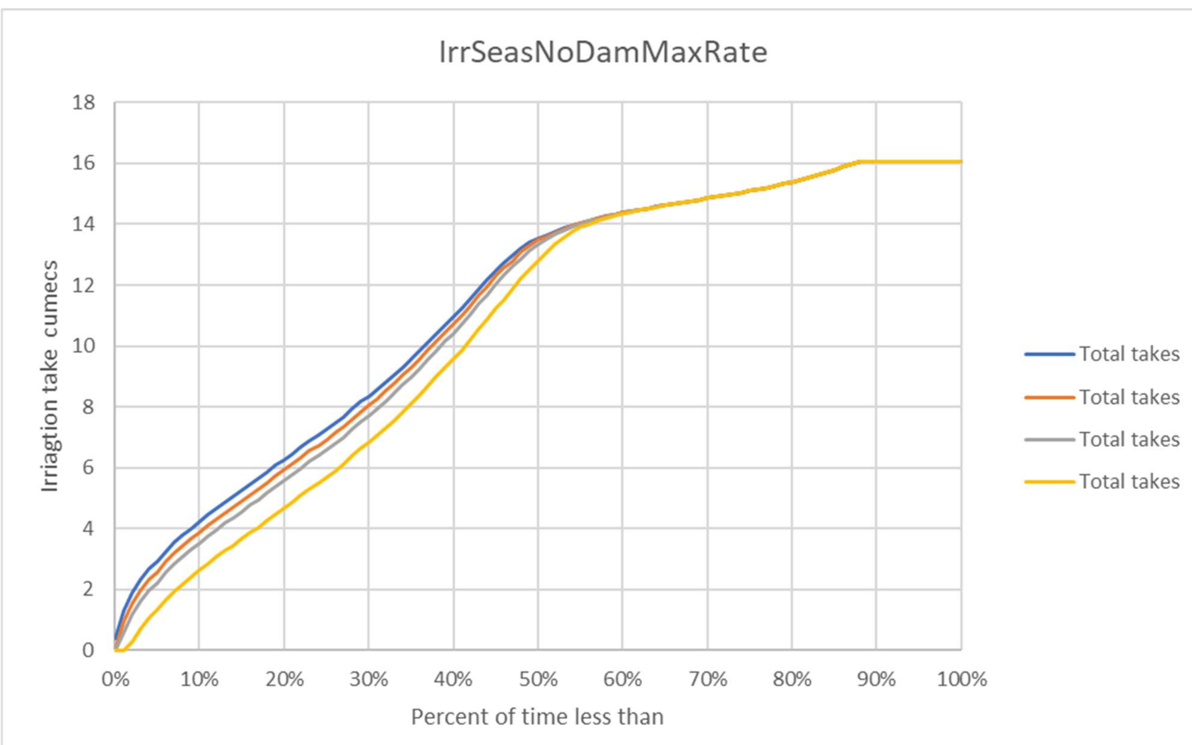


Figure 5-14: Flow duration curves for total catchment water take under four scenarios. Scenarios 1 to 4 as per Table 5-1.

5.4 Irrigation season, no dam, maximum actual rates of take

The water meter data show that in common with other Otago catchments (Lindis, Cardrona) the maximum consented take rate rarely if ever occurs, for many reasons related to climate variability, farm management, annual volume restrictions, variability of flow in parts of the catchment etc.

Analysis of the water meter data used in the flow naturalisation process described in Section 3.3 shows that over all the meters represented here, 68% of the maximum rate actually occurred between July 2014 and July 2019. For each sub-catchment, the total water use is summed, and the maximum of that record on a daily basis is used as the maximum actual rate. This evens out minor fluctuations in the hourly data. This fraction utilised varies from 32% of maximum rate at Ophir + Pool Burn, to 100% at the individual major race meters. Those meters (Blackstone, Omakau and Manuherikia IC) all have instances of water use recorded at more than twice the maximum consented rate, and since they are represented in the model individually, their apparent overuse does not get merged and smoothed out. We have restricted them to 100% of maximum rate to ensure that this scenario does not have greater water use than the previous maximum consented rate scenario.

The body of Table 5-5 shows the reliabilities for eleven sites and the whole catchment under the four different minimum flow scenarios. As may be expected, this scenario has higher reliabilities than the maximum consented rate scenario. It can be viewed as a likely maximum envelope of water demand.

Table 5-5: Reliability for four scenarios with no dam and maximum actual rates. The right-hand column combines the results for all sections of the catchment. Maxrate consented is shown in cumecs.

Max Actual, No Dam, Irrigation Season				Dunstan				Ophir			Campground	
Scenario 1 (Status Quo)				0				0.82			0.9	
Scenario 2 (Low Range)				0.4				1.5			1.25	
Scenario 3 (Mid Range)				0.6				1.75			1.6	
Scenario 4 ('Naturalised')				0.75				2.5			2.5	
MaxRate actual	0.745	0.466	0.716	1.075	1.057	0.403	1.981	0.87	2.703	0.326	0.338	10.680
Ratio to consented rate	78%	87%	33%	67%	55%	100%	100%	32%	96%	77%	73%	67%
Scenario 1 (Status Quo)												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	78%	81%	74%	96%	83%	99%	86%	86%	78%	70%	72%	83%
R1	53%	58%	47%	86%	60%	98%	70%	81%	65%	66%	69%	43%
R50	77%	82%	72%	98%	85%	99%	87%	87%	75%	68%	72%	85%
R2	100%	100%	100%	100%	99%	99%	97%	93%	99%	78%	75%	100%
Scenario 2 (Low Range)												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	78%	81%	74%	89%	83%	97%	85%	80%	81%	67%	66%	81%
R1	53%	58%	47%	76%	60%	97%	69%	75%	65%	65%	65%	43%
R50	77%	82%	72%	90%	85%	98%	86%	81%	78%	66%	66%	83%
R2	99%	99%	100%	99%	99%	98%	96%	87%	99%	70%	68%	100%
Scenario 3 (Mid Range)												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	78%	81%	74%	84%	83%	97%	84%	79%	79%	64%	63%	80%
R1	53%	58%	47%	71%	60%	96%	69%	73%	64%	63%	63%	43%
R50	77%	82%	72%	85%	85%	97%	86%	79%	75%	65%	64%	82%
R2	99%	98%	99%	96%	98%	97%	95%	85%	99%	65%	64%	99%
Scenario 4 ('Naturalised')												
Site Name	Lauder	Thomsons	Chatto	Dunstan	Mt Ida	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	77%	80%	74%	80%	82%	93%	80%	71%	75%	60%	59%	77%
R1	53%	58%	47%	67%	60%	91%	68%	68%	61%	60%	59%	43%
R50	77%	82%	72%	80%	85%	93%	81%	71%	71%	61%	59%	77%
R2	97%	96%	98%	93%	96%	94%	90%	75%	97%	60%	59%	98%

5.5 Falls Dam effects

Without a long series of the operation of Falls Dam, or a model of this operation that could be varied, only limited data are available to illustrate the effect of the dam storage on the river and the water demand. Data from Pioneer Energy Ltd are available from 2014 to 2018, which coincides generally with the availability of water meter data elsewhere in the catchment.

To simulate the effects of the dam and ensure that the actual operation is used rather than some modelled version, we remove the modelled flows at the dam suite from all reaches downstream to Campground. Then we add either the calculated inflows to the dam, or the measured outflows from the dam, back to those downstream reaches. Then we run the water use model (CHES or spreadsheet) to calculate the available water and results in the river as before. Thus, the difference between these two scenarios is representative of the dam operation and its effect on downstream water.

An important difference is that these scenarios using the actual dam records are net of Mt Ida Race as this water is already used upstream of the dam, and thus not part of the measurements at the dam. Also, the shorter record used means that overall flows are less than for the previous scenarios from 1973, and flow duration curves are less smooth as individual events have more influence.

The actual maximum rates assessed from the water meter data are used in these dam scenarios.

Table 5-6 shows reliabilities with the calculated dam inflows over four irrigation seasons. This is a similar scenario to that in section 5.4, but with fewer years and measured data at the dam. Table 5-7 shows reliabilities with the measured dam outflows propagated down the river. Table 5-8 shows the reliability differences between these two and is thus an indication of the effect of the dam releases and storage, on the reliability downstream.

There are little to no differences in tributary reliability at Dunstan Creek since it relies on its own minimum flow rule. There are some benefits at other tributaries as a result of more water at Ophir and Campground with the dam. The largest effects are on the reliability of the main stem takes, since dam releases augment low flows and allow water to be taken at times when the catchment is naturally in a very low flow state. The overall catchment volumetric reliabilities (R) are improved by 3.6%, and the overall catchment R50 reliability by an average 5%, from 70-80% to 74-86%.

Effects in the river at minimum flow control points are very similar to the no dam simulations. Amount of time spent at minimum flow is still substantial, and the river still has the potential to be dried up below the major takes such as Omakau IC and Manuherikia IC.

Table 5-6: Reliability for four scenarios with calculated dam inflows and maximum actual rates. The right-hand column combines the results for all sections of the catchment. Maxrate consented is shown in cumecs.

Max Actual, Falls Dam Inflows 2014-2018, Irrigation Season				Dunstan			Ophir			Campground	
Scenario 1 (Status Quo)				0			0.82			0.9	
Scenario 2 (Low Range)				0.4			1.5			1.25	
Scenario 3 (Mid Range)				0.6			1.75			1.6	
Scenario 4 ('Naturalised')				0.75			2.5			2.5	
MaxRate actual	0.745	0.466	0.716	1.075	0.403	1.981	0.87	2.703	0.326	0.338	10.680
Scenario 1 (Status Quo)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	71%	64%	92%	99%	83%	80%	72%	60%	61%	76%
R1	41%	43%	36%	79%	98%	62%	76%	55%	54%	57%	33%
R50	64%	71%	60%	93%	100%	87%	80%	68%	57%	61%	80%
R2	100%	100%	100%	100%	99%	97%	86%	99%	71%	67%	99%
Scenario 2 (Low Range)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	71%	64%	81%	97%	81%	75%	75%	56%	54%	75%
R1	41%	43%	36%	61%	96%	62%	69%	54%	53%	52%	33%
R50	64%	71%	60%	84%	97%	84%	75%	72%	56%	54%	79%
R2	99%	98%	100%	96%	97%	95%	80%	99%	59%	56%	99%
Scenario 3 (Mid Range)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	70%	64%	74%	95%	80%	73%	73%	53%	50%	73%
R1	41%	43%	36%	55%	95%	62%	67%	53%	51%	49%	33%
R50	64%	71%	60%	76%	96%	83%	74%	68%	53%	51%	76%
R2	98%	96%	100%	90%	96%	94%	79%	99%	54%	51%	99%
Scenario 4 ('Naturalised')											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	67%	70%	63%	69%	90%	75%	64%	67%	47%	45%	68%
R1	41%	43%	36%	51%	89%	59%	59%	48%	46%	45%	33%
R50	64%	71%	60%	69%	90%	76%	64%	62%	47%	46%	70%
R2	94%	93%	96%	88%	91%	88%	70%	95%	47%	46%	96%

Table 5-7: Reliability for four scenarios with measured dam outflows and maximum actual rates. The right-hand column combines the results for all sections of the catchment. Maxrate consented is shown in cumecs.

