Modelling streamflow depletion from recorded abstractions;

application to the Greater Wellington & Manawatu-Wanganui regions

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Contents

Tables

Figures

Executive summary

Calculation of streamflow depletion resulting from water abstraction is necessary for water accounting and effective environmental reporting. However, systematic methods for gathering the necessary data and calculating regional patterns in streamflow depletion have not been developed in New Zealand. The purpose of this work was to demonstrate potential methods and assess data availability necessary to calculate streamflow depletion at sufficiently fine spatial and temporal scales to feed information to river flow management, water accounting and environmental reporting.

Numerical methods to estimate daily time-series of streamflow depletion resulting from recorded abstractions from surface and groundwater were developed and applied across two example regions of New Zealand. Recorded flow time-series and additional meta-data for each record were required as inputs to the model. The required meta-data were:

- position;
- source (surface water or groundwater);
- abstraction or discharge; and
- bore depth (screen depth where relevant), storativity and transmissivity for groundwater takes.

Recorded flow time-series were downloaded from web-services after having sought permission from Greater Wellington Regional Council (GWRC) and Horizons Regional Council (Horizons). Automated routines were applied to access these recorded time-series without the need for manual data compilation. Each record was often accompanied by its units of measurements and position. Other required meta-data were not always easily accessible. We obtained bore depth, storativity and transmissivity data through a combination of inspecting council web-services, requests to council staff, and data used in previous projects. Position, bore depth, storativity and transmissivity data were also obtained from monitoring bores in the regions of interest. Statistical models trained using all available data were used to in-fill any missing values of bore depth, storativity and transmissivity at sites with recorded groundwater abstractions. Results indicated that these statistical models were unbiased and could explain patterns in the observed data.

Streamflow depletion resulting from both groundwater and surface water was estimated for every day of the period July 2015 to July 2018, for every influenced reach of the national river network (version 2.4). There were only very minor differences in streamflow depletion resulting from groundwater abstraction calculated using a simpler one-layer and a more sophisticated two-layer model. The minor differences in calculated streamflow depletion between the two models is explained by differences in how aquifer parameters of each model influence the streamflow depletion calculation. This is because different aquifer parameters are likely to change the streamflow depletion estimates between models.

The main findings of this work were as follows:

- daily time-series records of water abstraction (and some diversions) were available for two example regions, and these data can be obtained using automated methods to access data provided by regional councils;

- the format of the currently available time-series data was appropriate for the task of estimating streamflow depletion;
- some meta-data necessary to estimate spatially distributed time-series of streamflow depletion were not readily available for automated download, specifically, locations, source, record type (abstraction vs discharge) and information relating to groundwater bore characteristics;
- replicable and transparent methods of estimating daily time-series of streamflow depletion were applied;
- many records commenced, ceased or contained gaps of missing data during the three-year period of interest;
- visual inspection showed that some records contained suspicious patterns such as large spikes and possible changes in measurement units that may compromise streamflow depletion calculations;
- quality assurance of abstraction data is not straightforward since, unlike most river flows, they are likely to contain zero values and strong daily variations; and
- interpretation of the results was aided through use of an interactive app displaying streamflow depletion across the regions and through time.

Results indicated that the magnitude of likely streamflow depletion varied in both space and time. Different catchments could be dominated by groundwater abstraction, surface water abstraction or a mix of both. Many recorded abstractions indicated strong seasonal patterns. Seasonally constant abstractions were rare but present. Widespread groundwater abstractions caused reaches to be relatively uniformly abstracted across some catchments. This contrasted with localised impacts in catchments with larger abstractions particularly in upstream tributaries.

It was demonstrated that estimation of streamflow depletion resulting from water abstraction is feasible at relatively fine spatial and temporal scales. However, some impediments to reliable streamflow depletion calculations across multiple regions remain. These impediments include inconsistent methods for data storage between regional councils, availability of the required meta-data, missing data and indeterminant quality of recorded abstraction time-series data.

1 Introduction

1.1 Background

Water abstraction from rivers and aquifers has considerable potential to alter flow regimes in many countries (Dalin et al., 2017), including across New Zealand (Booker 2018), thereby influencing the physical, chemical and ecological wellbeing of freshwater ecosystems (Poff et al., 2010, Booker et al., 2016a). The economic and social benefits of abstraction need to be balanced against its potentially deleterious consequences for hydrologically-driven ecological functions, ecosystem services, cultural values and recreation (MFE, 2015). Legislative requirements therefore often require river managers to deploy catchment planning frameworks. These frameworks often aspire to maintain ecological health and life-supporting capacity of rivers, including regulation of water abstractions to limit alteration of river flows (e.g., Richter et al., 2012).

In New Zealand, the National Policy Statement for Freshwater Management (NPS-FM) directs regional councils to set limits on the use of water resources for all waterbodies. The limit is intended to enable the council to manage the actual and potential cumulative impacts of abstraction and reduce allocation of the hydrological resource in over-allocated catchments (MFE, 2015). The NPS-FM defines a freshwater management unit as the water body, multiple water bodies or any part of a water body determined by the regional council as the appropriate spatial scale for setting freshwater objectives and limits, and for freshwater accounting and management purposes.

The NPS-FM defines a freshwater quantity accounting system as "a system that, for each freshwater management unit, records, aggregates and keeps regularly updated, information on the measured, modelled or estimated: a) total freshwater take; b) proportion of freshwater taken by each major category of use; and c) where limits have been set, the proportion of the limit that has been taken. A freshwater quantity accounting system will keep account of how much water is allocated, as well as how much is being taken from freshwater bodies and broadly what that water is being used for (e.g., municipal, irrigation, hydroelectric power)" (MFE, 2015).

Water accounting and environmental reporting of water quantity could be applied at the broadest spatial and temporal scale by summing all consumptive abstractions within a freshwater management unit over a relatively long period (e.g., quantifying the volume of water abstraction within a freshwater management unit over a year). However, this method would not represent the timing or spatial pattern in either water supply or pressures on river flows resulting from abstraction across the freshwater management unit. This is important because spatial and temporal patterns in abstraction will vary with water demands (e.g., crop type), soil type, and weather conditions. Even in the absence of abstraction, river flow regimes vary in space due to spatial variations in catchment size, climate, geology, and vegetation (Booker, 2013). River flows at any site are also known to vary in time due to temporal variations in weather, soil moisture, and groundwater levels. Spatial and temporal flow variations will result in spatial and temporal variations in conditions for flow-dependent in-stream values such as habitat for fish, conditions for mahinga kai gathering, or aesthetic appeal. Spatial and temporal variations must therefore be incorporated for environmental reporting and water accounting to be relevant to policy development, river managers, and the public. However, presenting records of water abstraction and streamflow depletion at a very fine temporal resolution (some abstractions are measured at 5 minutes intervals) may not be practical to achieve, or easy to communicate.

Methods for water accounting need to strike a balance between: a) providing sufficient spatial and temporal detail to distinguish patterns relevant to in-stream and out-of-stream values; versus b) not being overly costly to produce, and cumbersome to communicate. Communication of patterns that vary in space and through time may not be possible using traditional data display techniques (e.g., maps or tables). Tools that allow the viewer to interact with the data may be beneficial in communicating complex datasets. For example, interactive apps may allow a user to view results for a selected date or site of interest.

1.2 Aims

In this project we set out to assess the feasibility of estimating streamflow depletion resulting from water abstraction at relatively fine spatial and temporal scales. We wished to demonstrate a method for calculating streamflow depletion, and to test whether the data, methods and infrastructure are in place to quantify the impacts of abstractions on natural river flows across catchments on a daily time-step. The main aim was to develop and apply a model to estimate daily time-series of streamflow depletion resulting from recorded abstractions from surface and groundwater across two example regions of New Zealand. The work had the following objectives:

- to investigate the availability of continuous (i.e., daily time-series) records of water abstraction;
- to demonstrate how records of water abstraction can be obtained from regional councils using automated methods;
- to assess the appropriateness of the currently available data for the task of estimating streamflow depletion;
- to specify meta-data relating to records of water abstraction that are necessary to estimate spatially distributed time-series of streamflow depletion;
- to develop a replicable and transparent method to estimate spatially distributed time-series of streamflow depletion;
- to estimate streamflow depletion across two regions;
- to develop an interactive app that displays streamflow depletion results across the regions and through time;
- to provide recommendations that would enable improved estimates of streamflow depletion and application across more regions; and
- to make suggestions on how streamflow depletion estimates could be used for river management and environmental reporting.

2 Input data

2.1 Spatial framework

The River Environment Classification (REC; Snelder and 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. Here we used version 2.4 of the digital national river network because it represents the most up-to-date and accurate representation of New Zealand's river network. This river network comprises 590,000 segments. Each segment of the digital national river network 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 segments within the network. This has allowed the river network to provide a basis for various national-level analyses of hydrology (Booker and Woods 2014), geomorphology (Booker 2010), invertebrates (Booker et al. 2014), fish (Crow et al. 2012), and potential impacts of consented abstractions (Booker, 2018). 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 2.4) was therefore used as the spatial framework for all analysis in this project.

2.2 Data requirements

Three types of data were required as input to our approach. The first data type was rate of consumptive abstraction from each record on each date. We collated these data into a matrix of abstraction rates with a column for each abstraction record and a row for each date (e.g., Table 2-1). "NA" was used to indicate missing data (e.g., the period before a record began). All values were specified as daily volumes in units m^3 day^{-1}. Positive rates were treated as abstractions from surface water or groundwater. If present, negative rates would be treated as augmentations to surface water or groundwater. The distinction between positive and negative rates meant that our method could include any of the following situations:

- records with only positive rates to describe consumptive abstractions taken from surface water or groundwater and not returned to the same location;
- records with only negative rates to describe discharges of water added to a river such as those caused by a river diversion scheme; and
- records with positive and negative rates to describe streamflow abstractions (reductions in natural river flows) and discharges (increases in natural river flows) respectively as might result from a non-consumptive hydropower scheme such as an in-river dam.

Table 2-1: Required data describing abstraction rates (m^3 day^{-1}).

Date	Unique Record Identifier				
	Record_001	Record_002	Record_003_a	Record_003_b	Record identifiers continue…
16/02/2017	NA	0	1568	0.25	
17/02/2017	NA	100	6832	1.258	
18/02/2017	0	100	985	2.568	
19/02/2017	25	0	23165	0	
Dates continue…					

The second data type was meta-data describing each abstraction record (Table 2-2). Location and source of each record were required to implement our streamflow depletion method. Our streamflow depletion method also required inputs of bore depth, storativity and transmissivity for each groundwater abstraction record, however, these estimates were not available for every record. Our solution was to create statistical models to predict bore depth, storativity and transmissivity, which could then be used to in-fill any missing values. The third data type was therefore meta-data describing groundwater monitoring sites that took the same format as Table 2-2.

