A pressure-state-impact model for freshwater flows

with example application to Canterbury

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Executive summary

Work towards a nationwide pressure-state-impact model for freshwater flows was conducted as part of this project. This work has produced several benefits. A data schema designed as part of this project provides the architecture for a national database containing information describing how water is allocated and how much water is consented across New Zealand. These data could be used to assess the degree to which consent conditions are collectively consistent with conditions specified in regional plans. The schema also provides a potential format under which all future water consents could be administered. A common format for administering consents to take water would have various benefits including:

- Removing ambiguity from consent conditions.
- Ensuring the locations of all takes are recorded.
- Ensuring all consents are linked to management zones.
- Ensuring all consents have a recorded commencement and expiry date.
- Ensuring the possibility of linking all consents with rules in regional plans.
- Easier comparisons between environmental flows specified in regional plans and the consented water use.
- Determining which downstream river reaches are being influenced by each take.
- Easier calculation of cumulative effects.
- Easier calculation of potential headroom.

For a variety of reasons, requested data was not provided to the Ministry for the Environment (MfE) by most regional councils. A full dataset was provided by Environment Canterbury (ECan). This allowed application of a pressure-state-impact model to the Canterbury region for the 2013-14 hydrological year. The pressure-state-impact model was used to quantify how much water is actually available after environmental flow restrictions are applied. The model was also used to calculate maps and time-series of accumulated consented takes, restricted takes and recorded takes down the river network. This downstream accumulation allowed calculation of various states, including the downstream cumulative totals of recorded takes or consented takes, and the proportion of consented water that was recorded to have been taken for those takes being recorded.

A national rainfall-runoff model was tested and then used to estimate naturalised flows. Both cumulative recorded and consented takes were compared with estimated naturalised flows to estimate flows that would have occurred in each reach on each day under each flow scenario. This allowed calculation of estimated river flow states across broad regions on a daily basis. In this project, flow-environmental relationships were developed, tested and then used to convert estimated flow states to estimated potential environmental impacts. In this report, changes in wetted width of river habitat are used to demonstrate an estimated environmental impact.

Results for pressures of the freshwater resource indicated that:

- Takes from surface water are distributed across Canterbury, whereas groundwater takes are concentrated towards the lower lying eastern areas of mid-Canterbury.

- The number of consented activities varied across type of activity and type of take (groundwater or surface water). Irrigation had by far the greatest number of activities, with various numbers of other activities (e.g., public water supply, industrial use, hydro-electric power generation).
- Some consents had constant periods (30 years), whereas others had common expiry dates (e.g., 2027). No consents spanned a period greater than 35 years.
- Many consents are due to expire around 2030.
- The amount of consented water (as represented by maximum daily take) was strongly related to the irrigated area, but this is not always the case.
- Results indicated that many reaches located further from the coast were only influenced by a few upstream takes, whereas there were around 1000 takes on rivers flowing into Te Waihora/Lake Ellesmere.
- Relatively few differences between maps of accumulated consented takes and accumulated consented takes after restrictions were applied indicated that the majority of users were not restricted by environmental flow rules during 2013-14.
- Relatively large differences between allowable takes and recorded takes indicated that, the users who supplied records were not utilising their full allocation. This was particularly the case in early and late summer but less so in late February, when recorded use was nearer to restricted use.

Results for states of the freshwater flows indicated that:

- For individual activities, there was a variety of behaviours relating to compliance and headroom.
- 5% of abstractors were non-compliant when averaged over all time. However, 35% of abstractors with records were non-compliant on their day of maximum take.
- The majority of takes were unrestricted for all of the year. However, some restrictions were enforced all year round. These are takes that are linked to control sites whose flows or groundwater levels never reached levels that allowed any abstractions to occur. Other takes experienced intermittent periods of restriction.
- Cumulated recorded takes were far less than the cumulated consented values, even after having restrictions applied, however, a large proportion of the consents had no associated records.
- The flow that is estimated to not be exceeded 5% of the time under estimated naturalised conditions (natural low flow conditions) is not exceeded for more of the time when greater abstractions occur. Low flows would be particularly prolonged for large proportions of the time in small rivers if all abstractors were allowed to exercise their full consents.

Results for impacts on wetted width of river habitat indicated that:

- Under the Consented scenario (all abstractors take their full allocation and no restrictions are applied) many river reaches would lose their entire wetted width. This is particularly the case for small river reaches, but also extends to the larger rivers.
- Under the Consented scenario (all abstractors take their full allocation and no restrictions are applied) many rivers reaches would lose various amounts of suitable physical habitat for adult brown trout, torrentfish and food production. This is particularly the case for small river reaches. Some grains in habitat were estimated in some larger rivers.

This report also provides discussion on the meaning of “headroom” within specified water resource use limits. It is suggested that the concept of headroom can be applied to an individual abstractor, a collective of abstractors, or potential future abstractors. This results in at least three different definitions of headroom. Within defined water resource use limits, maximising headroom for a collective of existing abstractors will have the effect of minimising potential headroom for potential future abstractors.

Discussion of the benefits and potential areas for improvement for the pressure-state-impact model for freshwater flows is also provided.

This work was originally completed in June 2015. Minor alterations were applied in March 2017 following improved understanding of ECan’s consent database. These alterations resulted from: a) the need to exclude consents that were in-date, but not active because they had been terminated or transferred; and b) an improved method to deal with many-to-many associations between consents and records of take. These alterations did not alter the conclusions or the major findings of the work.

1 Introduction

1.1 Pressure-state-impact frameworks

The “drivers, pressures, state, impact, response” (DPSIR) framework has been commonly applied in relation to environmental reporting. In this framework, drivers and pressures are indicators of human activities and resulting pressures on the environment. This framework is an extension of the pressure-state-response model developed by the Organisation for Economic Co-operation and Development (OECD). State and impact indicators are the resulting conditions in the environment and the implications for the health of ecosystems and humans. The response indicators measure the reaction of human society to the environmental issue. This framework is designed such that environmental reporting tends to focus on three key areas: scientific credibility; policy/social relevance; and practical monitoring and data requirements.

The DPSIR framework proposes a base to organise environmental indicators (Martins et al. 2012). It provides not only a set of categories to support the selection of indicators, but it also encourages discernment of the causal relationships between these indicators. It encourages identification of the human motivations (driving forces) to act into the environment, the human actions performed with potential to change environmental states (pressure), the status and the potential changes on natural resources (state and impact), and the preventive or curative measures that may be applied by society to improve the system concerning the environment and socio-economic aspects (response).

1.2 Aims and purpose

The aim of this project was to develop a model that allows the pressure-state-impact framework to be applied to river flows across New Zealand. This model enables estimation of the state of freshwater flow regimes throughout New Zealand, the pressures on those flows, and their impacts on the environment and supply of freshwater for out-of-stream use which might impact our economy and society.

The purpose of this project was to enable the Ministry for the Environment to report on the availability of freshwater in New Zealand (i.e., freshwater flows). For a particular reporting period, we seek to answer the questions: how much water is being taken through resource consents, and what are the impacts (both positive and negative) of these takes on our environment, and on the reliability of supply and potential for headroom in respect of out-of-stream water use?

1.3 Spatial framework

The River Environment Classification (REC; Snelder & Biggs 2002) is a deductive (i.e., a priori defined) natural flow regime classification of New Zealand’s rivers mapped onto a digital representation of the river network. This river network comprises 570,000 reaches. Each reach is associated with a suite of attributes. These attributes include those that pertain to local conditions (e.g., altitude), attributes that pertain to the upstream catchment (e.g., upstream catchment area), and attributes that describe inter-connectivity (upstream and downstream connections). These attributes are often available for all reaches within the network. This has allowed the river network to provide a basis for various national-level analyses on hydrology (Booker & Woods 2014), geomorphology (Booker 2010), invertebrates (Booker et al. 2014) and fish (Crow et al. 2012). The nationwide nature of these data allows methods to be applied consistently, and for results to be reported at national, regional or catchment levels. New Zealand's national river network, as defined in the REC (version 1) was therefore used as the spatial framework for all analysis in this project.

1.4 Note on 2017 update

This work was originally completed in June 2015. Minor alterations were applied in March 2017 following improved understanding of ECan's consent database. These alterations resulted from: a) the need to exclude consents that were in-date, but not active because they had been terminated or transferred; and b) an improved method to deal with many-to-many associations between consents and records of take. These alterations did not alter the conclusions or the major findings of the work.

2 Input data

2.1 Schema for data collation

In New Zealand, regional councils and unitary authorities are responsible for various aspects of managing freshwater resources. They administer consents to take and use water. They hold records of water use and observed river flows. They also delineate management units, and set planning provisions in regional plans. Local government agencies therefore hold a great deal of information that is critical for the application of a national freshwater flows pressure-state-impact model.

During September and October 2014 discussions were held between staff from NIWA, MfE and various regional councils (ECan, Horizons, Marlborough District Council (MDC), Otago Regional Council (ORC), Auckland Council (AC), Bay of Plenty Regional Council (BoPRC) and Greater Wellington Regional Council (GWRC)) relating to availability and transfer of data that would be required by the national model. These discussions resulted in the creation of a data schema designed to allow collation of all data required by the model. This schema also allowed MfE to collate data on water consents and takes for their own additional needs. This schema consisted of 13 separate tables. A brief description of these tables is given in Table 2-1. A detailed description of these tables is given in Appendix A. Definitions of categorical variables are given in Appendix B. Some examples of data contained within these tables is given in Appendix C.

Table 2-1: Brief description of each table within the data schema.

Table name	Associated information	Notes
Table 1	The location, primary use, secondary use, river names etc. associated with each take	
Table 2	REC NZreaches associated with each take	Many NZreaches can be associated with a single groundwater take
Table 3	The depth, screen heights etc. associated with groundwater takes.	
Table 4	The commencement data, termination date, status etc. associated with each consent.	
Table 5	The use, irrigated area, crop type, etc. associated with each activity within each consent	Many consents have several activities (e.g., irrigation and frost protection)
Table 5a	Consent conditions associated each activity within each consent, such as maximum rates of and links to low flow control sites and low flow control bands	A consent can have many associated rates (e.g., specified per second, day, year) and can be controlled by various conditions at several control sites.
Table 6	Values of recorded takes	Negative values are discharges
Table 7	Rates of restriction making control rules associated with each band at each control site	
Table 8	Recorded values at control sites, such as discharge or groundwater levels	Can be specified at various time resolutions

Table 9	The start date, end date, verification method for reach record of take
Table 10	The locations, names and types of each control site
Table 11	A linking data containing associations between records, takes, and consents
Table 12	Information relating to who supplied the data

2.2 Provided data

The data used in this report were provided by ECan in January 2015. This dataset closely followed the design of the provided data schema (Table 2-1).

2.3 Permitted activities

Taking of water for certain permitted activities (e.g., stock water drinking, firefighting) may take place without the need for a resource consent so long as these activities comply with any requirements, conditions and permissions specified in the Resource Management Act (RMA).

It was planned that data describing estimated takes under permitted activities be provided by MfE. These estimates were to be based on estimated water requirements of animals and data describing the number of animals within a watershed. Unfortunately, these data were not available within the duration of this project due to confidentiality issues. Therefore water uses due to permitted activities were not considered within this project.

2.4 Large schemes and dams

Large water transfer schemes and dams have can have a large influence on river flow downstream of their structures. These schemes are also often subject to Environment Court hearings or Water Conservation orders. Some large water schemes are also known to cross regional boundaries. It is therefore possible some large water transfer schemes and dams may not be included in the databases provided to this project by regional councils. We therefore wished to check that they were adequately accounted for in the dataset we received and in the models applied to it.

For this project we were supplied with data relating to consents by ECan. We then checked both input data and model results to ascertain whether the effects of well-known large schemes within Canterbury had been incorporated after having applied our model to the data supplied by ECan.

Data describing large water schemes were obtained from:

- Electricity industry sources regarding power schemes.
- Irrigation New Zealand's web site for an irrigation scheme list.
- Canterbury Regional Council's consent database for a list of large consented water takes (greater than 4 cumecs).

Locations of structures and consent take points where available were plotted in a Geographic Information System (GIS) and the nearest river reach to intake and discharge points were identified where possible. Expert knowledge of various NIWA staff was also used in attempting to reconcile these disparate sources.

The resulting list is presented as Table 2-2. Of the 86 schemes listed, 16 (all of them dams or power stations), did not appear in the list of consents provided by ECan. Also it was not possible to unambiguously identify all schemes against their consents because of imperfect knowledge of intake or discharge locations, and the fact that owner details are not part of the database supplied. Only 8 schemes out of 86 (all dams or power stations) did not involve some inter-reach transfer of water.

Table 2-2: List of large water-using schemes in Canterbury. The table shows the number of identified schemes, either from the consent database or other knowledge.

River Source	Dam	Power Station	Intake	Irrigation Scheme	Irrigation & Stockwater	Stockwater	Grand Total
Acheron R			1				1
Ashburton R and two spring fed creeks				1			1
Drains and GW near Ashburton				1			1
Harper R			2				2
Hurunui R				2			2
Hurunui R (5)				1			1
L Coleridge			1				1
L Ohau			1				1
L Pukaki			1				1
L Tekapo		2	1				3
Little R		1					1
Ohau Pukaki and Tekapo		3					3
Ohau R	2		1				3
Ohau R below weir				1			1
Okuku R				1			1
Opuha and Opihi		1		1			2
Pukaki R	1						1
Rakaia near Rakaia Sth bank				8			8
Rakaia R (3) and Barhill Chertsey Irrigation Scheme (0.7)				1			1
Rakaia R (40)				1			1

Rakaia R at Highbank				5			5
Rakaia u/s Highbank nth bank				4			4
Rakaia u/s Highbank Sth bank				4			4
Rangitata Diversion Race				2			2
Rangitata Diversion Race & North? Ashburton				1			1
Rangitata near Arundel				4			4
Rangitata R			1	2		1	4
Rangitata R at Arundel Bridge				1			1
Rangitata Sth Ashburton Rakaia		1					1
RDR		1					1
Sth Ashburton R			1				1
Tasman R trib		1					1
Tekapo R	2						2
Upper Waitaki				1			1
Waiau R (11) & Waiareka Stm (0.45)				1			1
Waimakariri at Gorge Bridge (25)				1			1
Waimakariri R at Brown's Rock				2	1	1	4
Waitaki		3					3
Waitaki at Borton's Pond				1			1
Waitaki at Stonewall				1			1
Waitaki R				1			1
Waitaki R (6+14.2)				1			1
Waitaki R at Bell's Pond				3			3
Wilberforce Harper Acheron Ryton		1					1
Wilberforce R			1				1
Grand Total	**5**	**14**	**11**	**53**	**1**	**2**	**86**

3 Methods

3.1 Comparing consents with recorded takes

We wished to compare allowable take for each consented activity with their associated recorded values. This comparison would be straightforward given a one-to-one relationship between consented activities and recorded takes (i.e., each consented activity was associated with a single take and each take was associated with a single consented activity). However, a consented activity can allow takes from several locations, and therefore be associated with many recorded takes. Furthermore, a recorded take could be associated with many consented activities.

To compare consented activities with associated recorded takes whilst avoiding miss-matching between activities and takes we applied the following steps to construct a set of virtual consented activities and a set of virtual takes that could be compared legitimately.

1) List all takeIDs that are associated with each activityID.
2) For each activityID, list all additional activitiyIDs that share associations with any takeIDs.
3) Collect sets of activityIDs that share sets of common takeIDs into sets to make virtual activities.
4) For each day of the year, sum together the consented rates for all activities in each virtual activity to obtain a time-series of maximum consented rate for each virtual activity.
5) Collect together sets of takeIDs to make virtual takes which can be compared with each virtual activity.
6) For each day of the year, sum together the recorded takes for all takeIDs in each virtual take to obtain a time-series of take for each virtual take.
7) Compared with each virtual take time-series with each virtual activity time-series.

After having followed these steps, 6373 consented activities were turned into 5843 virtual consented activities, and 8175 takes were turned into 5843 virtual takes. Each consented activity can only appear in one virtual consented activity. Each take can only appear in one virtual take. Some (63) consented activities could not be translated into virtual consented activities because they were not associated with any known takes.

Creation of virtual activities and virtual takes revealed 4325 activities were associated with single takes. Many virtual activities contained single activities associated with more than one take (Table 3-1) (i.e., consented activities that allow water to be taken from several locations). Some virtual activities contained multiple activities associated with single takes (i.e., several consented activities that allow water to be taken from the same location). A few virtual activities contained multiples activities associated with multiple takes (i.e., more than one consented activity that can take from more than one location from which other consented activities are also allowed to take from).

Table 3-1: For each virtual consented activity, the number of associated consented activities and the number of takes.

Number of records	Number of consented activities							
	1	2	3	4	5	6	7	8	14
1	4325	211	23	11	1	3	1	2	1
2	658	56	7	1	1	0	0	0	0
3	253	43	7	0	0	0	0	0	0
4	104	12	0	1	0	1	0	0	0
5	44	10	1	0	0	0	0	0	0
6	20	6	0	0	0	0	0	0	0
7	12	5	2	0	0	0	0	0	0
8	4	0	1	0	0	0	0	0	0
9	7	0	0	0	0	0	0	0	0
10	1	2	0	0	0	0	0	0	0
11	0	2	0	0	0	0	0	0	0
12	0	1	0	0	0	0	0	0	0
13	3	0	0	0	0	0	0	0	0

3.2 Locating takes on the river network

Table 2 of our data schema was designed to hold information on the reach(s) on the river network (NZreach) most strongly associated with each take. Where this information was not provided (all cases to date), it was automatically generated. For each surface water take, the reach whose river line was nearest to the co-ordinates of the take was identified. This was done by first identifying the 20 reaches (of all 570,000) whose centroids were nearest to the location of the take. Distances between the location of the take and all points describing the REC river lines of these 20 reaches were then calculated. These distances were then used to identify the reach whose river line was closest to the location of the take.

The 20 reaches (of all 570,000 REC reaches) whose centroids were nearest to the location of the take were also identified for each groundwater take. The shortest distance between each point describing the river line and the location of the take was then calculated for each of these 20 reaches. Therefore for each groundwater take, the nearest 20 reaches were identified and the shortest distance between the location of take and river lines for each of these 20 reaches was calculated.

3.3 Downstream routing and accumulation

Our model attempted to quantify the hydrological effects of recorded takes and the maximum potential hydrological effects of all water takes on river flows. Many small takes can combine to create considerable cumulative effects. Therefore, for each day of the year, for each take, various values were routed and accumulated in the downstream direction. This allowed calculation of the sum of all upstream takes for each day for each reach of the river network. Table 3-2 provides definitions of different values which were accumulated downstream. These different values are referred to as different scenarios hereafter. All reaches being influenced by each take were identified by identifying all reaches between that take and the sea. This allowed the downstream cumulative effects of multiple takes to be accumulated across the river network.

Table 3-2: Definitions of values being routed and accumulated down the river network.

Name	Source of values	Meaning of values
Consented	Maximum daily consented rate of take on a specified day regardless of any low flow restrictions specified in the consent	Maximum volume of water that could be taken on a specified day of the year
Restricted	Maximum daily consented rate of take on a specified day after having accounted for any low flow restrictions specified in the consent	Maximum volume of water that could be taken on a specified day after low flow restrictions have been applied
Restricted with records	Maximum daily consented rate of take on a specified day after having accounted for any low flow restrictions specified in the consent for consents with recorded values only	Maximum volume of water that would be expected to be recorded if all recorded takes took at their maximum consented rate on a specified day of the year

All accumulations were calculated on a daily time-step for the hydrological year 2013-14 (1st July 2013 to 30th June 2014). All accumulations were calculated for each day separately. Therefore no temporal lags were applied to account for the time of travel of effects downstream from each take point.

3.4 Stream depletion from groundwater takes

We used the provided data on connectivity of each groundwater take to decide which groundwater takes would be allowed to deplete river flows. Groundwater takes whose connectivity was classified as being either "Direct", "High", "Moderate" were included in the stream depletion calculations. However, many groundwater takes did not have a recorded connectivity. In these cases we inferred connectivity. Takes whose secondary source was recorded as being either "Bore+Gallery","Excavated Pit" or "Infiltration Gallery" were inferred as having high connectivity. Takes whose secondary source was recorded as being either "Water Hole" or "Thermal Bore" were inferred as having low connectivity. In the absence of a secondary source takes whose depth of take was less than 10 m in depth were inferred as having high connectivity.

3.4.1 Analytical solution for estimating the effects of groundwater abstraction on streamflow

We calculated effects of groundwater abstraction from wells on streamflow using an analytical approach developed from the Glover-Balmer solution (Glover and Balmer 1954; Equation 1).

$$Q_s = Q_w \,.\, erfc(\overline{\sqrt{d^2 S/(4Tt)}}) \qquad \text{Equation 1}$$

Where Q_s is the rate of streamflow depletion (Ls^{-1}) at time t (in days), Q_w is the rate of pumping at the well (Ls^{-1}), erfc is the complimentary error function, d is the distance (meters) between the well and the stream, S is the storativity of the aquifer (dimensionless), and T is the transmissivity of the aquifer (m^2s^{-1}).

Analytical solutions to stream depletion of this type assume (from Jenkins 1968b):

1. The aquifer is homogeneous, isotropic, and extends to infinity away from the stream.
2. The aquifer is confined, and the transmissivity and saturated thickness of the aquifer do not change with time: however the solution can also apply to water-table aquifers when it can be assumed that drawdown caused by pumping is small compared to the initial saturated thickness of the aquifer.
3. Water is released instantaneously from storage (and there are no delayed-drainage effects characteristic of water-table aquifers).
4. The stream that forms a boundary with the aquifer is straight, fully penetrates the thickness of the aquifer, is infinitely long, remains flowing at all times, and is in perfect hydraulic connection with the aquifer (that is, no streambed and streambed sediments impede flow between the stream and aquifer).
5. The temperature of the stream and aquifer are the same and do not change with time. This assumption is necessary because variations in temperature affect the hydraulic conductivity of streambed and aquifer sediments.
6. The well pumps from the full saturated thickness of the aquifer.

It is expected that these assumptions will be met to varying degrees throughout the country. However, potential exists to improve regional estimates of groundwater abstraction effects on streamflow by better incorporating regional aquifer characteristics into this model.

Aquifer recharge from irrigation was not incorporated into the model as it was assumed that all irrigation was 100% efficient; therefore all irrigated water is assumed to be lost through evaporation. We applied this methodology because it is easily understood and represents a worst case scenario for stream depletion. An alternative methodology could be to apply a constant recharge component as a percentage of the pumping rate. For example, Duncan et al. (in review) estimated that the recharge component was approximately 18% of the pumping rate, based on lysimeter results in Canterbury.

3.4.2 Division of well pumping effects between multiple adjacent reaches

Distance (d) was calculated as the distance from each well to the nearest-point of the nearest stream reach. In situations where more than one stream reach are located within 2km of a bore, the fraction of the pumping rate at the bore assigned to the segment containing each stream reach was calculated using the equation of Reeves et al. (2009) (Equation 2).

$$f_i = \frac{\frac{1}{d_i}}{\sum_{j=1,n} \frac{1}{d_i}}$$ Equation 2

Where *fi* is the fraction of the captured water attributed to valley segment *i*, *n* is the number of reaches being influenced, and d_i is the distance from the proposed well to the centre point of stream reach *i*. To calculate streamflow depletion effects of the well on stream reach *i* by combining Equation 1 and Equation 2:

$$Q_{si} = f_i \,.\, Q_w . erfc(\sqrt{d_i^2 S/(4Tt)})$$ Equation 3

3.4.3 Effects of multiple wells on single stream reaches

Where more than one well was located within 2km of a single stream reach, the effects of *m* wells pumping were treated as additive, according to Barlow et al. (2012):

$$Q_s = \sum_{j=1}^{m} Q_{wj} . erfc(\sqrt{d_j^2 S_j/(4T_j t)})$$ Equation 4

Where Q_{wj}, d_j, S_j, and T_j are pumping rate, distance to the stream reach, storativity, and transmissivity of j^{th} well.

3.4.4 Adjustment for variable pumping rates

Equation 1 assumes a constant pumping rate over the duration of the consent period. To incorporate seasonal changes in pumping rate, and account for lag effects of expired consents on streamflow we incorporated pumping rate changes as below (Equation 5).

$$Q_s = \sum_{k=1}^{K} Q_{wk} \{erfc(\sqrt{\frac{d^2 S}{4Tt}}) - erfc(\sqrt{\frac{d^2 S}{4T(t+1)}})\}$$ Equation 5

Where Q_w is the pump rate of a well at time *k*.

3.4.5 Estimation of transmissivity and storativity

Since there were missing values of transmissivity and storativity in the well dataset, it was necessary to apply a method for estimating values for these parameters at new locations. In this work, we applied the Random Forest regression technique (Breiman 2001) to estimate transmissivity and storativity. Random Forest regressions can be used for classification and regression, and it normally includes two steps, i.e. training and prediction. Random forest regressions have several advantages. These include allowing for flexible relationships and interactions between explanatory variables, and also the ability to provide predictions for each site as if that site was withheld from the fitting process. These predictions are known as the out-of-bag (OOB) predictions. Testing using OOB prediction provides an indication of model performance at ungauged sites.

We used variables from the Freshwater Environments of New Zealand (FWENZ) database, soil permeability and well depth as predictors and known transmissivity and storativity as the output to train the random forest and then used this regression model to predict missing transmissivity and storativity.

Out-of-bag (OOB) predictions of S and T were compared with observed values. OOB r^2 values for these models were given. These values indicate the amount of variation in the observed data that are explained by the OOB predictions.

3.5 Naturalised flow modelling

3.5.1 Description

We used results from an existing national New Zealand hydrological model called TopNet to represent naturalised flows. TopNet is a spatially distributed, time-stepping model. TopNet combines conceptual water balance models for each sub-catchment with a kinematic channel routing model to route streamflow to the basin outlet. The TopNet model and its constituent equations are fully described in Clark (2008). In brief, the water balance component is based on the established Topmodel concepts that subsurface storage controls both saturation excess surface flow and baseflow (Beven 1979). The saturated surface area is calculated based on the Topmodel assumption that the local depth to the water table at any location is directly related to the wetness index $a/\tan\beta$ where a is the upstream area and $\tan\beta$ is the local slope. Baseflow is calculated as an exponential function of the spatial average of the depth to water table. Also included in the water balance component are modules that represent canopy interception and storage, snowpack and soil zone. The canopy module simulates changes in storage caused by rainfall, throughfall and canopy evaporation, the last two being functions of the wetted leaf area. The snowpack module uses a simple degree day formulation to track snowfall and snowmelt. The soil zone module simulates infiltration (with maximum infiltration rate modelled using a Green-Ampt formulation), evapotranspiration, and drainage as a power function of the soil water fraction.

There are two components to flow routing within TopNet. First, outflow from each basin has a time delay imposed to simulate travel time through unresolved stream channels. The delay is simulated using a conceptual store with residence time distribution calculated based on the empirical frequency distribution of flow path lengths. Second, flow within the resolved channel network is routed using a 1D Lagrangian kinematic scheme, in which flow is treated as a series of particles that are propagated through the digitised river network.

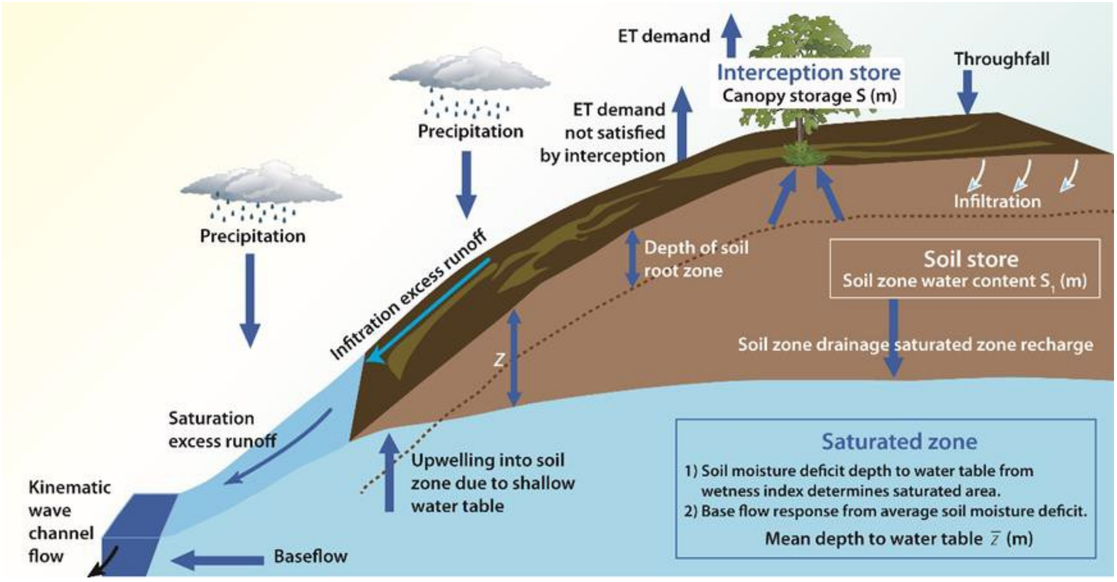

Figure 3-1: Schematic diagram of hydrological processes represented in the TopNet model.

The TopNet model was designed to have a sufficiently comprehensive description of catchment hydrology to be used in the diverse range of hydro-climate landscapes present in New Zealand. For example, it can be used in snow-influenced catchments, it can simulate the effects of different vegetation types, and it can be used in conditions that generate either infiltration-excess or saturation-excess flow. The flexibility of the model means that the choice of a single model structure for the whole country is a reasonable simplification. Limitations of the model include the lack of a dedicated glacier component, no simulation of deep groundwater processes that transfer subsurface water between subcatchments, and the use of a single ground water store in each catchment which restricts the possible recession behaviour (McMillan 2011). TopNet is widely used in hydrological modelling applications in New Zealand, for example for operational flow forecasting (McMillan 2013), to predict the hydrological impacts of climate change (Poyck 2011, Gawith 2012), and for national water accounting (Henderson et al. 2011).

All TopNet parameters are related to physical processes and therefore *a priori* estimates of parameter values can be made using national datasets that describe New Zealand's topography, land cover and other physical properties. Practical experience has shown that the two TopNet parameters with the greatest impact on flow predictions are: 1) the Topmodel *f* parameter (which controls the exponential decline of subsurface hydraulic conductivity with depth); and 2) the surface saturated hydraulic conductivity. The sensitivity of these parameters is consistent with the findings of previous studies, for example Segui (2009) who showed that calibration of the hydraulic conductivity parameter resulted in significant performance improvement for a national French hydrological model. For these two parameters, additional effort was used to set prior estimates that would lead to accurate flow predictions. The Topmodel *f* parameter was estimated using an analysis of recession curve shapes for more than 500 New Zealand rivers. A relationship was derived between the recession shapes and geology, soil and climate parameters in each of 15 defined hydrological regions of New Zealand. This relationship was then used to predict the Topmodel *f* parameter for every subcatchment. The saturated hydraulic conductivity was estimated using an empirical relationship based on soil texture and land use/land cover information.

TopNet runs on an hourly timestep and is applied to a version of the New Zealand river network that has been coarsened to represent Strahler order 3 channels and greater. We extracted mean daily flows from TopNet for each reach of the New Zealand river network of interest. To calculate mean daily flows we calculated the mean from midnight to midnight for each day. To extract time-series for all river reaches of interest (including Strahler order 1 and 2) we found the nearest Strahler order 3 and then re-scaled by catchment area. This method assumed local flow per unit catchment area was the same.

We applied an additional post-processing step to the national TopNet model results, as previously described by Booker and Woods (2014), to correct the modelled flow duration curve (FDC) based on an independent statistical analysis. For a set of 485 flowgauges across New Zealand, with reasonable natural (as defined in Booker and Woods 2014) river flows, the observed flow duration curves were approximated using a three-parameter Generalised Extreme Value (GEV) distribution. The GEV distribution is suitable to represent the range of FDC shapes found across New Zealand (Booker and Snelder 2012). The Random Forests machine learning method, which uses an ensemble of regression trees, was used to establish a regression relationship between a set of nationally available catchment descriptors and the GEV parameters. FDCs could then be predicted for every New Zealand river reach and subsequently used to transform all Topnet results.

The transformation of TopNet modelled flows was implemented by calculating the TopNet-predicted FDC for each reach. Each daily TopNet flow value was then replaced with the equivalent percentile value from the Random Forest-predicted FDC for that reach. This correction has previously been shown to improve static signatures of the flow series (e.g., mean annual low flow, mean annual flood) (Booker and Woods 2014). Possible reasons for this improvement include compensating for the simplified simulation of deep groundwater processes that transfer subsurface water between subcatchments within Topnet. Flows estimated using this transformation of TopNet modelled flows are known as “Corrected” in the following analysis. Flows estimated without this transformation are known as “Uncorrected”.

3.5.2 Testing

We evaluated the ability of the model to reproduce the characteristics of observed flow regimes across New Zealand. In particular, we tested whether the model could simulate the variability in a range of flow indices, over space and over time. Over space, accurate prediction of flow variability would show that the parameterisation of the model using national datasets of soils, land use etc. has correctly identified the corresponding differences in hydrological behaviour. Over time, accurate prediction of flow variability would show that the dependence of the model behaviour on the input climate data has been correctly simulated, at time scales from hours to years. We therefore chose criteria for validation of the model set out in Table 3-3.

For testing, we used the same set of 486 flow gauges as in the study of Booker and Woods (2014). All flow values were calculated in mm d^{-1} to enable comparisons between catchments of different sizes.

Table 3-3: Hydrological indices used for model validation.

Index type	Index	Description	Calculation
Hourly flow series evaluation	DAILY	Daily flow series	Model simulation of entire daily flow series
Annual flow descriptor	MEAN	Mean annual flow	Mean flow in each hydrological year
	MAX	Annual flood	Maximum daily flow in each hydrological year
	MIN	Annual low flow	Minimum daily flow in each hydrological year
	QFEB	Proportion of flow in February	Mean flow in February as a proportion of mean annual flow, in each hydrological year
Multi-year flow descriptor	QFLOOD5	5-year flood	Maximum daily flow expected during a period of 5 years, using a Gumbel extreme value approximation.
	QLOW5	5-year low flow	Minimum daily flow expected during a period of 5 years, using a normal distribution.
	QVAR	Interannual variation	Interannual variation in mean flow
	QBAR	All-time mean flow	Mean flow over entire series
	MALF	Mean annual low flow	Mean of the annual minimum flows
	MAF	Mean annual flood	Mean of the annual maximum flows

To test the quality of the entire hourly flow series predicted by the model, we used three metrics: Nash-Sutcliffe efficiency (NSE2), per cent bias (pbias), and coefficient of determination (r^2). See Moriasi et al. (2007) and references therein for full details of these performance evaluation metrics. NSE is a dimensionless metric that determines the relative magnitude of the residual variance ("noise") compared to the observed data variance ("information") (Nash and Sutcliffe, 1970). NSE is very commonly used to evaluate hydrological model performance; we use the scaled version NSE2 that takes values between -1 (worst) and +1 (perfect model), with 0 representing a model that is no better than a constant prediction at the mean flow value. Percent bias measures the average tendency of the simulated data to be larger (negative pbias) or smaller (positive pbias) than their observed counterparts (Gupta et al., 1999). In a hydrological model, percent bias allows us to test whether the water balance of the catchment is correctly represented. Coefficient of determination r^2 measures the correlation between measured and simulated values. This measure allows us to test whether the model correctly predicts locations/years with low/high index values, even if there is systematic bias in the values. For each of these three metrics we tested model performance in linear space (emphasising high flow performance) and log space (emphasising low flow performance). We calculated the three performance measures at each site and plotted the results on a map.

For each of the annual flow descriptors (MEAN, MAX, MIN, QFEB; Table 1), we tested the model performance at each flow gauge individually by comparing yearly observed versus predicted values. The quality of the fit was assessed using the three metrics as before, and presented using maps. We map the results for both the uncorrected TopNet flows and the FDC-corrected TopNet flows, to check the ability of the correction procedure to improve different aspects of model performance.