Max Actual, Falls Dam Outflow 2014-2018, Irrigation Season				Dunstan			Ophir			Campground	
Scenario 1 (Status Quo)				0			0.82			0.9	
Scenario 2 (Low Range)				0.4			1.5			1.25	
Scenario 3 (Mid Range)				0.6			1.75			1.6	
Scenario 4 ('Naturalised')				0.75			2.5			2.5	
MaxRate actual	0.745	0.466	0.716	1.075	0.403	1.981	0.87	2.703	0.326	0.338	10.680
Scenario 1 (Status Quo)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	71%	64%	92%	99%	94%	86%	74%	61%	61%	80%
R1	41%	43%	36%	79%	100%	79%	82%	57%	55%	58%	34%
R50	64%	71%	60%	93%	100%	98%	87%	73%	58%	61%	86%
R2	100%	99%	100%	100%	99%	99%	91%	99%	71%	67%	99%
Scenario 2 (Low Range)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	71%	63%	81%	99%	92%	81%	77%	57%	55%	78%
R1	41%	43%	36%	61%	100%	77%	75%	56%	54%	53%	34%
R50	64%	71%	60%	84%	100%	96%	82%	74%	57%	55%	84%
R2	99%	99%	100%	96%	99%	99%	85%	99%	60%	57%	99%
Scenario 3 (Mid Range)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	71%	63%	74%	99%	91%	80%	75%	54%	52%	76%
R1	41%	43%	36%	55%	100%	76%	73%	55%	53%	51%	34%
R50	64%	71%	60%	76%	100%	94%	80%	71%	54%	52%	82%
R2	99%	99%	100%	90%	99%	99%	85%	99%	55%	53%	99%
Scenario 4 ('Naturalised')											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	68%	71%	63%	69%	98%	85%	70%	69%	48%	46%	72%
R1	41%	43%	36%	51%	98%	71%	63%	49%	47%	45%	34%
R50	64%	71%	60%	69%	99%	86%	70%	63%	48%	47%	74%
R2	99%	99%	99%	88%	98%	97%	76%	99%	48%	47%	99%

Table 5-8: Differences in reliability between calculated dam inflow and measured dam outflow scenarios.

With and without dam											
Scenario 1 (Status Quo)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	0.0%	0.0%	0.0%	0.0%	0.7%	11.2%	5.7%	2.7%	0.9%	0.0%	3.6%
R1	0.0%	0.0%	0.0%	0.0%	2.0%	17.0%	6.0%	2.0%	1.0%	1.0%	1.0%
R50	0.0%	0.0%	0.0%	0.0%	0.0%	11.0%	7.0%	5.0%	1.0%	0.0%	6.0%
R2	0.0%	-1.0%	0.0%	0.0%	0.0%	2.0%	5.0%	0.0%	0.0%	0.0%	0.0%
Scenario 2 (Low Range)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	0.1%	0.1%	0.0%	0.0%	2.9%	11.4%	6.4%	1.9%	0.9%	1.1%	3.7%
R1	0.0%	0.0%	0.0%	0.0%	4.0%	15.0%	6.0%	2.0%	1.0%	1.0%	1.0%
R50	0.0%	0.0%	0.0%	0.0%	3.0%	12.0%	7.0%	2.0%	1.0%	1.0%	5.0%
R2	0.0%	1.0%	0.0%	0.0%	2.0%	4.0%	5.0%	0.0%	1.0%	1.0%	0.0%
Scenario 3 (Mid Range)											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	0.3%	0.4%	-0.1%	0.0%	4.1%	11.0%	6.3%	1.9%	1.3%	1.1%	3.7%
R1	0.0%	0.0%	0.0%	0.0%	5.0%	14.0%	6.0%	2.0%	2.0%	2.0%	1.0%
R50	0.0%	0.0%	0.0%	0.0%	4.0%	11.0%	6.0%	3.0%	1.0%	1.0%	6.0%
R2	1.0%	3.0%	0.0%	0.0%	3.0%	5.0%	6.0%	0.0%	1.0%	2.0%	0.0%
Scenario 4 ('Naturalised')											
Site Name	Lauder	Thomsons	Chatto	Dunstan	Blackstone	Omakau	Ophir	WM0062	Galloway	Campground	Manuherekia
R	0.9%	1.1%	0.3%	0.0%	8.1%	10.3%	5.8%	1.5%	1.2%	0.9%	3.6%
R1	0.0%	0.0%	0.0%	0.0%	9.0%	12.0%	4.0%	1.0%	1.0%	0.0%	1.0%
R50	0.0%	0.0%	0.0%	0.0%	9.0%	10.0%	6.0%	1.0%	1.0%	1.0%	4.0%
R2	5.0%	6.0%	3.0%	0.0%	7.0%	9.0%	6.0%	4.0%	1.0%	1.0%	3.0%

5.6 CHES summary

A CHES model has been built using the TopNet output as described in Section 4. Rules for minimum flow are placed at Dunstan Creek, Ophir and Campground. Water takes are amalgamated on each of the major tributaries (Chatto Creek, Lauder Creek, Thomsons Creek, Dunstan Creek) to be effective at their respective confluences with the Manuherekia River. The exceptions are for Mt Ida Race, assumed to act at the Falls Dam, but only tapping into 30% of the flow there, and the Ida Burn and Manor Burn, whose takes are lumped together with other smaller ones at Ophir and Campground, respectively. Major takes on the main stem are treated individually.

The take scenarios modelled have used constant take rates throughout the year, but we have reported only on irrigation season (October through April) results. The main scenarios have used the maximum rate of take as consented and the maximum rate of take as measured for each of the lumped sub-catchments and individual meters modelled.

Effects of minimum flows on amount of water able to be abstracted and flow in the river below take points has been represented generally by flow duration curves for the irrigation season. Results show that where a minimum flow exists, it does provide a bottom line for the river, but that this minimum may become the resulting flow in the river for a significant fraction of the time (around 30%, 40% and 45% of the time at Dunstan Creek, Ophir and Campground, respectively). Downstream or upstream of these minimum flow points, major takes can still result in zero flow in the river.

6 Summary and next steps

A TopNet-CHES model has been developed for the Manuherekia River in Central Otago. Flow data have been naturalised by adding back measured water take data to the recorded flows in the river. The TopNet model is calibrated to those naturalised flows, with an emphasis on the low flow range. A CHES implementation provides results in the river and for irrigation water takes, based on maximum rates of take (consented and measured). Four minimum flow scenarios have been modelled, and results presented as flow duration curves, with some other illustrative output related to reliability over time and its seasonality.

The possible effect of the Falls Dam has also been modelled by substituting measured dam inflows and outflows for the modelled flows in the main stem downstream of the dam for a short period (three irrigation seasons) of recent time.

The work described in this report is a substantial proportion of the work to be done in what is now regarded as phase one of the project.

Important caveats are:

- The catchment modelled here is void of any storages, managed or otherwise;
- There are no redistribution facilities (water races etc);
- Water is deemed to be fully used once taken; i.e., none returns to the river either at the point of take or at any other location or through diffuse land surface recharge from irrigation.

Issues with CHES dealing with take points remote from their respective control points have been addressed. Mapping statistics onto the river network to illustrate the results remains a problem.

Phase two may include:

- Consideration of the water meter data QA and verification of the natural flows, and possibly use of a soil water balance model for return flows;
- Further measurements in the catchment to help understand natural recession behaviour and the relationships amongst tributary flows;
- Possible further development of scenarios by ORC; and
- Possible extension of the exploration of effects of abstraction into tributaries, as distinct from this phase which considers only main stem effects.

7 Glossary of abbreviations and terms

CHES	Cumulative Hydrological Effects Simulator
Q_{min}	The minimum flow in the river at the management reach for a given abstraction allocation and allocation block (also known as the management flow).
ΔQ	The total consented or proposed allocation
Q_{max}	The maximum flow cut-off, for a given abstraction allocation and allocation block. This is used in situations where an upper river flow condition is placed on the allocation. Such restrictions may be imposed to avoid abstraction of dirty water during flood flows.
reference scenario	The name of the scenario that will be used as a reference for display of attributes where a reference is needed.
active scenario	The name of the scenario that will be used as input when a CHES simulation is executed (using the “Run” button on the CHES Main Window), and for which a modified flow time series will be computed, and results visualised within CHES.
take	A simple abstraction type in which water is taken from the river and used directly.
Storage	An abstraction type, like a “take”, but including an offline storage pond, that is modelled as a rectangular basin of uniform depth. Water is taken from the river and put into the storage pond under the consented rules. The water is then taken from the storage pond and used based on additional rules. Constraints on maximum and minimum storage levels are applied. Water that cannot be stored because the pond is full is assumed to be used directly.
abstraction reach number	The reach number for an abstraction that defines the reach from which the water is physically taken from.
management reach number	The reach number of a reach at which the consented allocation rules are applied. Usually, this is the same as abstraction reach, but it need not be.
discharge reach number	The reach into which the water taken from the abstraction reach is diverted into.
touched reach	A reach that either contains an abstraction or is connected to an upstream reach that contains an abstraction. The flow in a touched reach will, in general, as a result of these abstractions, differ from the natural flow.

8 Acknowledgements

For provision of CHES base layers for the Otago region, Ude Shankar. For the CHES development, and work on coding problems, Jeremy Walsh at NIWA Christchurch.

For water meter data, Marc Ettema and other staff at ORC. For flow and temperature data, Pete Stevenson and other staff at ORC. For field checking of meters, Pete Ravenscroft and Jason Augspurger at ORC.

9 References

Bandaragoda, C., Tarboton, D.G., Woods, R.A. (2004) Application of TOPNET in the distributed model intercomparison project. *J. Hydrol.*, 298:178-201.

Beven, K.J., Lamb, R., Quinn, P., Romanowicz, R., Freer, J. (1995) TOPMODEL. In: *Computer Models of Watershed Hydrology*, edited by: Singh, V.P., Water Resour. Publ., Highlands Ranch, Colorado, 627–668.

Booker, D.J., Woods, R.A. (2013) Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology*, 508: 227-239.

Clark, M.P., Rupp, D.E., Woods, R.A., Zheng, X., Ibbitt, R.P., Slater, A.G., Schmidt, J., Uddstrom, M.J. (2008) Hydrological data assimilation with the ensemble Kalman filter: Use of streamflow observations to update states in a distributed hydrological model. *Advances in Water Resources*, 31(10): 1309-1324. 10.1016/j.advwatres.2008.06.005

Collins, D., Zammit, C., Willsman, A., Henderson, R. (2015) Surface water components of New Zealand's National Water Accounts, 1995-2014. Prepared for the Ministry for the Environment. *NIWA Client Report CHC2015-013*: 18.

Duan, Q., S. Sorooshian, and V. Gupta (1992). Effective and efficient global optimization for conceptual rainfall-runoff models, *Water Resour. Res*., 28(4), 1015–1031, doi:10.1029/91WR02985

Goring, D.G. (1994) Kinematic shocks and monoclinal waves in the Waimakariri, a steep, braided, gravel-bed river. *Proceedings of the International Symposium on Waves: Physical and Numerical Modelling*, University of British Columbia, Vancouver, Canada, 21–24 August, 1994, pp. 336–345.

Ibbitt, R.P., Woods, R. (2002) Towards rainfall-runoff models that do not need calibration to flow data, in: Friend 2002 – Regional Hydrology: Bridging the Gap Between Research and Practice, edited by: van Lanen, H. A. J. and Demuth, S., IAHS Publ., 274, 189–196.

McMillan, H., Clark, M., Bowden, W.B., Duncan, M.J., Woods, R. (2011) Hydrological field data from a modeller's perspective. Part 1: diagnostic tests for model structure. *Hydrol. Process*. 25 (4), 511–522.