Table 2-2: Required meta-data describing record characteristics and additional bore characteristics.

Column name	Description	Values
Record Identifier	Unique record identifier	Unique characters
Primary source	Is the abstraction from groundwater or surface water	Choose from two classes
Latitude	Grid position	Numeric value
Longitude	Grid position	Numeric value
Bore depth	For groundwater only, the depth of the bore	Numeric value (m below surface)
Screen depth	For groundwater only and where applicable, the depth at which water is taken where screens are deployed within a bore.	Numeric value (m below surface)
Storativity	For groundwater only, the volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer	Numeric value (unitless)
Transmissivity	For groundwater only, the rate at which groundwater flows horizontally through an aquifer	Numeric value (m^2 day^{-1})

Where possible, we downloaded data by connecting to web servers. We took advantage of spatial data conforming to Open Geospatial Consortium Web Feature Service (WFS). The WFS interface standard provides an interface allowing requests for geographical features and time-series data across the web using platform-independent calls. We requested time-series data in WaterML2 (WML2) format. WaterML2 is a data exchange standard in hydrology which can be used to exchange many kinds of hydro-meteorological observations and measurements. WaterML2 has several advantages including a consistent format for units, dates and co-ordinates. We applied conversion rates shown in Table 2-3 to convert the WML2 unit associated with each record to m^3 day^{-1}.

Table 2-3: Conversion rates for gaining abstraction records.

Units in WML2 Format	Conversion to m^3 day^{-1}
l/s	(60*60*24)/1000
mÂ³	1
mÂ³/sec	(60*60*24)

We collated records of abstraction covering the period 01-Jun-2015 to 01-Jul-2018. This period was chosen because it covered three full hydrological years starting 01-Jul-2015. We collated data for an extra month prior to 01-Jul-2015 to allow for a spin-up period for our calculations of streamflow depletion resulting from groundwater abstraction.

2.3 Greater Wellington Regional Council

We gained permission to access web-servers holding records of abstraction from GWRC. We wrote bespoke code in the R programming language to download abstraction time-series from GWRC's Hilltop server. All GWRC water abstraction records were held on a separate file on their Hilltop server. A total of 723 records containing a parameter labelled as either "WaterMeterReadings" or "WaterMeterVolume" were available from the appropriate file on GWRC's Hilltop server. Of these 723 records, 552 contained some observations within the period of interest. We downloaded these records and collated them into a record-by-date matrix as detailed in Table 2-1. Our code converted all units from the WML2 unit associated with each record to daily volumes (m^3 day^{-1}) using the conversion rates shown in Table 2-3.

We compiled information listed in Table 2-2 for each abstraction record from various sources. For example, 139 records were associated with latitude and longitude within GWRC's Hilltop server. We accessed these data from GWRC's Hilltop server using bespoke R code. Latitude and longitude for a further 373 records were gained by matching record identifiers with consent identifiers used in the study of Booker et al. (2016b). Latitude and longitude for a further 5 records were gained by matching record identifiers with record identifiers that had accompanying latitude and longitude values used in the study of Booker et al. (2016b). Latitude and longitude for a further 23 records were gained by matching record identifiers with record identifiers appearing in data supplied by GWRC describing their "active consents". Latitude and longitude for a single record was gained by matching with data supplied by GWRC describing their "northern groundwater consents". This left 11 records with unknown locations. We discarded these 11 records from our analysis.

Where possible we compared latitude and longitude for each record downloaded from GWRC's Hilltop server with those used in the study of Booker et al. (2016b). We found that co-ordinates gained from GWRC's Hilltop server showed site "292068/1" to be positioned in the Manawatu-Wanganui region. We therefore used the co-ordinates gained from GWRCs "active consents" data for this site. This positioned the site in the middle reaches of the Ruamahanga River catchment within the Wellington region.

The source for each record was gained by matching record identifiers with consent identifiers used in the study of Booker et al. (2016b).

A systematic data quality checking procedure was not applied. We made one manual change to correct for some unfeasibly large rates of abstraction for one surface record located on a very small tributary of the Ruamahanga River. We divided all records from RecordID "292300/2" by 1,000,000. We suspect this corrected for a record that had been multiplied by 1000 rather than divided by 1000 during a unit conversion. Mean flow at this site was 3,8790,832 m^3 day^{-1}. This is equivalent to 448,968 l s^{-1}. We divided all values in this record by 1,000,000 to obtain an average equivalent to 0.45 l s^{-1}.

We obtained additional information describing characteristics of monitoring bores (Table 2-2) across the Greater Wellington region. These data included 312 paired observations of storativity and transmissivity.

2.4 Horizons Regional Council

We gained permission to access web-servers holding records of abstraction from Horizons Regional Council. We applied the bespoke functions developed for GWRC data to download abstraction time-series and record locations from Horizons Hilltop server.

Unlike for GWRC, Horizons abstraction data were held within the same file as other monitoring data (e.g., groundwater levels, river flows). A Hilltop file may hold several "hilltop collections", each of which may contain several records. Examples of collections include "Groundwater-Telemetered", "Conductivity" and "Flow". We assumed that records held within all "hilltop collections" with labels starting "RGM-" contained data describing abstractions, diversions or discharges. Each of these records had parameter names specified as a number prefixed by "Flow" (e.g., "Flow1", "Flow2", etc). Of 321 records, 318 contained some observations within the period of interest. We downloaded these records and collated them into a record-by-date matrix as detailed in Table 2-1. Our code converted all units from the WML2 unit specified for each record to daily volumes (m^3 day^{-1}) using conversion rates shown in Table 2-3.

The source for each record was gained by matching record identifiers with consent identifiers used in the study of Booker et al. (2016b). We designated 26 records with unknown source as being abstractions from surface water in the absence of any further information. This designation applied an environmentally conservative method because it assumed a "worst-case scenario" from the prospective of impacts on streamflow.

Of the 318 records, 305 had specified co-ordinates within their hilltop files. Locations for four sites were obtained by cross-referencing data used in the study of Booker et al. (2016b). This left nine records with unknown co-ordinates, which we were unable to incorporate into our spatial analysis.

We obtained additional information describing characteristics of monitoring bores (Table 2-2) across the region from Horizons. Bore characteristics data from Horizons contained 1246 observations of transmissivity at 1127 locations (some bores include replicate observations). We calculated median transmissivity for locations with replicate observations. Some observations of storativity were present but all except two had zero values. We were therefore unable to use any data describing storativity from the region.

3 Methods

3.1 Locating takes on network

Co-ordinates describing the position of the point of take were available for each record. We applied the same method as Booker et al. (2016b) previously used to locate consents onto the river network. A brief description is supplied in the remainder of this section.

This information was used to assign each record to one (for surface water records) or many (for groundwater records) segments of the REC river network using an automated procedure. Each groundwater consent was associated with all segments on the New Zealand river network whose centroid was within a 2000 m radius of the coordinates describing the groundwater take point. This method assumed that a groundwater take would deplete river flows within the specified radius (Figure 3-1).

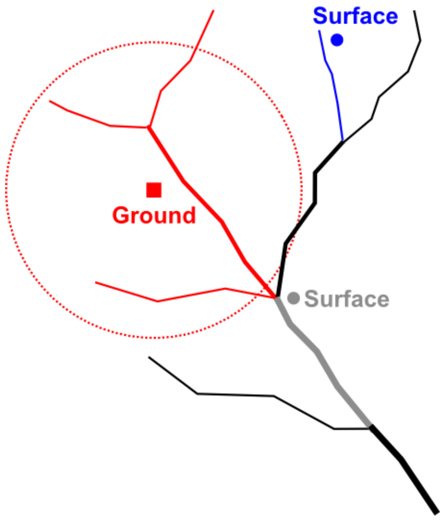

Figure 3-1: A schematic diagram showing the segment assignment for groundwater and surface water records. The colour of the segment depicts the take it has been assigned to. For groundwater consents, all segments within 2000 m were assigned to a given take (red), while surface water consents were assigned to the nearest segment (blue). If more than one segment was within 100 m of a surface water consent, the consent was assigned to the segment with the greatest seven-day mean annual low flow (grey).

Surface water records were assigned to a single segment on the New Zealand river network by identifying the nearest segment based on the distance to points describing river lines. Where more than one segment had some part of its river line within 100 m of the consent location, the segment with the largest estimated naturalised seven-day mean annual low flow (MALF) from Booker and Woods (2014) was assigned to the consent (Figure 3-1). This method was used in an attempt to avoid incorrectly associating surface water records with very small streams, and therefore overestimating the effect of abstraction on streamflows.

3.2 Proportioning takes between segments

We applied the same method as Booker et al. (2016b) previously used to proportion groundwater abstraction records between segments of the river network. A brief description is supplied in the remainder of this section.

We proportioned each groundwater record between its assigned segments as a function of distance and river low flow. The inverse distance squared was used to represent distance from recorded groundwater take to each river segment. The MALF from Booker and Woods (2014) was used to represent river low flows.

Assuming T_j is the jth groundwater record, Q_{ij} is river depletion rate at segment i resulting from the jth groundwater take, d_{ij} is distance from the jth groundwater take to the ith segment, and Q_i is the river depletion rate of the ith segment with $Q_i = \sum_j Q_{ij}$. River depletion from each groundwater take was proportional to the MALF of segments multiplying by inverse squared distance as follows:

$$w_{ij} = \frac{MALF_i/d_{ij}^2}{\sum_i \ (MALF_i/d_{ij}^2)} \qquad \text{Equation 1}$$

$$Q_{ij} = \{ \begin{matrix} w_{ij}T_j & (d_{ij} < 2km) \\ 0 & otherwise \end{matrix} \qquad \text{Equation 2}$$

3.3 Modelling storativity and transmissivity

A regression technique called Random Forests was used to apply a separate regression for bore depth, storativity, and transmissivity separately as a function of available characteristics (Table 3-1). This method uses machine-learning by combining many regression trees into an ensemble to produce more accurate regressions by drawing several bootstrap samples from the original training data and fitting a tree to each sample (Breiman, 2001; Cutler et al., 2007; Hastie et al., 2009). All characteristics were available for all locations on the New Zealand river network (REC) and were obtained in the Freshwater Environments of New Zealand (FWENZ) database. See Snelder and Biggs (2002), Snelder et al., (2005) and Leathwick et al., (2011) for further details.

Bore depth was used as a predictor of storativity, and transmissivity since these properties are known to be related to bore depth (Kuhlman et al., 2008). Inclusion of northing, easting and distance to coast provided a spatial component within the random forests models. Geological particle size was used to represent local geological conditions.