We note that all available data were used for testing flow estimates. We therefore compared performance across catchments that have differing lengths of flow series available. Alternative approaches to this could include sampling a certain number of years with replacement, or choosing a set period for validation.

For each of the multi-year flow descriptors (QFLOOD5, QLOW5, QVAR, QBAR, MALF, MAF), we calculated the observed and predicted values at each site (one value per site). We then used the three performance metrics to test the model ability to reproduce the differences in these metrics across sites. To summarise these results and the previous mapped results, we present all values using box-and-whisker plots.

3.6 Testing for the effects of large schemes and dams

Large schemes can be categorised in various ways useful for the assessment of effects. Key features include:

- Is water transferred from one river reach to another? In general dams or power stations do not but intakes with distribution or diversion of water do. If some water is not returned to the take point then there are river depletion effects, and restrictions such as minimum flow rules and rate or volumetric limits are to be expected.
- Is the primary effect one of river depletion or one of temporal redistribution of water? Temporal redistribution over days to seasons is a key effect of impoundments for storage. This might be for hydro-electricity generation or irrigation. The size of the active storage in the reservoir (volume between minimum and maximum control levels) and the relationship between this volume and inflow to the reservoir, are key components in determining whether the storage is significant or not. Effects in the river downstream of such a storage depend on whether all the water is released, as is usually the case with an in-river power scheme and dam, or whether much is diverted (as for example where the power station or irrigation discharge point, is located far away at the end of a canal).
- Is the magnitude of the effect adequately indicated by the consent parameters? While simple systems such as a small to moderate take point without storage can be modelled along with their minimum flow rules, release rules etc., more complex systems are more difficult to assess. Irrigation schemes with many owners or customers, on farm storage etc. or power stations that are part of the national network and affected by not only the river rules but also operations elsewhere in the country and market forces, are examples of complex systems that cannot be simply modelled with the available parameters attached to the consent.

In order to assess whether the effects of large schemes had been incorporated into our model appropriately, we created procedures for plotting the cumulative sum of various values (see Table 3-2). We plotted these cumulative sums for locations downstream of known large schemes such as the Waitaki Power Scheme and the Rangitata Diversion Race.

3.7 Wetted width modelling

The method described by Booker and Hicks (2013) which itself followed that of Booker (2010) for predicting width in any river at any discharge was followed to allow estimates of width at any discharge for all locations in the REC network. This procedure applied a mixed-effects model to calculate parameters describing the estimated at-a-station hydraulic geometry for width for each of 326 cross-sections located across New Zealand using 25,000 pairs of observed width and discharge.

In Booker (2010) a three parameter hydraulic geometry model was fitted. In Booker and Hicks (2013) a simpler two parameter model was fitted. The advantage of the two parameter model over the three parameter model is that the two parameter model will always predict increasing width with increasing flows. This is not the case for the three parameter model, which can predict decreasing width with increasing flows at very high flows due to curvature in the log-log relationship.

In Booker (2010) a standard stepwise multiple-linear regression was used to identify the minimally adequate (i.e., most parsimonious) model for each parameter as a function of the appropriate set of independent variables and their two-way interactions. However, when testing against independent data this stepwise minimally adequate model only performed slightly better than a linear model containing just catchment area and climate category from the REC. Therefore this simpler model was fitted to predict the two required parameters independently.

Hydraulic geometry parameters were used to predict river wetted width for each day, for each river reach influenced by takes, for each estimated flow value.

3.8 Availability of suitable physical habitat

Physical habitat models (e.g., PHABSIM, RHYHABSIM) are widely used to assess changes in the availability of suitable physical habitat as a result of change in flow regimes. Physical habitat models link hydraulic model predictions with microhabitat suitability criteria to predict the availability of suitable habitat at various discharge rates. The availability of suitable physical habitat is commonly expressed as weighted useable width (WUW) in m or weighted useable area (WUA) in m^2 per 1000m of river channel. WUW is an aggregate measure of physical habitat quality and quantity and will be specific to a particular discharge and taxa ⁄ life stage. In-stream habitat models can be used to assess WUW over a range of flows and therefore predict changes in availability of suitable habitat with changes in flow. Criticisms of this approach include lack of biological realism (Orth 1987) and failure of microhabitat suitability criteria to reflect the detailed mechanisms that lead to density environment associations (Mathur et al. 1985, Booker et al. 2004, Lancaster and Downes 2010). However, many microhabitat suitability models have a high degree of transferability between rivers and are therefore a useful bases for the physical management of stream catchments (Lamouroux et al. 2010). The models have been applied throughout New Zealand (Lamouroux and Jowett 2005) and the world (Dunbar and Acreman 2001), primarily to assess impacts of abstraction or river impoundment. PHABSIM in particular has become a legal requirement for many impact studies in the United States (Reiser et al. 1989) and a standard tool employed to define minimum flows in New Zealand (Beca 2008).

Physical habitat models have the advantage of linking environmental states directly to flow rates and applying a relatively transparent and replicable methodology. However, hydraulic models require collection of data describing channel shapes, and paired of water surface levels and discharges. These models are therefore typically costly to apply because they require intensive data collection in order to setup and calibrate hydraulic models. Physical habitat models are also often site-specific, and therefore produce results that represent conditions at a known reach of interest rather than over an entire catchment or region. This is a disadvantage in cases where the effects of abstraction are likely to be geographically widespread or where an environmental objective spans a broad area such as an entire catchment. Generalised in-stream habitat models (Lamouroux and Jowett 2005) have previously been developed by combining the results of many individual habitat studies conducted throughout New Zealand. These models generalise the relationship between flow and habitat in natural stream reaches based on simple reach-average hydraulic characteristics. See Jowett et al. (2008) and Lamouroux and Jowett (2005) for examples.

A methodology that mirrored the generalised habitat modelling approach of Lamouroux and Jowett (2005), but using updated habitat suitability criteria (HSC) and different model formulations was applied to predict changes in habitat with changes in flow. These models were developed and tested using available field data that had been previously collected at 266 sites with known locations (Figure 3-2) for the purposes of creating RHYHABSIM physical habitat models.

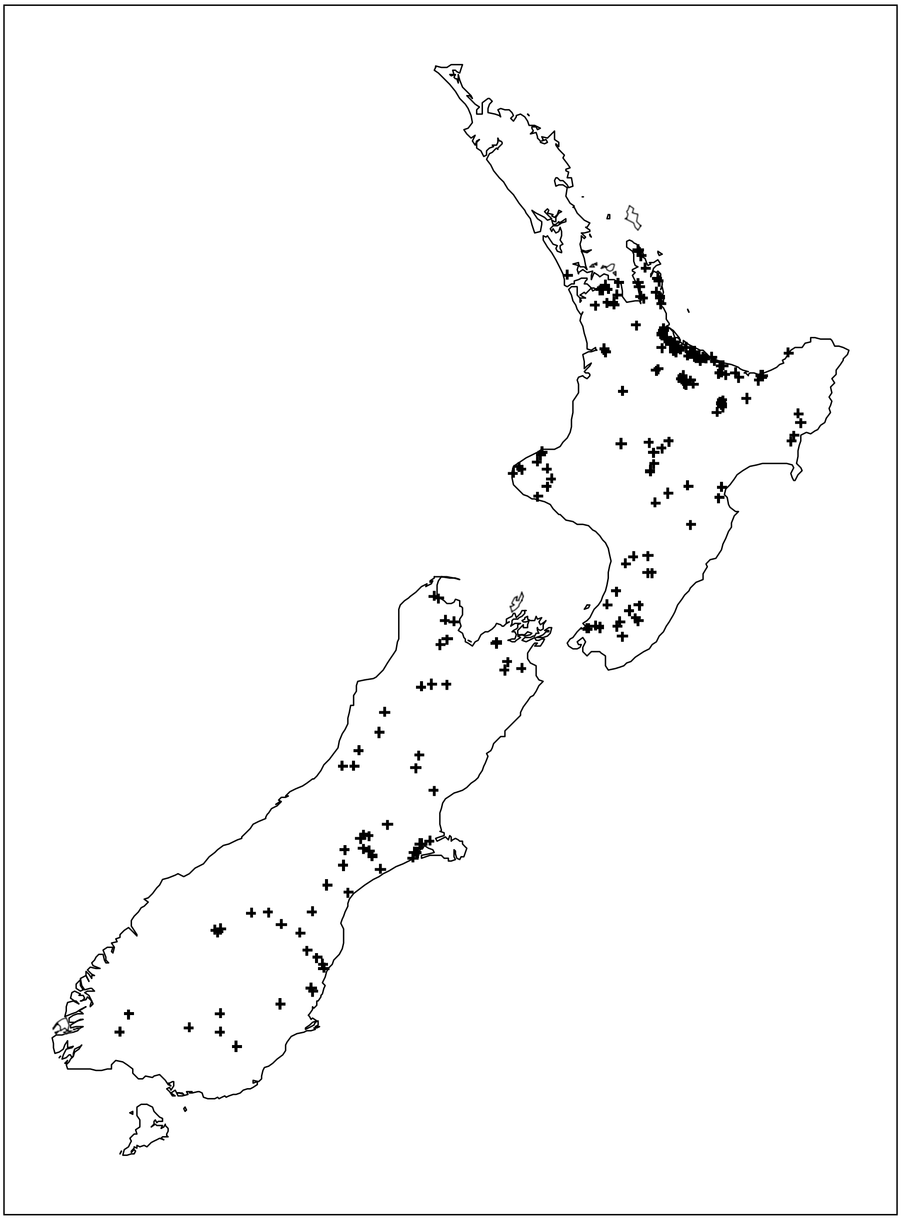

Figure 3-2: RHYHABSIM sites used in the analysis (n = 266).

These input files were used to calibrate hydraulic models and then calculate WUW over a range of flows for each site for each of seven sets of HSCs each representing a species/life-stage (Table 3-4). These HSCs were selected because they represent a range of habitat requirements. The Food Production HSC represents production of invertebrates suitable for predation by drift-feeding fish. Habitat was calculated for 100 increments of flow between zero and the median flow as calculated using the method of Booker and Woods (2013) for estimating flow duration curves at ungauged sites.

Table 3-4: Names and sources habitat suitability criteria applied.

Common Name	Source
Inanga feeding	Jowett 2002
Longfin > 300mm	Jowett & Richardson 2008
Banded kokopu adult	Jowett & Richardson 2008
Brown Trout adult	Hayes and Jowett 1994
Redfin bully	Jowett & Richardson 2008
Torrentfish	Jowett & Richardson 2008
Food production	Waters 1976, as referenced by Lamouroux and Jowett 2005

A two-step procedure that mirrored that outlined by Lamouroux and Jowett (2005) was applied. In the first step the Ricker growth equation was used to express the availability of suitable physical habitat (WUW) as a proportion of wetted width at the median flow (WW_{50}) as a function of Reynolds Number (Re), where Re is flow divided by wetted width.

WUW/WW50= A * Re * exp(-K*Re)

Non-linear mixed-effects models were fitted with various combinations of random-effects on parameters A and K. In their second step Lamouroux and Jowett (2005) fitted a model to predict A as a function of reach hydraulic characteristics (Froude Number at mean flow, Reynolds Number at mean flow, reach-average particle diameter, reach-average water depth at mean flow). Since no methods for estimating these hydraulic characteristics at ungauged sites are available, we applied an alternative approach. In our second step a random forest regression model was fitted to each of the random-effects produced by in the first step (by either Model1 or Model2 e.g., A) as a function of known catchment characteristics available from the REC and FWENZ national databases. We selected available catchment characteristics likely to be linked to hydraulic, geomorphological or substrate characteristics that influence availability of suitable habitat included as: site elevation; a measure of meso-habitat type; mean flow; mean annual flood and a measure of steepness in the upstream catchment. See Leathwick et al. (2005) for further details of how these variables were obtained. We also used the fixed-effects from our mixed-effects models, thus nullifying the need for this second step for all models.

The above procedures provided various methods for calculating WUW standardised by WW at the median flow from Re. In order to quantify uncertainty in converting from Re to Q introduced purely due to WW estimation, we multiplied by WW predicted by the at-site hydraulic models (akin to RHYHABSIM predictions of width), and also by WW as calculated using the generalised hydraulic geometry method of Booker and Hicks (2014). The method of Booker and Hicks (2014) provides at-site hydraulic geometry for ungauged sites across the New Zealand river network.

To provide a worst case benchmark against which all other models could be compared, we calculated a final set of predicted HV values by selecting substitute HV-Re values from a randomly selected site. This set of predictions was labelled as PermutedHV. We also calculated HV by applying the method of Jowett et al. (2008) for Brown Trout Adult and Food Production and multiplying by WW from the hydraulic geometry method and then dividing by WW at the median flow.

Several tests were carried out. For each prediction method, correspondence between observed HV values and predicted HV values across all flows and all sites for each species was assessed. For each method correspondence in estimates of change in habitat between two flow values was assessed. Habitat change (ΔH) between the mean daily flows that are not exceeded 5 and 10 percent of the time was calculated as $(HV_5-HV_{10}) / HV_{10}$. Habitat change was calculated for each method at each site for each species. We chose to test the ability the various models to predict ΔH between two relatively low flows, and because this is typically how WUW-Q relationships are used in flow setting processes. The 5th and 10th percentiles of flow were chosen because mean annual low flows (MALF) and proposed minimum flows are typically in this range. The percentage of sites that were correctly predicted as having either increasing or decreasing ΔH was also calculated.

4 Results

4.1 Model testing

4.1.1 Stream depletion from groundwater takes

From 100 input factors, the ten most important input factors were selected in the training process. These ten factors and ranked importance are listed in Figure 4-1. Well depth (DEPTH) and the latitude of the centroid of upstream watershed (usYcentroid) were the two most important factors for both storativity and transmissivity. Importance of the other predictors differed between storativity and transmissivity. There are clear physical explanations for the explanatory power of well depth and slope on storativity and transmissivity. Links between spatial co-ordinates on storativity and transmissivity is also understandable; storativity and transmissivity at a particular well is related to storativity and transmissivity at nearby wells. However, the physical links between some of the other explanatory variables and storativity and transmissivity is unclear. It is possible that variables such as solar radiation are reflecting patterns in geology or valley shape that actually control storativity and transmissivity. The established model produced OOB r^2 of 0.50 and 0.55 for transmissivity and storativity respectively. This indicates that approximately half the observed variability in the log of storativity and transmissivity was explained by the random forests models even when predictions were made independently of the fitted data. Scatterplots of observed and OOB predicted values also indicated that the regression models were unbiased but also had some associated uncertainties (Figure 4-2).

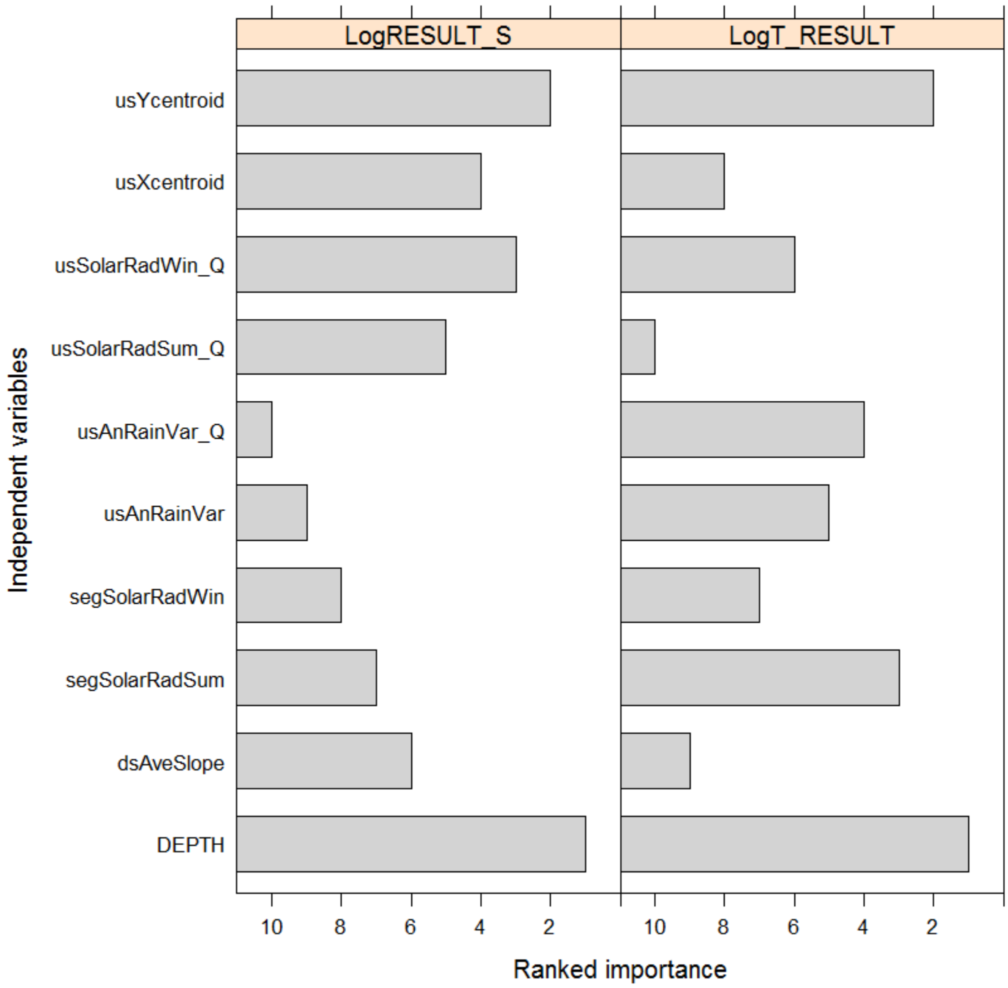

Figure 4-1: Ranked important of predictors in random forest models of log storativity. (“LogRESULT_S”) and log transmissivity (“LogT_RESULT”)

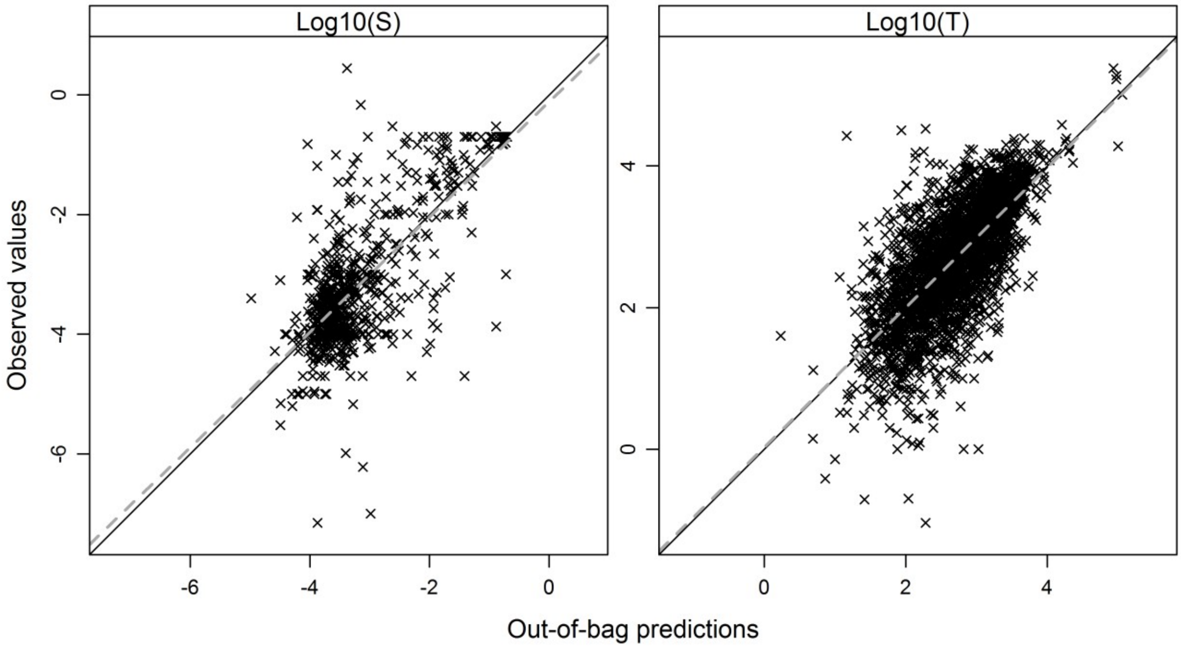

Figure 4-2: Scatterplots of observed and out-of-bag predictions of Storativity (Log10(S)) and Transmissivity (Log10(T)) at 2786 sites. Black line is 1:1. Dashed line is regression of observed against predicted.

4.1.2 Naturalised flow time-series

Figure 4-3 provides an overview of the model performance against the three selected performance measures. It allows us to compare performance of corrected and uncorrected modelled flow series, and to compare performance in linear space and transformed space, which emphasised prediction of low versus high values. It also allows us to compare the model performance in predicting different aspects of the flow regime such as low, medium and high flows.

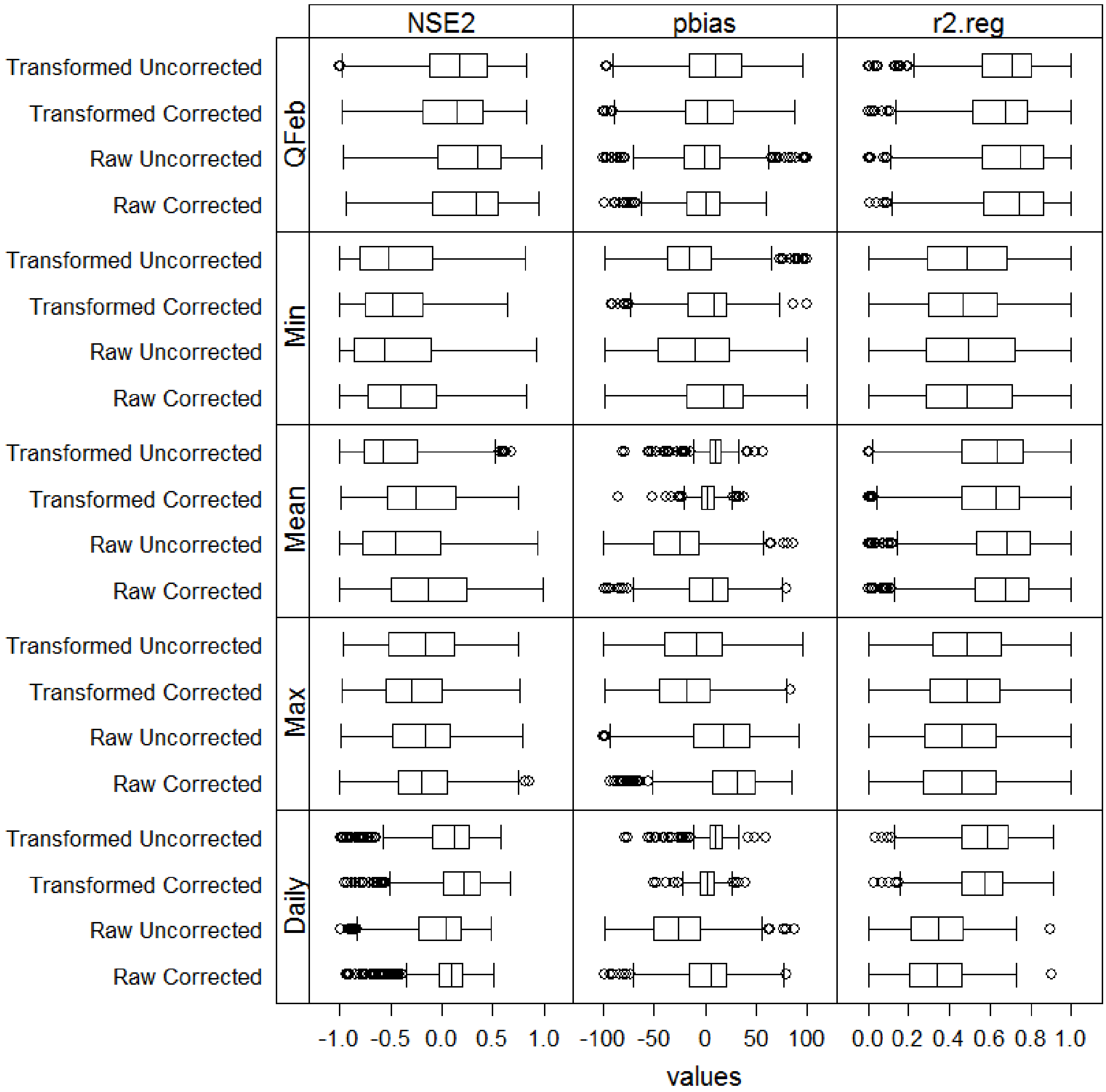

Figure 4-3: Box-and-whiskers plots for the 3 performance measures. NSE2: modified Nash-Sutcliffe efficiency, pbias: per cent bias, and r2.reg: r^2 coefficient of determination. Values are shown for uncorrected and FDC-corrected TopNet flow series, and for data in raw and transformed spaces. Values are given for the performance measures calculated on the four annual flow descriptors (Q5Feb, Min, Mean, Max), and for the performance measure is calculated on the whole daily flow series (Daily). Box indicates quantiles. Whiskers indicate 95th percentile. Other dots indicate outliers.

Comparing first the model performance at predicting the daily series (DAILY index), we see that the FDC-correction improves the NSE2 performance and reduces the bias. The r^2 measure is little changed, suggesting that the main effect of the correction was to remove systematic biases in each model prediction. Performance measures are generally higher in transformed (Log) space than in linear space, showing that the model has higher skill during recession and low flow periods than during flood events. Overall, the results show that the corrected daily flow series model has good skill in matching the flow pattern (e.g., high flow days versus low flow days), shown by the relatively high r^2 values, but there remain biases in the predicted FDC, shown by relatively low NSE2 values.

The four annual flow descriptors test the model ability to predict differences in the flow regimes between years. The performance scores for the mean annual flow and QFeb (the proportion of flow in February) are typically higher than for annual minimum and maximum flows. Mean and QFeb test the model ability to predict averaged behaviour over many days, which is less susceptible to climate or model errors than for extreme behaviour. The FDC-correction improves the NSE2 score and reduces the bias for the mean flow, but other than that has little effect. This is because the correction procedure emphasises performance in mid-range rather than extreme high or low flows. Performance scores are similar in raw and transformed spaces, suggesting equal performance across low and high flow years. As for the daily flow series, high r^2 values show good model skill in predicting differences in the flow indices between years.

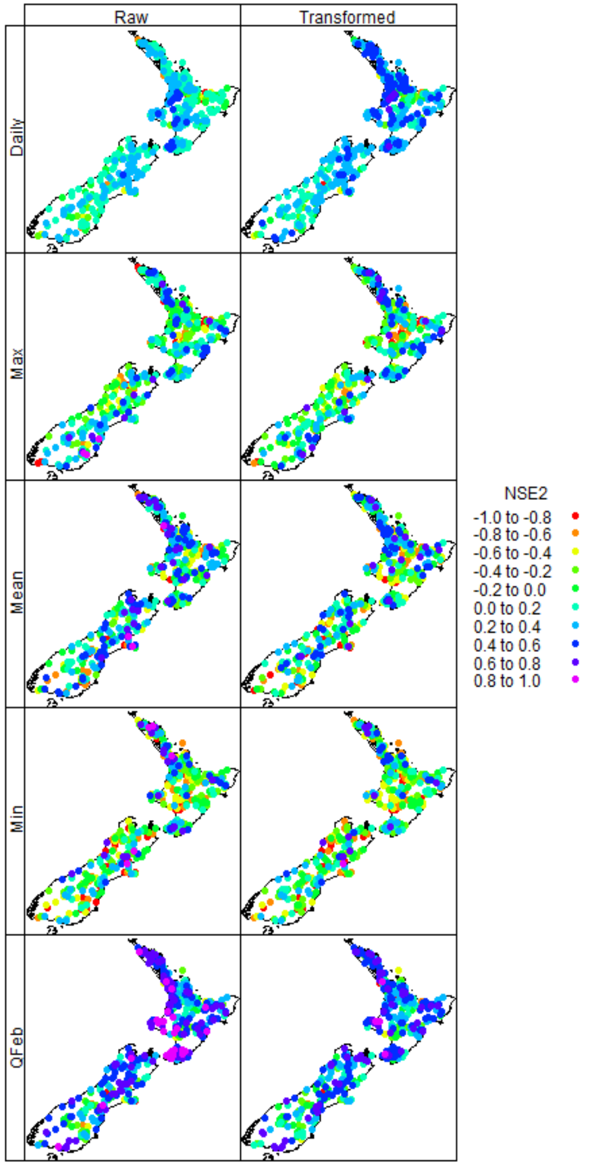

Figure 4-4: NSE2 scores for the daily flow series and annual flow descriptors, by location.

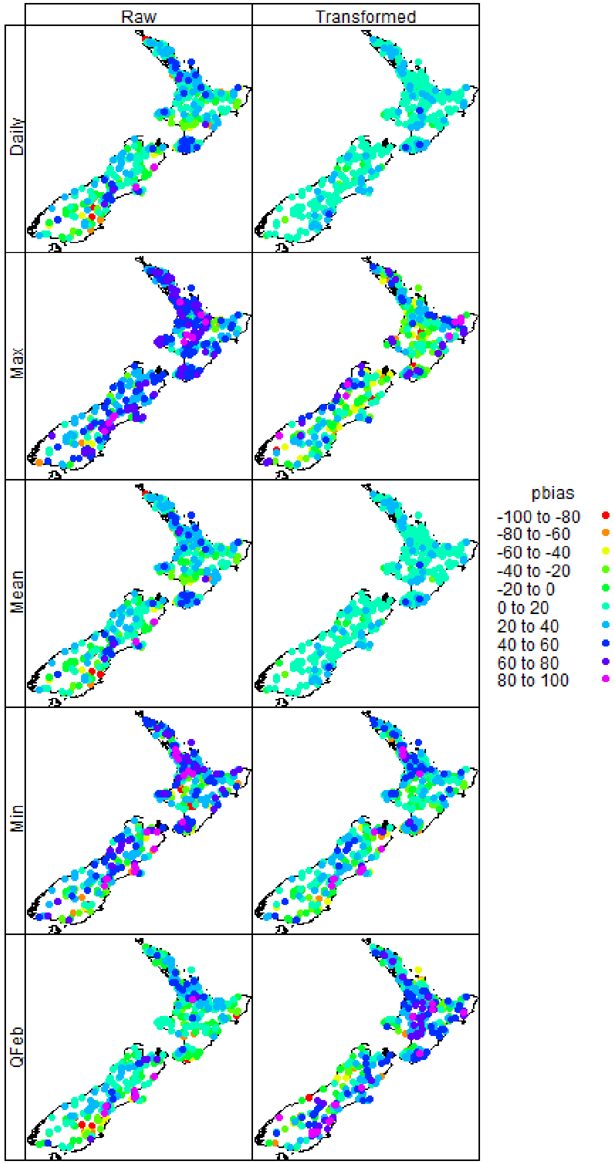

Figure 4-5: pbias scores for the daily flow series and annual flow descriptors, by location.

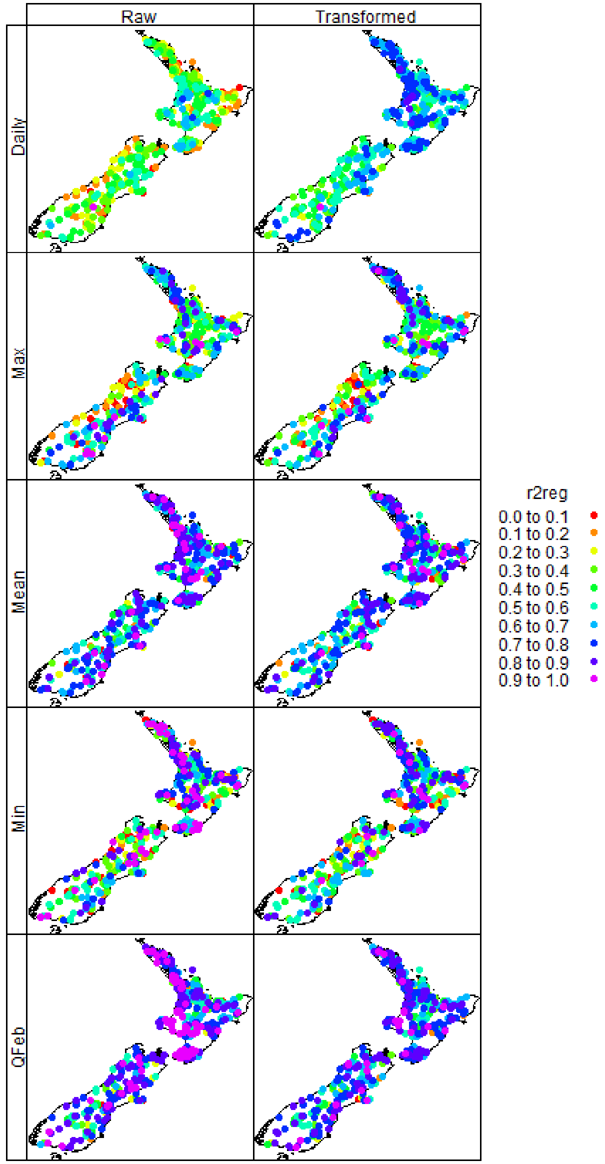

Figure 4-6: r^2 scores for the daily flow series and annual flow descriptors, by location.

Figure 4-4, Figure 4-5 and Figure 4-6 show the same model performance scores as discussed in the previous section, plotted by location. They allow us to evaluate whether model performance changes according to geographic location. Only the FDC-corrected model results are shown.

Where per cent bias is high, particularly for daily flows and mean flows, this suggests inaccuracies in the simulated catchment water balance, which could be due to rainfall measurement error or unmodelled interactions between river flows and groundwater. This performance measure was found to be worst in Northland, lower North Island and the east coast of the South Island. For the latter two areas, groundwater interactions are likely to be the culprit due to the known importance of aquifers in these areas.

The r^2 value, which tests correlation between modelled and measured values, shows that the model has good skill over most of the country for the annual flow descriptors. Areas where performance is poorer are in the mountainous areas of both islands: the West Coast of South Island and the central plateau of North Island. The reasons for this could be that the raingauge network is sparser in these areas, leading to poorer quantification of rainfall extremes. In the North Island central plateau and Bay of Plenty, volcanic soils and geology have a strong damping effect on flood peaks, making it particularly difficult for the model to accurately predict maximum flows in these areas. The NSE2 values test the model ability to simulate both absolute flow values and the pattern of flow values, and shows similar results to the r^2 measure.

Figure 4-7: Plots for the 3 performance measures. NSE2: modified Nash-Sutcliffe efficiency, pbias: percent bias, and r2.reg: r^2 coefficient of determination. Values are shown for uncorrected and FDC-corrected TopNet flow series, and for data in raw and transformed spaces. Values are given for the performance measures calculated on the six multi-year flow descriptors (QVAR, QLow5, QFlood5, Qbar, MALF, MAF).

Figure 4-7 tests the model ability to simulate multi-year flow descriptor values, and correctly simulate the differences in these values between sites. In general, this is a less severe test than the within-site tests shown in Figure 4-7, because part of the model skill derives from the strong climatic differences across New Zealand. Correspondingly, we see higher NSE2 values across all the performance measures. The best performances are seen for the Qbar index that represents all-time mean flow. Low biases and high NSE2 and r^2 measures show that the model has good skill in predicting differences in mean flow between sites. The MALF index is also predicted with reasonable skill; it does not perform poorly in any of the three performance measures.

As expected, the poorest performance is for the 5-year flow extremes, QLow5 and QFlood5; and FDC correction only marginally improves these results. The percent bias measure in fact deteriorates after FDC correction for the MAF and QFlood5 indices, showing as before that FDC correction may not be useful for the study of extreme high flows. These values are most difficult for the model to simulate because the catchment is displaying unusual and extreme hydrological processes at these times, and little data is available to understand these processes. However, even in this case NSE2 values of greater than 0.3 and r^2 values of greater than 0.6 suggest reasonable model predictive ability.