McMillan, H.K., Hreinsson, E.O., Clark, M.P., Singh, S.K., Zammit, C., Uddstrom, M.J. (2013) Operational hydrological data assimilation with the recursive ensemble Kalman Filter. *Hydrol. Earth Syst. Sci.*, 17, 21-38.

McMillan, H.K., Booker, D.J., Cattoen, C. (2016) Validation of a national hydrological model. *Journal of Hydrology*, 541: 800-815. 10.1016/j.jhydrol.2016.07.043.

Ministry for the Environment. (2017) *National Policy Statement for Freshwater Management*. Wellington, p. 31.

Newsome, P.F.J., Wilde, R.H., Willoughby, E.J. (2000) Land Resource Information System Spatial Data Layers, Technical Report, Palmerston North, Landcare Research NZ Ltd., New Zealand.

Olsen, D., Lu, X., Ravenscroft, P. (2017) Management flows for aquatic ecosystems in the Manuherikia River and Dunstan Creek: 92.

Snelder, T.H., Biggs, B.J.F. (2002) Multiscale river environment classification for water resources management. *Journal of the American Water Resources Association*, 38:1225-1239.

Stewart, D. (2012) Falls Dam Inflows 1975-2012. Report prepared for Aqualinc Research Ltd: 29.

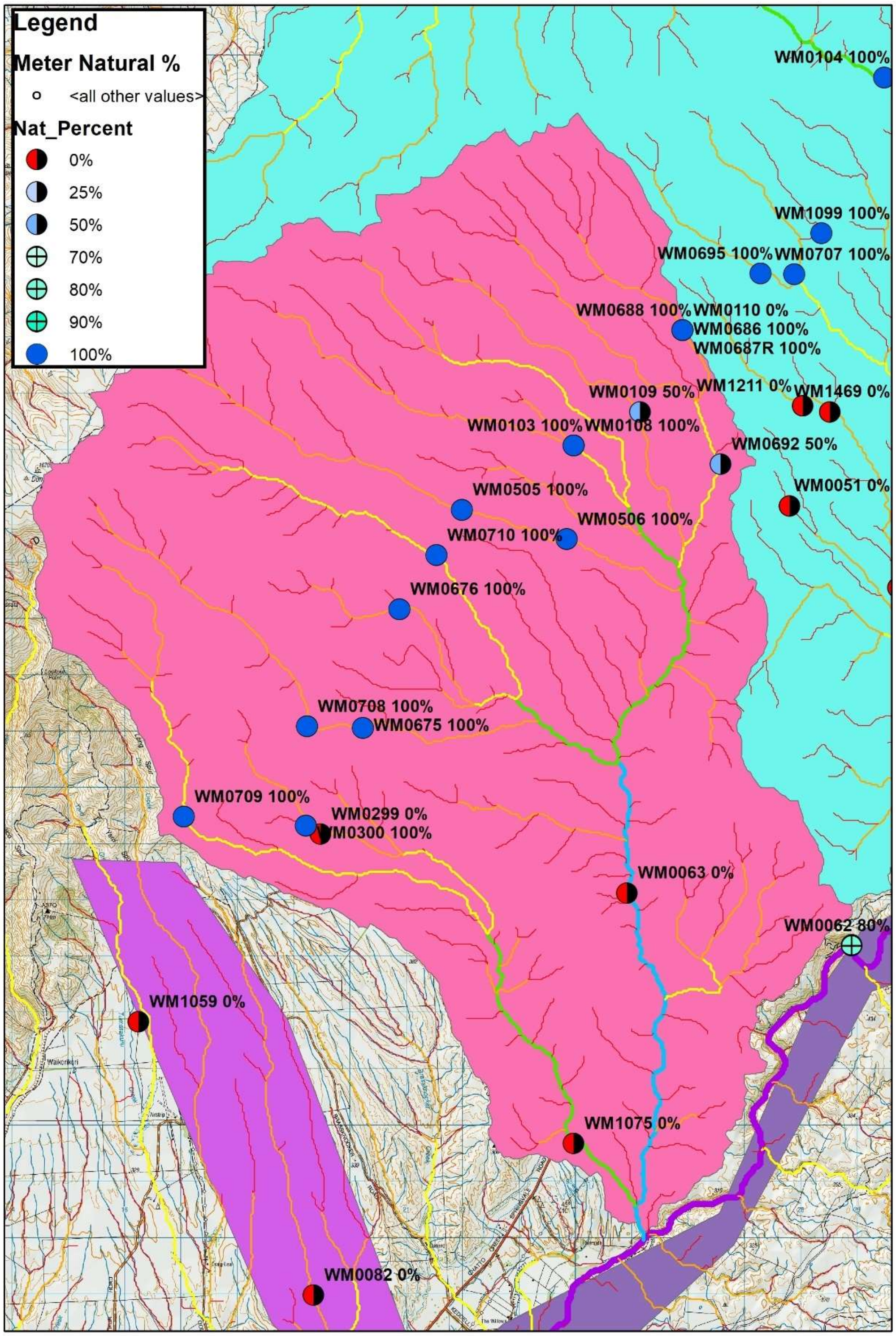
Tait, A., Henderson, R.D., Turner, R., Zheng, X. (2006) Thin plate smoothing spline interpolation of daily rainfall for New Zealand using a climatological rainfall surface. *International Journal of Climatology*, 26: 2097-2115.

Woods, R.A., Hendrikx, J., Henderson, R.D., Tait, A.B. (2006) Mean flow hydrology of New Zealand rivers. *Journal of Hydrology (NZ), 45*(2): 95-110.

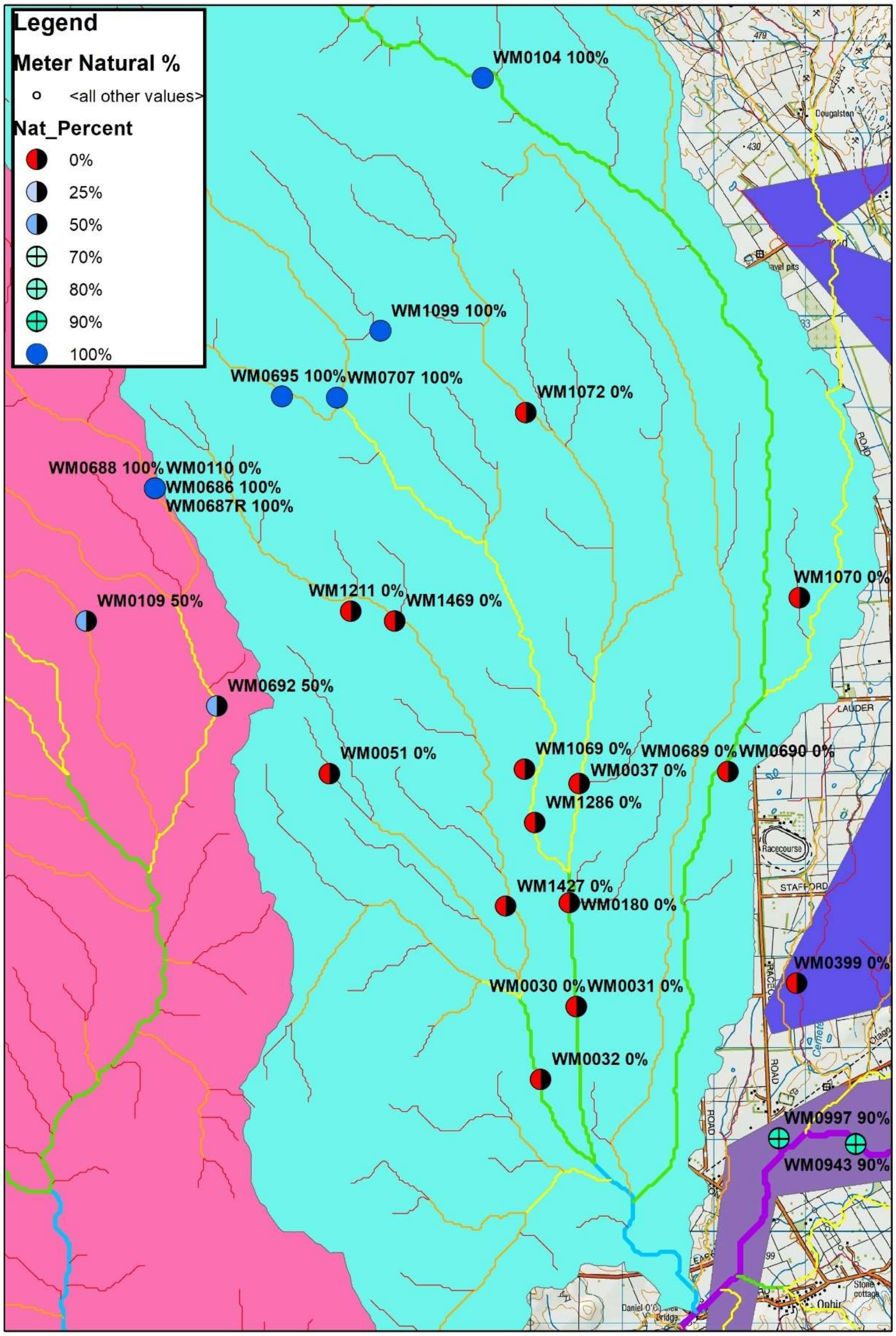
Yang, J., McMillan, H., and Zammit, C. (2016) Modelling Surface water-groundwater interaction in New Zealand: Model development and application. *Hydrological Processes*, 2017;31:925–934, DOI 10.1002/hyp.11075