Independent predictions (i.e., independent of the model fitting procedure) are made for each Random Forests tree from the observations that were excluded from the bootstrap sample. These excluded samples are known as the out-of-bag (OOB) samples. These predictions are aggregated over all trees (the OOB predictions) and provide an estimate of the predictive performance of the model for new cases (Breiman, 2001). Each random forest was developed by growing 500 trees. As the number of trees (*k*) increases the generalisation error always converges and it was assumed that 500 was sufficiently high to ensure convergence.

Table 3-1: Variables used in random forest models to predict bore depth, storativity and transmissivity.

Variable name	Description	Units
BoreDepth	Depth of the bore	m
Easting	Grid co-ordinate	m
Northing	Grid co-ordinate	m
Elevation	Local elevation	m
ParticalSize	Local geological particle size	Ordinal scale
Dist2Coast	Distance from the coast	m
GridSlope	Slope across the local watershed	°
SegmentSlope	Slope in the streamwise direction	°

3.4 Streamflow depletion

Abstracting groundwater from a well nearby a stream may deplete surface water flow within the stream. The rate of stream depletion may depend on many factors: groundwater pumping rate, hydraulic properties of the aquifers, hydraulic properties of confining layers between the pumping aquifer and stream, streambed sediments and hydraulic gradient between the two water bodies. As hydraulic properties between the pumping aquifer and stream effect the rate of depletion due to groundwater pumping, streamflow depletion reduces with the distance between bore and stream and the screen depth.

Data and information available for estimating stream depletion varies considerably within and between regions. Data gaps in some areas introduces uncertainty into selecting the most suitable model for estimating the streamflow depletion in a regional/national scale study. Therefore, we applied two different approaches to estimate streamflow depletion. The two approaches and the assumptions made under each approach were:

1. A one-layer model - The aquifer from which groundwater is abstracted is essentially a single unconfined aquifer. Therefore, the screen of the well is hydraulically connected (homogeneously through the aquifer material) to the stream(s) that depletes due to groundwater pumping. This is the same method implemented in Booker et al. (2016b).

2. A two-layer model - A two-model approach is used based on the screen depth of the groundwater well. The approach described in the above (1) is used for the groundwater abstraction (screen depths) within 0-30 m below ground level (i.e., it was assumed that the aquifer system up to 30 m depth is unconfined as that depth is generally used as the average thickness of the unconfined aquifer (e.g., Ministry of Health, 2010). Whereas the takes below 30 m are assumed to be pumped from a semi-confined aquifer overlain by an aquitard and an upper aquifer. The streamflow depletion due to pumping from the bottom aquifer is estimated using an analytical model developed by Ward and Lough (2011).

A detailed description of the one-layer model (single aquifer approach) can be found in Booker et al. (2016b). However, a brief description of this approach is given in Section 3.4.1. The two-layer model is described in Section 3.4.2.

It is expected that these assumptions used in both models 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. (2016) estimated that the recharge component was approximately 18% of the pumping rate, based on lysimeter results in Canterbury. The recharge component of the pumping rate may vary in other regions/area as the recharge is a function of soil water holding capacity, irrigation application depth and climate (evapotranspiration).

3.4.1 One-layer aquifer model

This model conceptualises that all wells are located within unconfined aquifers, which are hydraulically connected directly to the stream that is subjected to depletion as a result of groundwater pumping, through the aquifer material. 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 3).

$$Q_s = Q_w \, . erfc(\sqrt{d^2 S/(4Tt)}) \qquad \text{Equation 3}$$

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 (m) 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 1968):

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.

Equation 3 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 4).

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

Where Q_{wk} is the pump rate of a well at time k.

3.4.2 Two-layer aquifer model

The two-layer model uses a two-fold approach to estimate the stream depletion:

1. Bores which have a depth of up to 30 m are conservatively considered as located within unconfined aquifers and stream depletion is estimated based the single aquifer approach described in Section 3.4.1.

2. Bores whose screen depths are greater than 30 m are assumed to be located in a semi-confined aquifer overlain by an aquitard and an upper aquifer.

This two-fold approach is likely to represent aquifer stratification more accurately when pumping from deeper aquifers, which generally have lower hydraulic connection to the streams compared with shallow aquifers and level of stream depletion. However, the accuracy of the estimates are largely dependent on availability of aquifer parameters. This model simulates a two-aquifer system and therefore requires more parameters than that was required by the one-layer model.

The solution developed by Ward and Lough (2011) to simulate the stream depletion in the context of a two-layer leaking aquifer system was used. Water is pumped from a well in a semi-confined bottom aquifer. Figure 3-2 shows the plan and cross-sectional view of stream depletion occurring in a two-layer aquifer.

This solution is based on transmissivity (T_1) and specific yield (S_1) of the upper aquifer, and transmissivity (T_2) and storativity (S_2) of the bottom aquifer as well as the thickness (*B'*) and hydraulic conductivity (*K'*) for the aquitard and streambed conductance. The notations used in the solution are listed in Table 3-2.

As this solution is a function of the distance of the pumped well from the stream, depth of the pumping aquifer (i.e., depth of the aquitard and upper aquifer) and hydraulic properties of the confining layers, it provides a more realistic effect of groundwater abstraction from deeper wells on streamflow. The mathematical formulation of this solution can be found at Ward and Lough (2011).

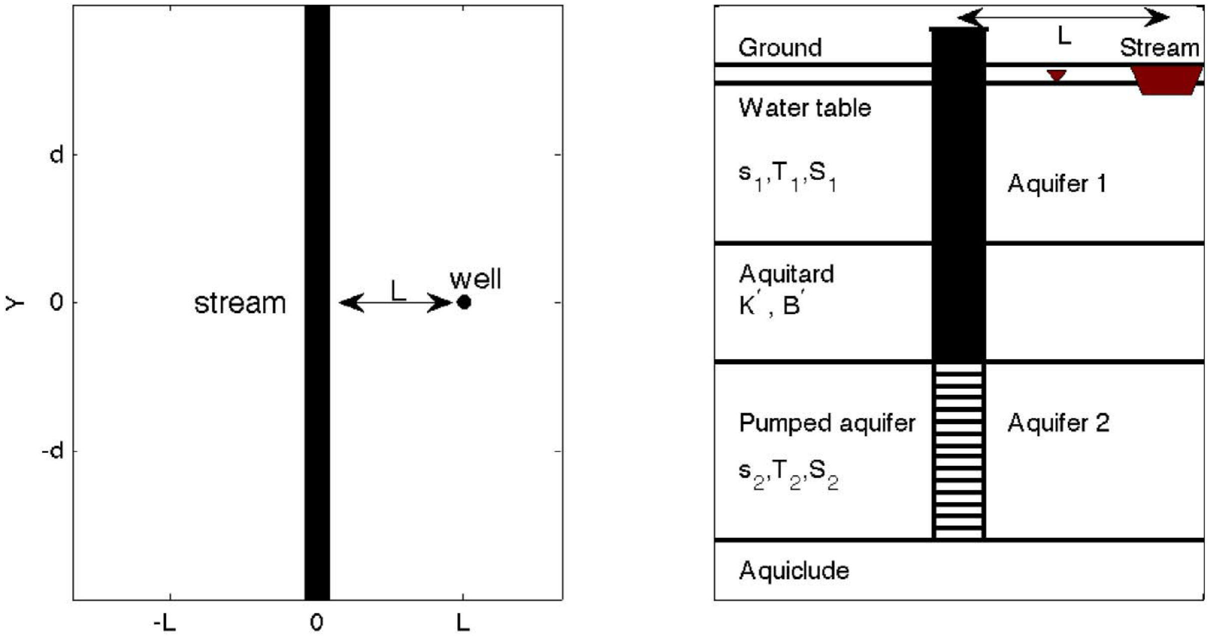

Figure 3-2: Stream depletion in a leaky two-layer aquifer system separated by an aquitard. A well pumps water from the bottom aquifer while the top aquifer remains unpumped. Source: Ward and Lough, 2011.

Table 3-2: The notations used in the two-layer aquifer model for estimating streamflow depletion (Ward and Lough, 2011). Note that the solution generally uses with nondimensional variables.

Notation	Name/ description	Unit
L	Distance of well from stream	m
Q	Well pumping rate	m^3/day
s_1	Drawdown in Aquifer 1	m
s_2	Drawdown in Aquifer 2	m
S_1	Specific yield in Aquifer 1	dimensionless
S_2	Storativity in Aquifer 2	dimensionless
T_1	Transmissivity in Aquifer 1 (Transmissivity is the rate of flow under a unit hydraulic gradient through a unit width of aquifer of thickness)	m^2/day
T_2	Transmissivity in Aquifer 2	m^2/day
K'	Aquitard hydraulic conductivity	m/day
B'	Aquitard thickness	m

3.4.3 Division of well pumping effects between multiple adjacent reaches

Distance (*d*) was calculated as the distance from each well to the centre of the nearest stream reach. In situations where more than one stream reach are located within 2 km 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 5).

$$f_i = \frac{\frac{1}{d_i}}{\sum_{j=1,n}\frac{1}{d_i}} \qquad \text{Equation 5}$$

Where f_i 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 reach *i* by combining Equation 3 and Equation 5:

$$Q_{si} = f_i \,.\, Q_w \,.\, erfc(\sqrt{d_i^{\,2} S/(4Tt)}) \qquad \text{Equation 6}$$

3.4.4 Effects of multiple wells on single stream reaches

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

$$Q_s = \sum_{j=1}^{m} Q_{wj} \,.\, erfc(\sqrt{d_j^{\,2} S_j/(4T_j t)}) \qquad \text{Equation 7}$$

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. Equation 7 shows the formulation for additive effect for the one-layer model. A similar additive approach is used to estimate the additive effect pumping under the two-layer model.

3.5 Downstream accumulation

For each surface water abstraction record, we estimated a streamflow depletion time-series for a single river segment. For each groundwater abstraction record, we estimated a streamflow depletion time-series for several segments being directly influenced by that groundwater abstraction record. We then combined these local streamflow depletion time-series to calculate their influence on the downstream river network. For each day in the period of interest, we routed all surface water streamflow depletions downstream to the sea. For each day at each influenced segment, we summed all upstream streamflow depletion values to gain the estimated total streamflow depletion resulting from all upstream surface water abstractions. We repeated this procedure for groundwater abstraction records. Finally, we summed surface water and groundwater to calculate the estimated total streamflow depletion. We assumed that, for each daily time-step, streamflow depletion calculated for each segment would result in the same level of streamflow depletion for all downstream segments. This method did not account for any in-channel hydraulic processes such as dispersion, retention or flow event attenuation.