4.1.3 Testing for the effects of large schemes and dams

We plotted the cumulative sum of various values (see Table 3-2) influencing particular reaches. These plots were then used to assess whether the effects of large schemes had been incorporated into our model appropriately. Figure 4-8 shows cumulative sums at a reach just downstream of the Rangitata Diversion Race (RDR). In this case there are two relatively large consents (30 and 20 m^3s^{-1}) and a further three relatively small consents. The two large consents both supplied records, but only one took any water. This large consent is the RDR. This scheme takes water from the Rangitata at a relatively constant rate, except when restrictions are applied. This matches with our expectations for the behaviour of the cumulative sum of takes upstream of this reach.

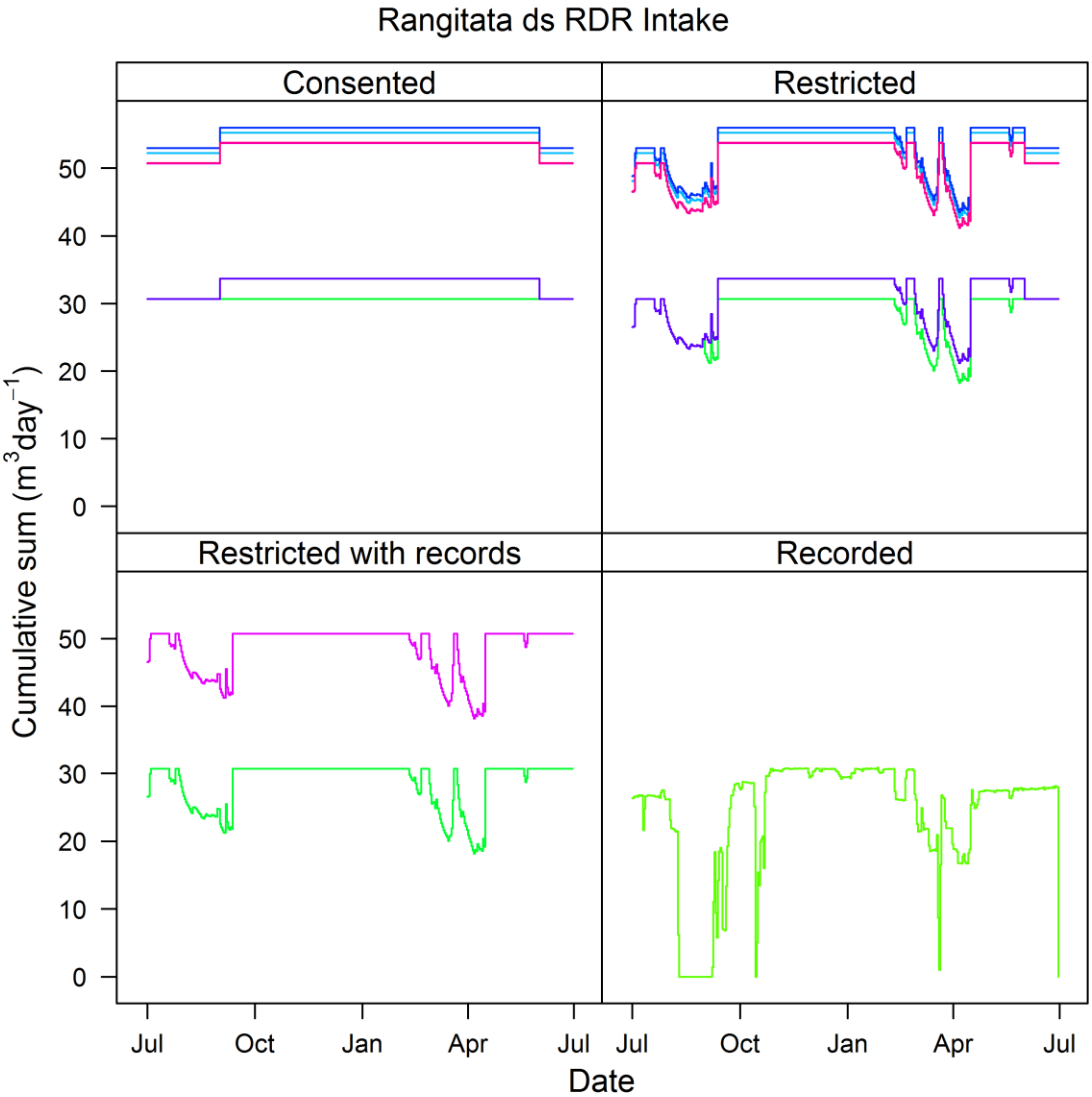

Figure 4-8: Cumulative sums for all consents upstream of the Rangitata Diversion Race specified reach.

Figure 4-9 shows cumulative sums at a reach just downstream of Lake George Scott on the Tekapo River. The figure shows that the database contains a number of small consents totalling nearly 0.8 cumecs. Some have a seasonal component reflecting irrigation demand in summer, and some are a constant value. Nearly two-thirds by volume have records, and the total used in the illustrated season was less than 0.5 cumec. The selection of consents excludes those defined as 'non-consumptive' and thus the removal of up to 130 cumecs via the Tekapo Canal does not appear in this illustration. This is the major impact on the Tekapo River. A similar situation obtains in the Pukaki River downstream of the Pukaki Dam and the upper Ohau River below the Ohau Weir.

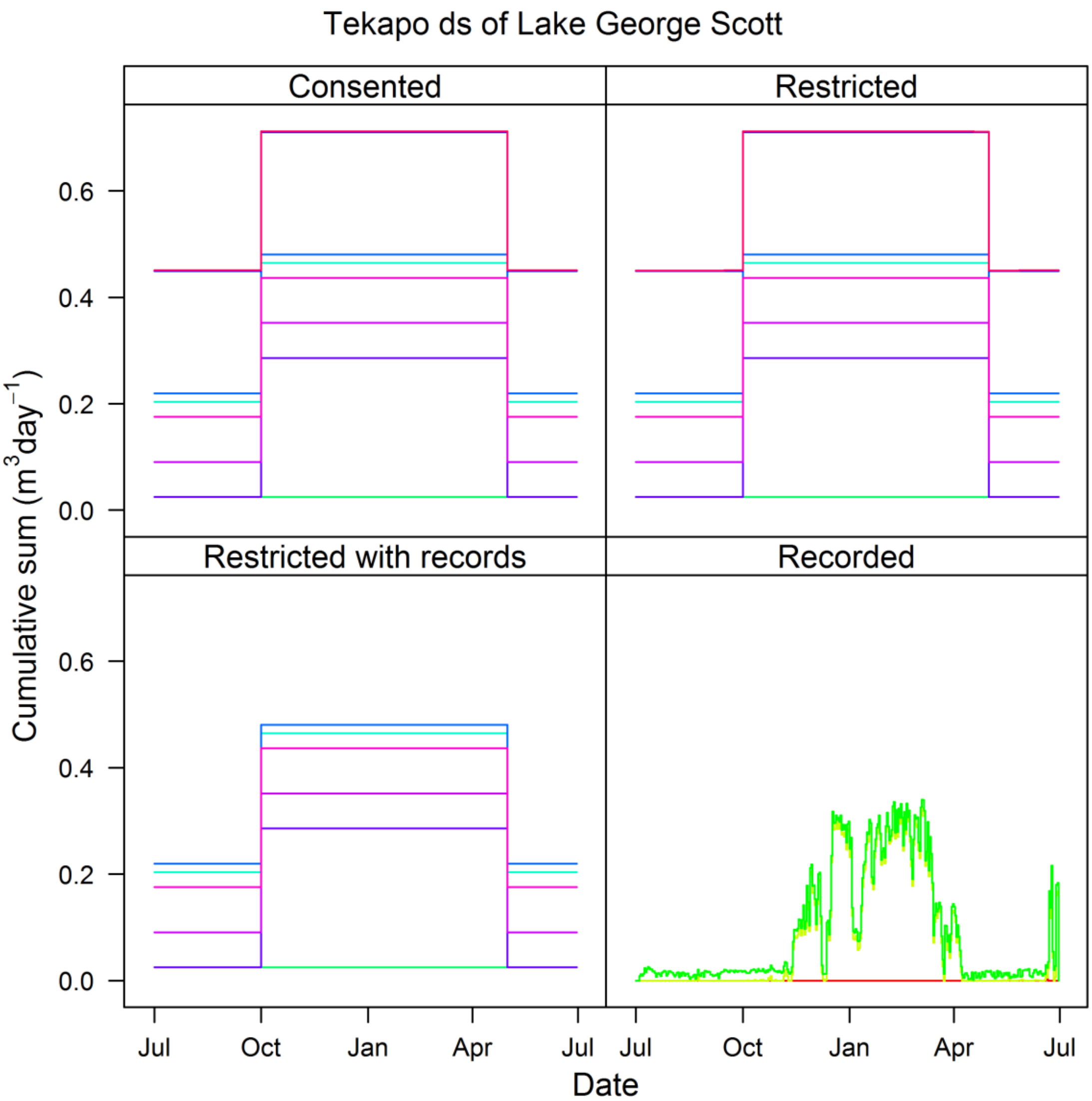

Figure 4-9: Cumulative sums for all consents on the Tekapo River upstream of and including Lake George Scott. Diversions to the Tekapo Canal occur upstream of this point.

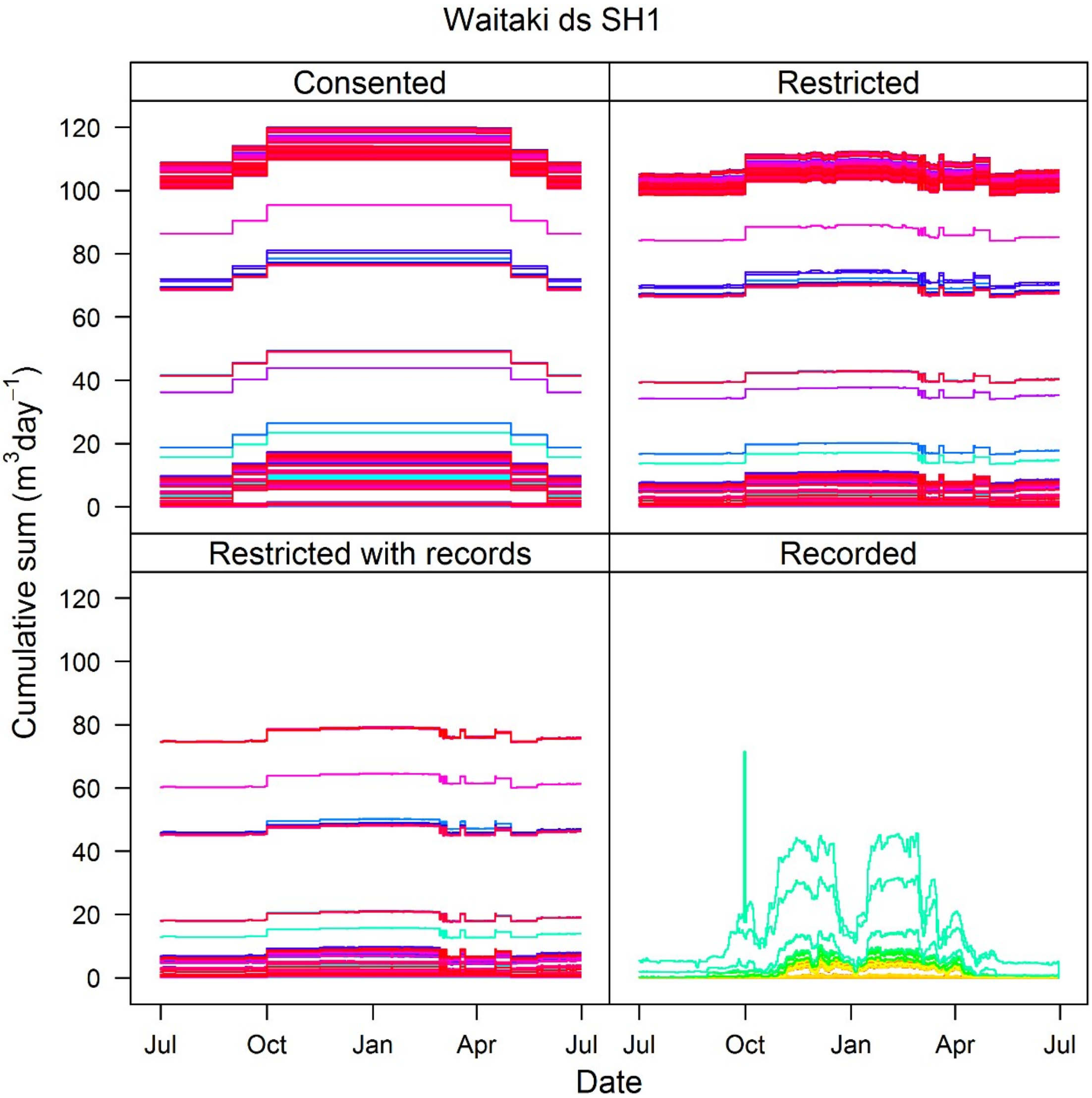

Figure 4-10: Cumulative sums for all consents on the Waitaki River upstream of SH1. All major consents and most minor consents are upstream of this point.

Figure 4-10 shows cumulative sums upstream of the Waitaki River at SH1. This is downstream of all major and most minor takes from the Waitaki River. There are several large consents and many small ones totalling nearly 120 cumecs. Inspection of Figure 4-10 indicates that the total sum is dominated by five large consents. Records are available for approximately 80 cumecs of this total. The actual recorded takes approach a maximum of 50 cumecs in the 2013-14 summer, except for a notable spike possibly due to a data error.

From our experience working in this catchment, we would expect to see a total sum of consented takes to be less than that shown in Figure 4-10. There may be several possible explanations for this:

- There may be consents that are correctly entered that we did not expect to see. These might be consents that are very rarely (or never) exercised. For example, the 260 cumec consent for the North Bank Tunnel is in the database but is now unlikely to be taken up.

- There may be mistakes in data entry such as wrong units. For example, one of the (non-consumptive) consents for Tekapo hydro operation is listed as 13 cumecs rather than 130 cumecs.
- There may be multiple entries for the same consents. For example, there are 36 separate entries for takes of around 500L/s from a single location in the Ahuriri catchment, with the same consent number.
- There may be consents that are entered as consumptive when they would more appropriately be designated as non-consumptive. These include the canal diversions of the upper Waitaki.

We are also able to produce maps showing where the consented values are located throughout a catchment. Figure 4-11 shows the locations and consented rates of take (before any restriction are applied) for all consents in the Waitaki River catchment upstream of SH1.

Our model allows us to produce figures such as Figure 4-10 and Figure 4-11 for any reach that is influenced by a consumptive consent. Above we have demonstrated how these figures can be used for checking that both the data and the model match with expected patterns.

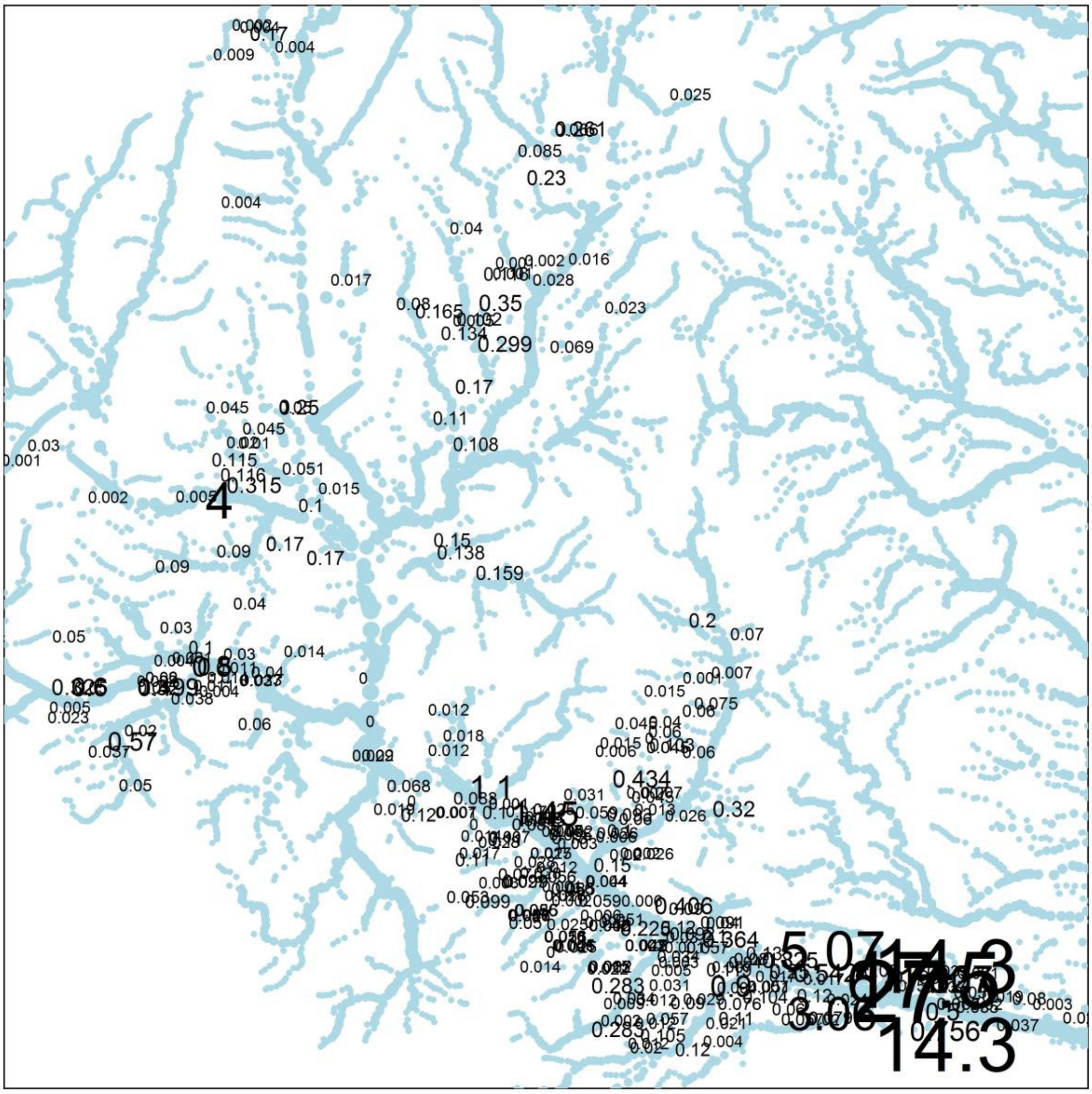

Figure 4-11: Map of consumptive consented takes in the Waitaki River catchment upstream of SH1. Black numbers show consented takes before restrictions on 07/03/14 in cumecs.

4.1.4 Wetted Width

Predicted wetted widths from the national hydraulic geometry method of Booker and Hicks (2013) corresponded well with those given by hydraulic models derived from field observations of water levels and discharge (Figure 4-12). Tests were applied in log10 space for 25 estimated widths spread equally between zero flow and the median flow for each of 266 sites. The regression slope was 0.89 (f = 33870 on 1 and 6648 DF, p-value: < 2.2e-16) with an r^2 value of 0.84. Nash-Sutcliffe efficiency was 0.82 (NSE2 = 0.70) and RMSD was 0.18. This indicates that overall, widths were well predicted.

When the same tests were applied to each site separately, results indicated a range of performance across sites (Figure 4-13). High r^2 values and slope (BETA) values around one indicated that the relative change in width across flows was well predicted for the majority of sites. However, some low

NSE2 values indicated that there were some discrepancies between the two sets of widths at some sites.

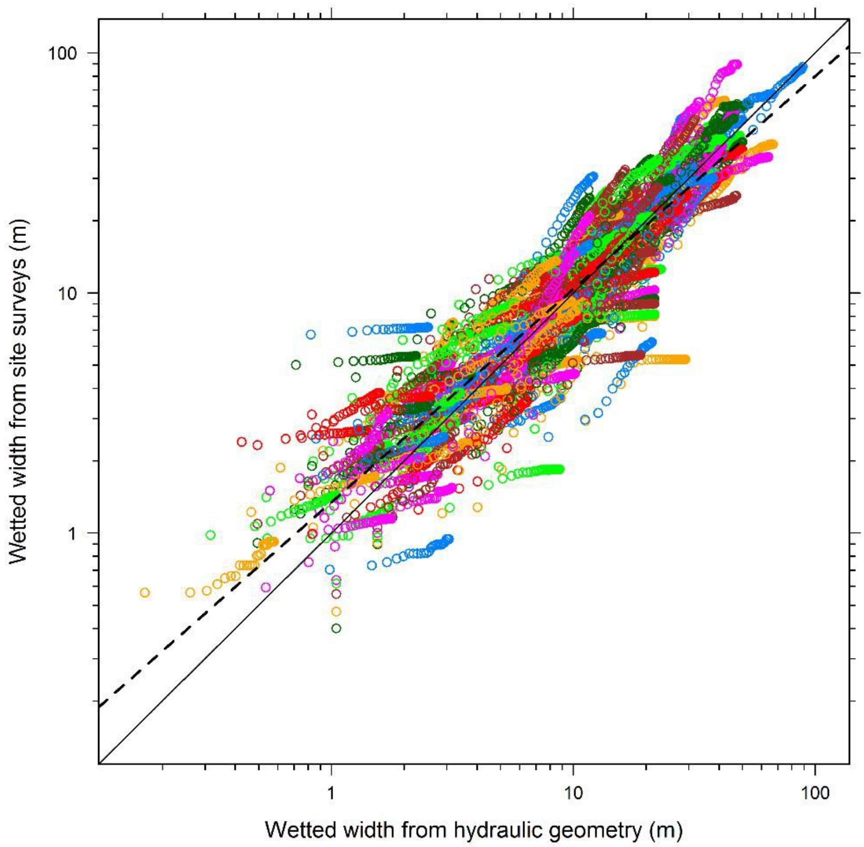

Figure 4-12: Scatterplot of wetted widths estimated using the national hydraulic geometry method and those given by hydraulic models derived from field observations. Results are for 25 flows equally spaced between the median flow and zero for each of 266 sites. Each site is a different colour.

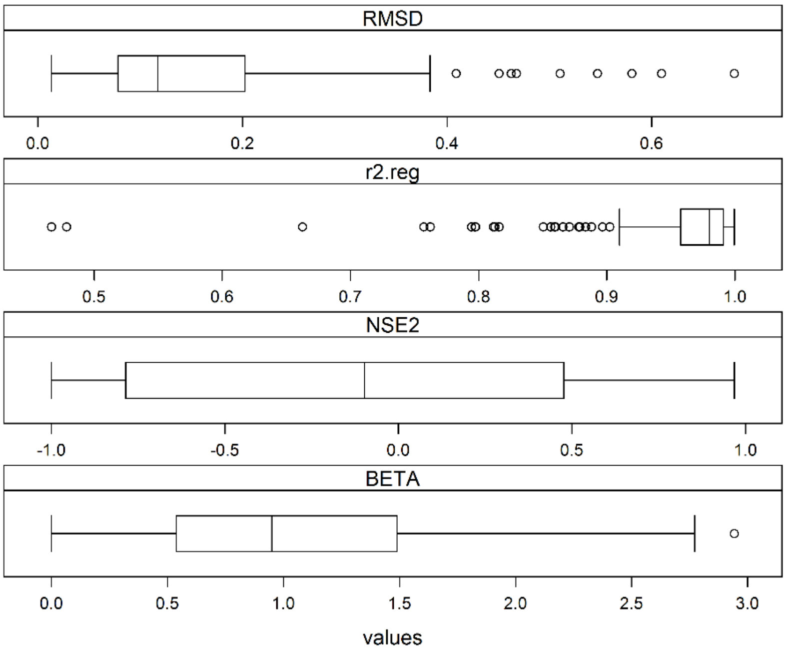

Figure 4-13: Performance for wetted widths estimated using the national hydraulic geometry method and those given by hydraulic models at each of 266 sites.

4.1.5 Availability of suitable physical habitat

Figure 4-14 shows performance results when all sites were tested together. BETA values near to one, high NSE values, high r^2 values and low RMSD values for Level1 models indicated that for all HSCs, the Ricker formulation fitted well to the data when its parameters were allowed to vary between sites. This was particularly the case when random-effects were applied to both A and K. The Jowett2008 method only provides an estimate of relative habitat, therefore only r^2 values are informative for this method. Values of r^2 for the Jowett2008 method showed that that method performed less well than the Ricker model for both Brown Trout and Food Production.

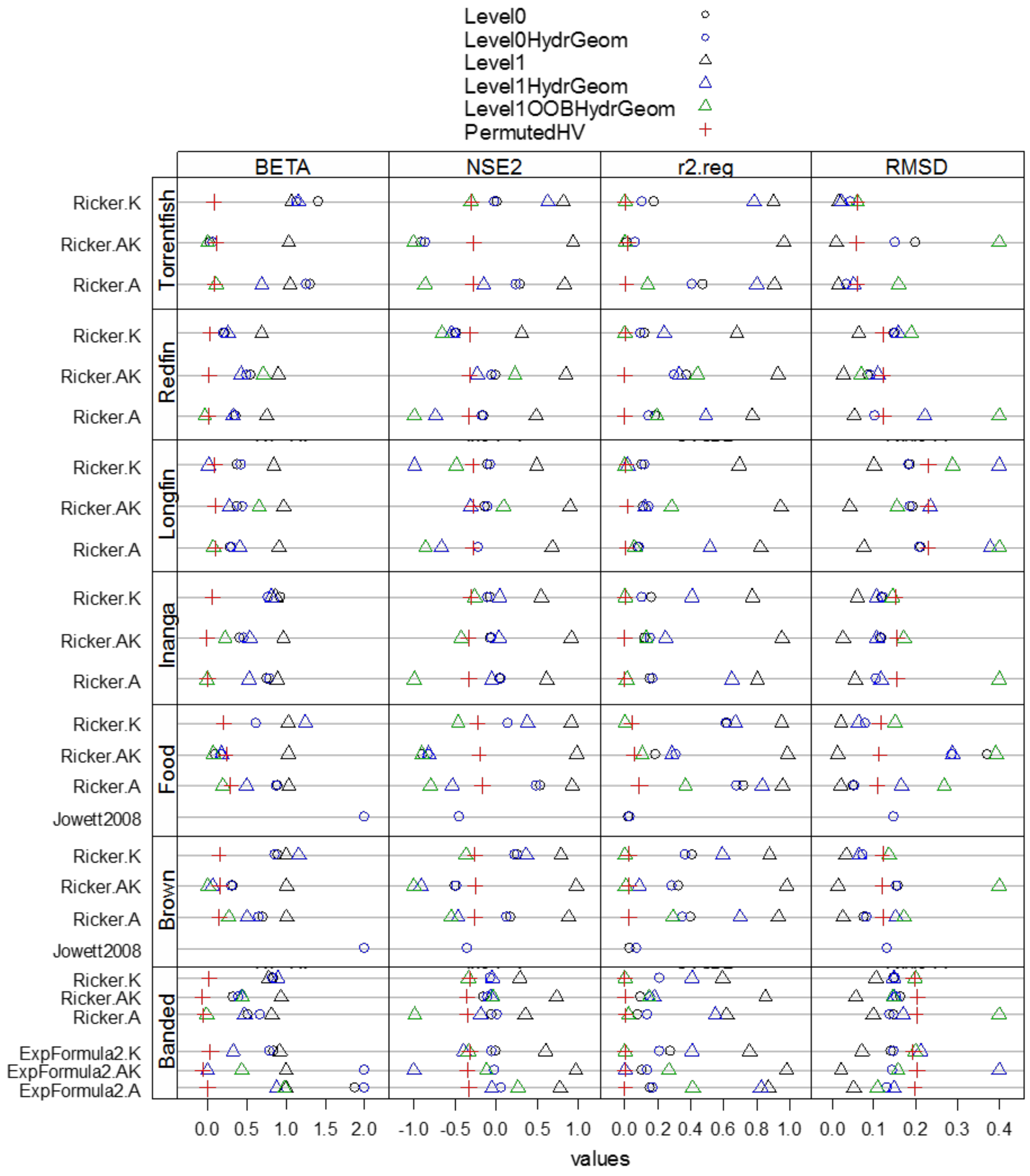

Figure 4-14: For each habitat suitability criteria, four different performance measures for various methods of estimating HV over all sites together. Ricker = Ricker Model. ExpFormula2 = two parameter exponential decay curve. Jowett2009 = method of Jowett et al. (2008). A = random effects on A parameter A. K = random effects on K parameter. AK = random effects on A and K parameters.

Figure 4-15 shows performance results when change in habitat between the 5th and 10th percentiles of flow were calculated using various methods. Figure 4-16 shows the percentage of sites correctly predicted as having either increasing or decreasing habitat between the 5th and 10th percentiles of flow. We inspected all results across each HSCs in order to recommend the most appropriate models for application across unvisited sites. We also inspected final predicted habitat-Reynolds curves and compared predicted curves with those calculated using RHYHABSIM. Our recommended methods are given in Table 4-1.

Table 4-1: Recommended models for each habitat suitability criteria.

Habitat suitability curve	Model form	Random-effects	Level
Torrentfish	Ricker	A	0
Redfin bully	Ricker	AK	1
Longfin > 300mm	Ricker	AK	1
Inanga feeding	Ricker	AK	1
Food production	Ricker	A	0
Brown Trout adult	Ricker	A	0
Banded kokopu adult	Exp2	AK	1

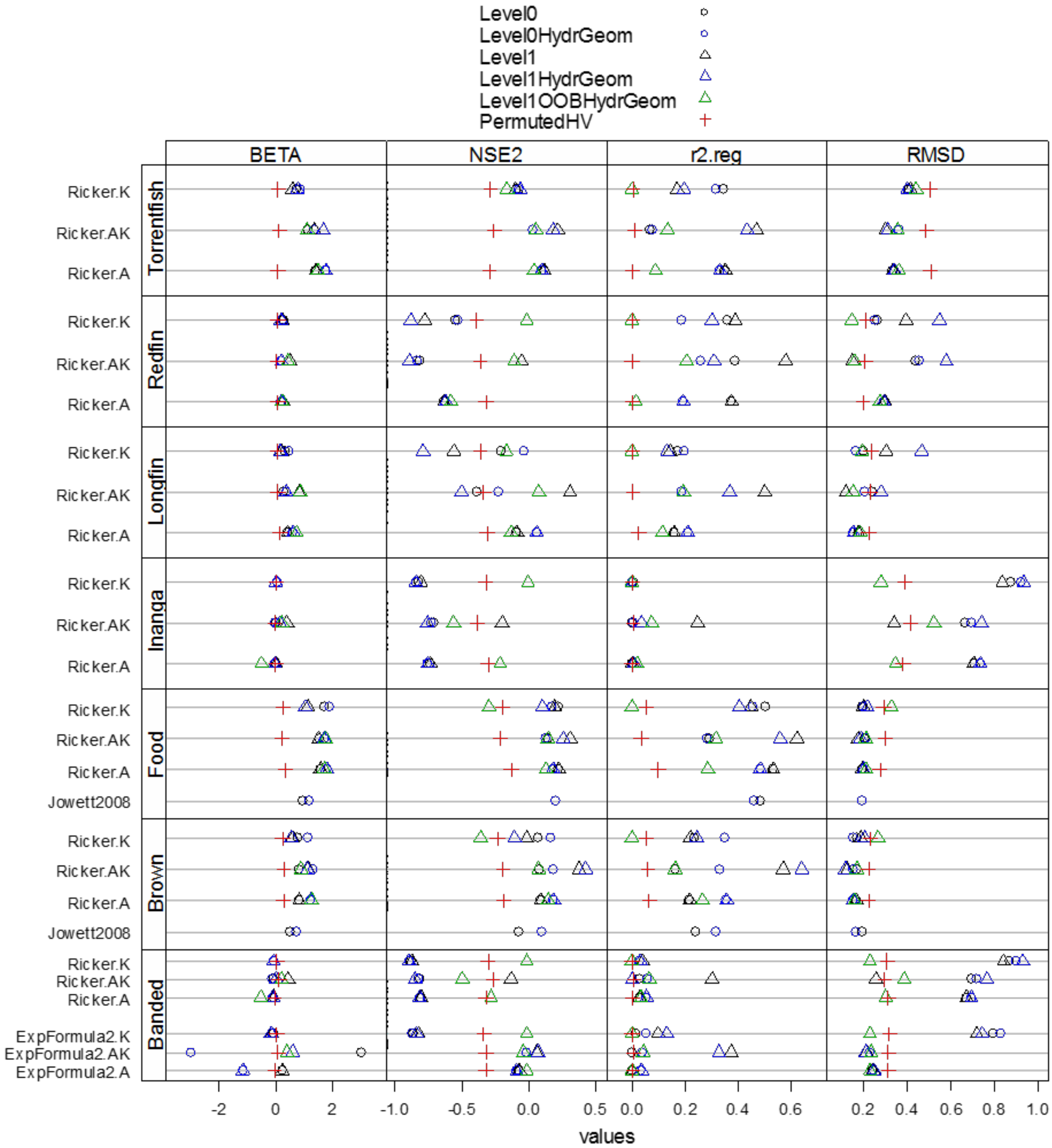

Figure 4-15: Four different performance measures for various methods of estimating change in HV between the 5th and 10th percentiles of flow.

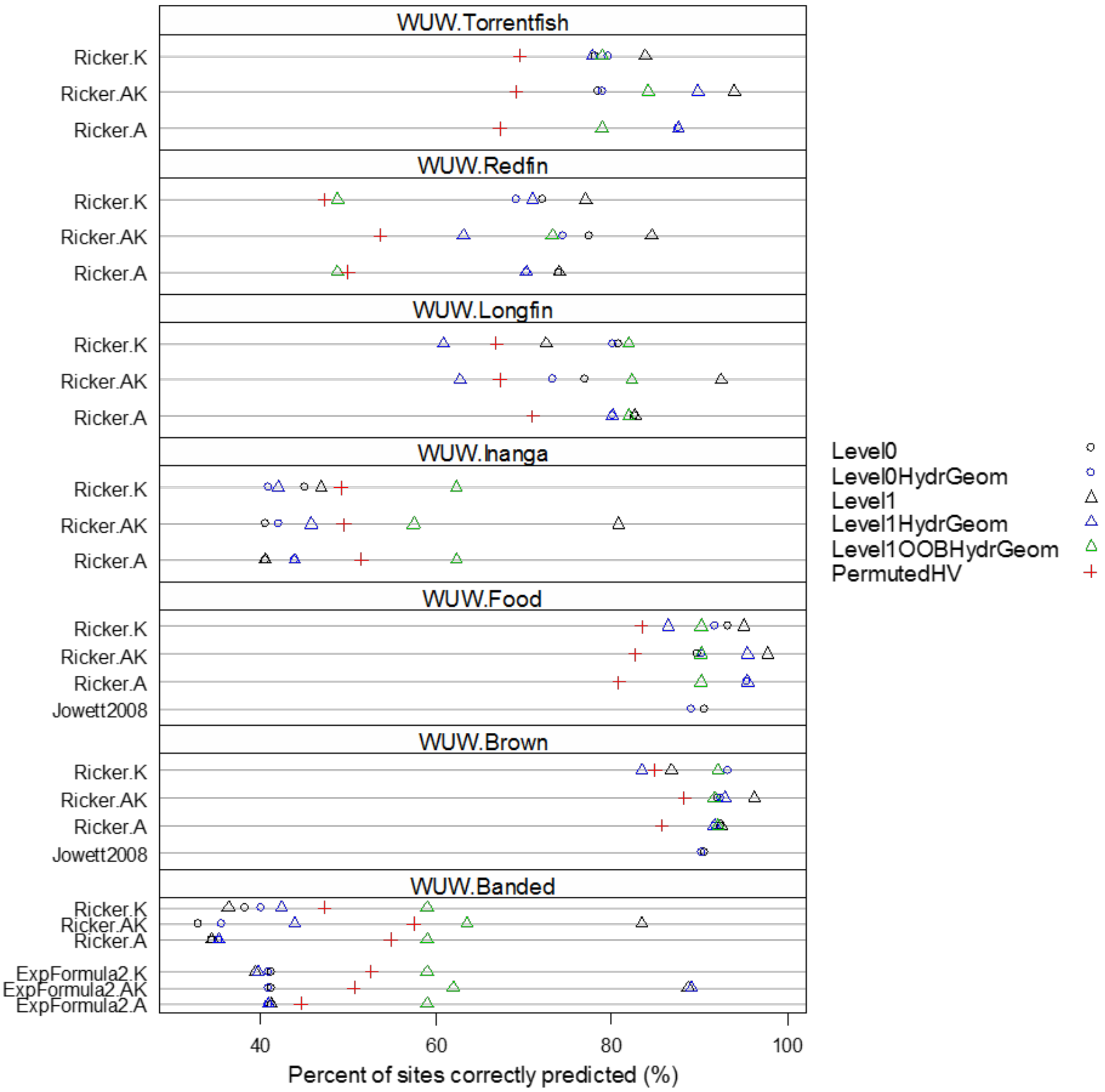

Figure 4-16: Percentage of sites correctly predicted as having either increasing or decreasing habitat between the 5th and 10th percentiles of flow.