Appendix A Sub-catchment maps of meters

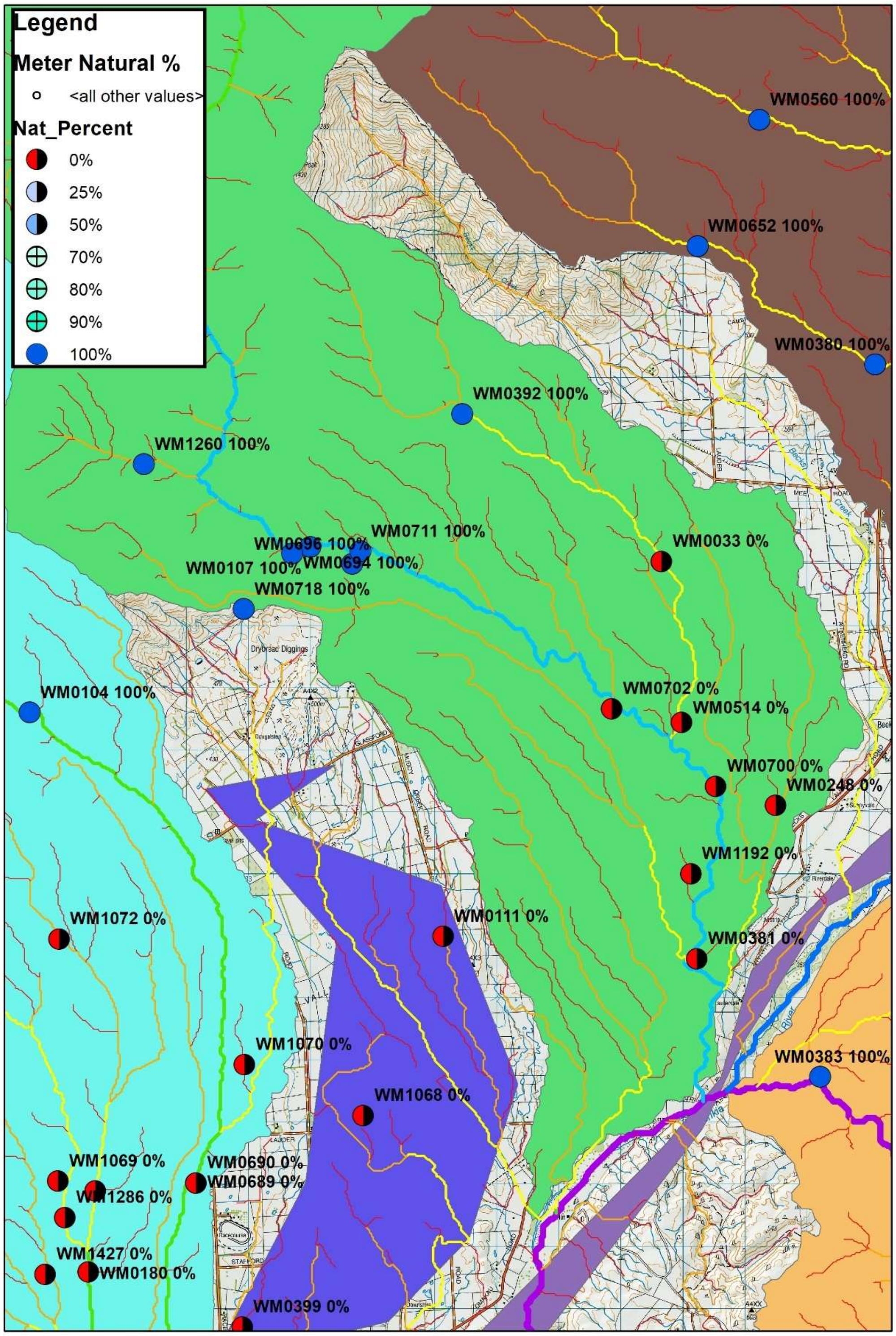
Map of Chatto Creek catchment



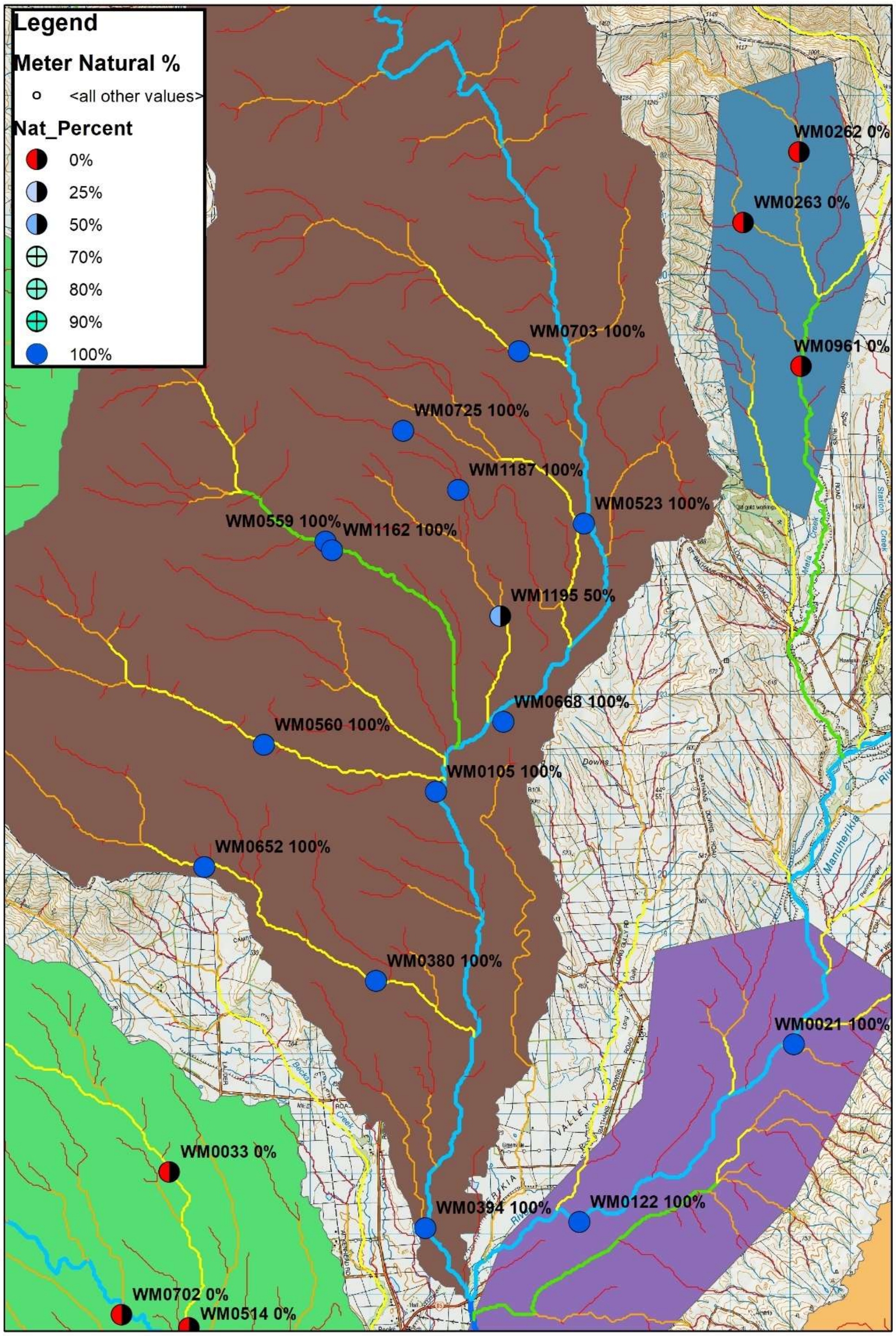
Map of Thomsons Creek



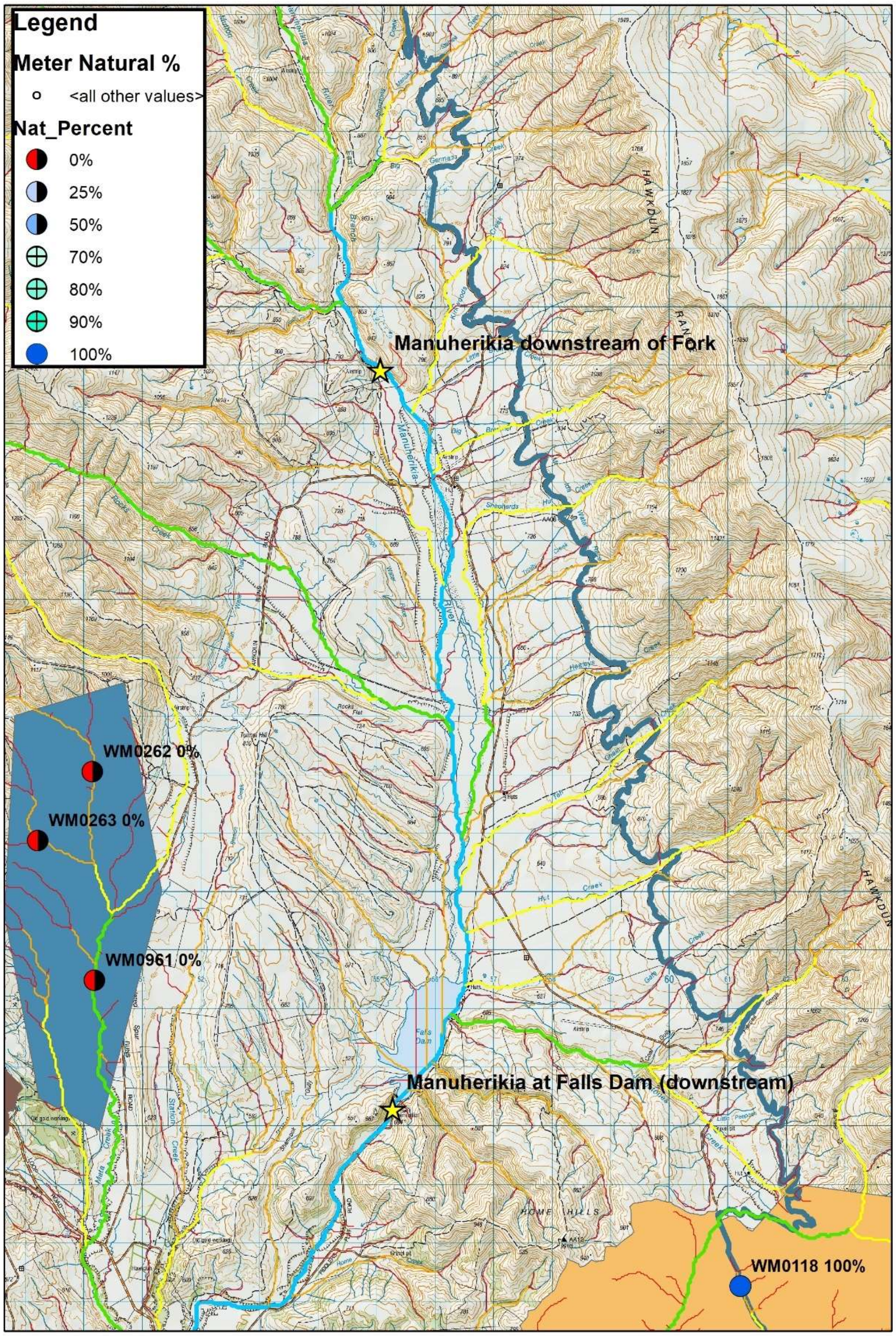
Map of Lauder Creek



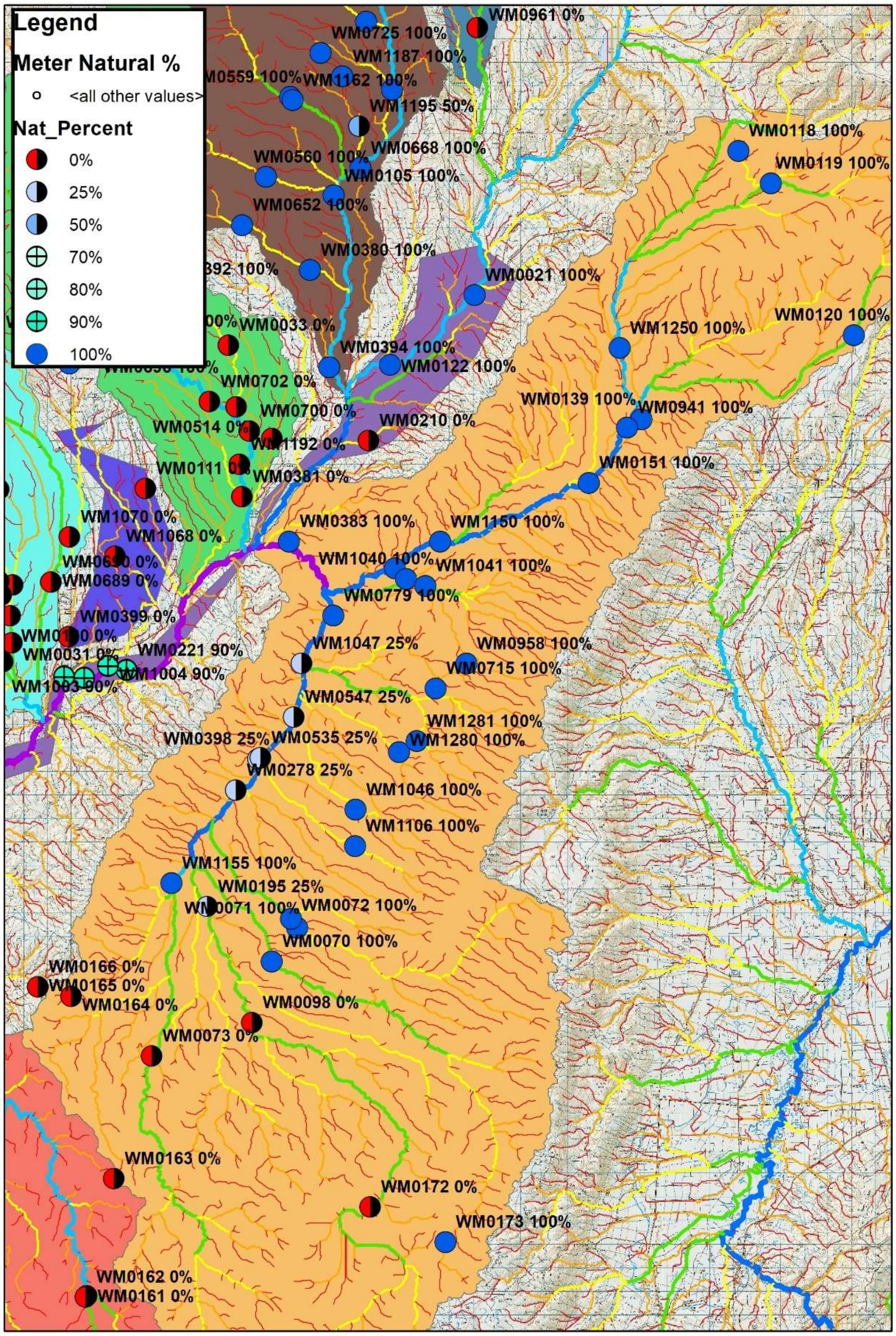
Map of Dunstan Creek



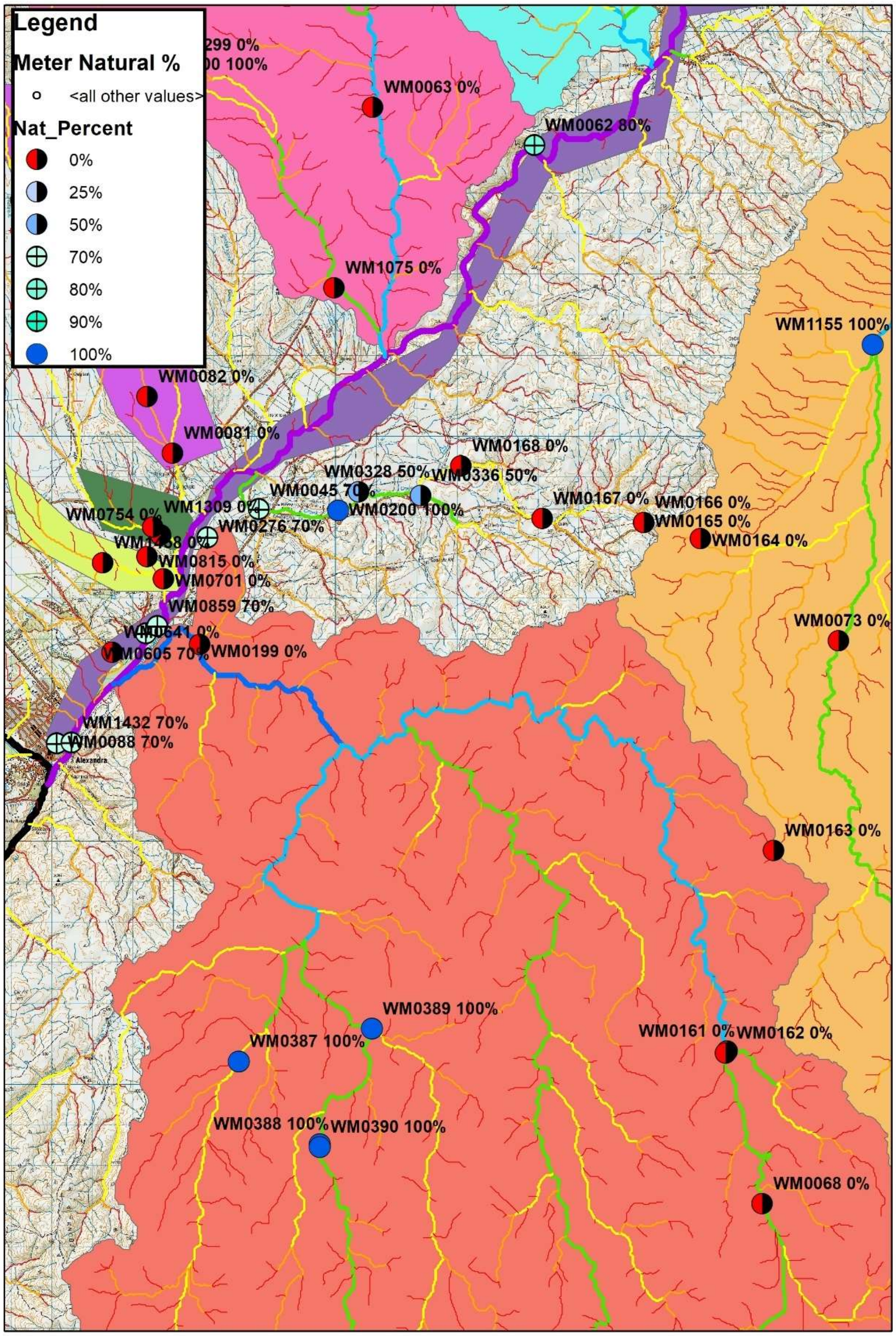