3.6 Displaying stream depletion information

Record locations were mapped by source. Several records were associated with the same set of co-ordinates in some cases. This situation may arise when one record ceases and is later replaced by another record measuring at the same abstraction. This situation may also arise where separate records are measuring at the same location to assess different uses or different consent conditions. In these cases, we separated the location of each record by a small distance to allow separate records mapped at the same location to be viewed. This separation was made for display purposes only, and only after having already associated the location of reach record with a river reaches (or several reaches for groundwater records).

Recorded daily volume time-series were displayed to show temporal patterns in recorded takes. Maps of estimated streamflow depletion on different dates were displayed to show both spatial and temporal patterns in accumulated streamflow depletion.

3.7 Interactive app

Results were also displayed using an interactive app made available to the Ministry for the Environment (Figure 3-3). For more information about this app please contact the Ministry for the Environment (info@mfe.govt.nz).

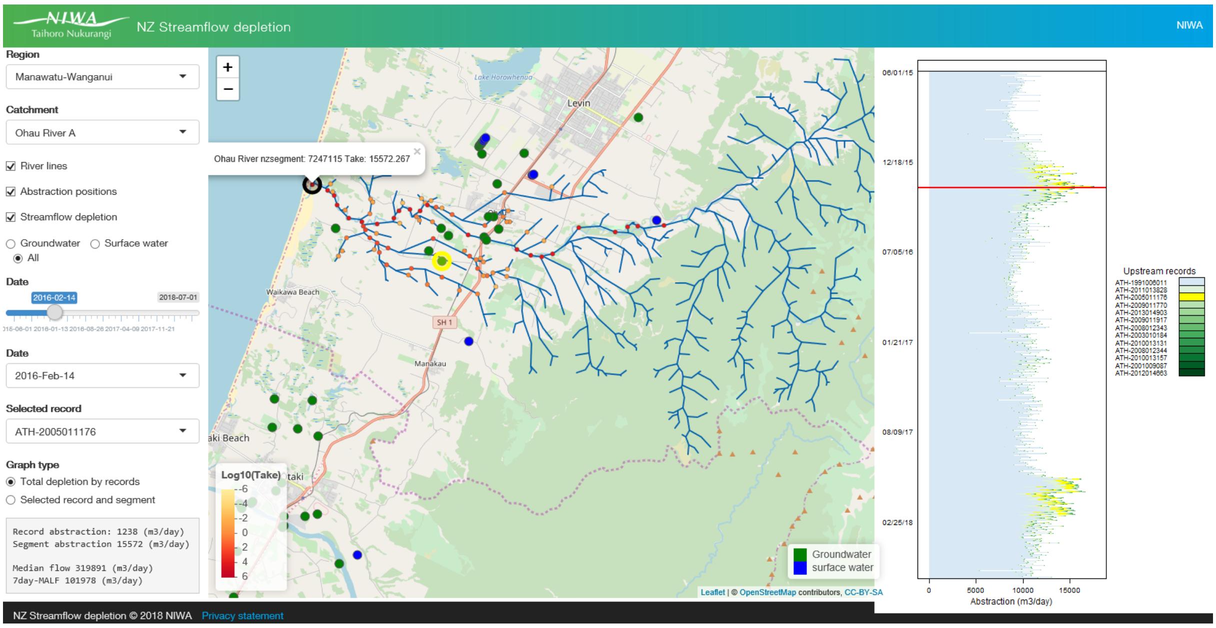

Figure 3-3: Screen capture showing the streamflow depletion interactive app.

The streamflow depletion interactive app contains several components.

- Left panel displays user choices and selected record information
  - Region drop down menu: for changing region viewed

    - Catchment drop down menu: to select a catchment influenced by recorded abstractions in the selected region (catchment names are the names of water bodies flowing to the sea)
    - River lines check box: select to view a graphical representation of the river network for the selected catchment
    - Abstraction positions check box: select to view locations of recorded abstraction coloured by source (blue is surface water, green is groundwater)
    - Source selection: select to display results from groundwater, surface water or all (groundwater and surface water together)
    - Date slider: drag pointer to change date of interest
    - Date selection: manually specify a date of interest by typing, or click to select a date
    - Selected record: manually specify an abstraction record by typing, or click to select a date
    - Graph type: select which graph type to show in the right-hand panel. "Total depletion by records" shows a time-series of total streamflow depletion coloured by each upstream abstraction record, "Selected record and segment" shows streamflow depletion for the selected segment alongside recorded abstraction for the selected record
    - A print-out of the recorded abstraction on the selected date, the total accumulated upstream streamflow depletion on the selected date for the selected segment, the estimated naturalised median flow and naturalised MALF (Booker and Woods, 2014) for the selected segment.
- Central panel displays a map
    - Large dots represent consents. Colours by use or source. Green for groundwater. Blue for surface water.
    - Small dots represent values at river segments. Coloured by streamflow depletion values.
    - Yellow circle represents the selected record
    - Black circle represents the selected river segment
    - Blue lines represent a simplified representation of the national river network
- Right panel displays time-series plots, either
    - when "Total depletion by records" is selected, a time-series of total streamflow depletion at the selected segment coloured by each upstream abstraction record. Shades of green represent streamflow depletion from groundwater takes. Shades of blue represent streamflow depletion from surface water takes. Yellow represents streamflow depletion from the selected record. Key shows Record

identifier for all upstream records. Vertical lines show estimated naturalised 7-day MALF and median flow (these will not appear if they exceed the bounds of the axis because takes are much smaller than MALF and median flow). Horizontal red line represents the selected date.

- when "Selected record and segment" is selected, a streamflow depletion time-series for the selected segment alongside recorded abstraction for the selected record. Horizontal red line represents the selected date.

4 Results

4.1 Record locations

GWRC record locations were not evenly distributed across the Greater Wellington region. Record locations in this region were most densely located, in the Hutt River catchment, the Ruamahanga River catchment, and various small catchments towards the north-west coast of the region (Figure 4-1). 402 GWRC records related to abstraction from groundwater, whilst 150 records related to abstraction from surface water.

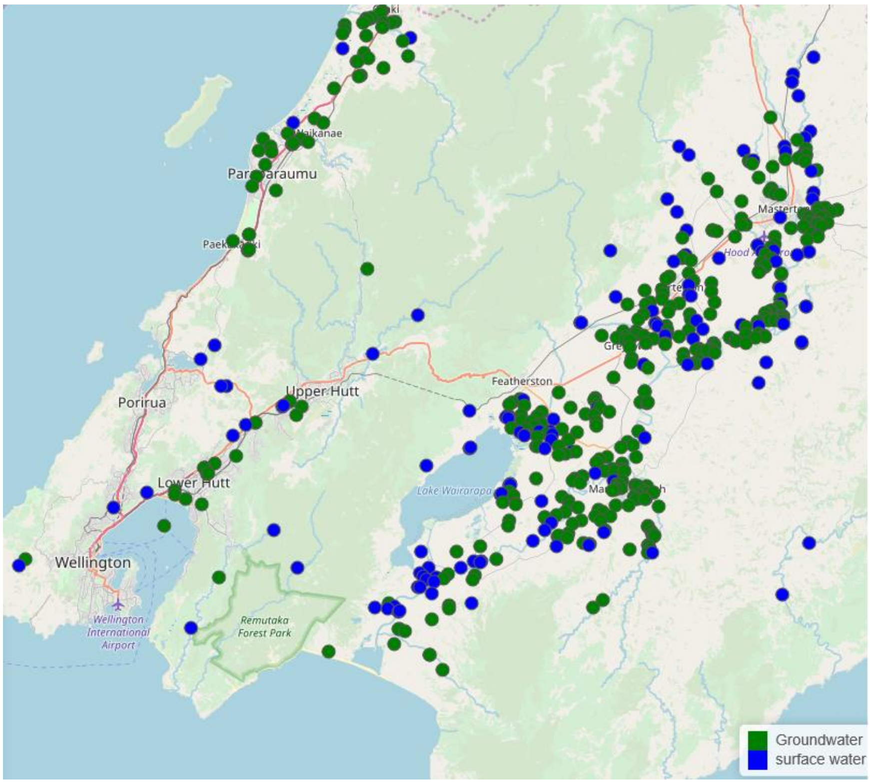

Figure 4-1: Locations of records across the Greater Wellington region.

Horizons records relating to abstraction from groundwater were concentrated towards the west of the Manawatu-Wanganui region, with records relating to abstraction from surface water spread more widely across the region (Figure 4-2). 185 Horizons records related to abstraction from groundwater, whilst 133 records related to abstraction from surface water.

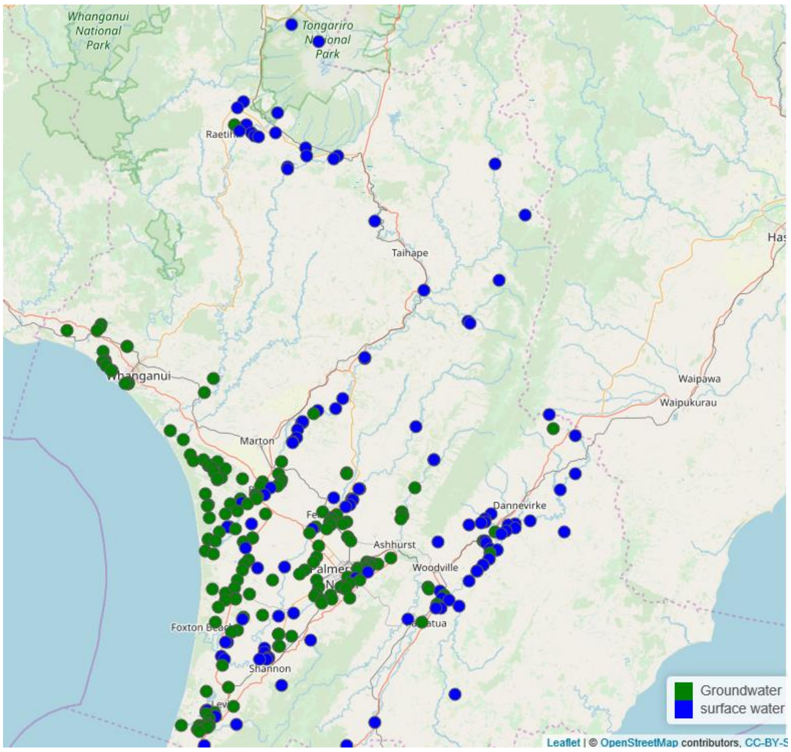

Figure 4-2: Locations of records across the Horizons region.