4.2 Pressures

Takes from surface water are distributed across Canterbury, whereas groundwater takes are concentrated towards the lower lying eastern areas of mid-Canterbury (Figure 4-17). Some management zones had a higher proportion of groundwater takes (e.g., Selwyn-Waimakariri), whereas others have a higher proportion of takes from surface water (e.g., the various Waitaki zones).

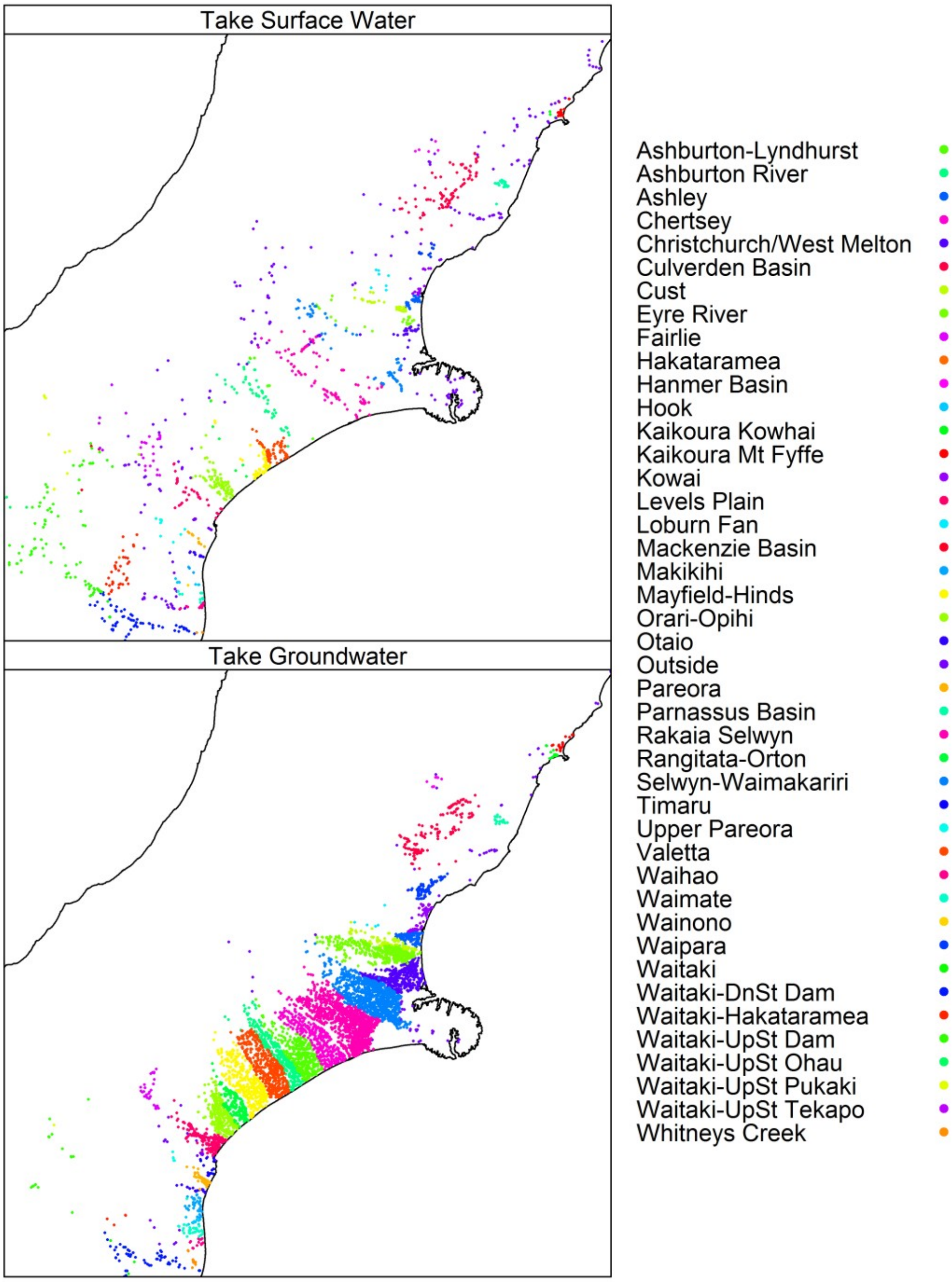

Figure 4-17. Locations of takes in Canterbury grouped by management zone and primary source.

The majority of groundwater takes were classified as having no connectivity to rivers (Figure 4-18). The connectivity to rivers was not recorded for many groundwater takes. When connectivity was inferred from secondary source and well depth, 79% were re-classified as having low connectivity and 21% were re-classified as having high connectivity (Figure 4-18). This matched well with the ratio of high versus low connectivity in the original data.

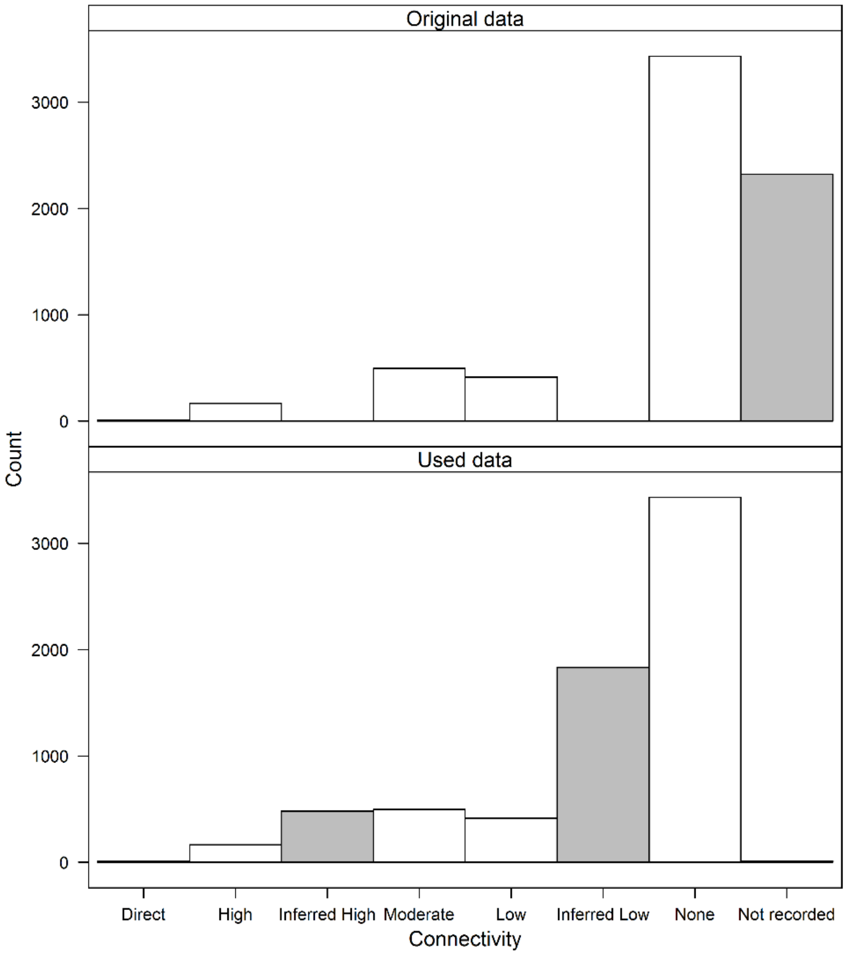

Figure 4-18. Histogram of bore connectivity.

The number of activities varied across type of activity and type of take (Figure 4-19). Irrigation had by far the greatest number of activities, with various numbers of other activities.

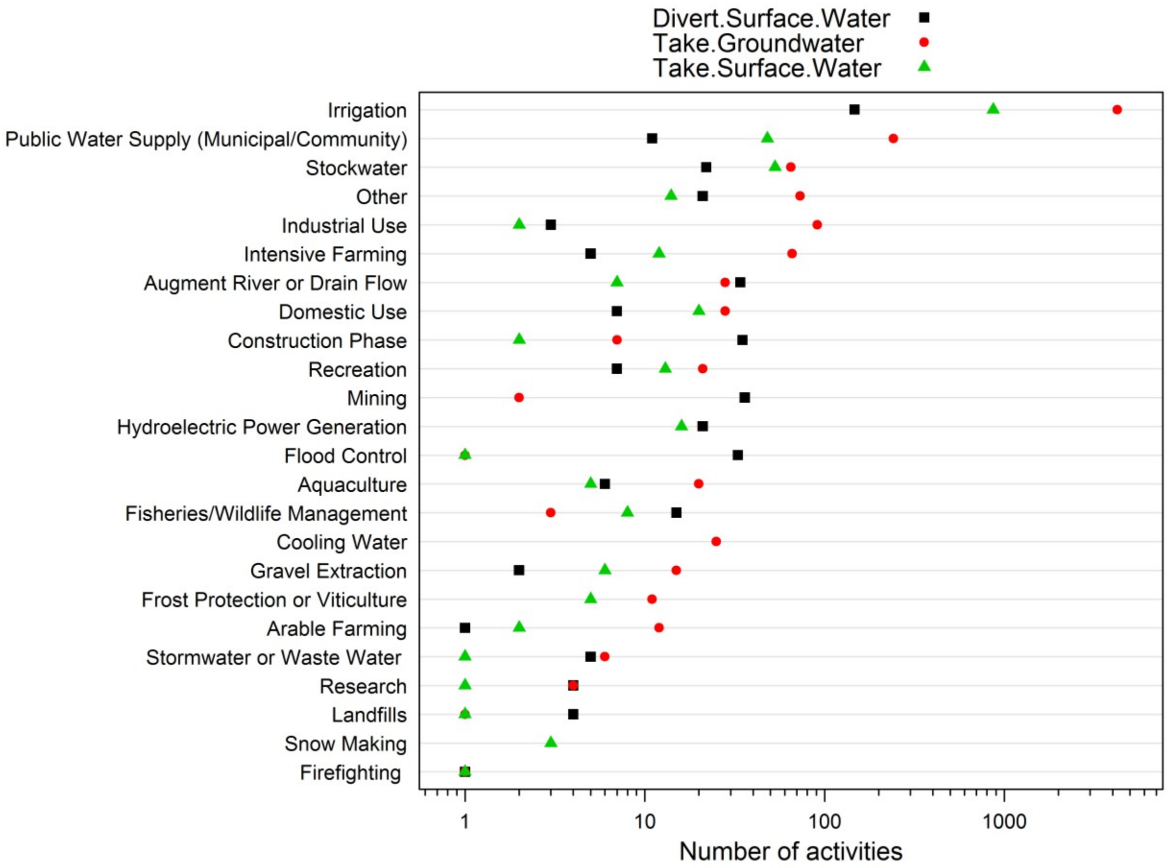

Figure 4-19. Number of activities by Use Type and Water Take Type.

Some interesting patterns were evident in the timing of commencement and expiry of all consents across the region (Figure 4-20). No consents appear to span a period greater than 35 years. Many consents that commenced in the mid-1990s were issued with 35 year consents. There has been an increasing trend towards issuing consents for shorter periods and towards issuing constant expiry dates within management zones. For example, many consents are due to expire during 2030 in the Fairlie zone and during 2034 in the “Levels plain” zone.

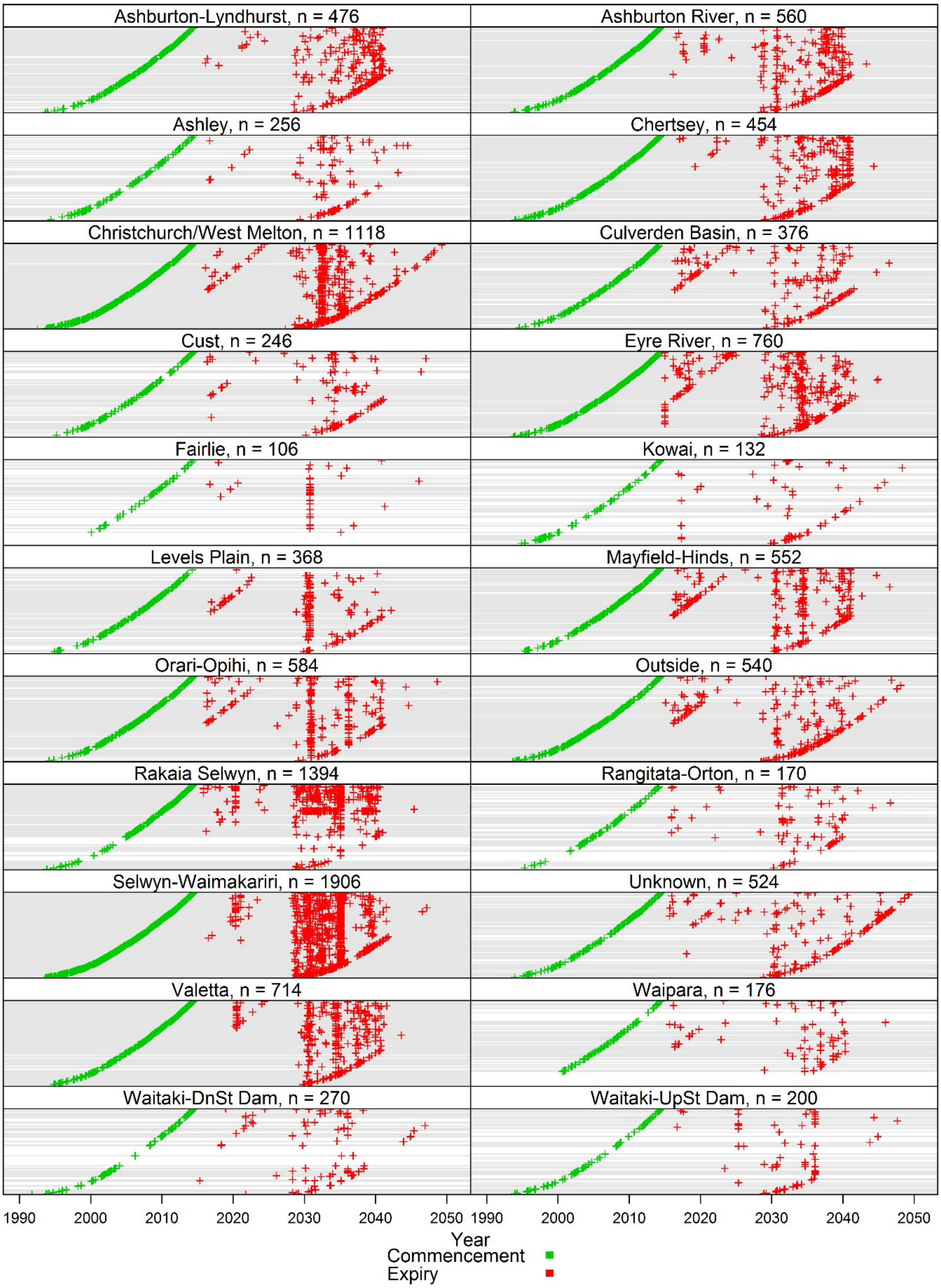

Figure 4-20. Timings of all consents. Each row is a consent.

There were many different crop types relating to the activities. The data indicated that various forms of pasture, mixed crop types and horticulture were recorded has having the greatest total irrigated areas (Figure 4-21). However, it should be noted that these total areas were dominated by a few consents with very large areas for some crop types (Figure 4-22). For example, two consents for horticulture irrigation cover very large areas. Note that not all consents were associated with an irrigated area. For example, many stockwater takes were not associated with irrigated areas.

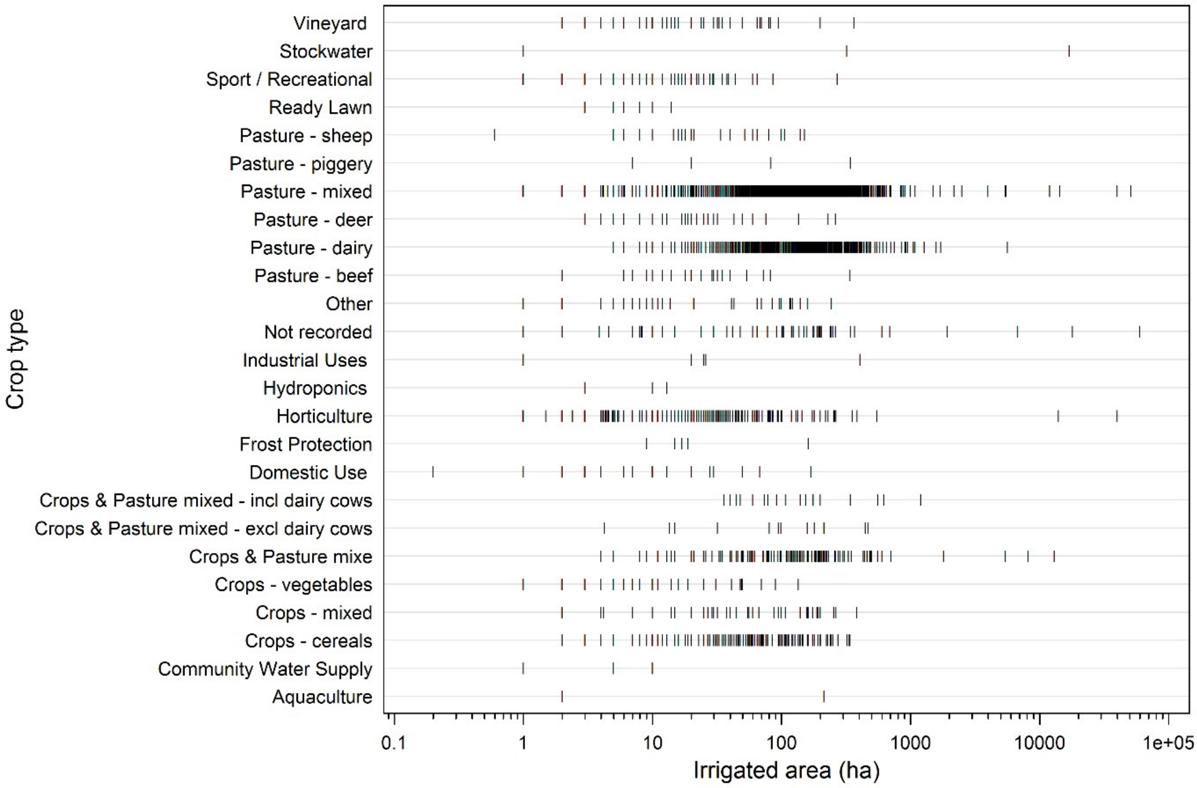

Figure 4-21. Irrigated area for each activity by Use Type.

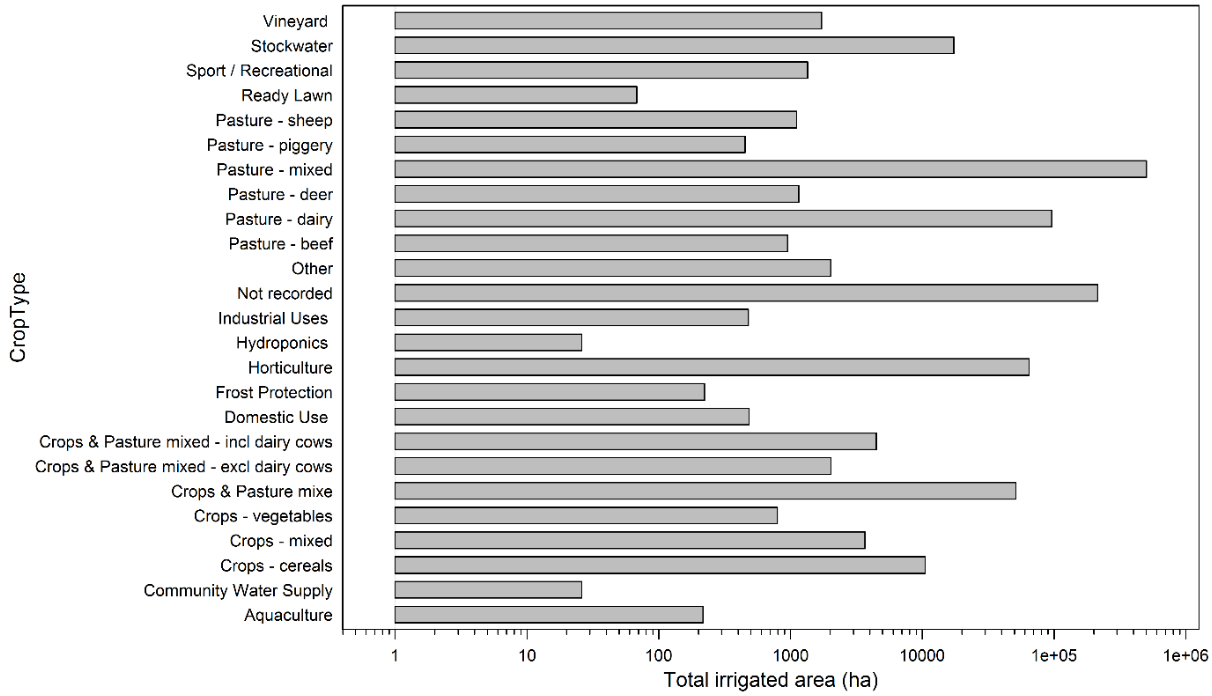

Figure 4-22. Total irrigated area for each Use Type.

The amount of consented water (as represented by maximum daily take) was strongly related to the irrigated area (Figure 4-23). However, there was variability in this relationship. There was variability between different crop types, within each crop type and depending on whether the takes were from groundwater or surface water. Variability within crop types indicates that some users have been allocated more water than others with the same crop type and area of land. Lack of differences in the relationship between groundwater and surface water takes may indicate that maximum daily take is more strongly related to irrigated area than to river flow. This hypothesis is supported by a lack of relationships between maximum daily take and river catchment area (Figure 4-24) although this graph also suggests the possibility that some surface water takes could have been erroneously associated with very small rivers rather than nearby larger rivers.

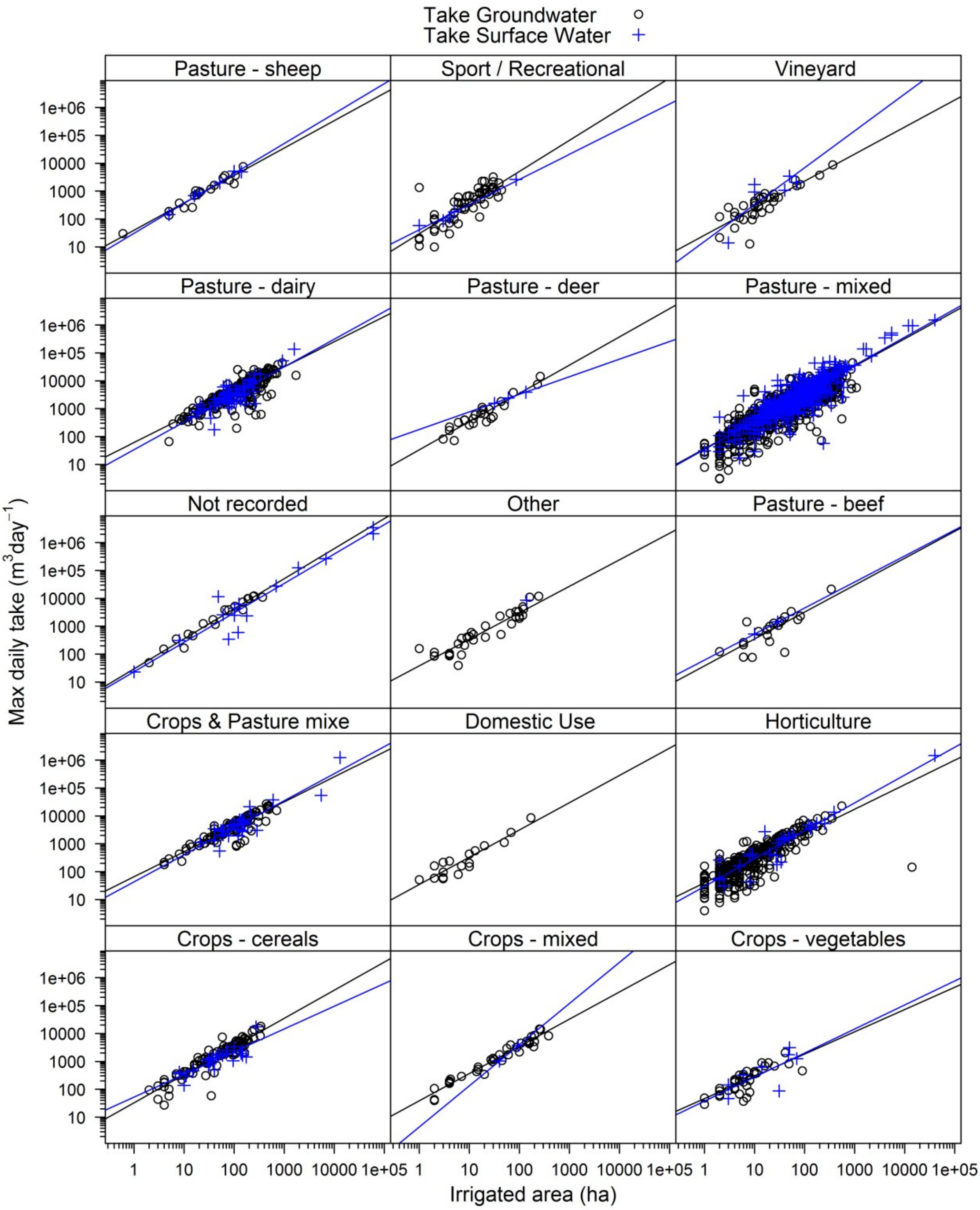

Figure 4-23. Scatterplot of maximum daily take against irrigated area for each activity. Blue line is a regression.

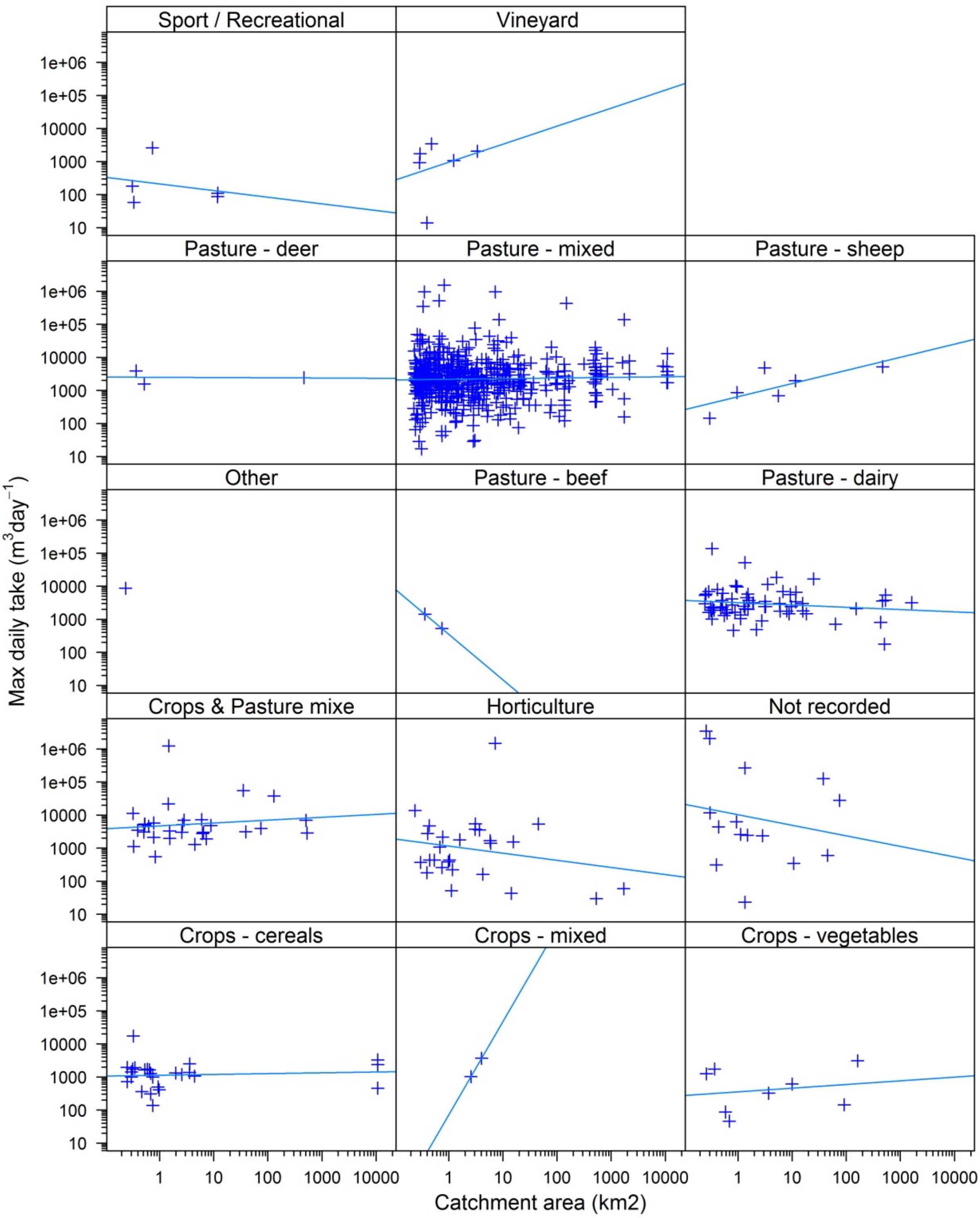

Figure 4-24. Scatterplot of maximum daily take against catchment area for each activity. Blue line is a regression.

Maximum consented daily take varied widely across the region (Figure 4-25). Although this map indicates the spatial extent of water demand across the region, it provides little information on the spatial extent of impacts on river flows and impacts on river environments.

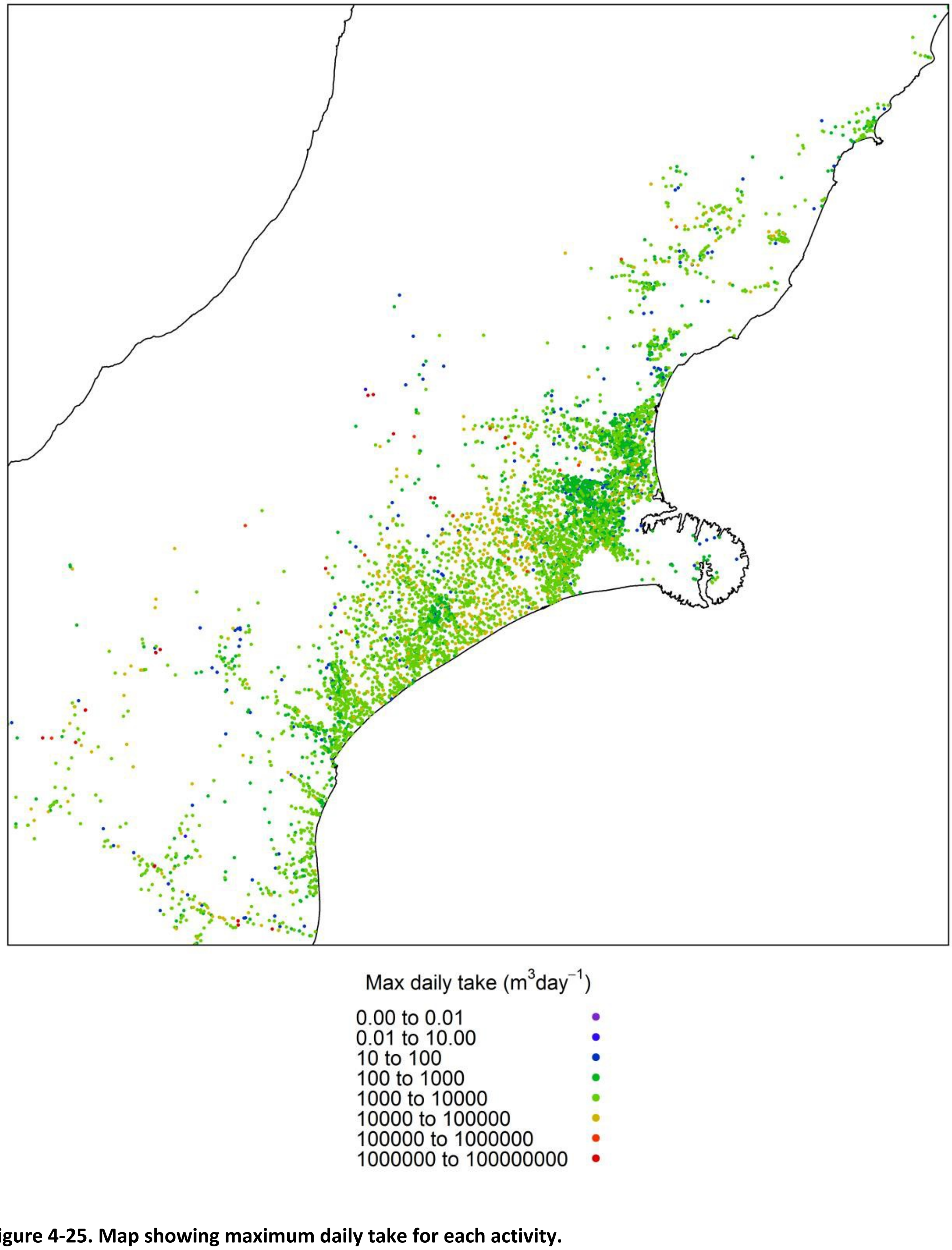

Figure 4-25. Map showing maximum daily take for each activity.

We routed and accumulated various values down the river network in order to assess the cumulative effects of many takes. For example, Figure 4-26 shows the number of takes upstream of each river reach. Results indicated that many reaches located further from the coast were only influenced by a few upstream takes, whereas there were around 700 takes with the catchment that flows into Te Waihora/Lake Ellesmere.