Map of Above Falls Dam



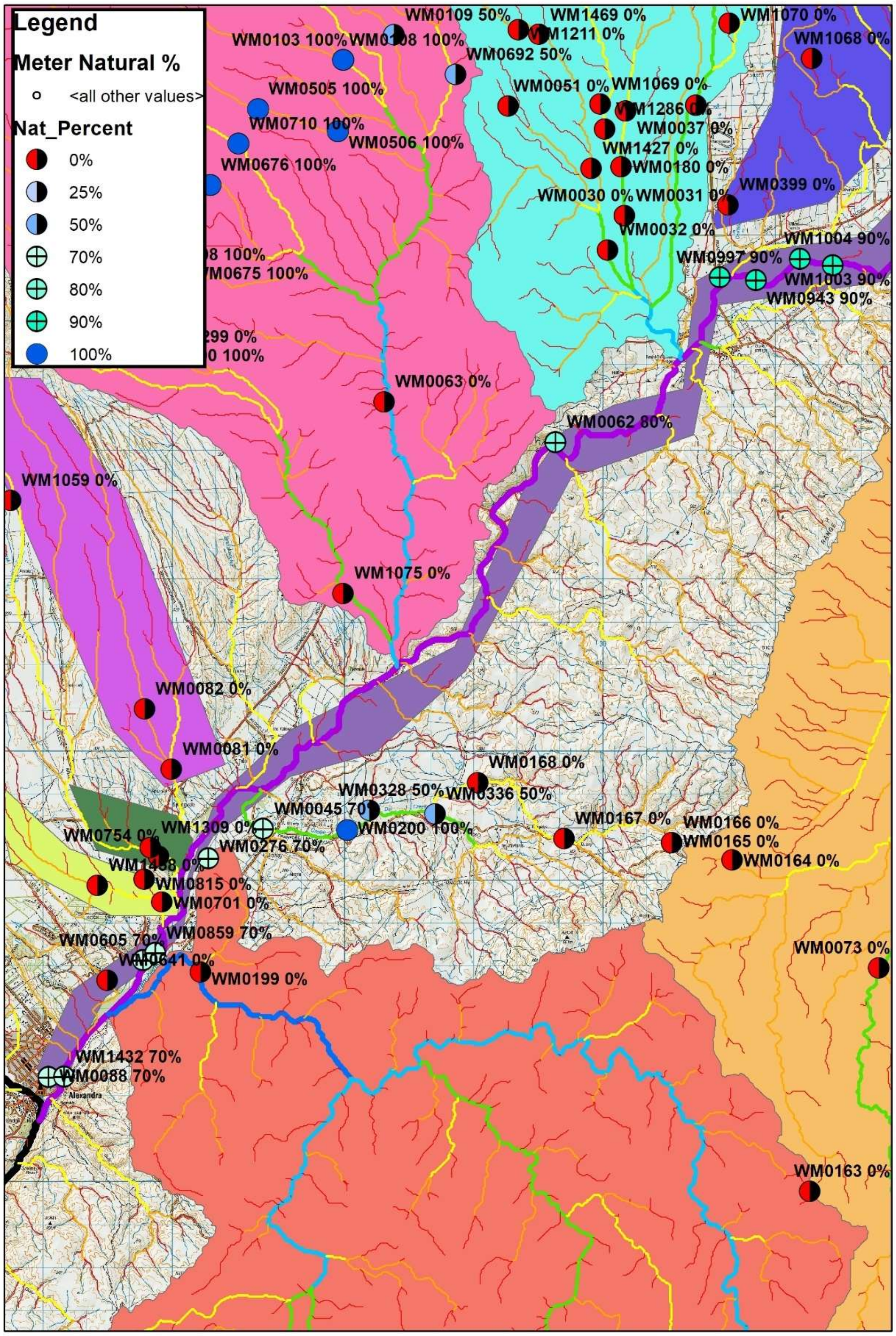
Map of Pool & Ida Burn



Map of Manor Burn



Map of Main Stem



Appendix B Time series plots of water use by sub-catchment

Chatto Creek water use

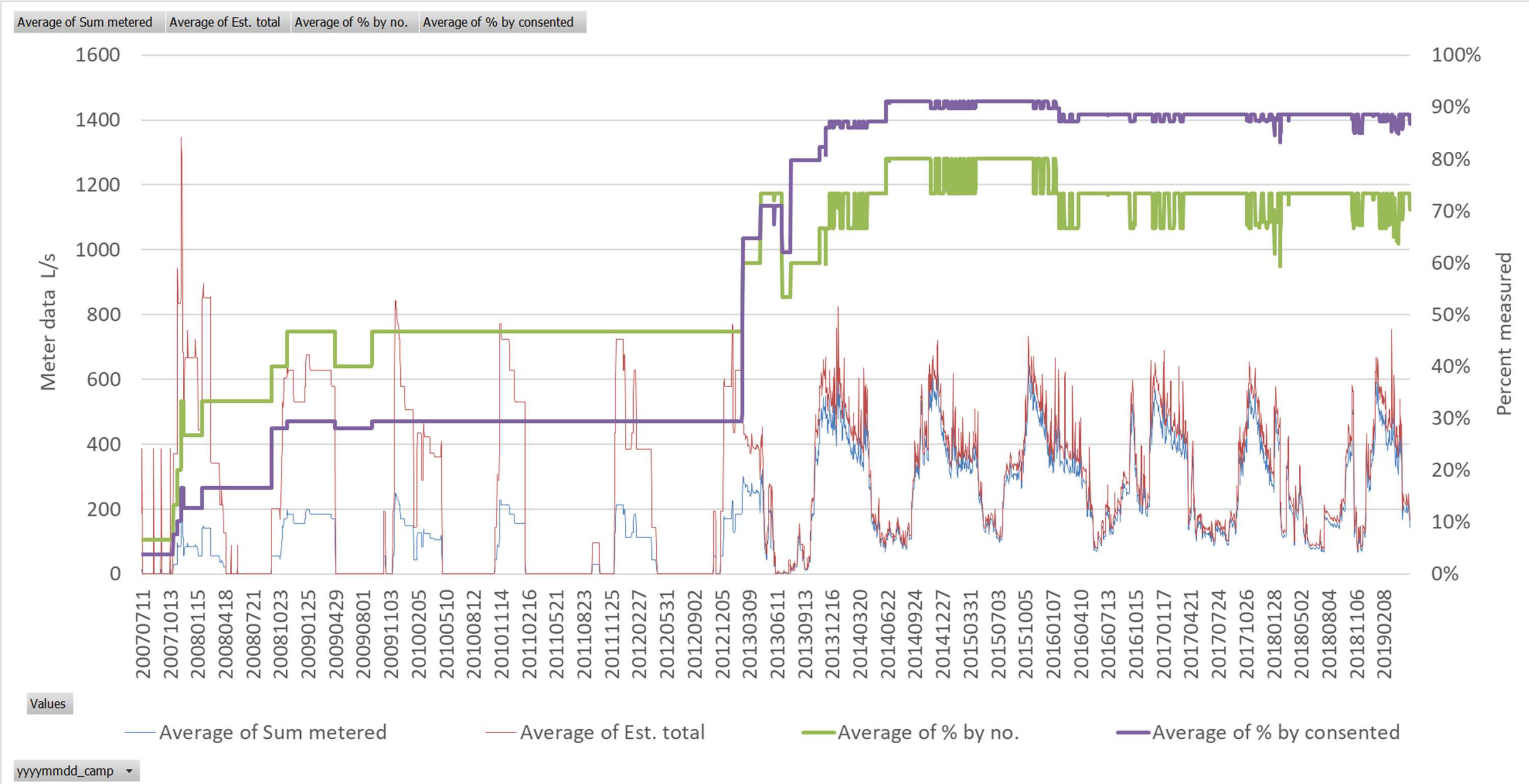


Figure B-1: Chatto Creek naturalisation. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Thomsons Creek water use