4.2 Data completion and quality

Many records from both GWRC and Horizons were complete across the period of interest, but some records contained missing values. The number of missing values varied between records (Figure 4-3). Missing values could occur intermittently within a record (Figure 4-4). This occurred for several GWRC records. Missing values in both regions also occurred because a record either ceased or commenced part way through the period of interest (Figure 4-4). Several Horizons groundwater abstraction records ceased, whilst others commenced during the 2016-2017 summer. It is unknown from Figure 4-4 whether each newly commenced record represented a replacement for a recently ceased record. Some missing data towards the end of the period of interest suggested that not all GWRC data had been uploaded at the time of download for this analysis (4 months after the end of the period of interest).

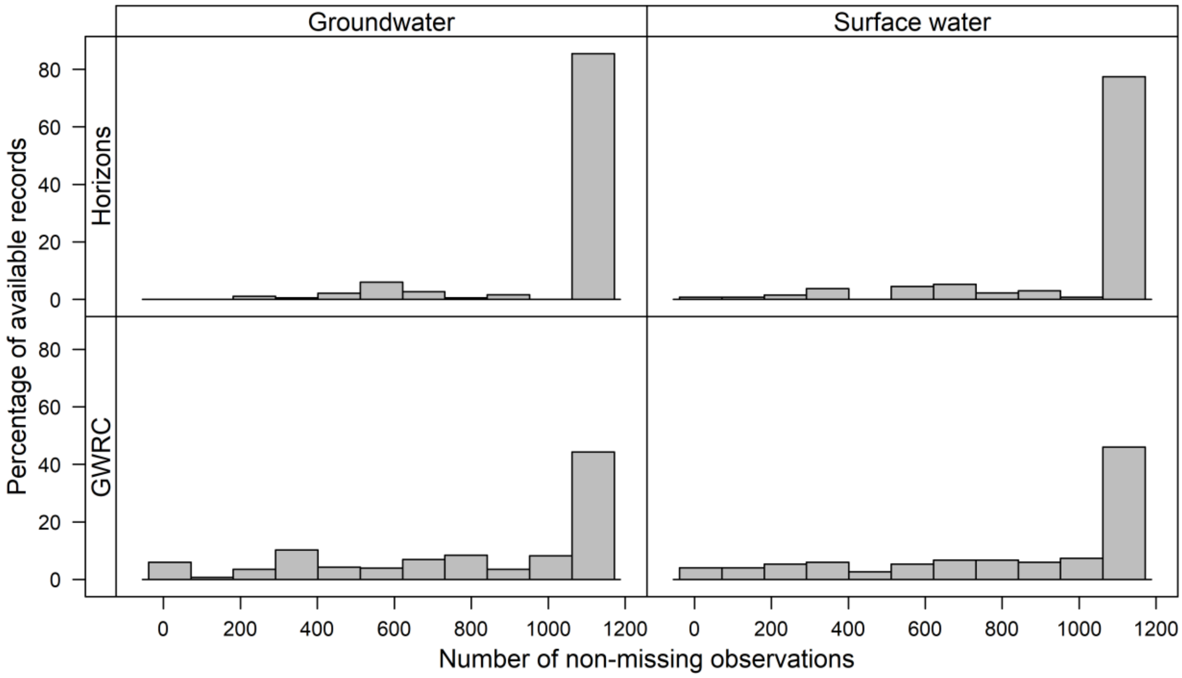

Figure 4-3: Record completion by regional council and source. Total record length was 1110 days meaning that 80% of Horizons groundwater records contained no missing data.

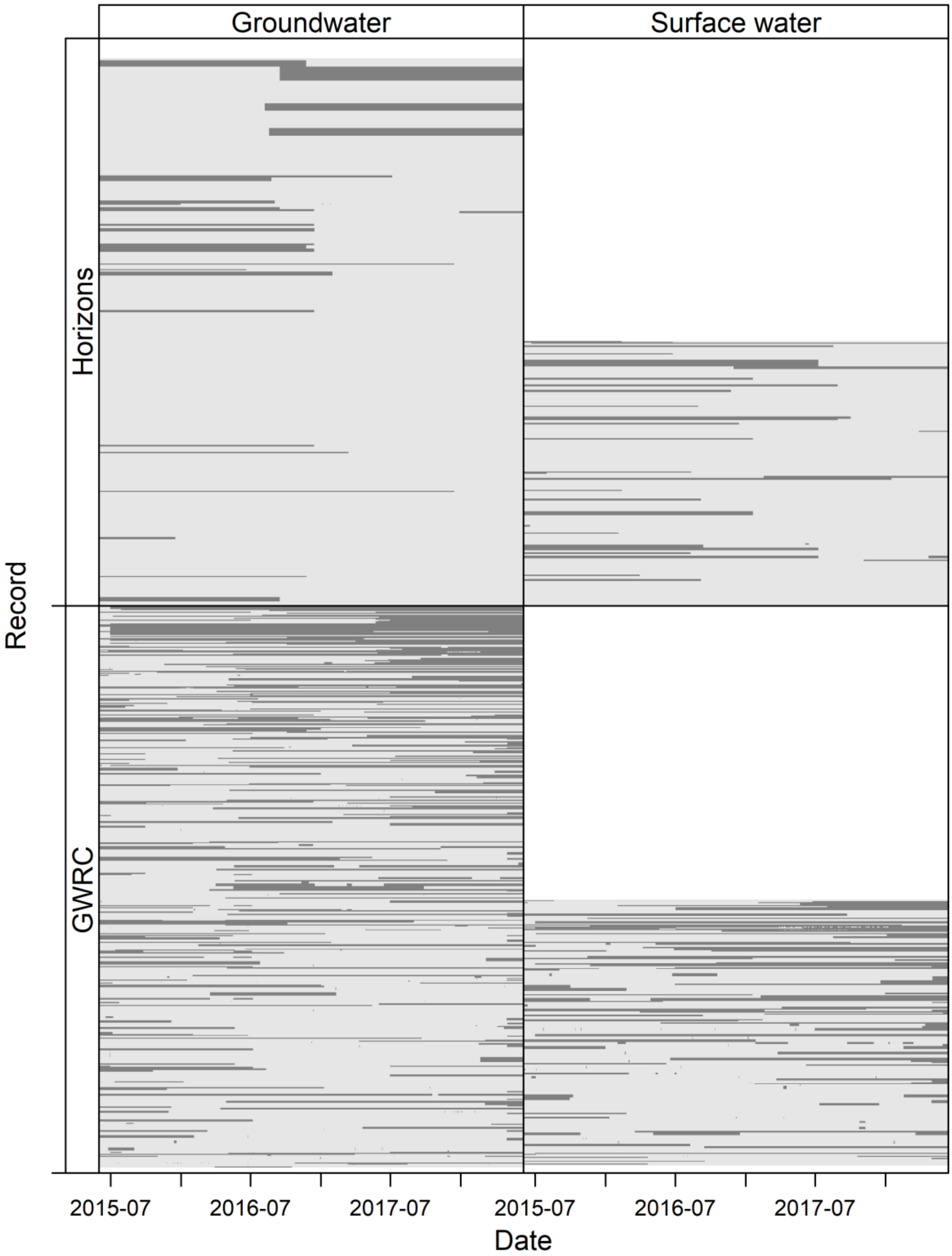

Figure 4-4: Time distribution of missing values for records by source and regional council. Ranked from bottom to top by total abstraction. Dark grey indicates missing values. Light grey indicates non-missing values.

Of the 552 GWRC records, 69 contained negative values (Figure 4-5). Many of these 69 records each contained very few negative values, whilst others contained many negative values (Figure 4-5). It is unclear whether these negative values represent discharges to rivers or to groundwater (as can be legitimately represented within our method, see Section 2.2), or whether these negative values were erroneous.

Only one record from Horizons contained any negative values. This site contained three negative values of relatively small magnitude (-0.10, -0.05, and -0.02 m^3 day^{-1}).

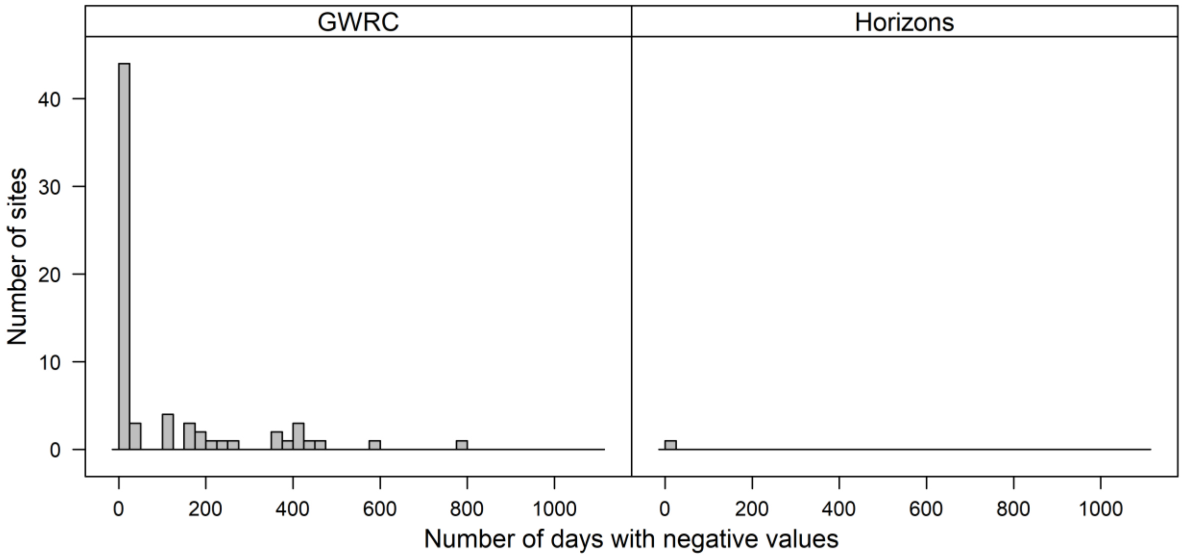

Figure 4-5: Count of negative flow days for each record by regional council. Total record length was 1110 days.

There was a contrast between the two regions in relation to completeness of bore depth, storativity, and transmissivity (Figure 4-6). Observed bore depth were obtained for nearly all GWRC groundwater abstraction records. Observed values of storativity and transmissivity were also obtained for the majority of GWRC groundwater abstraction records. Whilst some observed bore depths (Figure 4-7) and transmissivity values (Figure 4-8) were obtained for Horizons groundwater abstraction records, no observations of storativity were obtained for that region (Figure 4-9).