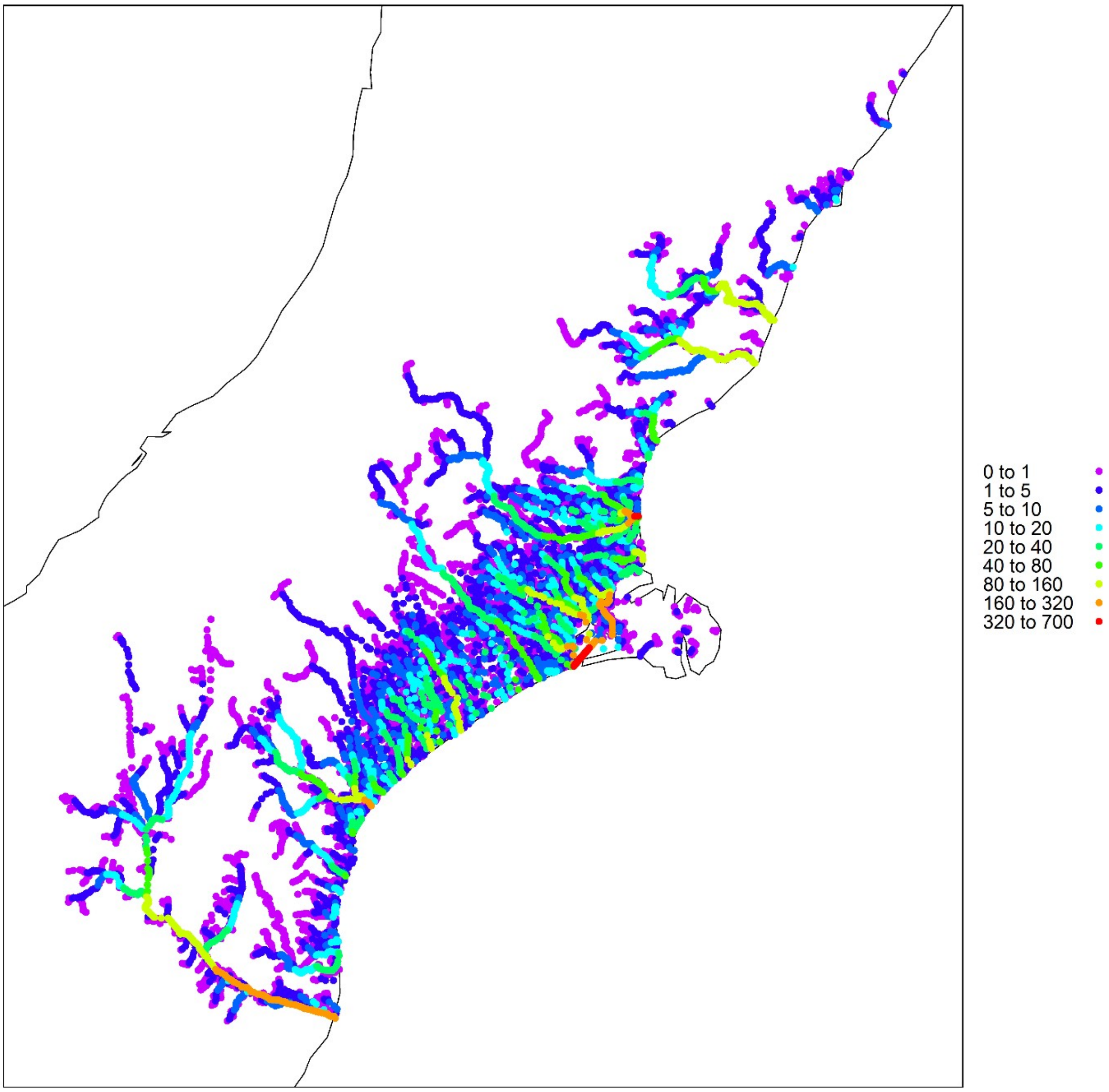

Figure 4-26. Map showing number of upstream takes from both surface water and groundwater.

Various values representing observed or potential takes (see Table 3-2 for explanations) were accumulated down the river network for each day of the 2013-14 hydrological year. Figure 4-27 shows various accumulated values for four days throughout the year. “Consented” represents the quantity of water (relative to catchment size for each reach) that would be expected to be abstracted had all users taken all water that was consented to them regardless of any restrictions. Results indicate that there were only very small variations in these values between the four days shown, with many rivers having cumulative upstream consents of at least 10 m^3 d^{-1} km^{-2} throughout the year. Relatively few differences between the Consented maps and the Restricted maps indicates that the majority of users were not having their abstractions restricted on the dates shown. Relatively large differences between RestrictedWithRecords and Recorded indicates that, the users who supplied records were not utilising their full allocation. This was particularly the case in July and October but less so in late January, when recorded use was nearer to restricted use.

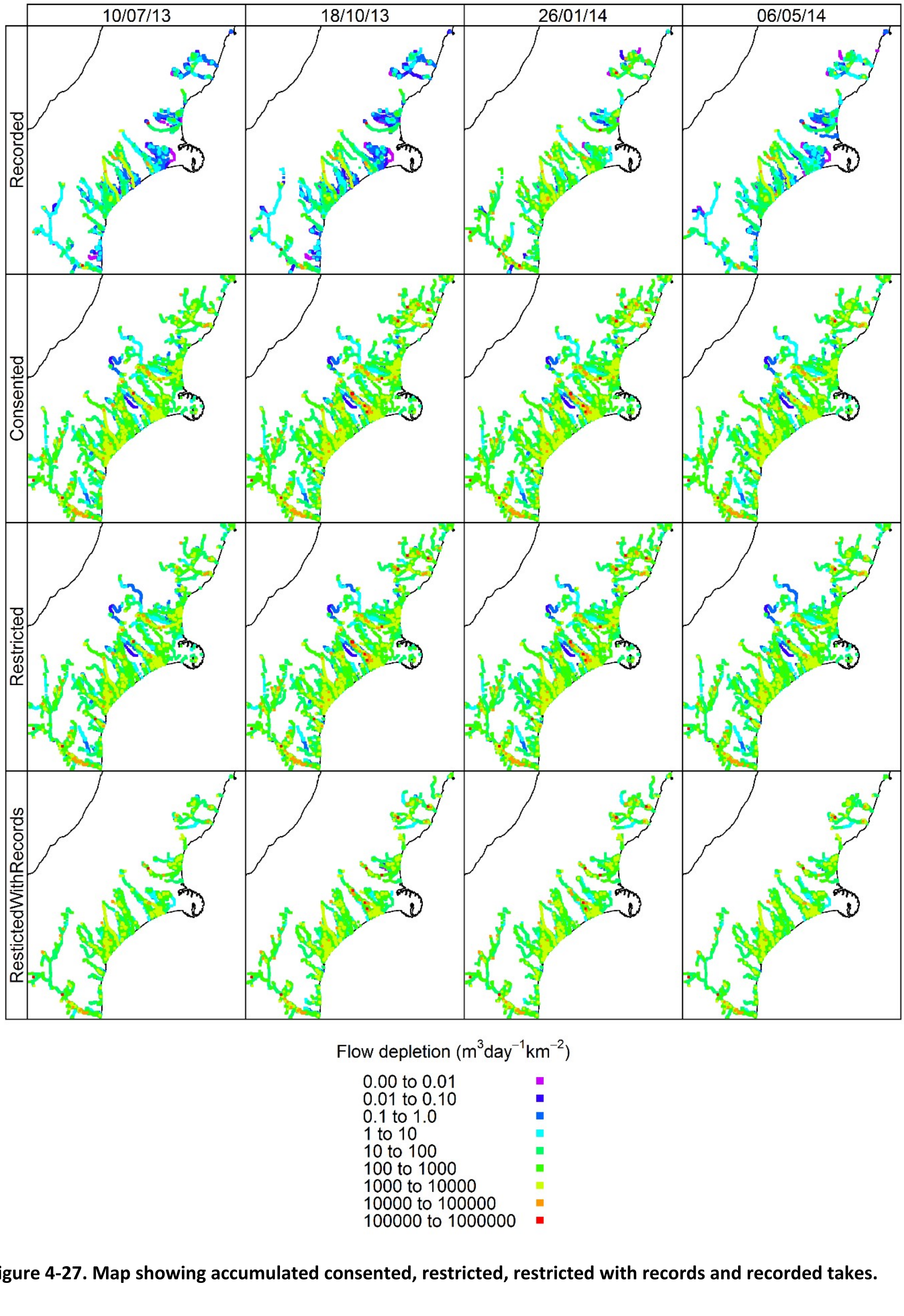

Figure 4-27. Map showing accumulated consented, restricted, restricted with records and recorded takes.

4.3 States

Inspection of time-series' for individual activities indicated that there was a variety of behaviours relating to compliance and headroom (Figure 4-28). Some abstractors were recorded to have taken consistently far less than their consented values even after having restrictions applied. These abstractors could be described as being compliant, but also as having headroom within their consents. Other abstractors occasionally had recorded takes that exceeded their consented or restricted takes. These abstractors could be described as being compliant on average, occasionally being non-compliant, but still having some headroom. Other abstractors consistently had recorded takes that met or exceeded their consented or restricted takes. These abstractors could be described as being consistently non-compliant and having no headroom for increasing their takes within their current consent conditions (except perhaps in mid-winter). For a few abstractors recorded values were consistently greater than their consented or restricted takes. They could be described as being consistently non-compliant, as having no headroom within their current consents, and perhaps as denying other (possibly more compliant) abstractors of the opportunity to abstract.

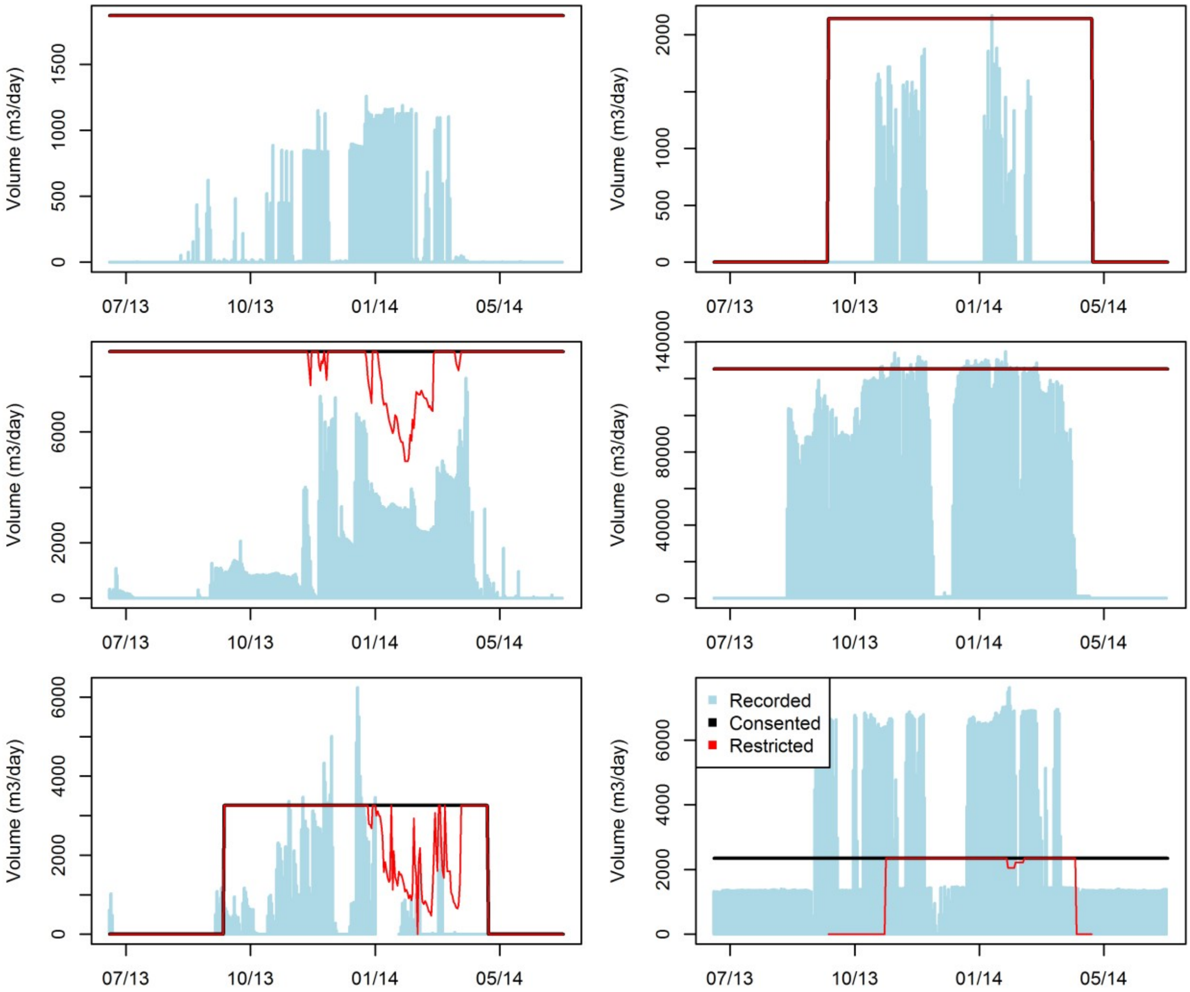

Figure 4-28. Time-series of recorded takes (blue bars), consented daily volume (black line) and allowable volume after restrictions have been applied (read line).

Plots of recorded volume against restricted volume averaged over the year indicate the balance of compliance to headroom on average over the year (Figure 4-29). Points located in the bottom right of this plot are compliant and have some headroom on average over the year, whereas those in the top left were non-compliant and had no headroom even when averaged over the year. Plots of recorded maximum volume against maximum restricted volume indicate the balance of compliance to headroom for the most water hungry day of the year. Figure 4-29 indicates that on average over time the vast majority of users were compliant, and that there is considerable headroom when viewed across all users. In contrast, Figure 4-29 also indicates that this is not the case during the most water hungry days of the year. Further analysis showed that 5% of abstractors were non-compliant when averaged over all time. However, 35% of abstractors with records were non-compliant on their day of maximum take. It should be noted that no margin for error was applied in this analysis. This meant that every occasion when observed values only marginally exceeded maximum restricted volume were counted as non-compliant.

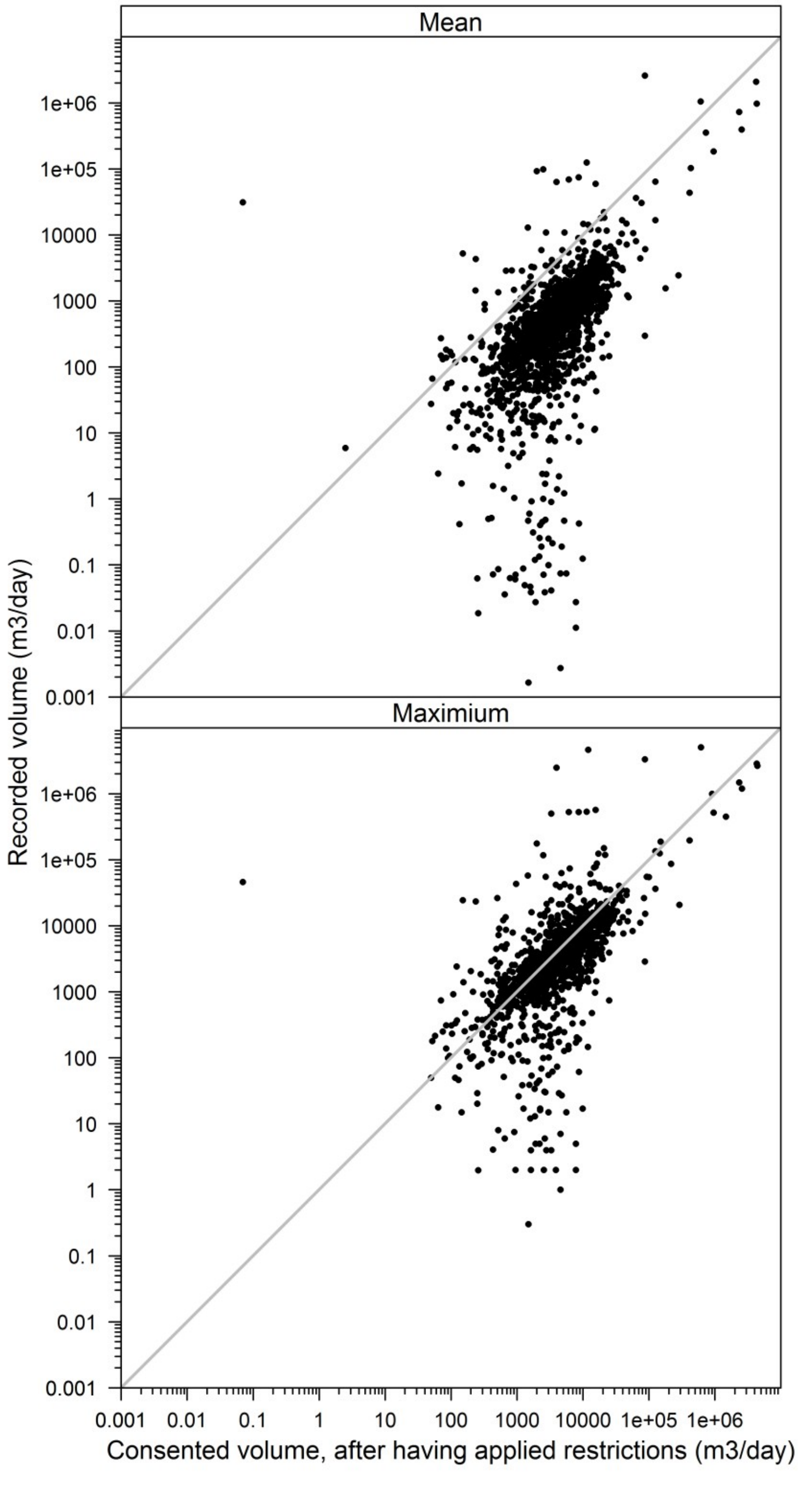

Figure 4-29: Mean and maximum of recorded virtual takes against allowable volume after restrictions have been applied.

Figure 4-30 shows similar information to that shown in Figure 4-28 for compliance, except results are shown for all activities with at least 300 days of recorded take data. Each row is an activity. Results indicate that the majority of takes were compliant for the majority of the time. This is similar to

Figure 4-29. However, Figure 4-30 indicates that the times of non-compliance often coincided across the region. For example, a period of non-compliance occurred between days 190 and 240 (06/01/14 to 25/02/14). Non-compliance during this period could have resulted from increased restrictions due to lower flows at control sites, and/or increased takes due to higher water demand.

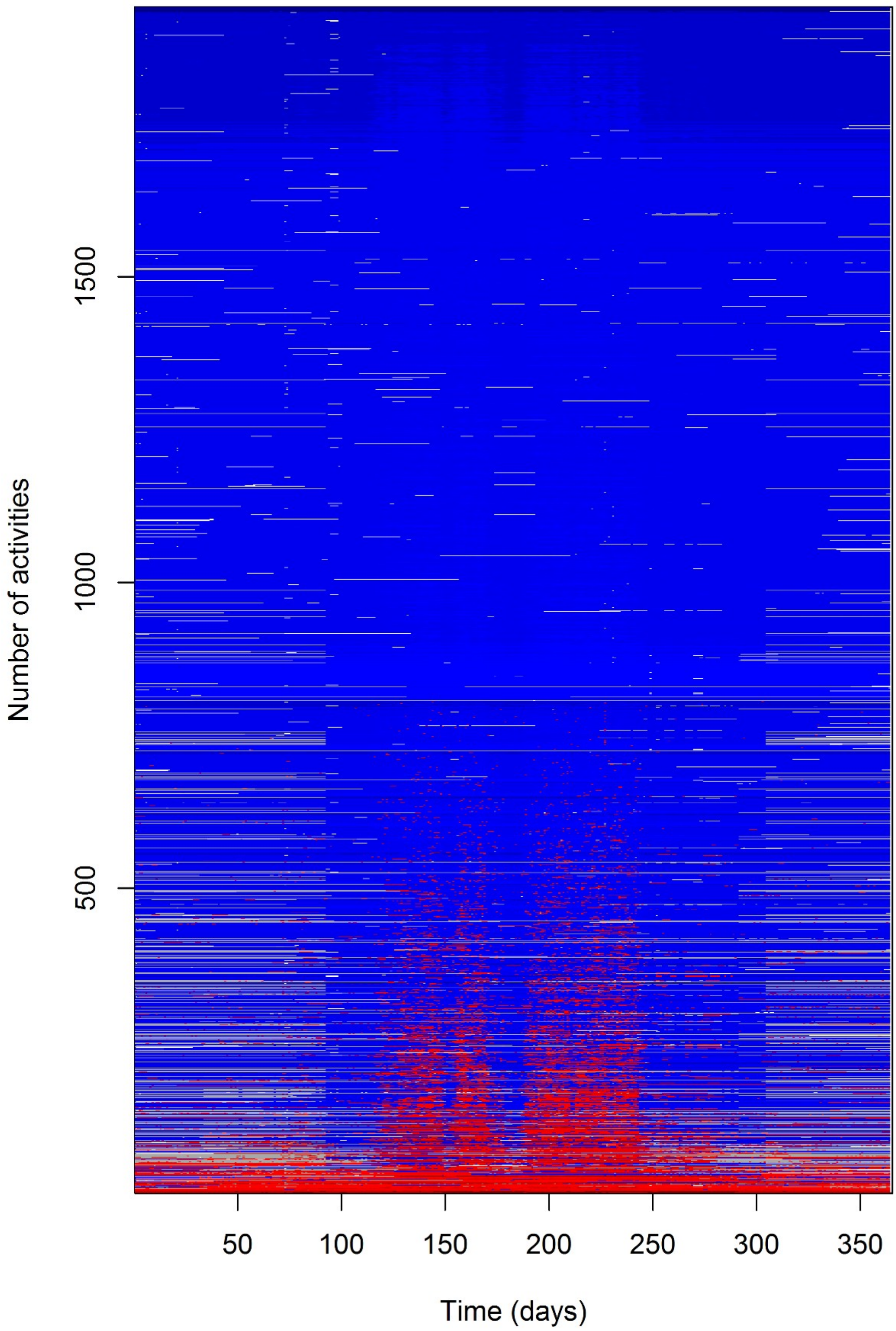

Figure 4-30: Time-series of compliance (or headroom) for 1941 virtual takes with more than 300 days of recorded use in 2013-14. Red indicates non-compliance. Blue indicates compliance. Grey indicates zero allocation. White indicates missing data.

Figure 4-31 shows similar information to that shown in Figure 4-30, but for restriction. Each row is an activity. Rows are the same activities shown in the same order as Figure 4-30. Results indicate that the majority of these takes were unrestricted for all of the year. This may occur because their consent conditions do not have any facility for enforcing restrictions or because conditions at control sites did not trigger any restrictions. However, some restrictions were enforced all year round. These are takes that are linked to control sites whose flows or groundwater levels never reached levels that allowed any abstractions to occur. Other takes experienced intermittent periods of restriction. These periods did not coincide across activities, but more restrictions occurred between days 240 and 300 (25/02/14 to 26/04/14) than at other times of the year. Note that this period did not match exactly with the period of greatest non-compliance (Figure 4-30). This indicates that the majority of non-compliance occurred due to increasing demand for water in mid-summer rather than increasing restrictions in late-summer.

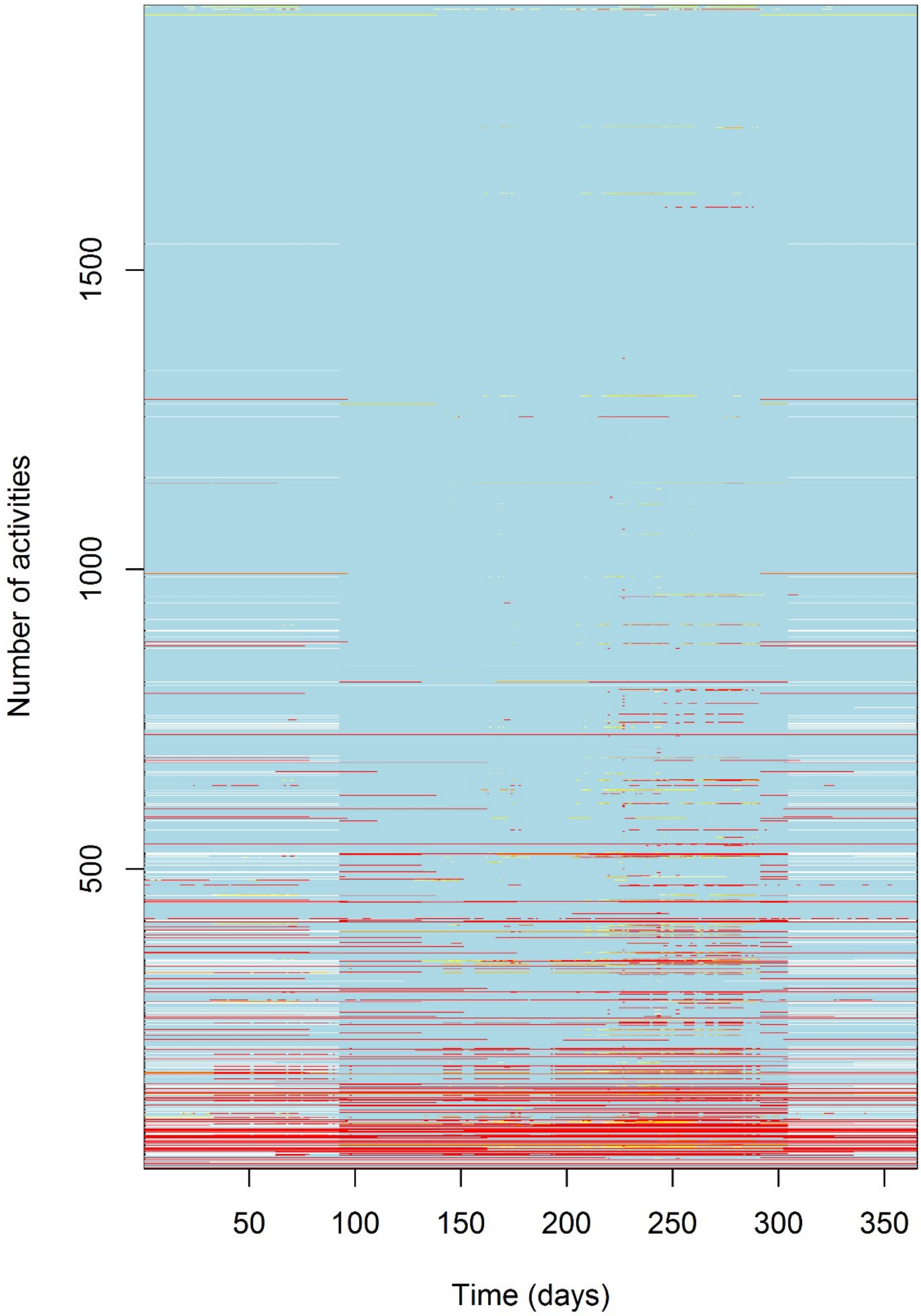

Figure 4-31: Time-series of restriction for 1941 virtual takes with more than 300 days of recorded use in 2013-14. Red indicates full restiction. Orange indicates partial restriction. Light blue indicates no restrictions. White indicates missing data.

Figure 4-32 shows time-series of estimated stream depletion (the amount of water estimated to be depleted from this reach as a result of all upstream takes after having taken into account delays from groundwater takes) for an example river reach. Results indicate that some restrictions were applied to some, but not all, takes in this catchment during this year. Cumulated recorded takes were far less than the cumulated consented values, even after having restrictions applied. However, a large proportion of the consents had no associated records. Comparison of cumulated recorded takes with their cumulated restricted values indicated that cumulative recorded use was often near to its cumulative limit. This indicated that a large proportion of takes were not recorded, and therefore comparisons between actual use and potential consented use are problematic.

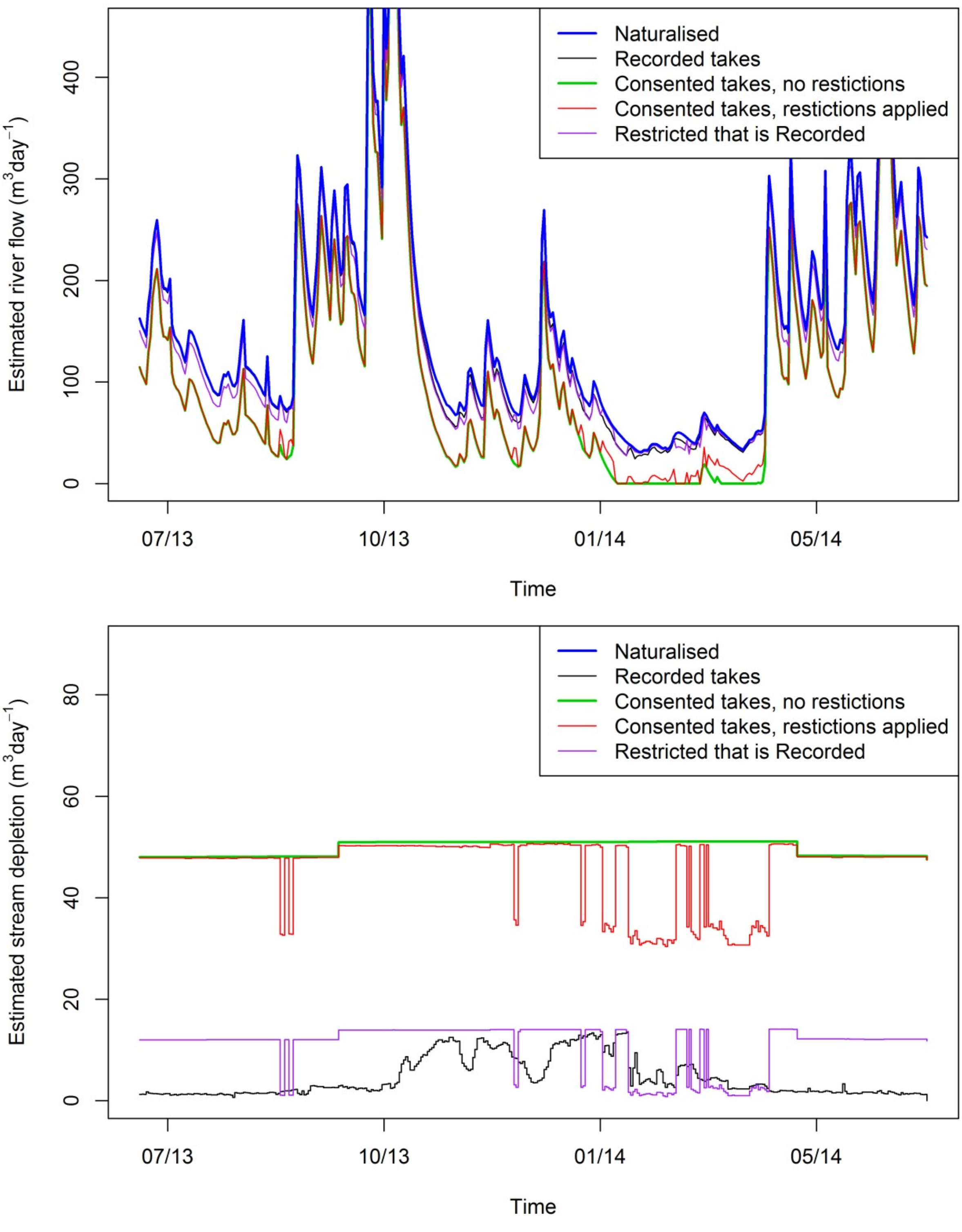

Figure 4-32: Example from Lower Waimakariri of estimated naturalised flow time-series, plotted alongside accumulated recorded takes and accumulated allowable takes.

Figure 4-32 also shows time-series of estimated flows (naturalised flows minus cumulative takes) for the same location. Results indicate that, had all abstractors taken their allocation and ignored their restrictions, flow at this location would be zero during February and March. The red line was obtained by accumulating the amount of water each abstractor could have taken on that day after having applied their restrictions on that day. If all users utilised their full consents in this manner, then flow at the control site would be lower, there would be more restriction, and therefore all users would not be able to take the amount that was originally calculated. Therefore, the position of this red line should be interpreted with caution. It represents the total that would have been taken had all abstractors simultaneously abstracted to their limit. It does not indicate the total available water on that day if target environmental flows were maintained.

We calculated time-series such as that shown in Figure 4-32 for each location across the region. Each of these time-series can be summarised in a variety of ways. For example, the lowest flow of each time-series can be compared (Figure 4-33). Figure 4-33 indicated that relatively few reaches were dry on the day of lowest flow of the naturalised flow regime. However, this proportion increased when cumulative recorded takes were subtracted from the naturalised river flow. The proportion increased further when cumulative restricted and consented takes were subtracted from the naturalised river flow.

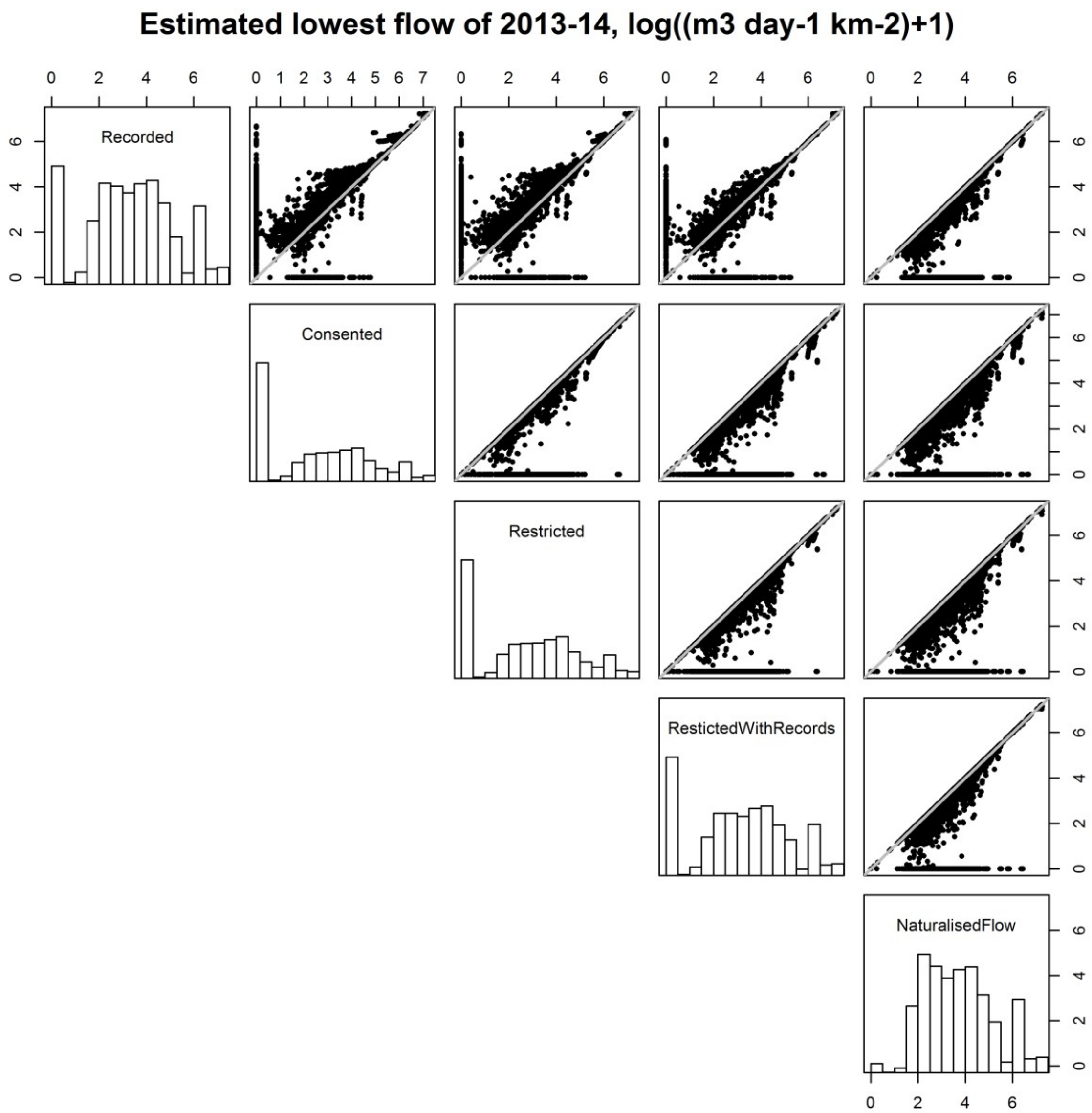

Figure 4-33: Estimated lowest flow of 2013-14 for each impacted REC reach across the region.

The flow that is not exceeded 5% of the time under naturalised conditions represents a natural low flow. This index is also known as the 5th flow percentile. We estimated the percent of the time that the 5th flow percentile would not be exceeded under various conditions. This represents the duration for which low flows would occur under various conditions. Figure 4-34 shows how the flow that is estimated to not be exceeded 5% of the time under estimated naturalised conditions is not exceeded for more of the time when greater abstractions occur. When recorded takes were estimated to be depleted from naturalised flows, a small proportion of reaches are estimated to experience low flows for up to 40% of the time. In this scenario, no rivers are estimated to experience low flows for more than 50% of the time. However, under the Consented scenario some rivers were estimated to experience low flows 100% of the time.