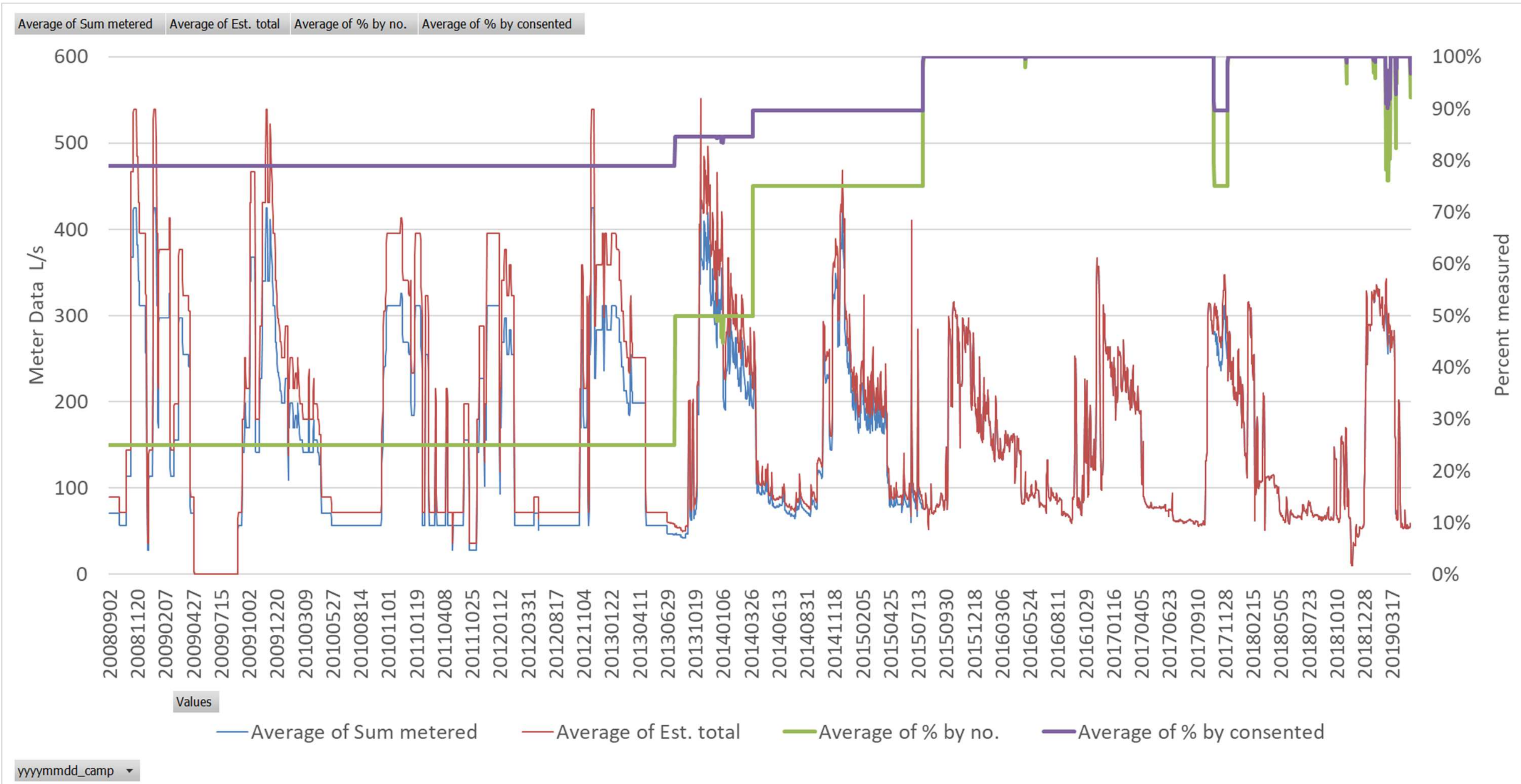


Figure B-2: Thomsons Creek naturalisation. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Lauder Creek water use

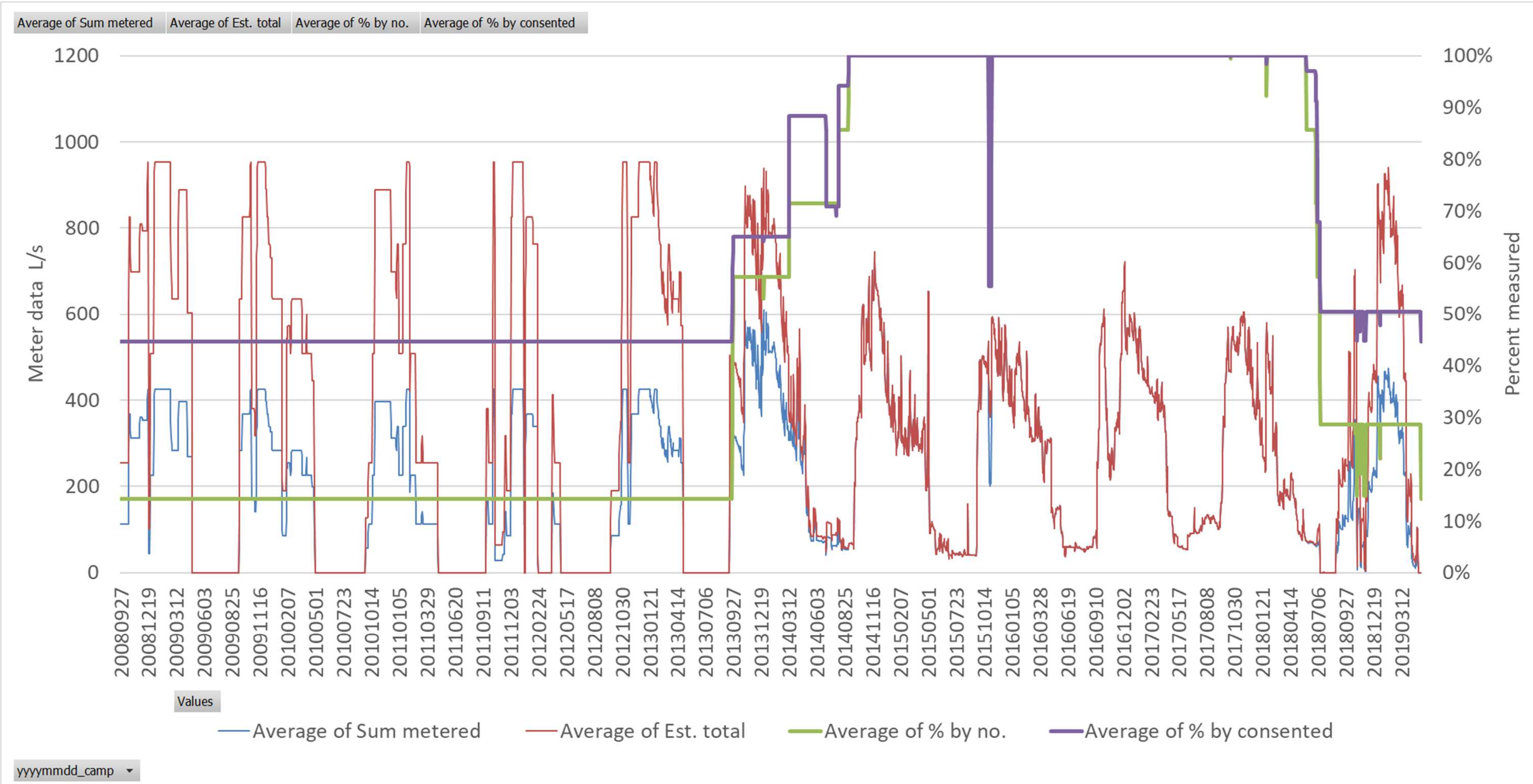


Figure B-3: Lauder Creek naturalisation. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Dunstan Creek water use