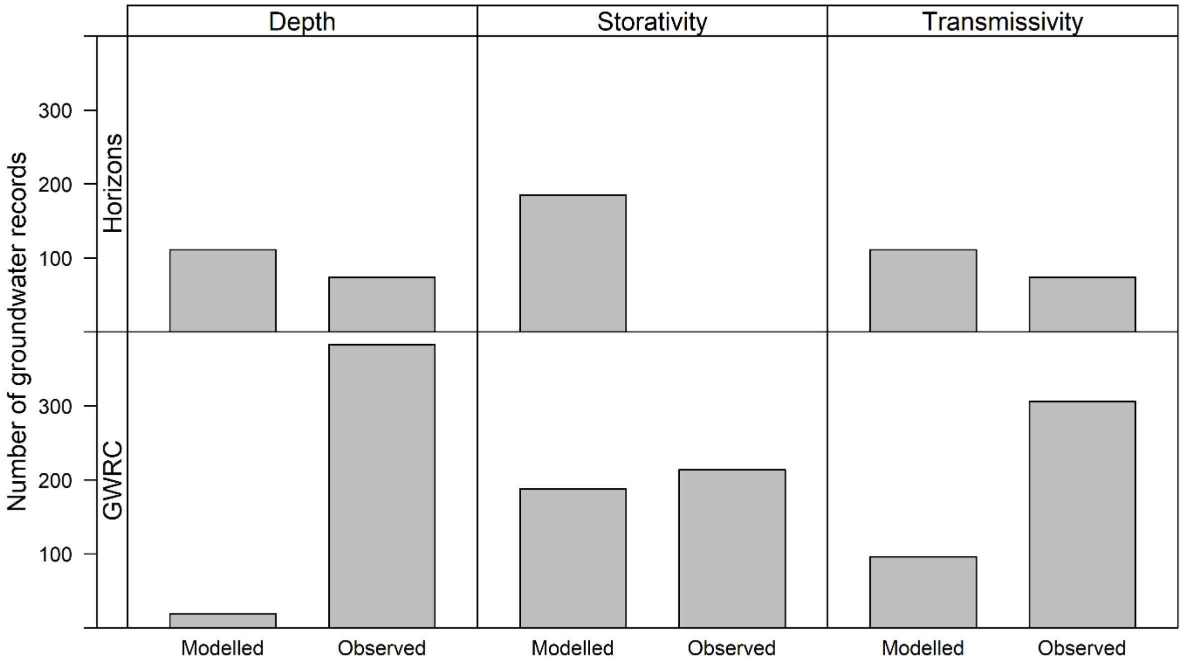

Figure 4-6: Number of groundwater abstraction records using modelled and observed bore depth, storativity and transmissivity.

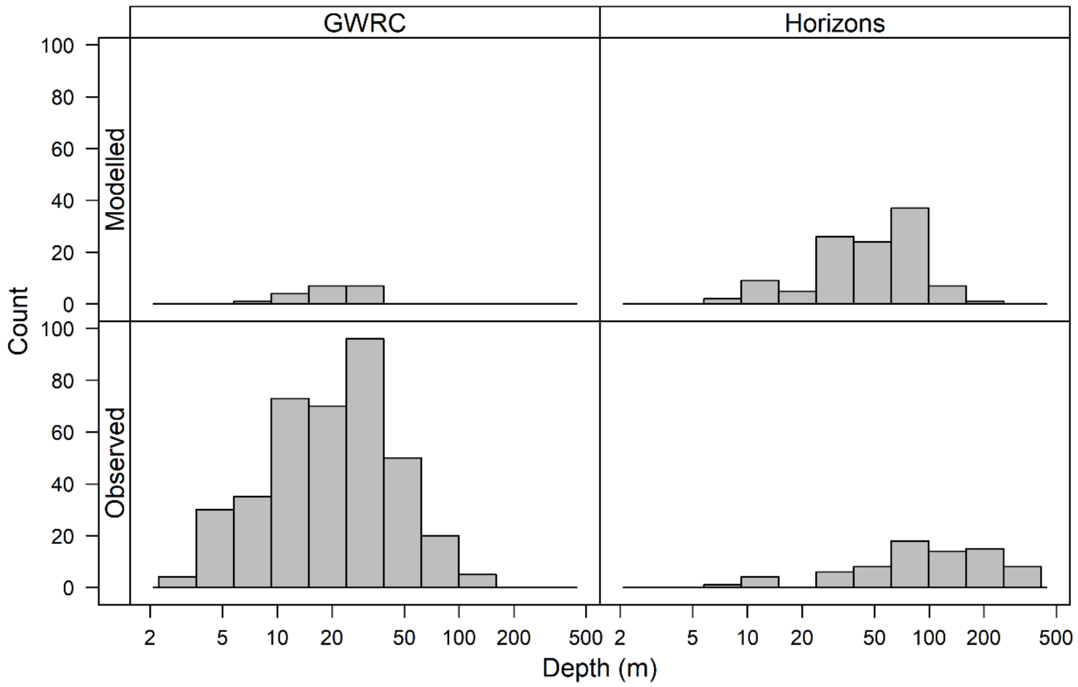

Figure 4-7: Distribution of observed and predicted well depths at groundwater abstraction points.

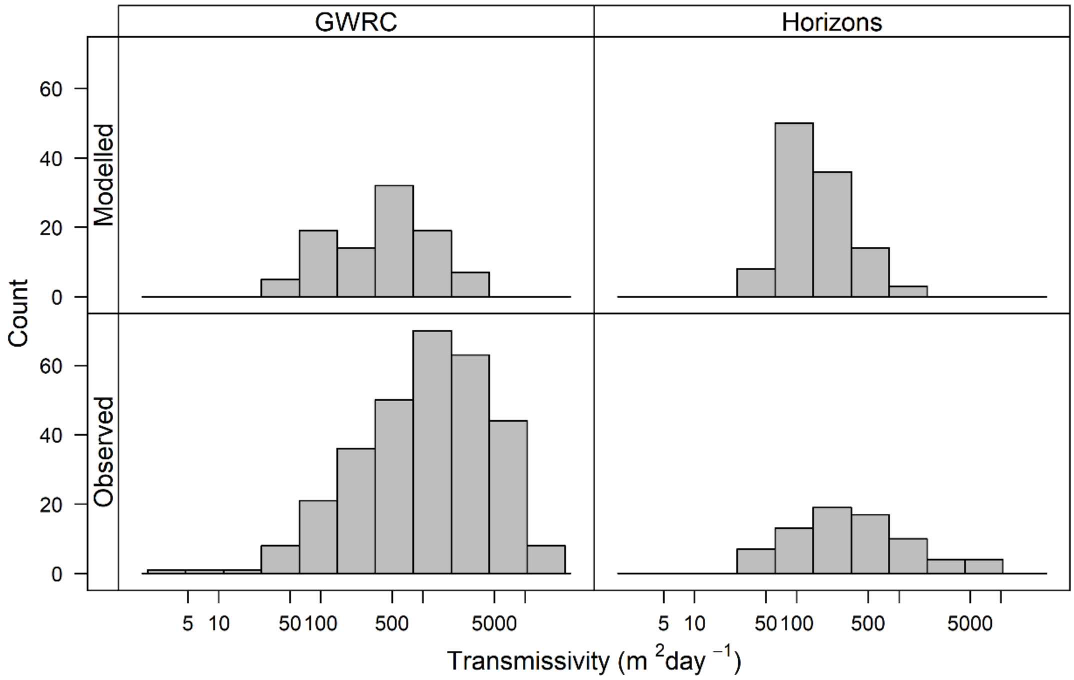

Figure 4-8: Distribution of observed and predicted transmissivity at groundwater abstraction points.

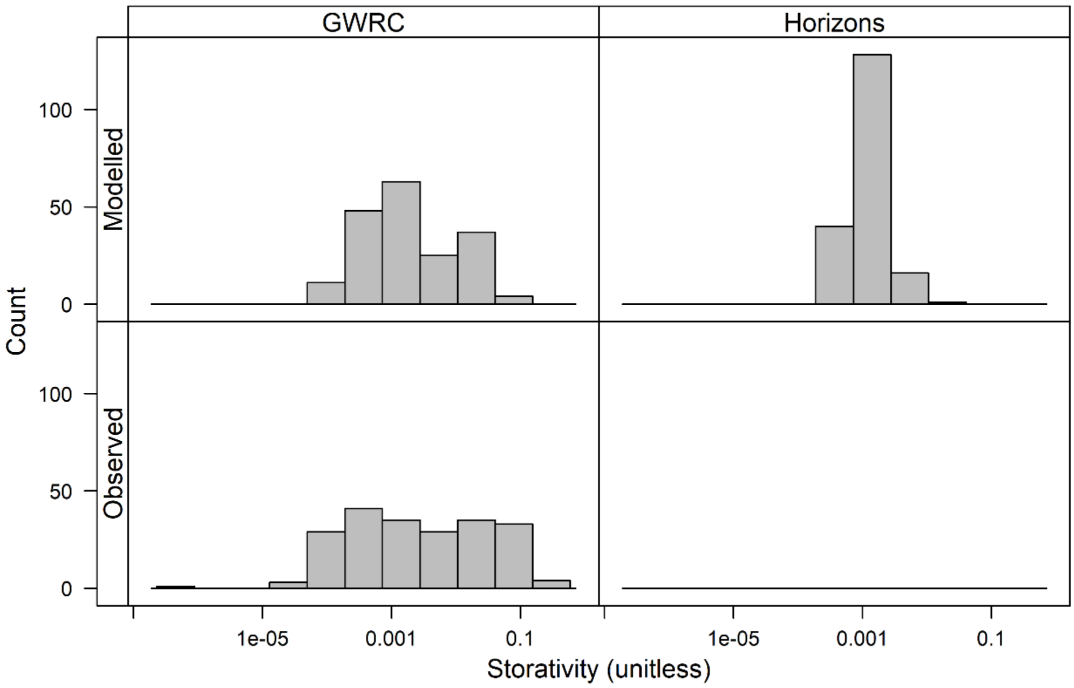

Figure 4-9: Distribution of observed and predicted storativity at groundwater abstraction points.

Visual inspection showed that, whilst many records contained feasible values of abstraction, a small proportion of records appeared to contain some suspicious patterns. Several types of suspicious pattern, and their likely cause were observed:

- very high values across an entire record possibly caused by incorrect unit specification;

- apparent changes in units during a record possibly caused by incorrect or inconsistent unit specification;
- long periods with the same value possibly caused by interpolation; and
- single high values (spikes) possibly caused by instrument failure.