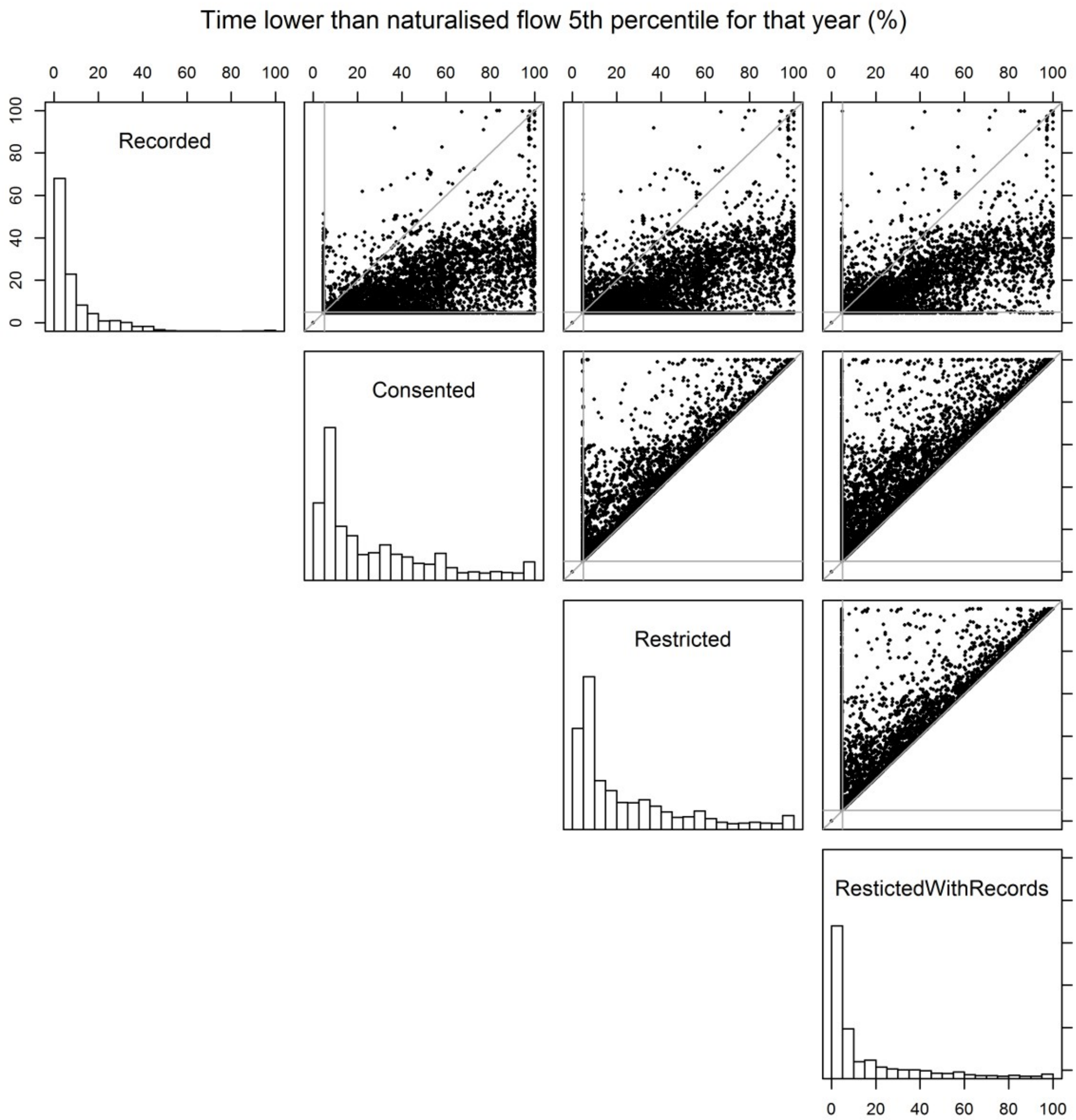

Figure 4-34: Paired plot for each REC reach of time lower than the flow that is not exceeded 5th of the time in the naturalised flow record.

The same results are mapped in Figure 4-35. Stream orders one and two are small rivers. Stream orders seven and eight are the bigger rivers. The results indicate that flows would be lower than naturalised for much greater proportions of the time for many smaller rivers under the Consented scenario. This was far less the case under the Recorded scenario than would be the case under the Consented scenario. However, there are still localised patches of small rivers that would have prolonged periods of low flow relative to naturalised under the Recorded scenario.

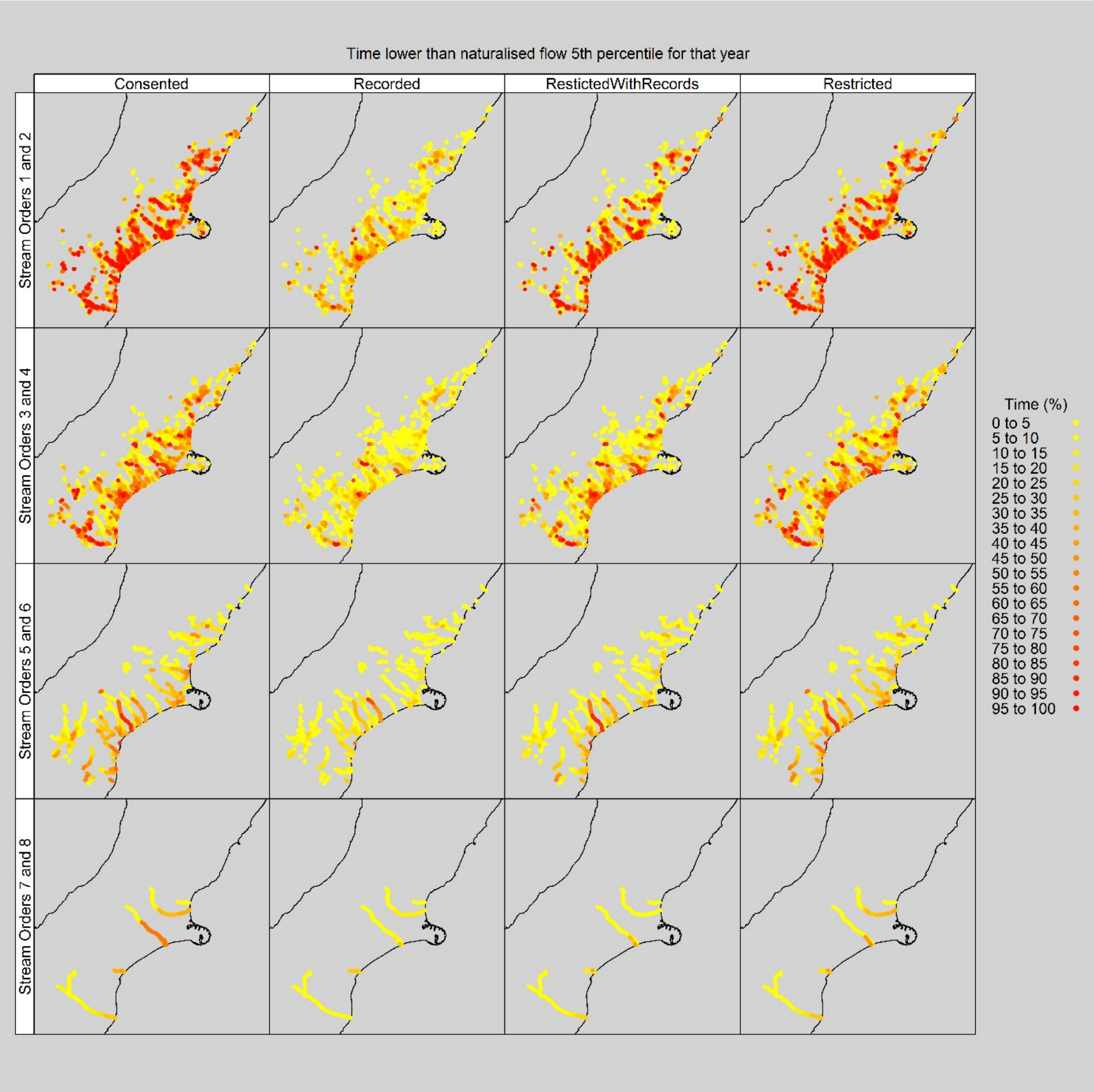

Figure 4-35: Map of estimated time lower than 5th flow percentile.

4.4 Impacts

Figure 4-36 and Figure 4-37 show estimated changes in river width across different sizes of river for four days of the 2013-14 hydrological year under the Consented and Recorded scenarios respectively. This is one example of how potential environmental impacts could be displayed. Results indicate that under the Consented scenario (all abstractors take their full allocation and no restrictions are applied) many rivers would lose their entire wetted width. This is particularly the case for small river reaches, but also extends to the larger rivers. The results indicate that the greatest losses in river width would be in mid-February compared with the other three dates shown.

However, results for the Recorded scenario (Figure 4-37) somewhat contrast with those for the Consented scenario (Figure 4-36). Under the Recorded scenario far less width is estimated to have been lost. This is especially the case for the larger river reaches. The difference between the Consented and Recorded scenarios is explained by a combination of reasons: only a proportion of the consents have associated recorded take data; if triggered, restrictions would reduce the impact of the Consented scenario; and large proportions of water on the large rivers are consented to be used, but were not recorded to have been used.

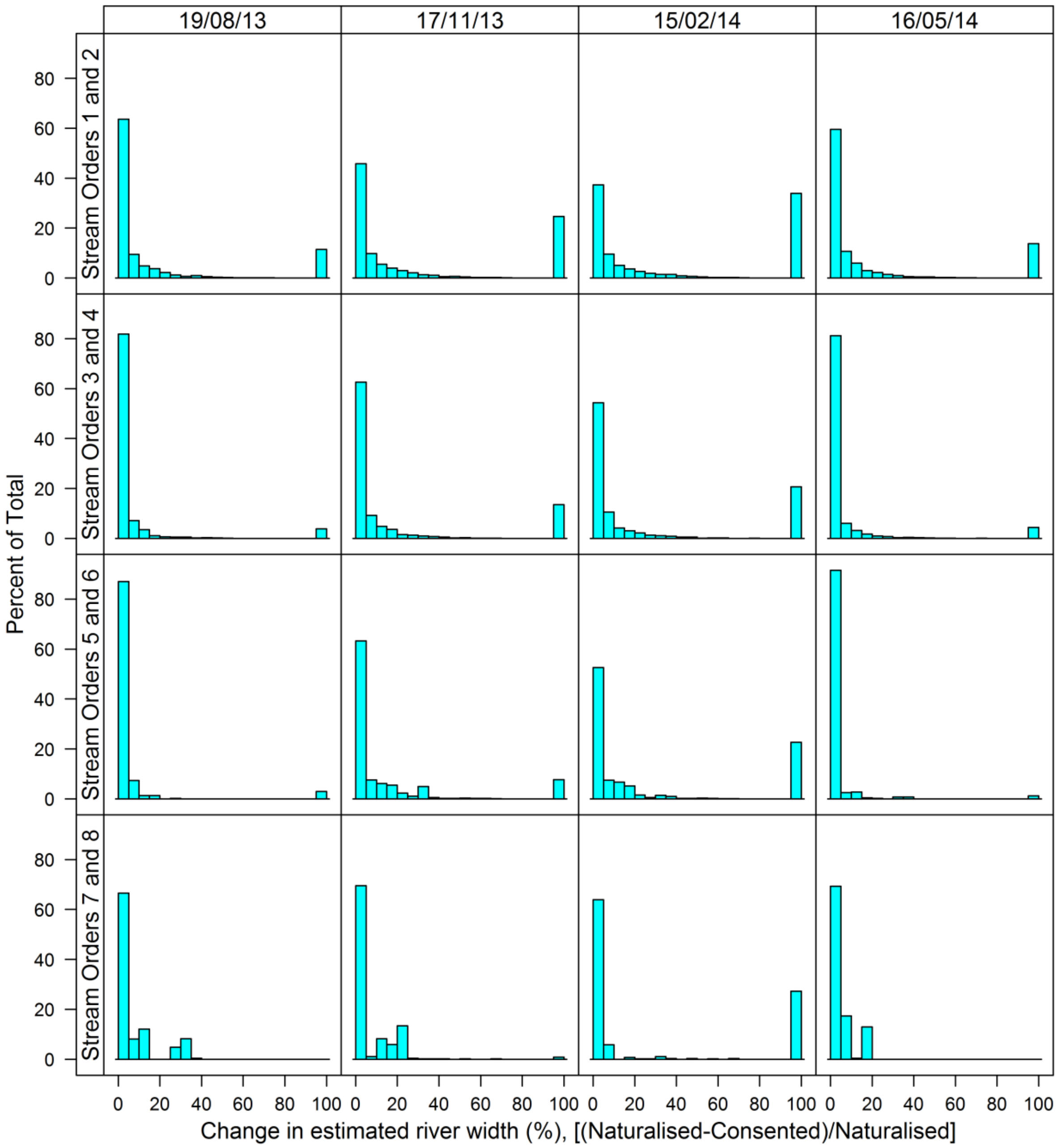

Figure 4-36: Histograms of change in width for each REC reach calculated from the naturalised flow and the naturalised flow minus the consented (with no restrictions) takes, for different sized rivers for four days through the year.

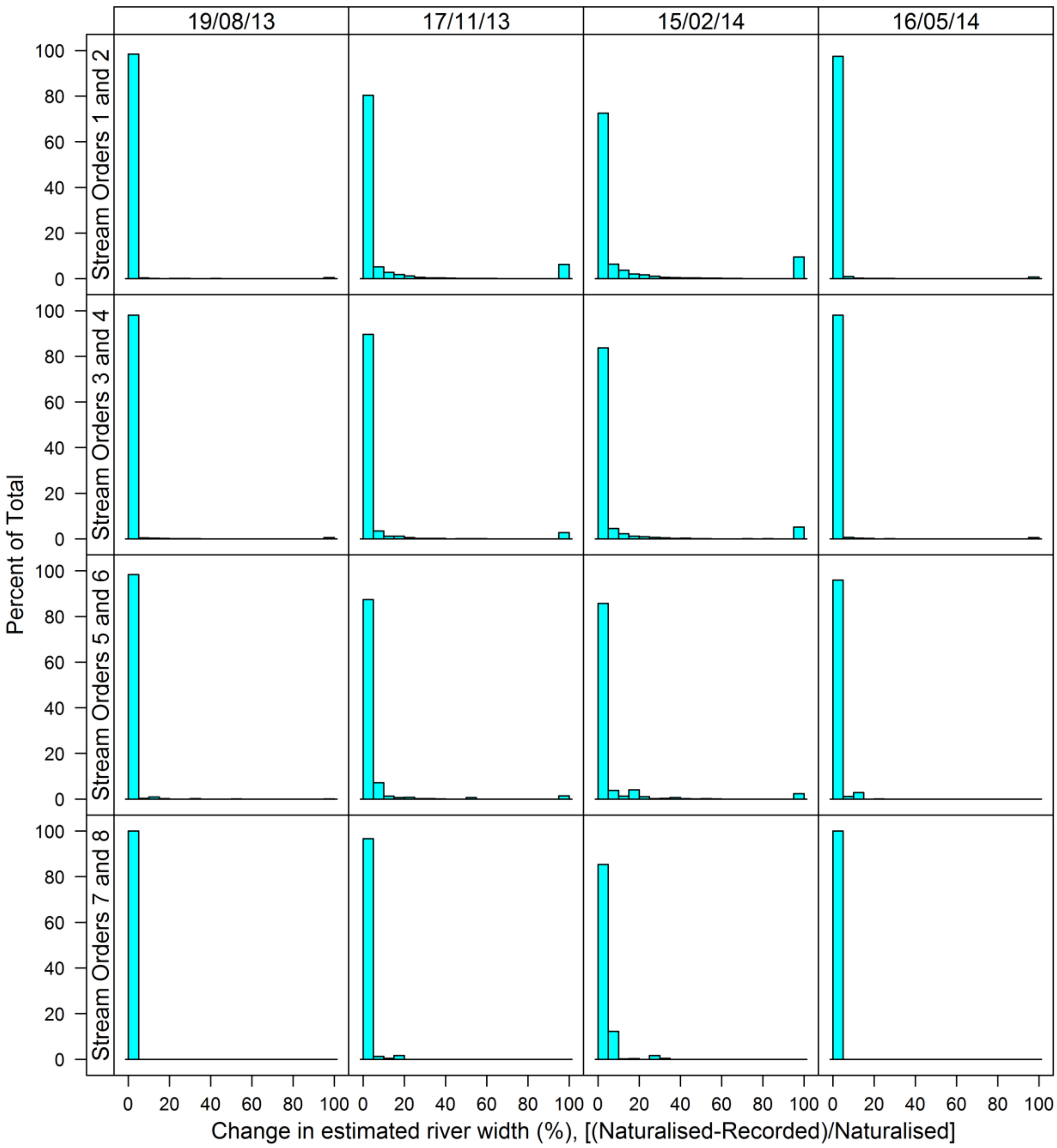

Figure 4-37: Histograms of change in width for each REC reach calculated from the naturalised flow and the naturalised flow minus the recorded takes, for different sized rivers for four days through the year.

Figure 4-38, Figure 4-39 and Figure 4-40 shows changes in availability of physical habitat suitable for adult brown trout, torrentfish and food producing habitat respectively. Positive values are losses in availability of suitable physical habitat. Negative values are gains in suitable physical habitat. Results indicate that some differences between changes in availability of physical habitat suitable for adult brown trout, torrentfish and food producing habitat. However, there were greater differences between sizes of river and dates than there were between adult brown trout, torrentfish and food producing habitat. In general, the greatest habitat losses occurred in smaller rivers. Greater losses occurred on the 15th of February in comparison with the other three dates shown. Some increases in availability of suitable physical habitat occurred with reductions in flows, particularly in large rivers for torrentfish. This is understandable as physical habitat requirements for torrentfish include relatively swift shallow water. Some reductions in flow can therefore result in increases in availability of suitable physical habitat because of reductions in depth in the larger, deeper rivers. Many smaller rivers were estimated to have lost 100% of habitat under the Consented flow scenario. This is because these river reach are estimated to be dry.

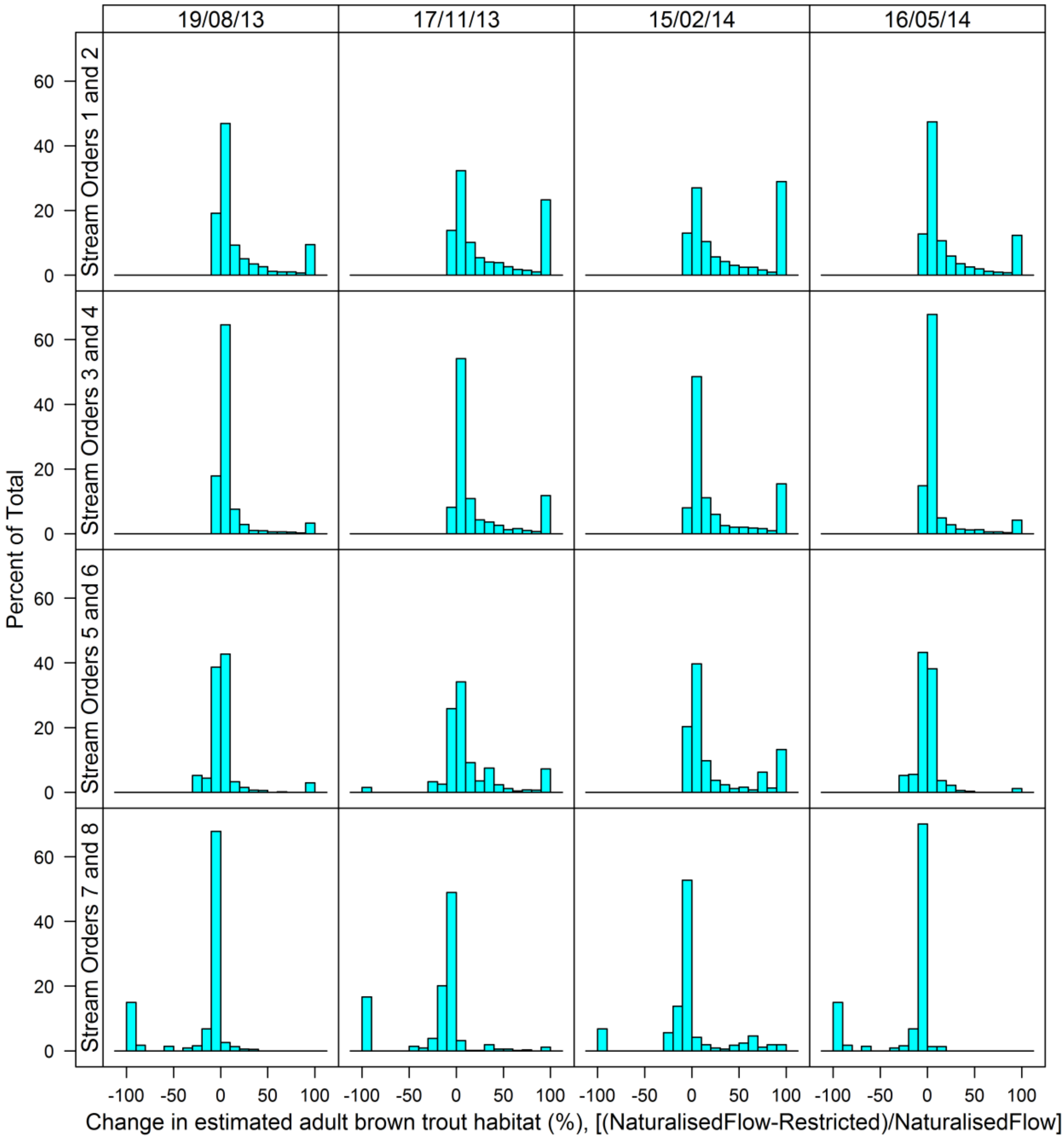

Figure 4-38: Histograms of change in availability of physical habitat suitable for adult brown trout for each REC reach calculated from the naturalised flow scenario and the restricted flow scenario, for different sized rivers for four days through the year.

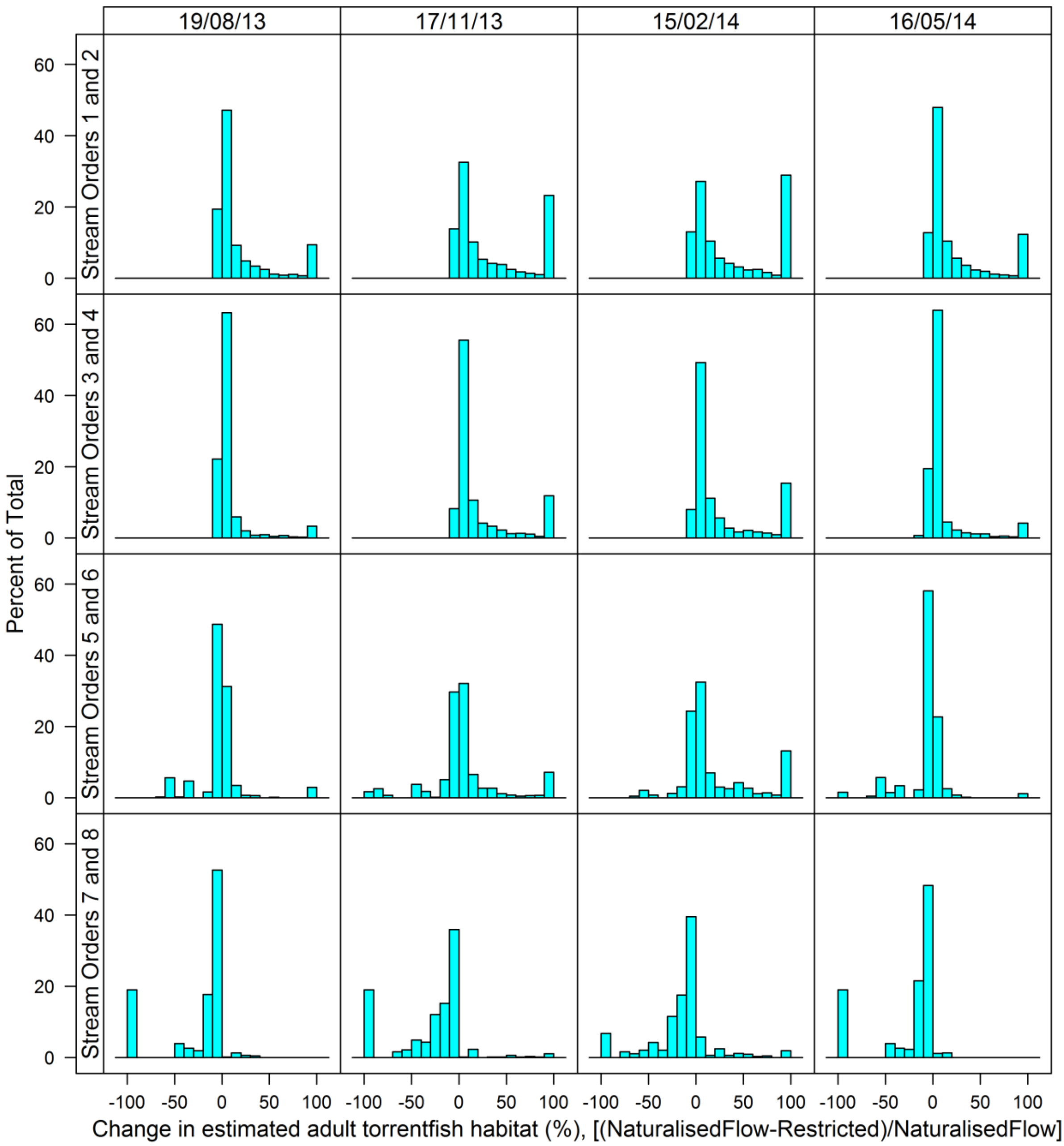

Figure 4-39: Histograms of change in availability of physical habitat suitable for adult torrentfish for each REC reach calculated from the naturalised flow scenario and the restricted flow scenario, for different sized rivers for four days through the year.

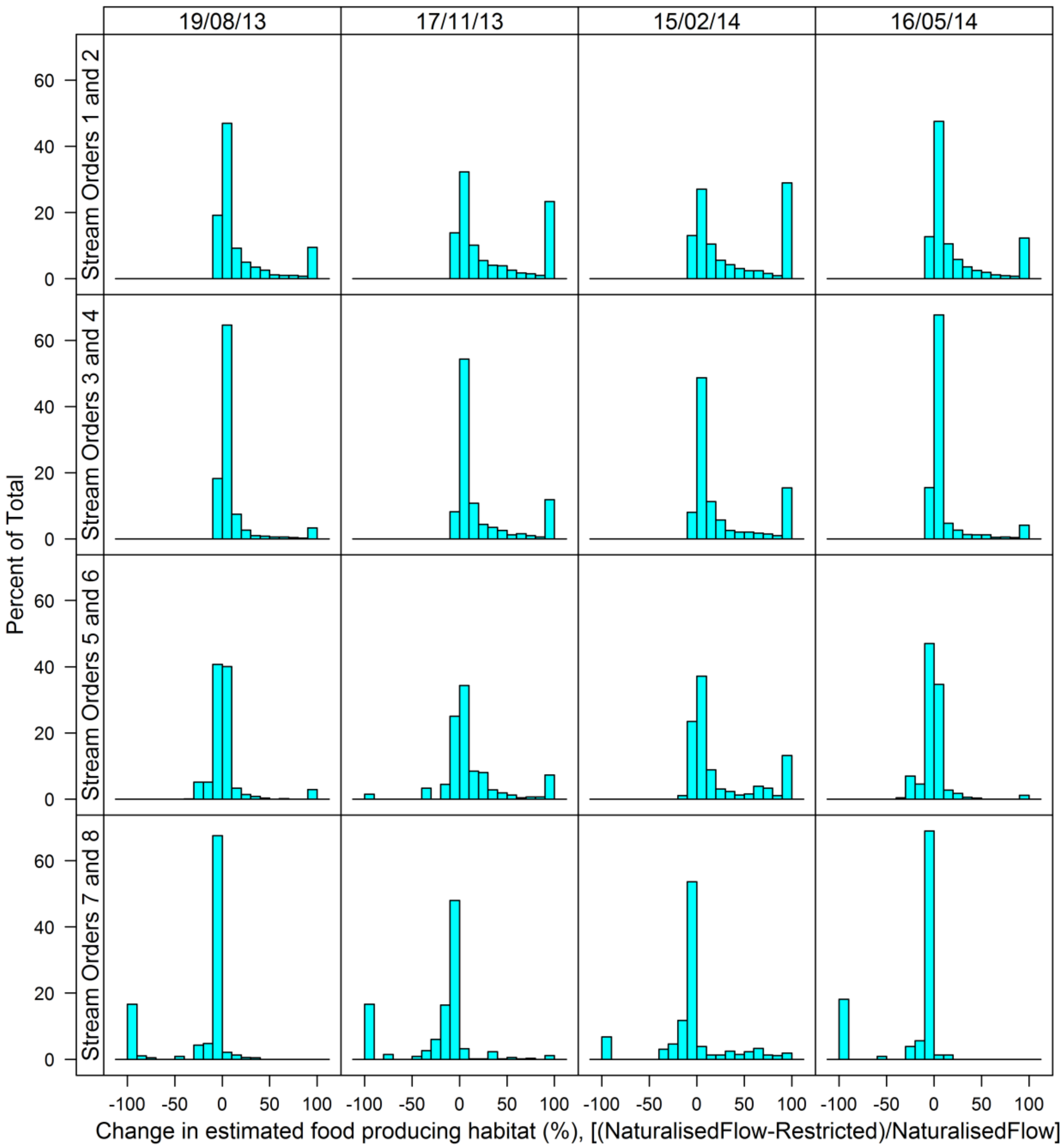

Figure 4-40: Histograms of change in availability of physical habitat suitable for food production trout for each REC reach calculated from the naturalised flow scenario and the restricted flow scenario, for different sized rivers for four days through the year.

5 Discussion

5.1 Benefits

Work undertaken during this project has produced several benefits. To date there has been no national database containing information describing how water is allocated across New Zealand. The data schema produced as part of this project allows for the collation of data describing consents to take and use. Population of the schema, as demonstrated for the Canterbury region, allows us to answer questions relating to:

- Where is water being used?
- From what type of water body is water being taken?
- What purposes is water being used for?
- How much more water could have been taken by each abstractor?
- What were the likely effects of water takes on river flows?

The schema also provides a potential format under which all future water consents could be administered. A common format for administering consents to take water would have various benefits including:

- Removing ambiguity from consent conditions.
- Ensuring the locations of all takes are recorded.
- Ensuring all consents are linked to management zones.
- Ensuring all consents have a recorded commencement and expiry date.
- Ensuring the possibility of linking all consents with rules in regional plans.
- Easier comparisons between environmental flows specified in regional plans and the consented water use.
- Determining which downstream river reaches are being influenced by each take.
- Easier calculation of cumulative effects.
- Easier calculation of potential headroom.

Our model allowed accumulated consented takes, restricted takes and recorded takes down the river network on a daily basis. This downstream accumulation allowed us to:

- Calculate the proportion of consented water that is being recorded for takes with records.
- Calculate the downstream cumulative totals of recorded takes or consented takes.
- Calculate the likely effects of takes on river flows.
- Calculate the likely effects of takes on environmental conditions such as river wetted area.

- Calculate whether allocated, but unused, water could be transferred between water users.

We used NIWA's national rainfall-runoff model to estimate naturalised flows across an entire region. We then compared both cumulative recorded and consented takes with estimated naturalised flows to estimate flows that would have occurred in each reach on each day under each scenario. This allowed us to provide estimates river flow states across broad regions on a daily basis. We then demonstrated how potential environmental impacts can be estimated by converting river flows into environmental parameters such as wetted width.

We demonstrated the utility of the data schema and model through application to the Canterbury region. Application to the Canterbury region was a good test bed for the model because Canterbury spans a broad range of landscape types and because water takes in the region are many and varied.

5.2 What is headroom?

We investigated recorded takes (water recorded as being taken), consented takes (water that would have been taken had no restrictions been applied) and restricted takes (what that could have been taken by each abstractor after having applied any restrictions). See Table 3-2 for full definitions. Inspection of these values can be used to infer headroom for individual abstractors. Where headroom is defined as the ability of a single abstractor to have taken more water under their current consent conditions including when restrictions are applied. In this case headroom could be described as water that was available to that abstractor after having applied any restrictions. However, if all users utilised their full consents in this manner, then flows and groundwater levels at the control sites would be lower, there would be more restrictions, and therefore (the next day) all users would not be able to take the amount that was originally calculated. Furthermore, target environmental flows at control sites would not be maintained. Therefore, summing of water that is available to each user does not constitute calculation of headroom that would be available to the collective users. This calculation of collective headroom requires some rules around sharing or priority of the available water and understanding of why some users have been placed in bands that are more restrictive than other bands (because they have higher minimum flows). Table 5-1 shows various possible definitions of headroom with respect to water availability. The data and model used in this project would allow further explanation of these concepts. For example, within defined water resource use limits, maximising headroom for a collective of existing abstractors will have the effect of minimising potential headroom for potential future abstractors.

Table 5-1: Possible definitions of headroom.

Term	Who it applies to	Definition of headroom
Individual headroom	Individual abstractors	The ability of a single abstractor to have taken more water under current consent conditions including when restrictions are applied.
Collective headroom	A collective of abstractors	The ability to abstractors to take as much water as possible within their existing consent conditions without collectively breaking environmental flow conditions such as minimum flows or total allocations.

Term	Who it applies to	Definition of headroom
Future headroom	New abstractors	The ability to provide new users with consents without compromising the reliability of supply to existing users or breaking environmental flow conditions such as minimum flows or total allocations.

5.3 Future work

5.3.1 Application to other regions

We devised procedures for estimating cumulative effects of recorded, restricted and consented takes across Canterbury using data provided by ECan. To some extent, these procedures were designed to apply to the provided ECan data (the ECan data matched with our data request well). Discussions with various councils have suggested that new procedures, or adaptation of the existing procedures will be required for applying similar methodologies to other regions. This is because data supplied by different councils is likely to take different formats (despite being given the same data request), and because there are regional differences in the way in which consents are administered. For example, ECan consents are controlled by groundwater levels at groundwater sites and/or river flow at river flow sites. However, we know that MDC also have controls relating to conductivity at groundwater sites. Incorporating this type of situation into our model would require changes to the model procedures.

Obtaining data from all regional councils is the next major step in completing a national pressure-state-impact model. There are several possible ways of encouraging councils to provide these data:

- Provide a web portal for councils to upload their data in the correct format.
- Align our data request with that of LAWA (Land And Water Aotearoa).
- Our model has functionality that would be beneficial in the planning processes of many regional councils. Demonstrating model utility by providing results back to councils would encourage delivery of input data.

5.3.2 Water management scenario modelling

Our model was designed to provide information for environmental reporting. We demonstrated application of the model to consent conditions and recorded control conditions from 2013 to 2014. However, the model could be used to investigate various other aspects of water management using hypothetical consent conditions or control conditions. This could include:

- What residual flows and water availability would result from alignment of all consent conditions with environmental flow conditions stated in regional plans?
- What potential is there for storage schemes or collective co-operation between abstractors to use water that has already been consented but is underutilised.
- What residual flows and water availability would result from different hydrological conditions as a result of climate change.

5.3.3 Dams and diversions

We did not include any effects of non-consumptive consents when calculating the cumulative effects of recorded, restricted or consented takes. This method essentially assumed that all consents that were recorded as being non-consumptive had no effect on river flows and all consents that were recorded as being consumptive would deplete river flows with no return flows. This method is unsatisfactory in the case of either large dams or diversions that are recorded as being non-consumptive. This is particularly the case for diversions that transfer water between catchments (e.g., the Rangitata Diversion Race diverts water from the Rangitata to the Rakaia River) or dams whose storage capacity is sufficiently large to disrupt natural flow regimes over time periods of weeks to months (Tekapo, Pukaki, Benmore, Aviemore and Waitaki Dams combine to regulate flows in the Lower Waitaki River). Currently, the effects of both these types of situations are not fully included in our model. This is because the effects of dams are only included if a consumptive take is recorded, and the effects of a diversion on the abstracted river are included if the diversion is recorded as being consumptive, but the effects of a diversion on the receiving river is only included if a negative take is recorded.