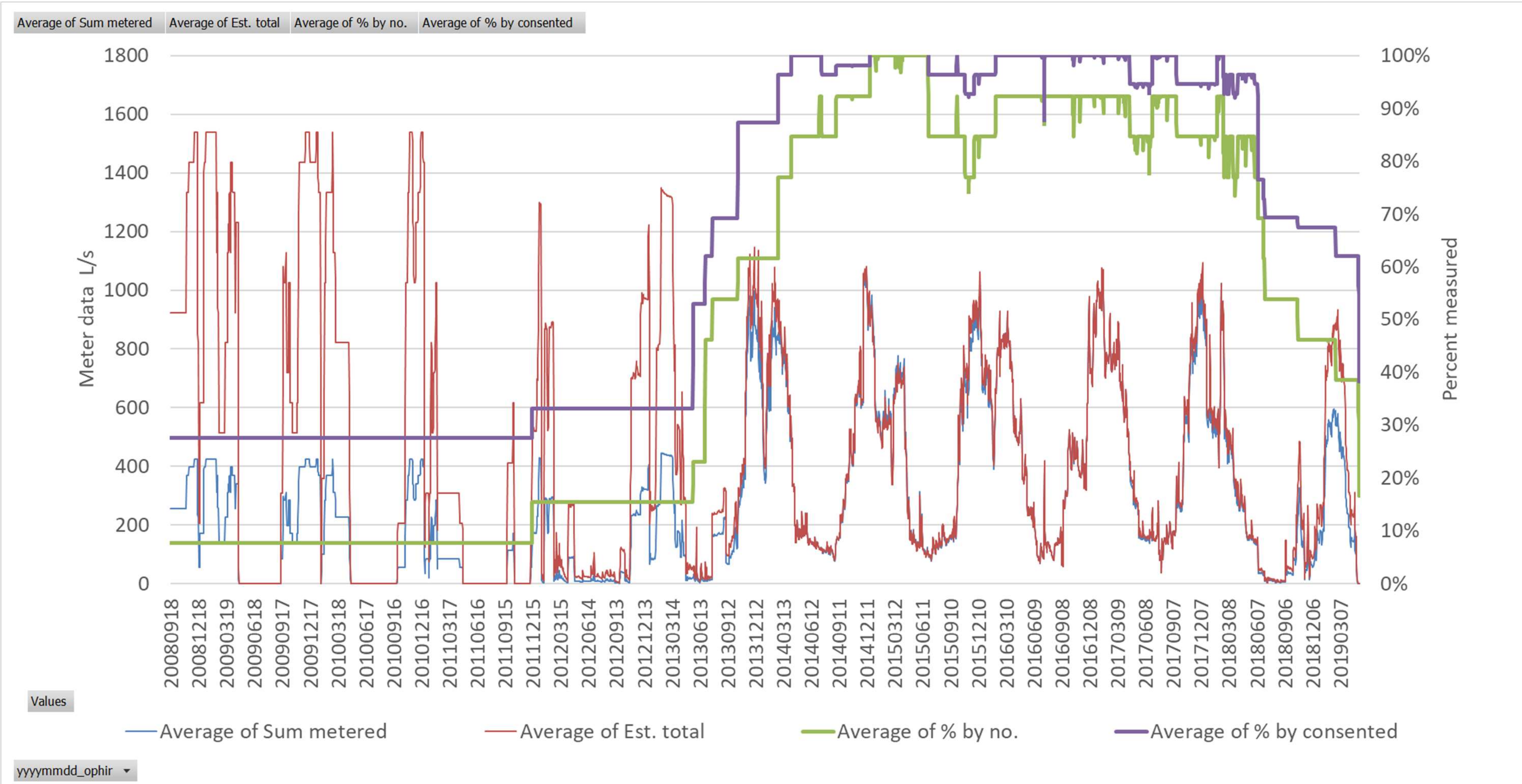


Figure B-4: Dunstan Creek naturalisation. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Above Falls Dam water use

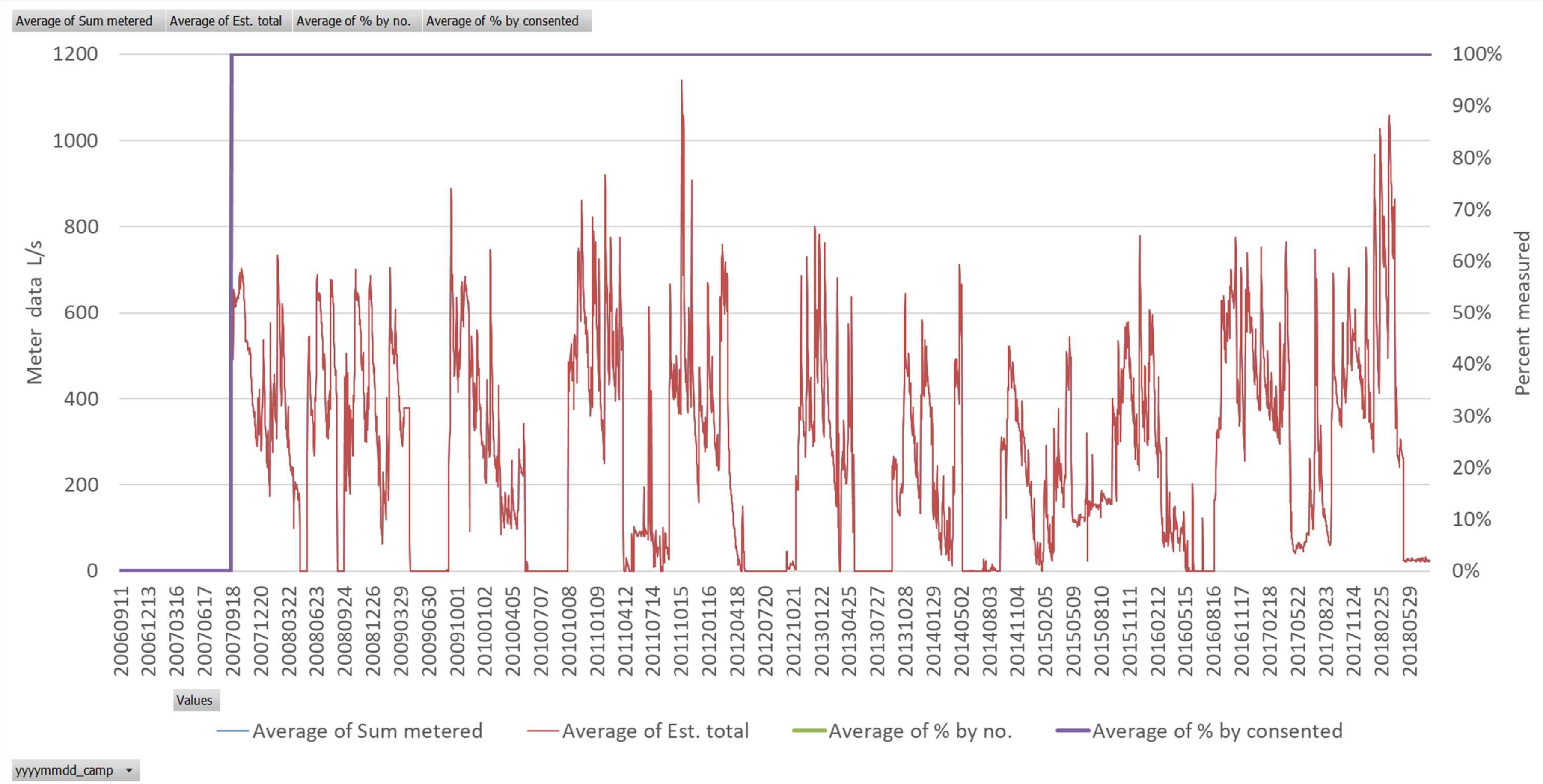


Figure B-5: Falls Dam water use. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick purple line shows percentage by consented maximum rate. The thin red line is the adjusted water use estimated from the percentage by maximum rate. In this case only one meter applies so adjustments are not needed.

Pool Burn and Ida Burn water use

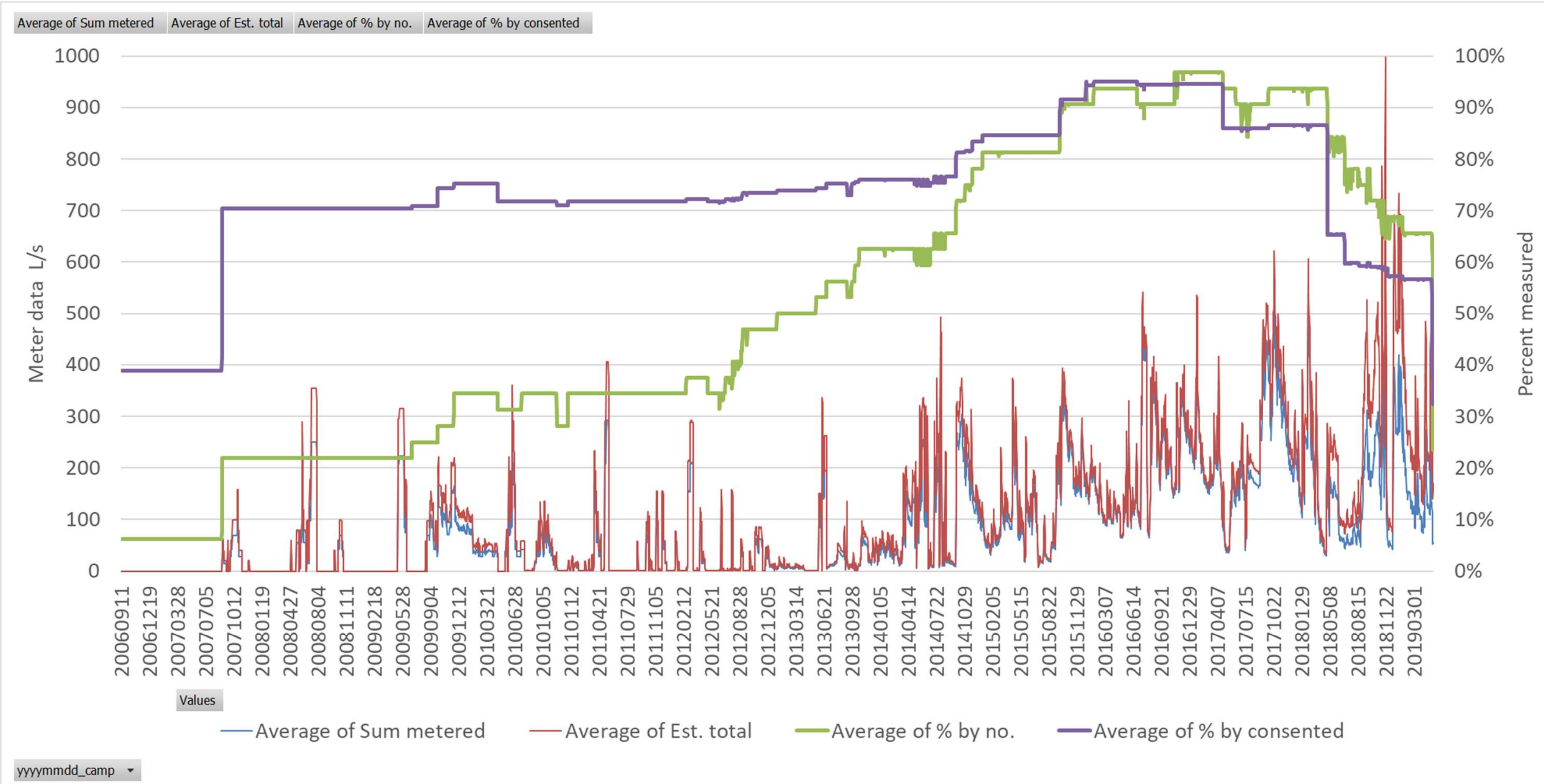


Figure B-6: Pool Burn and Ida Burn naturalisation. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Manor Burn water use