Suspicious patterns were particularly evident within records with the highest total abstractions for both Horizons (Figure 4-10) and GWRC (Figure 4-11). For example, one-off observations of one billion m^3 day^{-1} amongst consistent observations of around one thousand m^3 day^{-1} (top right panel in Figure 4-10) would appear to be unfeasible[1]. 317 consecutive days with recorded take of 6,728,477.190 m^3 day^{-1} also raises suspicion (bottom centre panel of Figure 4-10). Similar phenomena also appeared in some GWRC records (e.g., bottom right and bottom left panels of Figure 4-11).

The nature of abstraction records makes automated checking for these types of phenomena challenging. This is because (unlike most river flow records) abstraction records often contain zeros, can contain legitimately high one-off values, and can be relatively constant for long periods of time. For these reasons, no data were removed and all analysis proceeded using all available data.

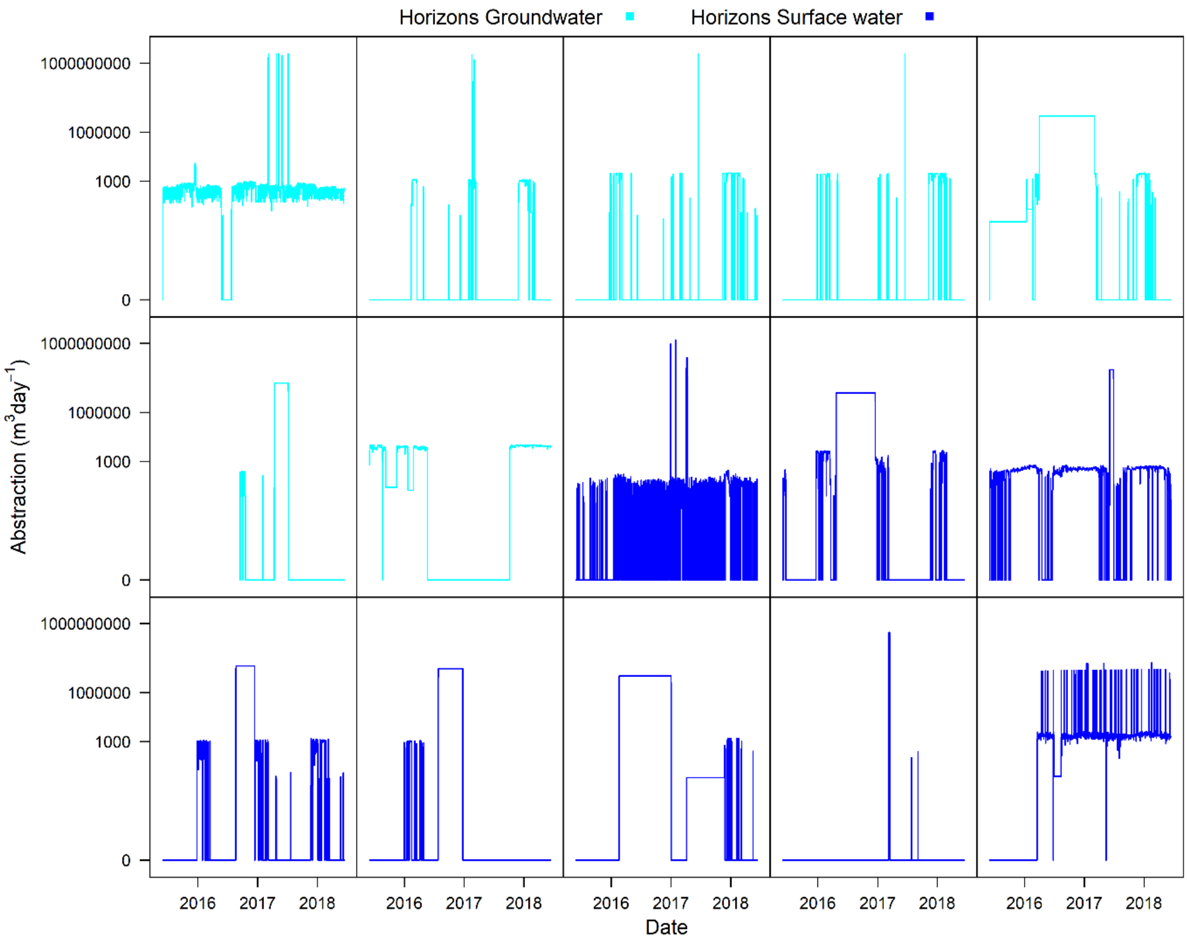

Figure 4-10: Time-series of the largest records from Horizons.

[1] This is equivalent to filling 400,000 compared to one half an Olympic size swimming pool per day.

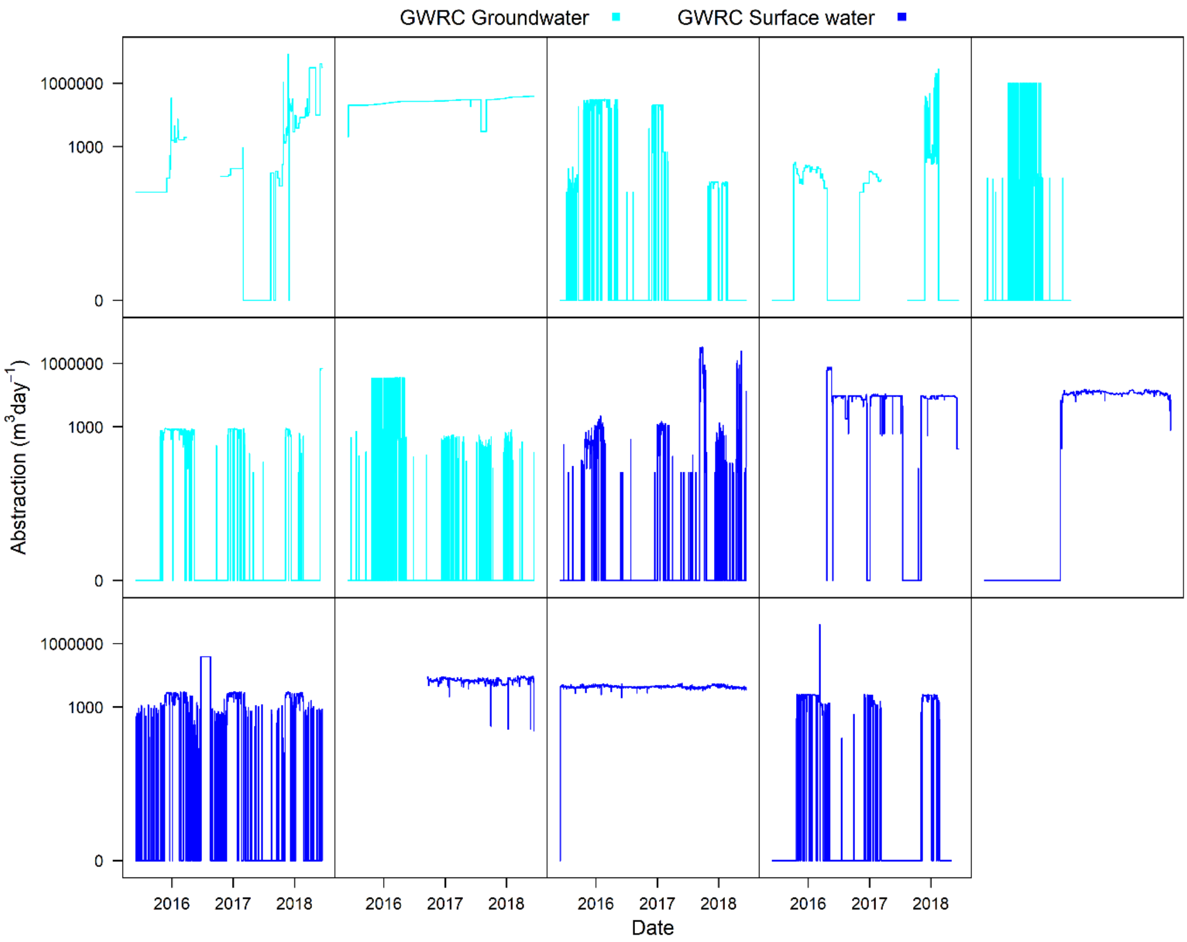

Figure 4-11: Time-series of the largest records from GWRC.

4.3 Recorded abstractions

Strong seasonal patterns were present for many records of abstraction from both groundwater and surface water (Figure 4-12). Strong seasonal patterns indicate that these records (e.g., Figure 4-13) most likely represent abstractions for irrigation purposes. There was strong consistency in seasonal patterns of abstraction between regions and between sources. In general, abstractions occurred for a longer period over the 2015/16 summer compared to the 2016/17 and 2017/18 summers. Abstraction ceased and then re-commenced consistently across many records for short periods towards the end of the 2016/17 and 2017/18 summers. These patterns may have been caused by lack of demand following rainfall events, or because of restrictions on abstraction enforced by the regional councils. Other records showed relatively constant values throughout the period of interest. Lack of seasonal patterns indicate that these records most likely represent abstractions for non-irrigation purposes such as industrial or domestic supply purposes.