Some procedures already exist that could improve the handling of the effects of both dams and diversions within our model. Dams could be included using NIWA's Cumulative Hydrological Effects Simulator (CHES), which is a tool that includes the ability to simulate the hydrological effects of large engineering structures on downstream flows on a daily basis. However, various information relating to dam characteristics (e.g., spill height, storage capacity) and operations (lake level, timings of flow releases) would be required. These types of data would have to be acquired in order to incorporate the effects of dams adequately. Collating data on dam operations appears to be particularly difficult due to commercial sensitivities.

We used information describing whether consents were classified as consumptive or non-consumptive, and whether consents were classified as takes from surface water, takes from groundwater or diversions. We assumed that any flow additions would be specified as negative takes and therefore included in the calculations. However, as we understand them, the present water regulations require recording of water takes and not necessarily recording of return flows. Lack of data describing the proportion of flows recorded as being taken that subsequently returns to a river may be important in certain situations (e.g., where water is taken from along a raceway that runs between two adjacent rivers).

Improved handling of diverted water that returns to natural river channels is technically feasible by incorporating all discharges as negative takes. However, this situation could be improved upon by being able to route takes between natural river channels. This would require addition of a set of reaches and nodes describing artificial flow pathways on top of the existing REC river network. Currently the REC river network only includes natural river channels, which always accumulate in one direction (downstream towards the sea). In this network flows cannot be split or routed between catchments.

5.3.4 Recharge

Our model does not currently apply a recharge component. This methodology assumes that all irrigation is 100% efficient; therefore all irrigated water is lost through evaporation. We applied this methodology because it is easily understood and represents a worst case scenario for stream depletion. Further work is required to develop and test a more reliable approach to incorporating recharge to rivers from irrigated water. One alternative methodology could be to apply a constant recharge component as a percentage of the pumping rate. For example, in recent work Duncan et al. estimated that the recharge component was approximately 18% of the pumping rate, based on lysimeter results in Canterbury. In theory, recharge rates should be related to crop type and weather conditions, and also rise with pumping rate per unit irrigated area. A second alternative methodology would be to apply a dynamic process-based coupled groundwater-surface water model to estimate stream depletion resulting from groundwater takes.

5.3.5 Methods for groundwater takes

We used the provided data on connectivity of each groundwater take to decide which groundwater takes would be allowed to deplete river flows. Where takes did not have a recorded connectivity this was inferred from secondary source and depth of take. We then applied an industry standard methodology for calculating stream depletion from groundwater takes. See Section 3.4 for details of the methodology and associated assumptions. Confidence in the applied approach would be improved upon by quantifying the sensitivity of the results to variations in the methodology applied. For example, groundwater takes were able to deplete rivers within 2 km. The benefit of this approach is that it is relatively easily explained and implemented. It would be informative to know how sensitive model results are to this distance, and whether this distance should vary across the landscape. Sensitivity of the results to estimated values or storativity and transmissivity would also be informative.

An alternative approach would be to estimate river depletion from groundwater takes using a spatially-distributed time-stepping groundwater-surface water model. To the best of our knowledge such a model with national coverage does not presently exist. The benefit of this approach would be that it may better simulate the cumulative effects of groundwater depletion. However, such a model would also be expensive to implement and require a great deal of input information to parameterise the boundary and initial conditions, as well as verify model predictions.

5.3.6 Additional impacts

We demonstrated model utility by linking river flows with wetted width and availability of suitable physical habitat for selected species to estimate how changes in hydrology could impact upon area of wetted and availability of suitable physical habitat. Improvement in estimation of availability of suitable physical habitat are possible. Further environmental impacts could be incorporated given flow-ecology relationships. These environmental impacts could include periphyton and macrophyte growth, physical habitat for fish and LIFE (Lotic Invertebrate Flow Evaluation) score. Future work on out-of-stream impacts could include estimates of potential economic productivity given sub-models on crop water demand and irrigation efficiency.

5.3.7 Improvements since 2015

The following publications were produced following original completion of this report in 2015:

1. McMillian, H.K., Booker, D.J., Cattoën-Gilbert, C. (2016) Validation of a national hydrological model. Journal of Hydrology, 541, 800-815, DOI: 10.1016/j.jhydrol.2016.07.043.

2. Booker, D.J. (2016) Generalized models of riverine fish hydraulic habitat. The Journal of Ecohydraulics, 1(1-2), pp.31-49. DOI: 10.1080/24705357.2016.1229141.

McMillan et al. (2016) improved upon that shown in Section 3.5, by providing improved tests, full description and additional discussion of methods for predicting time-series of flows in ungauged catchments across New Zealand. Booker (2016) provides tests and description of an improved method of estimating generalised physical habitat than that given in Section 3.8.

6 Conclusions

Work towards a nationwide pressure-state-impact model for freshwater flows was conducted as part of this project. This work has produced several benefits. The data schema designed as part of this project provides the ability to create a national database containing information describing how water is allocated and how much water is consented to be taken across New Zealand. These data could be used to assess the degree to which consent conditions collectively match with conditions specified in regional plans. The schema also provides a potential format under which all future water consents could be administered. A common format for administering consents to take water would have various benefits.

For a variety of reasons, requested data was not provided to MfE by most regional councils. A full dataset was provided by ECan. This allowed application of our model to the Canterbury region. The model was used to calculate maps and time-series of accumulated consented takes, restricted takes and recorded takes down the river network. This downstream accumulation allowed us to calculate various states, including the downstream cumulative totals of recorded takes or consented takes, and the proportion of consented water that is being recorded.

A national rainfall-runoff model was used to estimate naturalised flows. Both cumulative recorded and consented takes were compared with estimated naturalised flows to estimate flows that would have occurred in each reach on each day under each flow scenario. This allowed calculation of estimated river flow states across broad regions on a daily basis. Flow-environmental relationships were then used to convert estimated flow states to estimated potential environmental impacts. For example, changes in wetted width of river habitat was calculated.

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8 References

Beca (2008) *Draft guidelines for the selection of methods to determine ecological flows and water levels*. Report prepared by Beca Infrastructure Ltd for Ministry for the Environment, Wellington.

Beven, K.J. (1997) TOPMODEL: a critique. *Hydrological Processes,* 11: 1069–1085.

Booker, D.J., Hicks, D.M. (2013) Estimating wetted width and fish habitat areas across New Zealand's rivers. *NIWA Client Report*, CHC2013-075: 33.

Booker, D.J. (2010) Predicting width in any river at any discharge. *Earth Surface Processes and Landforms*, 35: 828-841.

Booker, D.J., M.J. Dunbar, Ibbotson, A.T. (2004) Predicting Juvenile Salmonid Drift-Feeding Habitat Quality Using a Three-Dimensional Hydraulic-Bioenergetic Model. *Ecological Modelling,* 177: 157-177.

Booker, D.J., Snelder, T.H., Greenwood, M.J., Crow, S.K. (2014) Relationships between invertebrate community composition and both flow regime and other environmental factors across New Zealand rivers. *Ecohydrology*, DOI: 10.1002/eco.1481.

Booker, D.J., Woods, R.A. (2014) Comparing and combining physically-based and empirically-based approaches for estimating the hydrology of ungauged catchments. *Journal of Hydrology*, 10.1016/j.jhydrol.2013.11.007.

Clark, M.P., Woods, R.A., Zheng, X., Ibbitt, R.P., Slater, A.G., Rupp, D.E., 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: 1309–1324.

Crow, S.K., Booker, D.J., Snelder, T.H. (2012) Contrasting influence of flow regime on freshwater fishes displaying diadromous and non-diadromous life-histories. *Ecology of Freshwater Fish,* 22: 82-94.

Dunbar, M.J. Acreman, M.C. (2001) Applied Hydro-Ecological Science for the Twenty-First Century. In: M.C. Acreman (Ed). *Hydro-Ecology: Linking Hydrology and Aquatic Ecology.* IAHS, Birmingham, UK: 1-18.

Gawith, D., Kingston, D. G., & McMillan, H. (2012) The effects of climate change on runoff in the Lindis and Matukituki catchments, Otago, New Zealand. *Journal of Hydrology (New Zealand)*, 51(2): 121.

Gupta, H.V., Sorooshian, S., Yapo. P.O. (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *J. Hydrologic Eng.,* 4(2): 135–143.

Henderson, R.D., R.A. Woods, S.K. Singh, Zammit, C.L. (2011) Surface Water Components of New Zealand's National Water Accounts. *NIWA Client Report* CHC2011-051 (SNZ11501) for Statistics New Zealand: 45.

Jowett, I.G., Hayes, J.W., Duncan, M.J. (2008) A guide to instream habitat survey methods and analysis. *NIWA Science and Technology Series*, 54: 121.

Jowett, I.G., Richardson, J. (2008) Habitat use by New Zealand fish and habitat suitability curves. *NIWA Science and Technology Series,* 55: 148.

Lamouroux, N., Capra, H. (2002) Simple Predictions of Instream Habitat Model Outputs for Target Fish Populations. *Freshwater Biology,* 47: 1543-1556.

Lamouroux, N., Jowett, I.G. (2005) Generalized Instream Habitat Models*. Canadian Journal of Fisheries and Aquatic Sciences,* 62: 7-14.

Lamouroux, N., Jowett, I.G. (2005) Generalized Instream Habitat Models. *Canadian Journal of Fisheries and Aquatic Sciences*, 62: 7-14.

Lamouroux, N., Souchon, Y. (2002) Simple Predictions of Instream Habitat Model Outputs for Fish Habitat Guilds in Large Streams. *Freshwater Biology,* 47(8): 1531-1542.

Lamouroux, N., Mérigoux, S., Capra, H., Dolédec, S., Jowett, I.G., Statzner, B. (2010) The Generality of Abundance-Environment Relationships in Microhabitats: A Comment on Lancaster and Downes (2009). *River Research and Applications,* 26: 915-920.

Lancaster, J., Downes, B.J. (2010) Linking the Hydraulic World of Individual Organisms to Ecological Processes: Putting Ecology Into Ecohydraulics. *River Research and Applications,* 26: 385-403.

Leathwick, J.R., Rowe, D., Richardson, J., Elith, J., Hastie, T. (2005) Predicting the Distributions of New Zealand's Freshwater Diadromous Fish. *Freshwater Biology,* 50: 2034-2052.

Martins, J.H., Camanho, A.S., Gaspar, M.B. (2012) A review of the application of driving forces – Pressure – State – Impact – Response framework to fisheries management. *Ocean & Coastal Management*, 69: 273-281.

Mathur, D., Bason, W.H., Purdy, E.J., Silver, C.A. (1985) A Critique of the Instream Flow Incremental Methodology. *Canadian Journal of Fisheries and Aquatic Sciences,* 42: 825-831.

McMillan, H.K., Clark, M.P., Bowden, W.B., Duncan, M.J. Woods, R.A. (2011) Hydrological field data from a modeller's perspective: Part 1. Diagnostic tests for model structure. *Hydrological Processes*, 25: 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,

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L. (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers,* 50: 885–900.

Nash, J.E., Sutcliffe, J.V. (1970) River flow forecasting through conceptual models: Part 1. A discussion of principles. *Journal of Hydrology,* 10: 282–290.

Orth, D. (1987) Ecological Considerations in the Development and Application of Instream Flow Habitat Models. *Regulated Rivers: Research & Management,* 1(2): 171-181.

Poyck, S., Hendrikx, J., McMillan, H., Hreinsson, E., Woods, R. (2011) Combined snow and streamflow modelling to estimate impacts of climate change on water resources in the Clutha River, New Zealand. *Journal of Hydrology (New Zealand)*, 50: 293-312.

Reiser, D.W., Wesche, T.A., Estes, C. (1989) Status of Instream Flow Legislation and Practices in North America. *Fisheries Management and Ecology,* 14: 22-29.

Segui, P.Q., Martin, E., Habets, F. Noilhan, J. (2009) Improvement, calibration and validation of a distributed hydrological model over France. *Hydrol. Earth Syst. Sci.,* 13(2): 163-181.

Snelder, T.H., Biggs, B.J.F. (2002) Multi-scale river environment classification for water resources management. *Journal of the American Water Resources Association,* 38: 1225–1240.

Appendix A Data schema

Table 1) Record Locations

This table contains information that relates to each location where water it taken from or discharged to. There should be one row of data for each location where water is abstracted from / discharged to. The Primary key is TakeID.

Variable	Description	Notes	Status
ID	Row identifier		Compulsory
TakeID	Unique identifier, as per council records, for each take location. Note: this is not Consent ID unless they are one in the same. There should be no duplicate entries.	For ECan this will be WellNo or SWAPNo.	Compulsory
X	The location of the point of take or point of discharge, NZTM projection (Easting). Ideally, this is the location of the take rather than the location of the use or some other location such as the location of the property.		Compulsory
Y	The location of the point of take or point of discharge, NZTM projection (Northing).		Compulsory
CoordsQualityCode	Quality of location co-ordinates. Based on NEMS schema.	ECan's QAR rating	Optional, is available. Is there a standard for this? Nominal versus Validated?
PrimarySource	The primary source of the take (or receiver of discharge). Define at the high level - either Groundwater or Surface water. Choose from: • Groundwater • Surface water • Not specified		Compulsory. See definitions in appendix.
SecondarySource	The water body that the water is taken from or discharged to. • River • Stream • Lake • Bore • Spring • Race/Drain • Dam • Collected stormwater • Gallery/Depleter/Riparian/Interface		Optional, if available. ***See definitions in appendix, and Please provide definitions if alternative categories are being provided.***

CatchmentNumber	Soil Conservation and Rivers Control Council (1956) “Catchments of New Zealand” numerical list. Also See “fwfd_catchment_number_dictionary.doc”.	Both ECan and Horizons use this, others may not.	Optional, if available.
ManagementZone	The name of the management zone. May be referred to as “Freshwater Management Unit” in NPS-FM.	ECan have three types, which complicates things.	Optional, if available.
SourceName	The name/description of the source, e.g., the name of the stream.		Optional, if available.

Table 2) NZreaches

This table contains information describing the reaches within the River Environment Classification (REC) river network from which the water can be assumed to be taken for surface water takes. This table is separated from Table 1 to allow for the possibility that several NZreaches can be associated with one TakeID. This may occur for groundwater takes. This table is all optional, if available. This can be generated automatically by NIWA using X and Y from Table 1, and can be sent to councils for checking. The Primary key is TakeID+NZreach.

Variable	Description	Notes from Councils	Status
ID	Row identifier		Compulsory
TakeID	Unique identifier, as per council records, for each take location. Note: This is a linking variable.		Optional, if available.
NZreach	The NZreach associated with the take, where it has been identified by council using REC version 1 (as available from http://www.mfe.govt.nz/environmental- reporting/about-environmental-reporting/classification-systems/fresh-water.html). Blank for when it has not been looked for. NA for where it has been looked for, but is inappropriate (e.g., a pond that is isolated from the river network, or a raceway that is part of the REC network).	ECan don't have NZReach. MDC have it as CatchmentID.	Optional, if available.
Method	How has the NZreach been defined? • Automated join • Manual assignment		Optional, if available.
Checked	If the NZreach has been automatically joined, has it been manually checked and corrected? (For example, by overlaying the network onto a map comparing: the position of the NZreach; the x-y co-ordinates of the take; and the name of the position of the in the network with). Default is No. • Yes • No		Optional, if available.
Authority	Which organisation assigned the NZreach? • Regional Council • Ministry for the Environment • NIWA		Optional, if available.

Table 3) Bore Characteristics

This table contains information describing the characteristics of groundwater takes. There may be some overlap with Table 10. For each bore, all depths must be consistently measured from the same datum (e.g., top of casing) across all tables (Table 3, Table 7 and Table 8). The primary key is TakeID.

Variable	Description	Notes	Status
ID	Row identifier		Compulsory
TakeID	Unique identifier for each take location. To link to Table 1.	For ECan this is the WellNo.	Compulsory
Depth	Depth of the bore (m)		Compulsory where available
ScreenDepthTop	Depth from which water is being abstracted (m). Where there are multiple screens, this is the depth that is nearest to ground level. Blank for where there is no screen.	Marlborough indicated may be important	Optional, if available.
ScreenDepthBottom	Where there are multiple screens, this is the depth that is farthest away from ground level. Blank for where there is no screen.	Workshop indicated may be useful.	Optional, if available.
Connectivity	Where available, how strongly connected is this bore to the nearby rivers? How likely is this abstraction to affect river flows in nearby rivers? • High • Medium • Low • unknown	This is held by Horizons. Different councils may have different methods for determining this and definitions of the categories.	Optional, if available. Potentially useful, but likely that different method have been applied by different councils. Please supply definitions of methods (See definitions appendix).
Transmissivity	Measure of how much water can be transmitted horizontally (m2/day). As estimated from observations. Not interpolated or default values.	ECan have now given us much data on this. Some of which does not relate to take points. Horizons suggested this should not be part of this request, as it is covered by “Connectivity to rivers”.	Optional, if available.
Storativity	The volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer (dimensionless). As estimated from observations. Not interpolated or default values.	ECan have now given us much data on this. Some of which does not relate to take points. Horizons suggested this should not be part of this request, as it is covered by “Connectivity to rivers”.	Optional, if available.

AquiferConfinement	Is the aquifer from which water it taken considered to be: • Confined • Unconfined • Unknown	This is not held by ECan. Ebop has it.	Optional, if available. Negated by "connectivity to rivers"?
AquiferName	Name of aquifer		Optional, if available.

Table 4) Resource Consents

This table contains information about consents. There is one row per consent. The Primary key is ConsentID.

Variable	Description	Notes	Status
ID	Row identifier		Compulsory
ConsentID	Unique identifier for each resource consent		Compulsory
ConsentType	As in s87 – water permit. Is the water being taken from the water body or discharged to the water body? • Take • Discharge • Diversion • Unknown	If it is a discharge then it may have a discharge consent.	Compulsory Does this go better in the Linking Table? Or in the activities Table?
Description	A description of the consent e.g., the description from the resource consent certificate.		Compulsory
CommencementDate	The commencement date of the consent as per section 116 RMA.		Compulsory
ExpiryDate	The expiry date of the resource consent.		Compulsory
TerminationDate	The end date of authorised exercise of resource consent. May be same as (simple expiry, no replacement), before (surrendered) or after (had 124 protection) ExpiryDate.		Need discussion regarding this. Termination date is ideal, but it sounds like many councils have status. If they provide a dump of data for 2013/14 in November 2014 only isolating consents that were "Active" in Nov 2014 then it may miss some.
Status	Status at time of query. • Active • Surrendered • Expired – s124 • Expired	In this case, the time of query will have to be recorded somewhere, and queries should be made on the same date.	Optional. See definitions appendix. Work around may be to get 'status at 1 Jan.'

TransferDate	If the consent has been transferred, when was this?	Optional. Needs discussion. If a consent is transferred, what else will change? Links to changes of consents also, not just transfers.
PlanProvisionID	The section of the council's water plan that was applicable at the time the consent was issued.	Optional. To be discussed.

Table 5) Consented activities

This table contains information describing what is authorised by a consent and allows for multiple activities within each consent. There is one row per consented activity. Some consents will only have one activity. Each consent may have one or more activities. The primary key is ConsentID+ActivityID.

Variable	Description	Notes	Status
ID	Row identifier		Compulsory
ConsentID	Unique identifier for each resource consent		Compulsory
ActivityID	Unique identifier within each consent for each activity. Default is “A”.		Compulsory
PrimaryUse	The primary use of the water. That is, what the water is used for. Distinct from the industry that uses the water. Choose from, or map to, a set selection. • Drinking • Hydro • Industrial • Irrigation • Stock • Frost protection • Not specified • Combined/Mixed. PrimaryUse is what the water is used for (e.g., irrigation) while UseType is the industry (e.g., Grape growing, Dairy Cattle farming – which both may be using the water for irrigation).		Compulsory. Choose from, or map to, a set selection. National selection yet to be defined. Please provide definitions in appendix.

UseType	The industry that uses the water. Choose from, or map to, a set selection.		Optional, if available. Choose from, or map to, a set selection. Selection to be defined. Doc linked here is what StatsNZ would prefer W1366378_Water use ANZSIC list.xlsx
NonConsumptive	According to the description of a non-consumptive take in Regulation 4(2) of the Water Take Regulations: Where (a) the same amount of water is returned to the same water body at or near the location from which it was taken; and (b) there is no significant delay between the taking and returning of the water. • Yes • No	ECan suggested this must be inferred from the description and other information. Northland has said that “Needs to be a council determination as it can’t always be inferred from the use type.”	Compulsory
Returned	Is the entire volume of abstracted water immediately returned to a different waterbody • Yes • No Yes for when groundwater is being pumped into a river.	There are examples of consents to take water from one source to be put into a river so that it can be abstracted further downstream.	Optional. Potentially useful, but very difficult to specify. Needs further discussion. Link to discharge volume account? Could be linked to discharge permit number, but this is not mentioned in this schema.
IrrigatedArea	If the consent authorises irrigation, the maximum consented area that can be irrigated (ha)		Optional, if available.

CropType	If the consent authorises irrigation, the crop type specified.	Horizons suggested meaningless/not useful	Optional, if available.

Table 5a) Consent conditions

The information should be as specified in the consent, not derived or calculated. There may be more than one row per ConsentID+ActivityID. This allows multiple conditions on single activities. The primary key = ID = ConsentID+ ActivityID + ConditionID.

Variable	Description	Notes	Status
ID	Row identifier		Compulsory
ConsentID	Unique identifier for each resource consent		Compulsory
ActivityID	Unique identifier within each consent for each activity. Default is "A".		Compulsory
ConditionID	Identifier within each consent and activity.		Compulsory
RateMaxVolume	Maximum Volume of water consented to be taken (m^3). Combining MaxVolume and PeriodType will give a rate. Example 1 = "0.1" Example 2 = "20"	You can take "RateMaxVolume" (m3) per RatePeriodType for RateTimeProportion of the time between RateStart and RateEnd. Example 1 = take at a rate of no more than $0.1m^3$ per second for a maximum of 100% of the time all year round (between 1st July and 30th June). Example 2 = take at a rate of no more than $20m^3$ per hour for a maximum of 23 days in January.	Compulsory. Units are consistent throughout the table.

RatePeriodType	The time period over which the MaxVolume applies. Combining MaxVolume, PeriodType and Duration will give a rate. • Second • Hour • Day • Month • Year Example 1 = "Second" Example 2 = "Hour"		Compulsory
RateTimeProportion	Proportion of time defined by RateStart and RateEnd that the volume can be taken. Defaults to 1. Example 1 = "1" Example 2 = "23/31" = "0.742"		Compulsory. Defaults to 1 - Should never be zero.
RateStart	The first day of the year on which this volume can be taken (dd/mmm). Default is 01/Jul. Example 1 = "01/Jul" Example 2 = "01/Jan"		Compulsory
RateEnd	The last day of the year on which this volume can be taken (dd/mmm). Default is 30/Jun. Example 1 = "30/Jun" Example 2 = "31/Jan"		Compulsory
OtherRate	If the maximum consented allocation rate does not fit into one of the predefined groups, describe here.	Councils indicated that some consents are controlled by variables other than flow such as conductivity or temperature. This could be recorded here.	Optional, catchall. For ones like: "Can only be used when following consents are not in use: 106749 and 106832"
ControlSiteID	For when the consent is controlled by conditions at a control site, identifier indicating the control site.		Compulsory where relevant. Linking variable to Table 7
ControlVariable	For when the consent is controlled by conditions at a control site, the variable at the control site that controls the consent. Defaults to "Flow". Could be "Conductivity" or "Temperature". Must match with ControlVariable in Table 7 Control Rules and ControlVariable in Table 8 Control Values.	Added to accommodate consent conditions relating to conductivity in MDC region.	Assuming "Flow" when this is not provided.

ControlUnits	For when the consent is controlled by conditions at a control site, the units in which ControlVariable is given. Defaults to "m3s-1" for flow.		Assuming "m3s-1" when this is not provided.
BandID	For when the consent is controlled by conditions at a control site, identifier indicating which band this activity is linked to. There may be many ConsentID+ActivityID linked to a ControlSiteID+BandID. A single ConsentID+ActivityID may be linked to single ControlSiteID + FlowBandID	Horizons said that in effect that each consent may have a different 'band'. MDC calls this Class.	Optional Linking variable to Table 7
ResidualSiteID	For when a consent specifies that the abstraction rate must be varied in order to ensure a specified river flow or groundwater depth, the siteID (consistent with ControlSiteID) where flow or depth must be ensured. "NA" for no residual flows specified. "AtPointOfTake" for a residual flow at the point of take. A ControlSiteID for when the residual flow is specified at a monitoring location.		Compulsory
ResidualAbsoluteValue	For when a consent specifies that the abstraction rate must be varied in order to ensure a specified river flow or groundwater depth, the absolute value for the residual flow or depth that must be maintained. Cumecs (m^3s^{-1}) for flow. Depth (m) for a groundwater depth. "NA" for when no absolute value for a residual flow is specified. Other conditions involving RateMaxVolume still apply.		Compulsory Example = 10. "You can abstract as long as you ensure that flow is at least $10m^3s^{-1}$ at ResidualSiteID"
ResidualShareValue	For when a consent specifies that the abstraction rate must be varied in order to ensure a specified river flow or groundwater depth, the proportion of allocated rate that can be taken. "NA" for when no share is specified. Other conditions involving RateMaxVolume still apply.		Compulsory. Example = "0.4" "You can abstract as long as you ensure that flow is 0.4 of the flow that would have been at ResidualSiteID"

MultipleControlSites	Is the consent controlled by more than one control site? If so do all conditions have to be meet in order for the take to operate, or does just one of many conditions have to be meet in order for the take to operate? • Single • All • Any Defaults to “Single”.	MDC require this.	Stops double counting. See definitions in appendix.

Table 6) Record values

This table contains information about how much water has been taken (or discharged) through each measuring system. Ideally, supplied records will cover the period July 2013 to June 2014 inclusive. Preferably daily data, but can be any temporal resolution. Recorded values represent those derived from one meter, several meters or other system for recording how much water is taken of discharge from the water source. The primary key = 1 to n.

Variable	Description	Notes	Status
ID	Row identifier		
RecordID	Unique identifier indicating the record		Compulsory
ObservationStart	Date and time (NZ standard time) at the start of observation.		Compulsory Allows variable time-steps
ObservationEnd	Date and time (NZ standard time) at the end of observation.		Compulsory
Volume	The volume of water taken between ObservationStart and ObservationEnd (m3). This is not the meter reading.		Compulsory.
QualityCode	NEMS data quality code. Default to 200.	ECan and Horizons have this.	Optional, where available.

Table 7) Control Rules

This table contains information about the rules that control when takes can be exercised in relation to river flows or groundwater depths. These rules often relate to conditions at gauging stations or monitoring bores that are used as control sites. The band defines the range of flows or depths within which the take can be exercised. A single control site may have one or many bands. The flow or depth range covered by bands at the same site can overlap. A band can relate to just one activity or many activities (as defined in Table 5). The primary key = ControlSiteID + BandID.

Variable	Description	Notes	Status
ID	Row identifier		
ControlSiteID	Unique identifier indicating the site where the Band is specified - as written in Table 5, including upper and lower case and spelling.		Compulsory For matching to Table 8. Suggest: "AtPointOfTake" for when a take is controlled by local flow conditions.
ControlVariable	The variable at the control site that controls the consent. Defaults to "Flow". Could be "Conductivity" or "Temperature". Must match with ControlVariable in Table 5a Consent Conditions and ControlVariable in Table 8 Control Values.	Added to accommodate consent conditions relating to conductivity in MDC region.	Assuming "Flow" when this is not provided.
ControlUnits	For when the consent is controlled by conditions at a control site, the units in which ControlVariable is given. Defaults to "m3s-1" for flow.		Assuming "m3s-1" when this is not provided.
BandID	Unique identifier for bands of (flow or depth) conditions for each site (ControlSiteID).		Compulsory Linking variable with consent conditions

FirstValue	For flow sites, FirstValue defines the lowest flow in the band (m^3s^{-1}). Related take rates will not be allowable when flow is less than this value. If this value is zero takes are never restricted because of low flows. For groundwater bore sites, FirstValue defines the deepest depth of the band (m). Related take rates will not be applicable when depth is greater than this value. If this value is "Inf" (Infinity) takes are never restricted because of low groundwater levels.	Would there be a band if there was no minimum flow? Note, for flow sites FirstValue is less than SecondValue. Note, for groundwater sites FirstValue is greater than SecondValue.	Compulsory
SecondValue	For flow sites, SecondValue defines the highest flow in the band. Related take rates will not be applicable when flow is greater than this value. If this value is "Inf" takes are never restricted because of high flows. For groundwater bore sites, SecondValue defines the shallowest depth of the band (m). Related take rates will not be applicable when depth is greater than this value. If this value is "Inf" (Infinity) takes are never restricted because of low groundwater levels.		Compulsory

Table 8) Control Values

This table contains information about observed values at river flow control sites and groundwater depth monitoring sites. There is a preference for one row per day, but other time periods (e.g., spot gaugings) can also be accommodated. All values are preferably m3s-1 for flows and m below a datum for groundwater levels. The primary key is 1 to n.

Variable	Description	Notes	Status
ID	Row identifier		
ControlSiteID	As written in other tables, including upper and lower case and spelling.		Compulsory
StartObservation	Date and time at the beginning of observation NZ standard time (preferably midnight).		Compulsory
EndObservation	Date and time at the end of observation NZ standard time (preferably midnight).		Compulsory
MeanValue	Archived value. A mean value between StartObservation and EndObservation. This is the best observed mean value after QA and any retrospective adjustments.	All values are m3s-1 for flows and m below ground level for groundwater levels.	Compulsory.
MaxValue	The maximum value observed between StartObservation and EndObservation. This value is taken after QA and any retrospective adjustments	Marlborough suggested daily max and daily min may be useful, especially in respect of hydropeaking.	Optional, if available.
MinValue	The minimum value observed between StartObservation and EndObservation. This value is taken after QA and any retrospective adjustments.		Optional, if available.

ValueAtDecision	Value visible to water user on the day of take.	Horizons suggested giving this. Some addiontal information about this may be required (e.g., what time of day does it represent? 3am?).	Optional. Not essential, but very interesting.
QualityCode	NEMS quality code for this observation. Defaults to 200.		Optional.
ControlVariable	The variable at the control site for which values are given. Defaults to “Flow”. Could be “Conductivity” or “Temperature”. Must match with ControlVariable in Table 5a Consent Conditions and ControlVariable in Table 7 Control Rules.	Added to accommodate consent conditions relating to conductivity in MDC region.	Assuming “Flow” when this is not provided.
ControlUnits	The units in which the values are given. Defaults to “m3s-1” for flow.		Assuming “m3s-1” when this is not provided.

Table 9) Record characteristics

This table contains information about the measuring systems used to record takes. They pertain to a system for recording takes or discharges. This system may be one meter or a set of meters or other system for recording water takes or discharges from the water source. The primary key is RecordID.

Variable	Description	Notes	Status
ID	Row identifier		
RecordID	Unique identifier indicating the measuring system.		Compulsory
X	NZTM easting		Optional
Y	NZTM northing		Optional
RecordsCommencementDate	The first date the site reported take data to the council.		Optional, if available.
RecordsCeaseDate	The last date the site reported take data to the council.		Optional, if available.
DeviceVerificationDate	The date the measuring device or system was last verified as accurate.		Compulsory, where available.
ReportingMethod	The method used by the consent holder to report water use to the council. Manual Logger Telemetry		Need a national list that covers all
LocationExemption	Whether the council has provided approval for the water measuring device to be further away from the point of take, as per regulation 10. • Yes • No		If available.
TakeMethod	The method of take for purposes of Water Take Regulations: Consistent with definition of full pipe in Regulation 3(1) - full pipe means a closed pipe or conduit that is full of water when it is conveying water. Full pipe is differentiated from “another method” referred to in Regulation 6(a)(ii) as “another method (including by an open channel or a partially full pipe)”.		Compulsory.

Table 10) Control Sites

This table contains information about all monitoring sites (any gauging stations or groundwater monitoring bores). Each site has one row. The primary key = ControlSiteID.

Variable	Description	Notes	Status
ID	Row identifier		
ControlSiteID	As written in Table 8, including upper and lower case and spelling.		Compulsory (as in NIWA SIMS database?) For matching to Table 8
SiteName	Name of the site (e.g., Selwyn at Coes Ford).		Optional
X	NZTM easting		Compulsory
Y	NZTM northing		Compulsory
NZreach	The NZreach associated with the site, where it has been identified by council using REC version 1 (as available from http://www.mfe.govt.nz/environmental-reporting/about-environmental-reporting/classification-systems/fresh-water.html). Blank for when it has not been looked for. NA for where it has been looked for, but is inappropriate (e.g., for a groundwater monitoring bore or a raceway that does not feature in the river network).		Optional See NestCat v2. We could supply this at the time of request.
ControlType	Is this a river flow site monitoring site or a groundwater level monitoring site? • RiverFlow • GroundwaterDepth		
Connectivity	For groundwater sites only. Where available, how strongly connected is this bore to the nearby rivers? How likely is this abstraction to affect river flows in nearby rivers? • High • Medium • Low • un-connected • unknown	This is held by Horizons. What are you defining as high medium or low.	Optional. Needs to be more tightly defined.
Transmissivity	For groundwater sites only. Measure of how much water can be transmitted horizontally (m2/day). As estimated from observations. Not interpolated or default values.		Compulsory

Storativity	For groundwater sites only. The volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer (dimensionless). As estimated from observations. Not interpolated or default values.	Compulsory

Table 11) Linking Table

This table contains information describing activities within consents, meters and locations. For example a consent that allows the taking of water for frost protection under certain conditions and for irrigation under a separate set of conditions. The primary key = 1 to n.

Variable	Description	Notes	Status
ID	Row identifier		
RecordID	Unique identifier indicating the meter		Compulsory
TakeID	Unique identifier, as per council records, for each take location.		Compulsory
ConsentID	Unique identifier for each consent		Compulsory
ActivityID	Unique identifier for each activity that can be distinguished within each consent. Defaults to "1" when activities cannot be distinguished or there is only one activity within a consent. The concatenation of ConsentID and Acivity ID should be unique within this table.	At MDC each new activity gets a new consent.	Compulsory if applicable Will be all the same if all consents have only one activity, or no activities can be distinguished within any consents.

Table 12) Processing Table

This table contains information about the council and the date the data was created. The primary key = 1 to n.

Variable	Description	Notes	Status
ID	Row identifier		
CouncilID	Name of the council for which these data relate to.		Compulsory
DateExtracted	Date the on which the data were extracted		Compulsory

Appendix B Schema definitions

CoordsQualityCode from Take Locations

Category	NEMS Definition
100	missing (ie not known).
200	present but don’t know how determined
300	synthetic co-ords (Google Maps or read off old hard copy maps)
400	GPS derived with accuracy +/- 100m
500	GPS derived with accuracy +/- 50m
600	GPS derived with accuracy +/- 10m

PrimarySource from Take Locations

Category	Definition
Groundwater	Water taken from any depth under the ground
Surface water	Water taken from a surface water body
Not specified	It is known whether water was taken from groundwater or surface water

SecondarySource from Take Locations

Category	Definition
River	
Stream	
Lake	
Bore	
Spring	
Race/Drain	
Dam	
Collected stormwater	
Stream deplete	
Gallery	
Riparian	
Interface	

Method from NZreaches

Category	Definition
Automated join	The NZreach was selected using an automated algorithm
Manual assignment	The NZreach was chosen by a person

Connectivity from Bore Characteristics and Control Sites
If the council has already determined definitions, then please do provide them.
Here are suggested definitions in the absence of a council having already defined these categories.

Category	Definition
High	There is evidence to suggest that this take is highly likely to influence flows in nearby rivers.
Medium	There is evidence to suggest the possibility that this take is likely to influence flow in nearby rivers.
Low	There is evidence to suggest that this take is unlikely to influence flow in nearby rivers.
unknown	The connectivity of this take to nearby rivers is unknown.

AquiferConfinement from Bore Characteristics
If the council has already determined definitions, then please do provide them.
Here are suggested definitions in the absence of a council having already defined these categories.

Category	Definition
Confined	
Unconfined	
unknown	The aquifer characteristics are unknown.

ConsentType from Resource Consents

Category	Definition
Take	A consent to only take water from a water body.
Discharge	A consent to only discharge water to water body.
Diversion	A consent to both take water from one water body and discharge water to another water body.
Unknown	A consent exists, but its type is unknown.