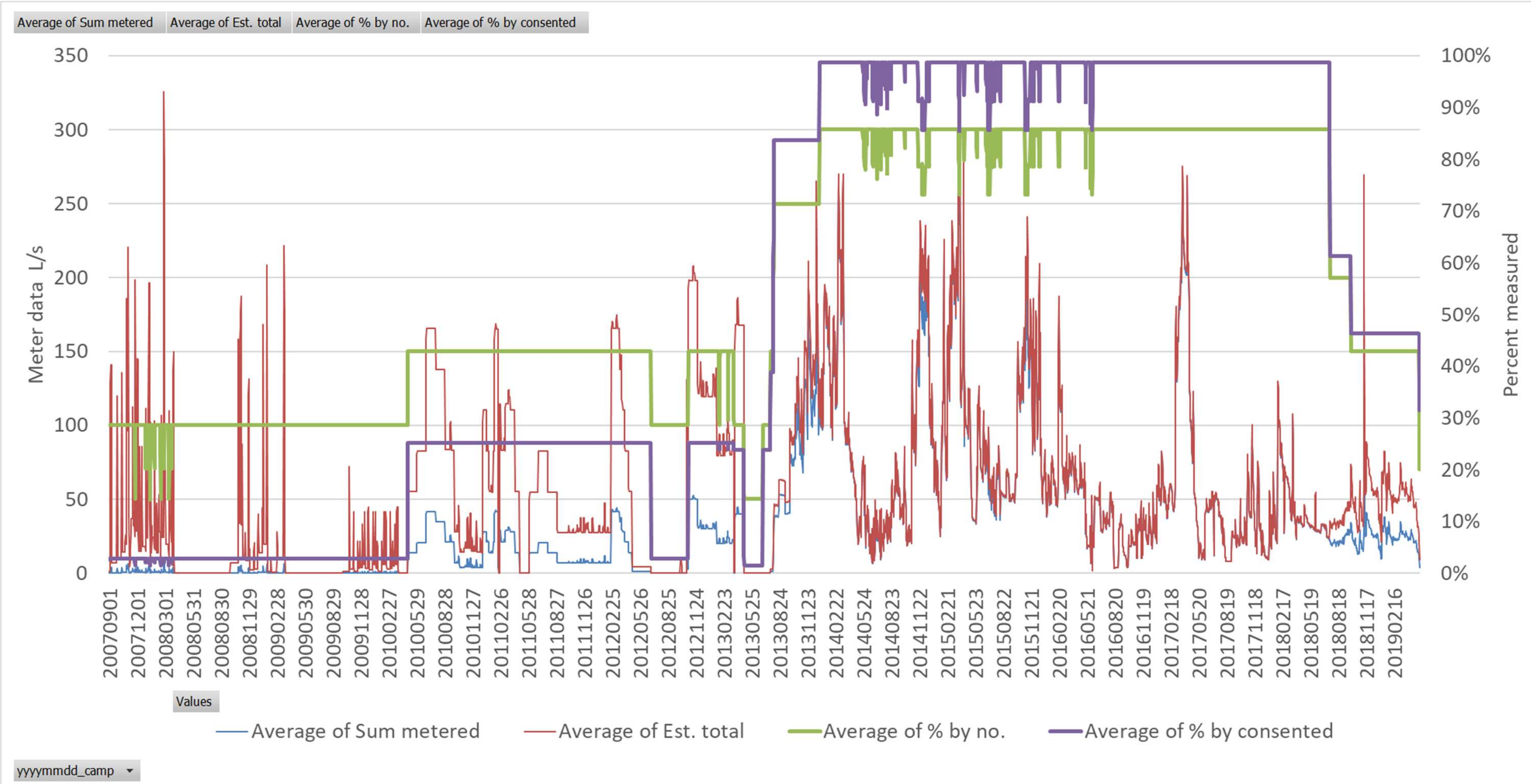


Figure B-7: Manor Burn naturalisation. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Main Stem water use below Falls Dam

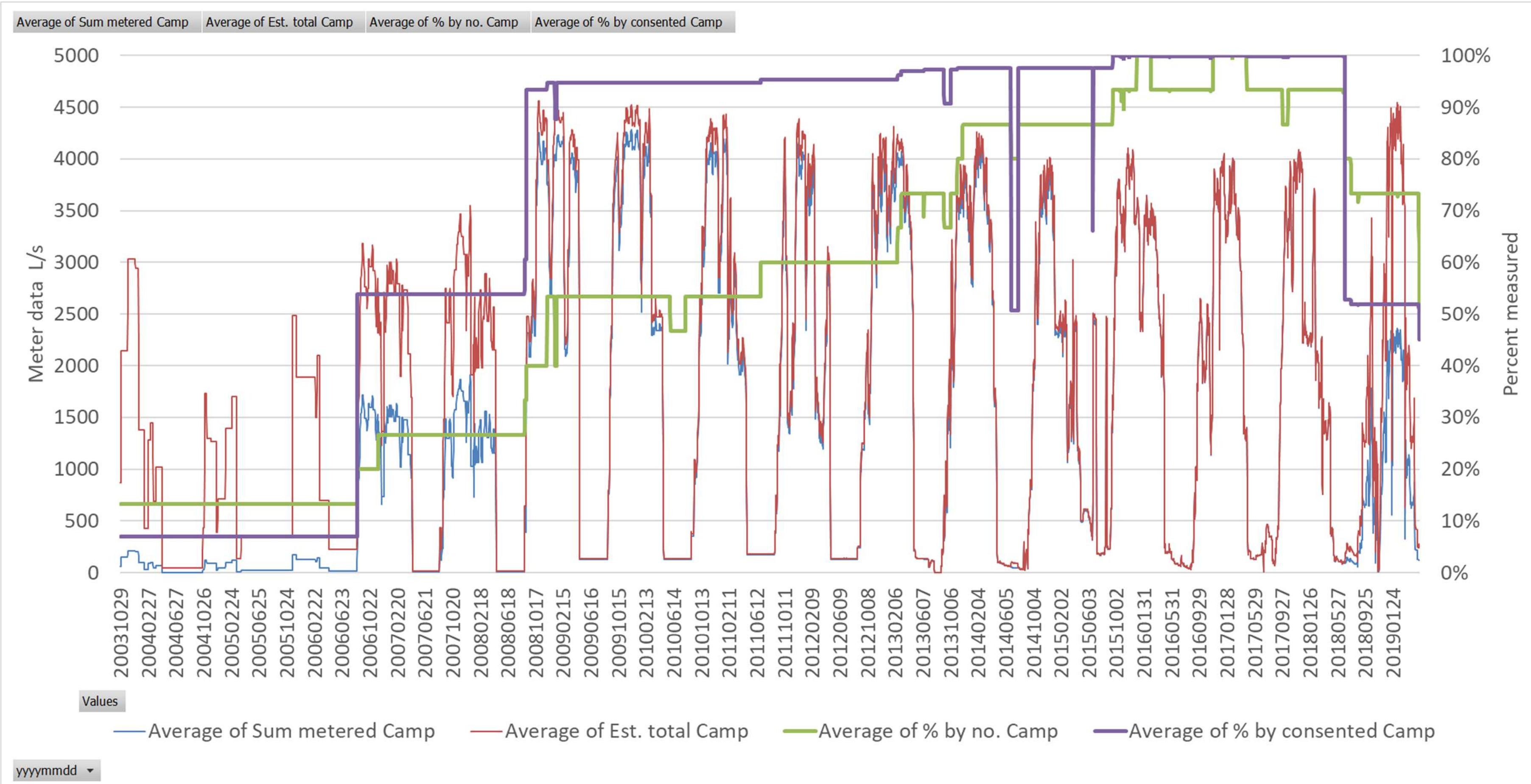


Figure B-8: Main stem naturalisation at Campground. Left Y-axis shows total water meter use, right Y-axis shows percent of total use measured. The thick green line shows percentage by number of meters, purple shows percentage by consented maximum rate. The thin blue line is the sum of the meters with data, and the thin red line is the adjusted water use estimated from the percentage by maximum rate.

Appendix C List of water meters by sub-catchment

Site	Max Rate (L/s)	sub-catchment	Natural Percent (%)
WM0103	84.9	Chatto Creek	100
WM0108	56.6	Chatto Creek	100
WM0109	28.3	Chatto Creek	50
WM0300	83.8	Chatto Creek	100
WM0505	83.3	Chatto Creek	100
WM0506	56	Chatto Creek	100
WM0675	111.111	Chatto Creek	100
WM0676	55.56	Chatto Creek	100
WM0686	253.13	Chatto Creek	100
WM0687R	55.56	Chatto Creek	100
WM0688	253.13	Chatto Creek	100
WM0692	83.33	Chatto Creek	50
WM0708	388.9	Chatto Creek	100
WM0709	388.9	Chatto Creek	100
WM0710	388.9	Chatto Creek	100
WM0104	424.5	Thomsons Creek	100
WM0695	55.55	Thomsons Creek	100
WM0707	30.55	Thomsons Creek	100
WM1099	55.54	Thomsons Creek	100
WM0107	424.5	Lauder Creek	100
WM0392	222.2	Lauder Creek	100
WM0694	55.55	Lauder Creek	100
WM0696	27.8	Lauder Creek	100
WM0711	111.11	Lauder Creek	100
WM0718	125.1	Lauder Creek	100
WM1260	125.1	Lauder Creek	100
WM0105	424.5	Dunstan Creek	100
WM0380	111.2	Dunstan Creek	100
WM0394	111.11	Dunstan Creek	100
WM0523	83.33	Dunstan Creek	100
WM0559	27.775	Dunstan Creek	100
WM0560	307	Dunstan Creek	100
WM0652	28	Dunstan Creek	100
WM0668	277.8	Dunstan Creek	100
WM0703	83.3	Dunstan Creek	100
WM0725	27.78	Dunstan Creek	100
WM1162	27.775	Dunstan Creek	100
WM1187	55.55	Dunstan Creek	100
WM1195	27.78	Dunstan Creek	50
WM0118	1,926	Above Falls Dam	100
WM0119	165	Ida Burn	100
WM0120	250	Ida Burn	100

Site	Max Rate (L/s)	sub-catchment	Natural Percent (%)
WM0139	5	Ida Burn	100
WM0151	227	Ida Burn	100
WM0504	192	Ida Burn	100
WM0779	28	Ida Burn	100
WM0941	5	Ida Burn	100
WM0958	97.26	Ida Burn	100
WM1040	28	Ida Burn	100
WM1041	28	Ida Burn	100
WM1150	42	Ida Burn	100
WM1250	28	Ida Burn	100
WM0070	141.5	Pool Burn	100
WM0071	141.5	Pool Burn	100
WM0072	84.9	Pool Burn	100
WM0173	622.6	Pool Burn	100
WM0195	27.8	Pool Burn	25
WM0278	27.5	Pool Burn	25
WM0383	27.77	Pool Burn	100
WM0398	28	Pool Burn	25
WM0535	48.6	Pool Burn	25
WM0547	27.73	Pool Burn	25
WM0715	83.33	Pool Burn	100
WM1046	115.55	Pool Burn	100
WM1047	21	Pool Burn	25
WM1106	277.77	Pool Burn	100
WM1155	27.8	Pool Burn	100
WM1280	6.9	Pool Burn	100
WM1281	6.94	Pool Burn	100
WM0200	83.33	Manor Burn	100
WM0328	5.24	Manor Burn	50
WM0336	4.95	Manor Burn	50
WM0387	83.33	Manor Burn	100
WM0388	83.33	Manor Burn	100
WM0389	55.6	Manor Burn	100
WM0390	55.6	Manor Burn	100
WM0021	403.4	Main Stem / Blackstone IC	100
WM0122	1981	Main Stem / Omakau IC	100
WM0221	138.88	Main Stem / Ophir	90
WM0943	55.5	Main Stem / Ophir	90
WM0997	35	Main Stem / Ophir	90
WM1003	83.3	Main Stem / Ophir	90
WM1004	83.3	Main Stem / Ophir	90
WM0062	2,830	Main Stem / Manuherekia IC	80
WM0044	424.5	Main Stem / Galloway IC	70
WM0045	424.5	Main Stem / Galloway IC	70

Site	Max Rate (L/s)	sub-catchment	Natural Percent (%)
WM0088	20	Main Stem / Campground	70
WM0276	13.9	Main Stem / Campground	70
WM0605	50	Main Stem / Campground	70
WM0859	2.9	Main Stem / Campground	70
WM1432	6.94	Main Stem / Campground	70