Status from Resource Consents

Category	Definition
Active	
Surrendered	
Expired – s124	
Expired	

PrimaryUse from Consented Activities

Category	Definition
Drinking	
Hydro	
Industrial	
Irrigation	
Stock	
Frost protection	
Not specified	

UseType from Consented Activities, (see StatsNZ definitions)

Category	Definition
A 01 016	Dairy Cattle farming
A 01 014	Sheep, and Beef Cattle and Grain farming
A 01 019	Other Livestock farming
A 01 012	Mushroom and Vegetable Growing
A 01 013	Fruit and Tree Nut Growing
A 01 013 0131	Grape growing
A 01 015 0159	Other Crop Growing e.g., Horticulture, Hay, Silage
	Other Agriculture water use not already included
B 06	Coal Mining
B 07	Oil and Gas Extraction
B 08	Metal Ore Mining
B 09	Non-Metallic Mineral Mining and Quarrying
B 10	Exploration and Other Mining Support Services
	Other Mining water use not already included
C	Manufacturing
D 26	Electricity Supply
D 27	Gas Supply
D 28	Water Supply, Sewerage and Drainage Services
D 29	Waste Collection, Treatment, and Disposal Services

	Other Electricity, Gas, Water and Waste Services use not already included
E	Construction
	Other water use not already included

MultipleControlSites from Consented Conditions

Category	Definition
Single	There is a single control site for this consent condition
All	There are many control sites for this consent condition. All conditions must be meet for this take to be allowable.
Any	There are many control sites for this consent condition. Any one of the conditions must be meet for this take to be allowable.

TakeMethod from Take Locations

Category	Definition
Full pipe	full pipe means a closed pipe or conduit that is full of water when it is conveying water. Referred to in Regulation 6(a)(ii).
Another method	"another method (including by an open channel or a partially full pipe)".
Unknown	

ResidualFlowType

Category	Definition
Proportion	The residual flow is a proportion of an observable flow. It is specified as a value between 0 and 1.
Cumecs	The residual flow is specified as a flow rate in m^3s^{-1}

RateCategory from Resource Consents

Category	Definition
< 5 l/s	Less than five litres per second
5 < 10 l/s	From 5 up to 10 litres per second
10 < 20	From 10 up to 20 litres per second
=> 20 l/s	20 litres per second or more
Defaults to greater than 20 l/s	Defaults to greater than 20 l/s. reg4(4)(d).

Appendix C Examples from Canterbury

There follows 12 sections; one for each requested Table. Example data are given. Where the data are categorical, all categories within the ECan data are given. Notes relating to the ECan data are then given. A brief description of what the data are being used for is then given. Examples of how the data can be displayed are then given.

Table 1) Record Locations

TakeID	X	Y	Coords Quality Code	Primary Source	Secondary Source	Catchment Number	Management Zone
M36/1866	1542811.6	5155385.2	3	Take Groundwater	Bore or Well	6832240	Rakaia Selwyn
M36/1871	1548082.8	5165554.2	4	Take Groundwater	Bore or Well	6800400	Selwyn-Waimakariri
M36/1873	1547064.8	5150064.6	3	Take Groundwater	Bore or Well	6832400	Rakaia Selwyn
M36/1874	1544377.5	5152385.4	3	Take Groundwater	Bore or Well	NA	Rakaia Selwyn
M36/1876	1543671.8	5151736.6	1	Take Groundwater	Bore or Well	6832310	Rakaia Selwyn
M36/1885	1554849.5	5165048	3	Take Groundwater	Bore or Well	6790510	Selwyn-Waimakariri
M33/0315	1572422.5	5251010.7	3	Take Groundwater	Bore or Well	6510910	Culverden Basin
M33/0318	1578642.1	5259514.3	4	Take Groundwater	Bore or Well	6510000	Culverden Basin
M33/0319	1569602.7	5253662.1	4	Take Surface Water	SW Abstraction Point	6510900	Culverden Basin
M33/0321	1573598.6	5256780.7	4	Take Surface Water	SW Abstraction Point	6510000	Culverden Basin
M33/0322	1564605.2	5261360	4	Take Surface Water	SW Abstraction Point	6510000	Culverden Basin
M33/0324	1576100.2	5250762.5	4	Take Surface Water	SW Abstraction Point	6510910	Culverden Basin

ECan used the following categories.

PrimarySource: "Take Groundwater", "Take Surface Water"

SecondarySource: "Bore or Well", "Bore+Gallery", "Excavated Pit", "Infiltration Gallery", "Spring", "Storage Pond", "SW Abstraction Point", "SW Discharge Point", "SW Diversion Point", "SW Gallery", "Thermal Bore", "Unknown", "Water Hole", "Well Cluster"

This information is used to locate takes on the river network and for discriminating between the treatment of groundwater and surface water takes.

Table 2) NZreaches

TakeID	NZreach	Method	Checked	Authority
M36/1866	13053993	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M36/1871	13050658	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M36/1873	13055397	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M36/1874	13054763	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M36/1876	13055095	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M36/1885	13050650	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M33/0315	13023734	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M33/0318	13021468	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M33/0319	13022989	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M33/0321	13022116	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M33/0322	13020752	AutomatedJoinToRiverLines	FALSE	NIWA_DJB
M33/0324	13023824	AutomatedJoinToRiverLines	FALSE	NIWA_DJB

NIWA used the following categories.

Method: “AutomatedJoinToRiverLines”, “ManualAssignment”

Authority: “Institution_Initials”

This table was generated by NIWA. The table was then supplied to ECan. Joining of the table with the REC or FWENZ databases provides information on the nearest river to each take. For example, stream order, climate category, geology category, estimates of MALF etc. The NZreach can also be used to extract simulated flows from any rainfall-runoff model that uses the REC river network as its spatial framework (e.g., NIWA’s national TopNet). The NZreach is required for routing and cumulating down the river network of recorded, consented and restricted values.

Table 3) Bore Characteristics

TakeID	Depth	Screen Depth Top	Screen Depth Bottom	Connectivity	Aquifer Confinement	Aquifer Name
M35/4136	6.8	NA	NA	None	Unknown	Springston Formation
M35/4138	18.3	NA	NA	NA	Unknown	Riccarton Gravel
M35/4146	24	18	24	NA	Unknown	Riccarton Gravel
M35/4175	10	NA	NA	None	Unknown	Springston Formation
M35/4194	34.4	NA	NA	None	Unknown	Riccarton Gravel
M35/4198	37.2	32.7	37.1	None	Flowing Artesian	Riccarton Gravel
M35/4207	25	NA	NA	None	Unknown	Riccarton Gravel
M35/4225	24.9	21.9	24.9	NA	Flowing Artesian	Riccarton Gravel

ECan used the following categories.

Connectivity: "Direct", "High", "Low", "Moderate", "None"

AquiferConfinement: "Flowing Artesian", "Joint/fractured rock", "Non-Flowing Artesian", "Semi-Confined", "Unknown", "Water Table"

This information is used in calculation of stream flow depletion resulting from groundwater takes.

Table 4) Resource Consents

ConsentID	ConsentType	Description	Commencement date	Expiry Date	Termination Date	Status	Transfer Date	Plan Provision ID
CRC000002.1	Take Surface Water	To take water from…	3/12/2003 0:00	7/09/2034 0:00	7/09/2034 0:00	Issued	7/09/2034 0:00	NA
CRC000023.1	Take Groundwater	to take groundwater via bore M35/8508…	15/11/2005 0:00	30/08/2034 0:00	30/08/2034 0:00	Issued	30/08/2034 0:00	NA
CRC000042.1	Take Surface Water	To take water at …	21/09/2004 0:00	8/09/2034 0:00	8/09/2034 0:00	Issued	8/09/2034 0:00	NA
CRC000045	Take Groundwater	to take groundwater via bore…	22/11/1999 0:00	18/11/2034 0:00	18/11/2034 0:00	Issued	18/11/2034 0:00	NA
CRC000047.3	Take Groundwater	To take and use groundwater.	29/10/2009 0:00	25/08/2034 0:00	25/08/2034 0:00	Issued	25/08/2034 0:00	NA
CRC000053.1	Take Surface Water	to take water at or about…	15/12/2008 0:00	15/12/2034 0:00	15/12/2034 0:00	Issued	15/12/2034 0:00	NA

ECan used the following categories.

ConsentType: "Divert Surface Water", "Take Groundwater", "Take Surface Water"

Information on commencement and expiry is used in calculation of stream flow depletion resulting from groundwater takes.

Table 5) Consented activities

ConsentID	ActivityID	PrimaryUse	UseType	NonConsumptive	Irrigated Area	Crop Type
CRC000002.1	ACT041177	Agricultural and Horticultural activities	Irrigation	FALSE	41	Pasture - mixed
CRC000023.1	ACT049625	Agricultural and Horticultural activities	Irrigation	FALSE	40	Pasture - mixed
CRC000042.1	ACT043920	Agricultural and Horticultural activities	Irrigation	FALSE	27	Pasture - mixed
CRC000045	ACT000282	Agricultural and Horticultural activities	Irrigation	FALSE	84	Pasture - mixed
CRC000047.3	ACT071145	Agricultural and Horticultural activities	Irrigation	FALSE	100	Pasture - mixed
CRC000053.1	ACT067894	Agricultural and Horticultural activities	Irrigation	FALSE	17	Pasture - mixed
CRC010281	ACT001817	Industrial and Commercial activities	Cooling Water	TRUE	0	NA
CRC010693.1	ACT060585	Hydro-electricity generation	Hydroelectric Power Generation	TRUE	0	NA

ECan used the following categories.

PrimaryUse: "Agricultural and Horticultural activities", "Hydro-electricity generation", "Industrial and Commercial activities", "Other activities", "Tourism and Recreational facilities", "Town and Community water supply",

UseType:"Aquaculture", "Arable Farming", "Augment River or Drain Flow", "Construction Phase", "Cooling Water", "Domestic Use", "Firefighting", "Fisheries/Wildlife Management", "Flood Control", "Frost Protection or Viticulture", "Gravel Extraction", "Hydroelectirc Power Generation", "Hydroelectric Power Generation", "Industrial Use", "Intensive Farming", "Irrigation", "Landfills", "Mining", "Other", "Public Water Supply (Municipal/Community)", "Recreation", "Research", "Snow Making", "Stockwater", "Stormwater or Waste Water",

CropType: "Aquaculture", "Community Water Supply", "Crops - cereals", "Crops - mixed", "Crops - vegetables",

"Crops - vegetables ", "Crops & Pasture mixe", "Crops & Pasture mixed - excl dairy cows", "Crops & Pasture mixed - incl dairy cows", "Domestic Use ", "Frost Protection", "Horticulture", "Hydroponics ", "Industrial Uses ", "Other", "Pasture - beef", "Pasture - dairy", "Pasture - deer", "Pasture - mixed", "Pasture - piggery", "Pasture - sheep", "Ready Lawn", "Sport / Recreational", "Stockwater", "Vineyard "

This information is used for various purposes including treatment of non-consumptive takes when calculating cumulative effects.

Table 5a) Consent conditions

Example 1: a simple example. Can take up to 0.02 m^3 per second, but not more than 864 m^3 per day. Both conditions apply all year round. Restrictions given by ControlsSiteID 68 and BandID 1 apply.

ConsentID	ActivityID	ConditionID	Rate Max Volume	Rate Period Type	Rate Time Proportion	Rate Start	Rate End	Other Rate	Control SiteID	BandID	Control Variable	Control Units	Rate Time Proportion	MultipleControl Sites
CRC000084.1	ACT055424	1	0.02	Sec	1	1-Jul	30-Jun	NA	68	1	Flow	m3/s	1	Single
CRC000084.1	ACT055424	2	864	Day	1	1-Jul	30-Jun	NA	68	1	Flow	m3/s	1	Single

Example 2: a seasonal example with multiple controls sites. Between October and April (inclusive), can take up to 0.115 m^3 per second, but not more than 3260 m^3 per day. Restrictions given in various Bands at various control sites apply.

ConsentID	ActivityID	ConditionID	Rate Max Volume	Rate Period Type	Rate Time Proportion	Rate Start	Rate End	Other Rate	Control SiteID	BandID	Control Variable	Control Units	Rate Time Proportion	MultipleControl Sites
CRC000485.1	ACT000353	1	0.115	Sec	1	1-Oct	30-Apr	NA	417	2	Flow	m3/s	1	All
CRC000485.1	ACT000353	1	0.115	Sec	1	1-Oct	30-Apr	NA	329	1	Flow	m3/s	1	All
CRC000485.1	ACT000353	1	0.115	Sec	1	1-Oct	30-Apr	NA	418	2	Flow	m3/s	1	All
CRC000485.1	ACT000353	2	3260.14	Day	1	1-Oct	30-Apr	NA	417	2	Flow	m3/s	1	All
CRC000485.1	ACT000353	2	3260.14	Day	1	1-Oct	30-Apr	NA	329	1	Flow	m3/s	1	All

CRC000485.1	ACT000353	2	3260.14	Day	1	1-Oct	30-Apr	NA	418	2	Flow	m3/s	1	All

Note, the following variables were not given as do not apply for ECan: ResidualSiteID, ResidualAbsoluteValue, ResidualShareValue.

ECan used the following categories.

RatePeriodType: "Day", "Sec", "Year" (not “Month”)

ControlUnits: "m", "m3/s"

MultipleControlSites: "All", "Single" (not “Any”)

This information is used for calculating consent conditions (Figure 8-1), and for calculating when restrictions apply (Figure 4-28).

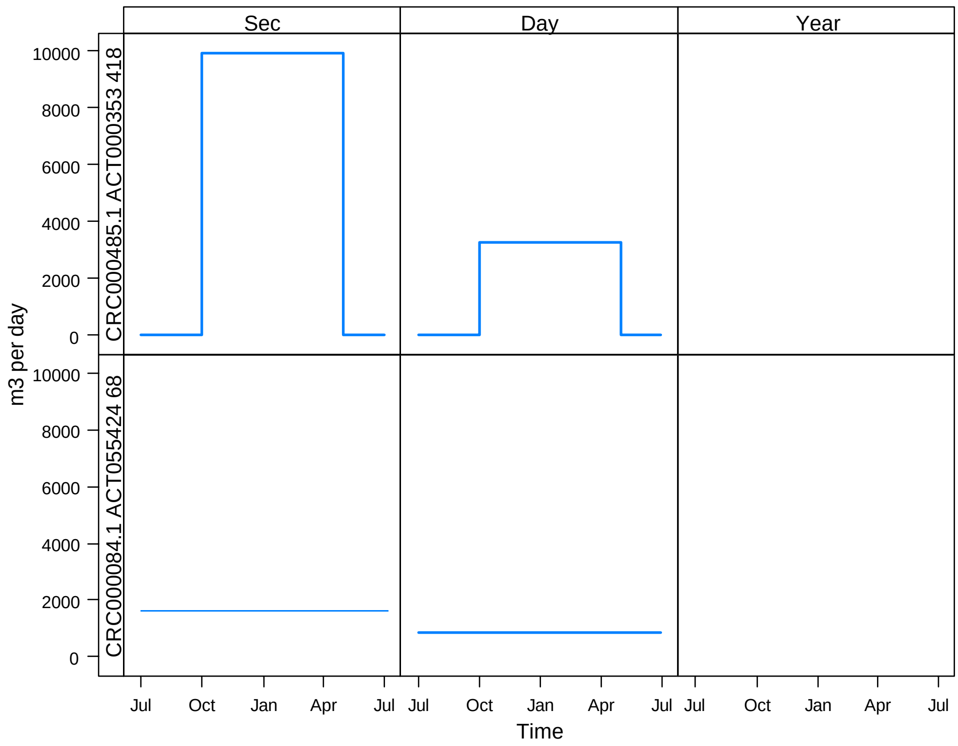

Figure 8-1: Rates of take specified in consent conditions for two activities (Example 1= bottom, Example 2 = top).

Table 6) Record values

Example of daily values.

RecordID	ObservationStart	ObservationEnd	Volume	QualityCode
L36/1298	23/10/2013 0:00	24/10/2013 0:00	0	200
L36/1298	24/10/2013 0:00	25/10/2013 0:00	0	200
L36/1298	25/10/2013 0:00	26/10/2013 0:00	1602	200
L36/1298	26/10/2013 0:00	27/10/2013 0:00	3559	200
L36/1298	27/10/2013 0:00	28/10/2013 0:00	2908	200
L36/1298	28/10/2013 0:00	29/10/2013 0:00	3835	200
L36/1298	29/10/2013 0:00	30/10/2013 0:00	3931	200
L36/1298	30/10/2013 0:00	31/10/2013 0:00	3941	200
L36/1298	31/10/2013 0:00	1/11/2013 0:00	3908	200
L36/1298	1/11/2013 0:00	2/11/2013 0:00	1707	200
L36/1298	2/11/2013 0:00	3/11/2013 0:00	0	200
L36/1298	3/11/2013 0:00	4/11/2013 0:00	0	200

This information is used for calculating and cumulating recorded takes (Figure 4-28).

Table 7) Control Rules

Example 1: ControlSiteID 1 has a simple on or off rule.
Example 2: ControlSiteID 4 has three bands, each has on or off rules, one of which has seasonal components.
Example 3: ControlSiteID 57 has a band with variable restrictions.

Control SiteID	BandID	First Value	Second Value	Low Flow Start Day	Low Flow End Day	TypeRestriction	Restriction Percent1	Restriction Percent2
1	1	0.15	Inf	1-Jan	31-Dec	100 percent	100	NA
4	1	0.05	Inf	1-Jan	31-Dec	100 percent	100	NA
4	2	0.1	Inf	1-Jan	31-Dec	100 percent	100	NA
4	3	0.075	Inf	1-Jan	28-Feb	100 percent	100	NA
4	3	0.11	Inf	1-Mar	30-Apr	100 percent	100	NA
4	3	0.11	Inf	1-Oct	31-Dec	100 percent	100	NA
4	3	0.18	Inf	1-May	30-Sep	100 percent	100	NA
57	1	0.12	0.22	1-Jan	31-Dec	From 50 to 100	50	100
57	2	0.181	Inf	1-Jan	31-Dec	100 percent	100	NA

ECan supplied TypeRestriction. RestrictionPercent1 RestrictionPercent2 were subsequently calculated. Supply of these data in either format is acceptable.

This information is used for calculating rules controlling restriction of takes (Figure 8-2, Figure 8-3, Figure 8-4).

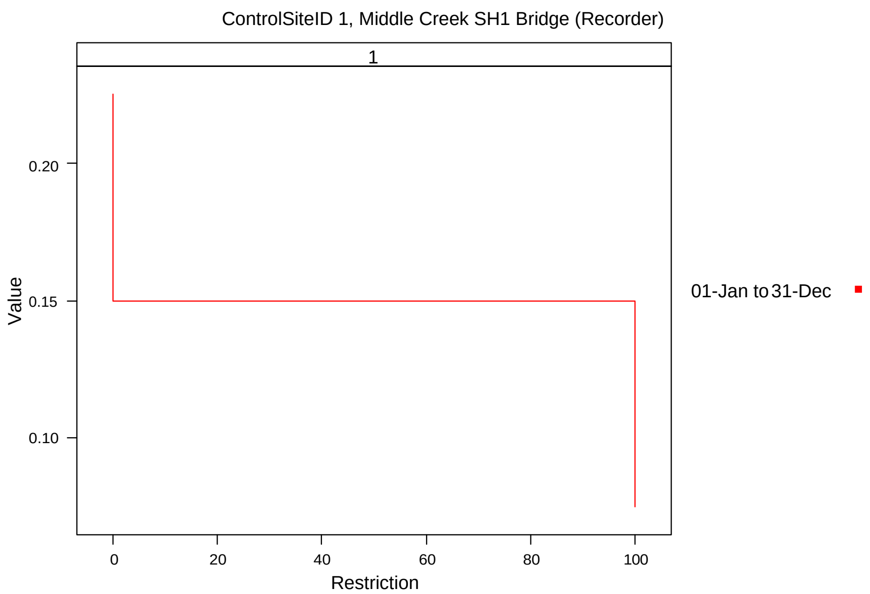

Figure 8-2: Rules governing restrictions for various bands within a ControlSiteID 1.

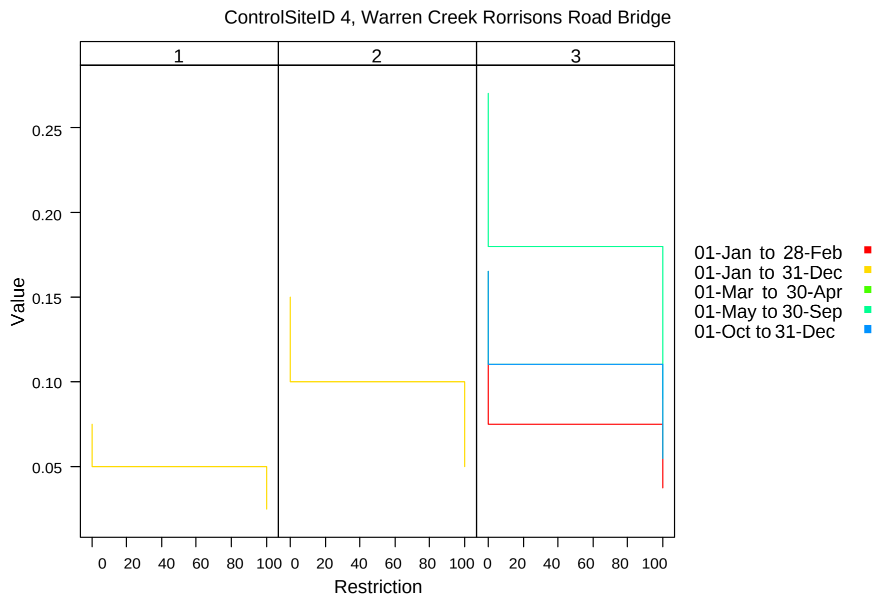

Figure 8-3: Rules governing restrictions for various bands within a ControlSiteID 4.

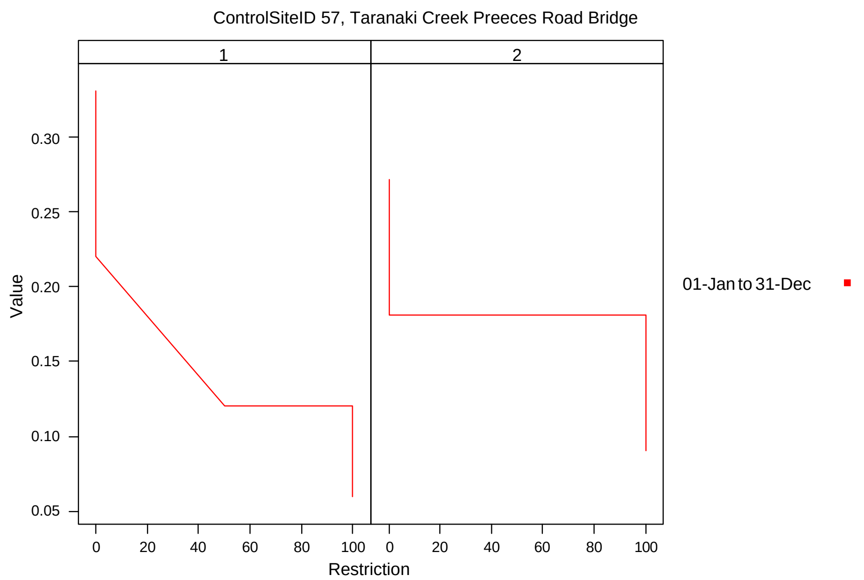

Figure 8-4: Rules governing restrictions for various bands within a ControlSiteID 57.

Table 8) Control Values

Example of daily control values.

ControlSiteID	StartObservation	EndObservation	ValueAtDecision
1	21/05/2014 0:00	22/05/2014 0:00	0.735
1	22/05/2014 0:00	23/05/2014 0:00	0.722
1	23/05/2014 0:00	24/05/2014 0:00	0.729
1	24/05/2014 0:00	25/05/2014 0:00	0.692
1	25/05/2014 0:00	26/05/2014 0:00	0.656
1	26/05/2014 0:00	27/05/2014 0:00	0.588
416	21/07/2013 0:00	22/07/2013 0:00	-15.095
416	22/07/2013 0:00	23/07/2013 0:00	-15.095
416	23/07/2013 0:00	24/07/2013 0:00	-15.095
416	24/07/2013 0:00	25/07/2013 0:00	-11.49
416	25/07/2013 0:00	26/07/2013 0:00	-11.49
416	26/07/2013 0:00	27/07/2013 0:00	-11.49

Note that ECan did not supply MeanValue, MaxValue, MinValue, QualityCode, ControlVariable (because all were flow or groundwater level), ControlUnits (because all were m3s-1 for flow and m above ground [mostly negative values] for groundwater).

This information is used for calculating restrictions of consented takes (Figure 8-5).

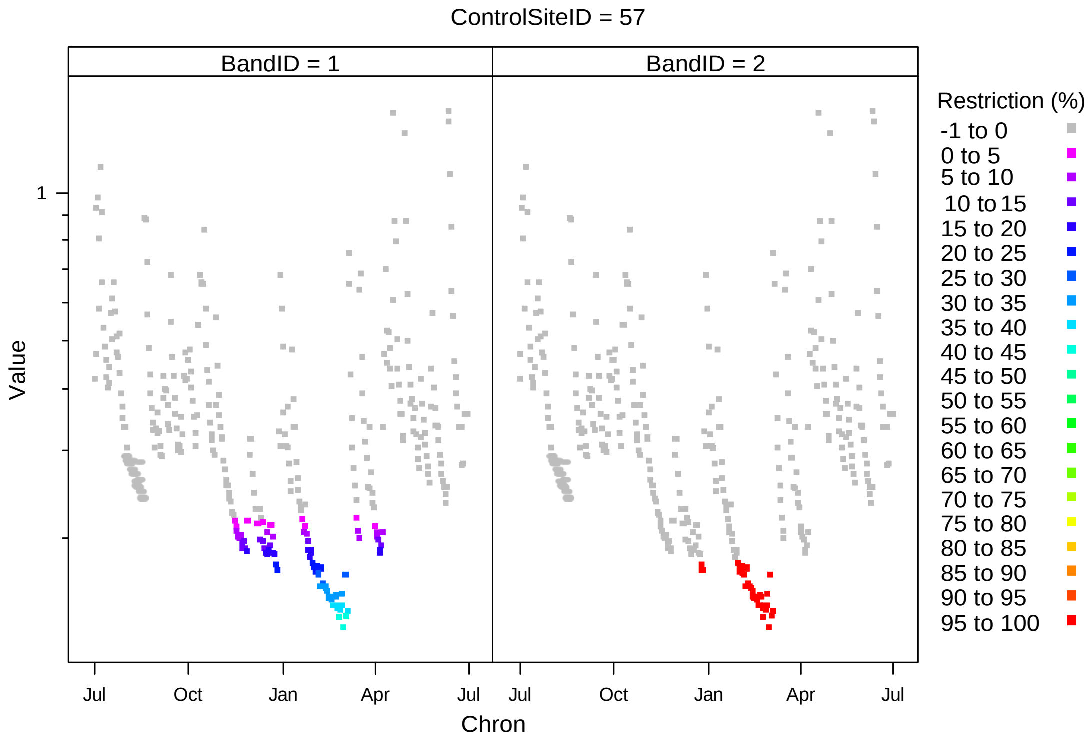

Figure 8-5: Observed time-series of control values with percent restriction for a river flow site.

Table 9) Record characteristics

ID	RecordID	X	Y	Records Commencement Date	Records Cease Date	Device Verification Date	Reporting Method	Location Exemption	Take Method
9954	J37/0056	1422818.72	5118355.58	NA	NA	NA	Yearly data File	NA	Alpe Delta Mechanical
9956	J37/0248	1426436.68	5126377.09	13/11/2003 0:00	18/07/2012 0:00	NA	Yearly data File	NA	Alpe Delta Mechanical
9957	J37/0250	1430095.78	5130518.21	1/10/2003 0:00	30/06/2013 0:00	NA	Yearly data File	NA	Alpe Delta Mechanical
9958	J37/0251	1430325.6	5131308.3	4/04/2000 0:00	14/04/2013 0:00	NA	Yearly data File	NA	Alpe Delta Mechanical
9960	J38/0009	1459891.05	5108937.59	1/12/2004 0:00	25/06/2013 0:00	NA	Yearly data File	NA	Alpe Delta Mechanical
9961	J38/0029	1448481.9	5097850.26	5/10/2010 0:00	30/06/2011 0:00	NA	Yearly data File	NA	Alpe Delta Mechanical

ECan used the following categories.

TakeMethod: 55 categories, see Figure 8-6.

This information is not currently being used in the PSI model. MfE may also use these data for other purposes relating to take-up of the water regulations.

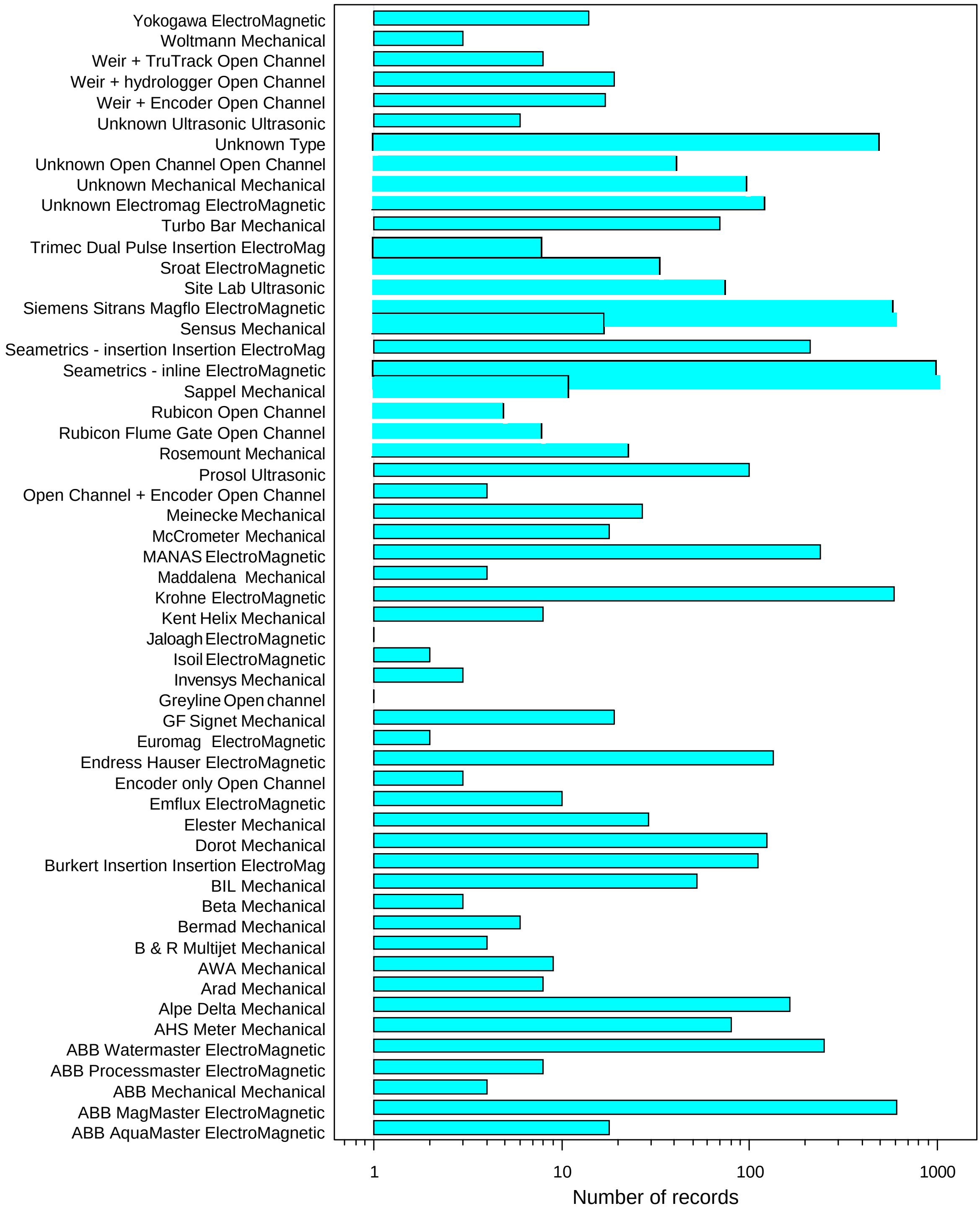

Figure 8-6: Counts of TakeMethod within the ECan dataset.

Table 10) Control Sites

ControlSiteID	SiteName	X	Y	NZTMX	NZTMY	GridReference	ControlType
13	Hanmer River Hanmer Road Bridge	1582601	5285949	NA	NA	N32:927-477	RiverFlow
20	Pahau River Top Pahau Road	1582199	5265356	NA	NA	N33:921-270	RiverFlow
25	School Creek McKenzie Property Downstream of Take.	1588796	5262357	NA	NA	N33:9896-2420	RiverFlow
26	Innes Drain McIntosh Property Downstream of Take	1587697	5263656	NA	NA	N33:977-253	RiverFlow
27	Unnamed Tributary of St Leonard Drain Unnamed Drain Downstream of Davison Intake	1593295	5263296	NA	NA	N33:033-249	RiverFlow
30	Chatterton River Downstream of take	1584582	5292307	NA	NA	N32:9458-5396	RiverFlow

Note Ecan gave coordinates for groundwater sites in NZTM co-ordinate system using two additional columns. ECan did not supply Connectivity, Transmissivity or Storativity in this table. They supplied these data separately. These columns are not essential.

This information is used for model assessment and quality checking purposes.

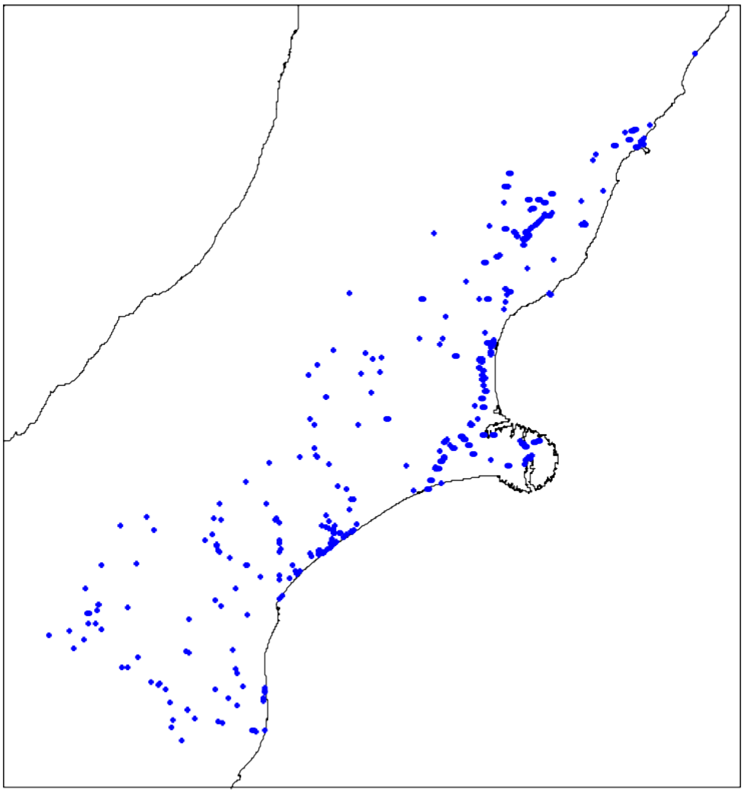

Figure 8-7: Locations of river flow control sites.

Table 11) Linking Table

RecordID	TakeID	ConsentID	ActivityID
J39/0162	J39/0162	CRC141367	ACT088672
K37/0637	K37/0637	CRC960963.4	ACT052975
K37/1607	K37/1607	CRC031009.1	ACT054593
L35/1116	L35/1116	CRC061925	ACT050736
L36/1758	L36/1758	CRC050195.3	ACT084083
M36/5656	M36/5656	CRC982193	ACT026267

This is essential information used to matching information between various tables.