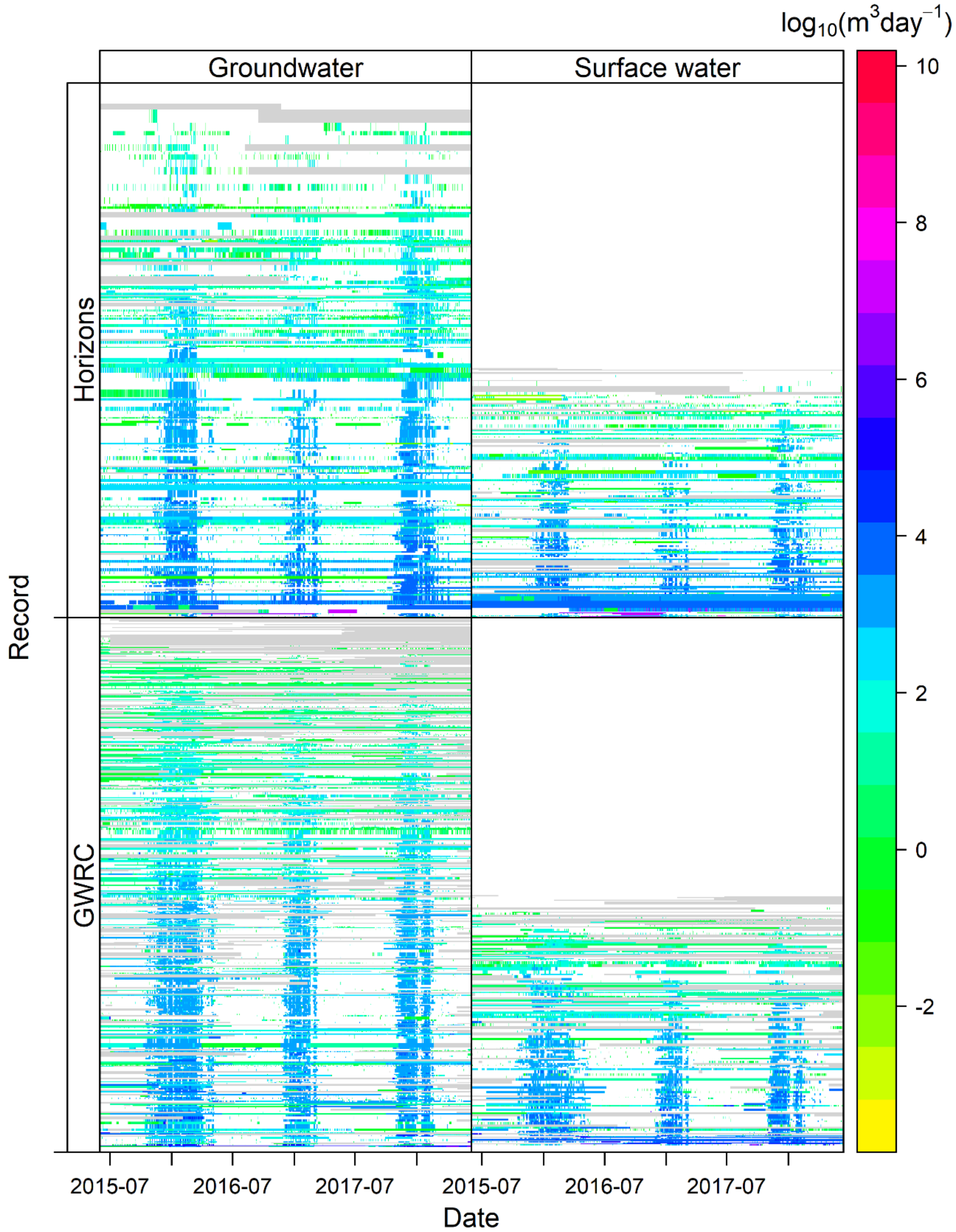

Figure 4-12: Observed records of abstraction by source and regional council. Ranked from bottom (highest) to top (lowest) total abstraction. Grey indicates missing values.

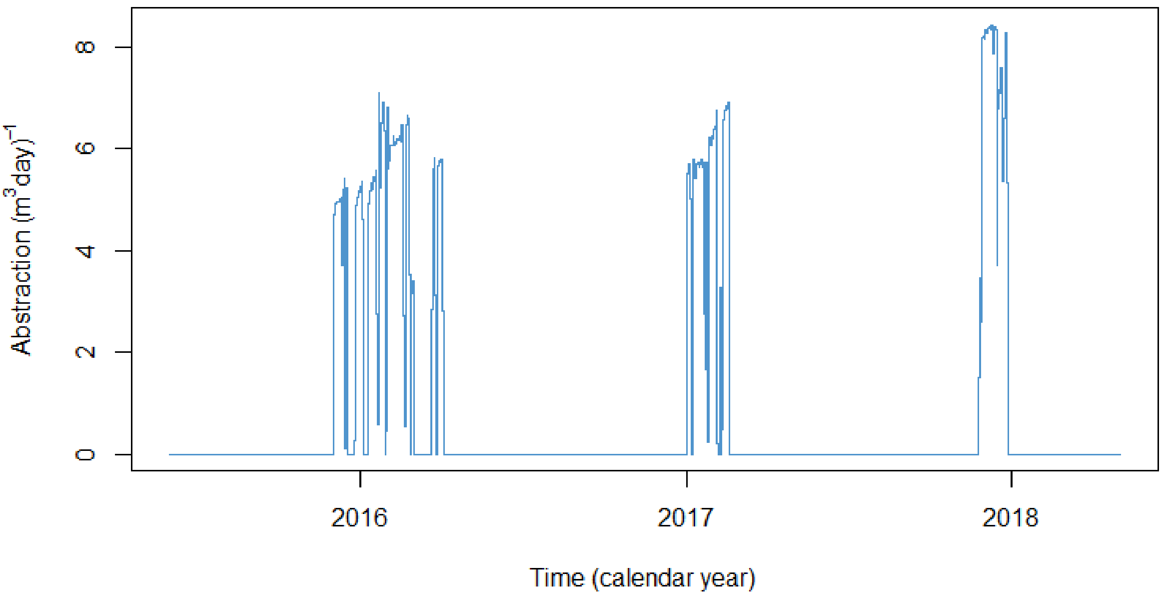

Figure 4-13: An example abstraction record from the Greater Wellington region.

4.4 Predicted bore depth storativity and transmissivity

Distributions of observed values of bore depth, storativity, and transmissivity were relatively symmetrical when plotted on a log scale (Figure 4-14). This supported fitting random forest models after having log transformed these variables. Storativity and transmissivity were strongly related to bore depth (Figure 4-15) and to several other predictors (Figure 4-16). High importance of northing, easting and distance to coast within the random forest models indicated a strong spatial component to these models. Geological particle size was the least important predictor for all three models. OOB predictive performance was 0.48, 0.56 and 0.53 for bore depth, storativity, and transmissivity respectively. This indicates that the models could explain about half the observed variation when predicting at new sites. Linear regressions of observed values as a function of OOB predictions indicated that each model was unbiased, but also contained some uncertainty (Figure 4-18). This indicates that whilst predictions at individual locations would be uncertain, on-average prediction at new locations would be correct.

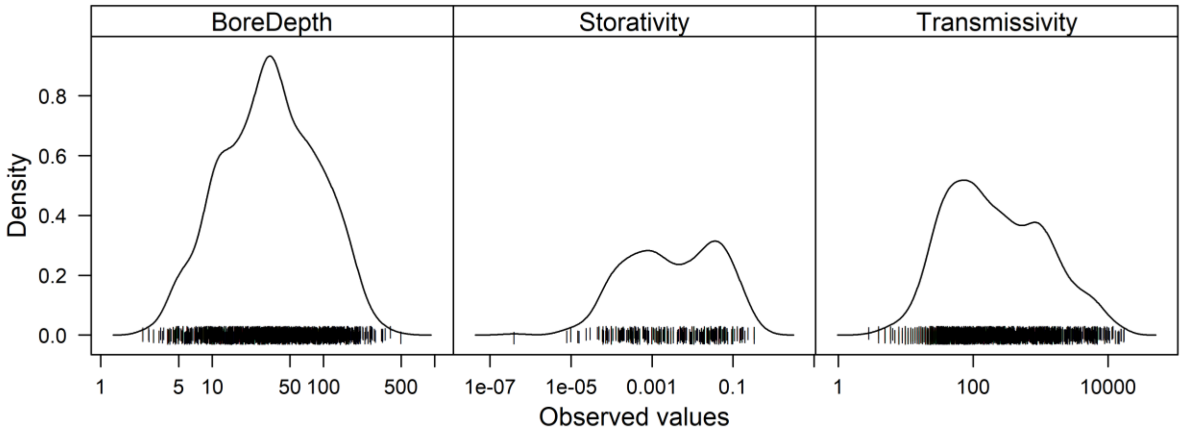

Figure 4-14: Observed values of bore depth (m), storativity (unitless), and transmissivity (m^2 day^{-1}).

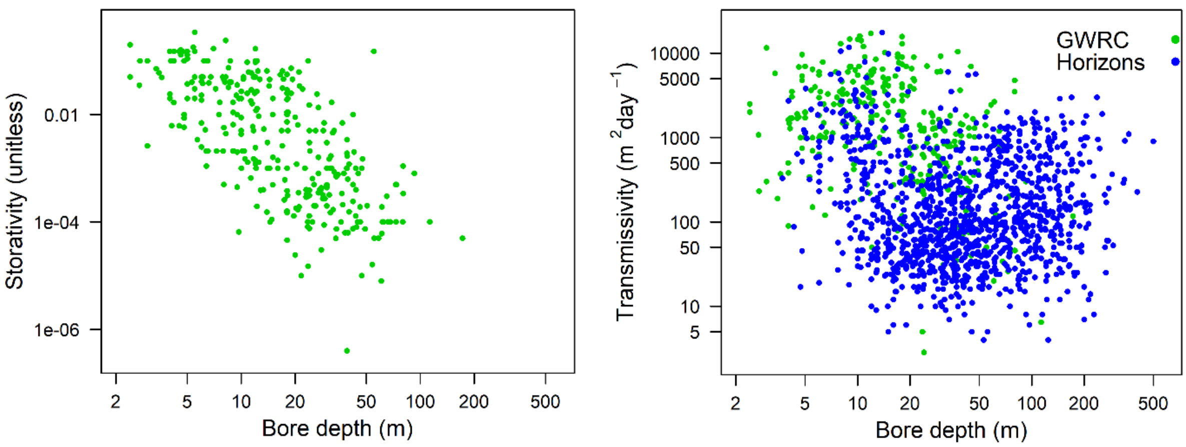

Figure 4-15: Bore depth against storativity and transmissivity by regional council.

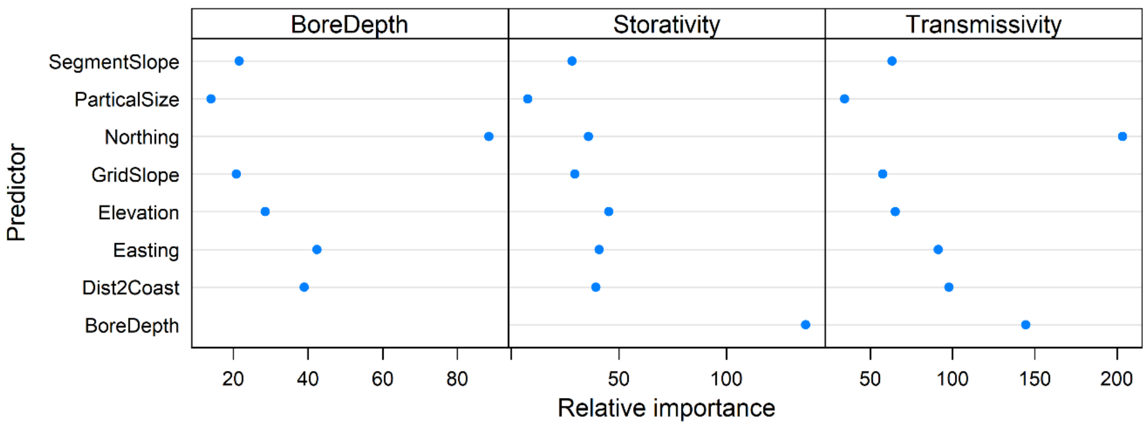

Figure 4-16: Importance of predictors for random forested models of bore depth, storativity, and transmissivity.

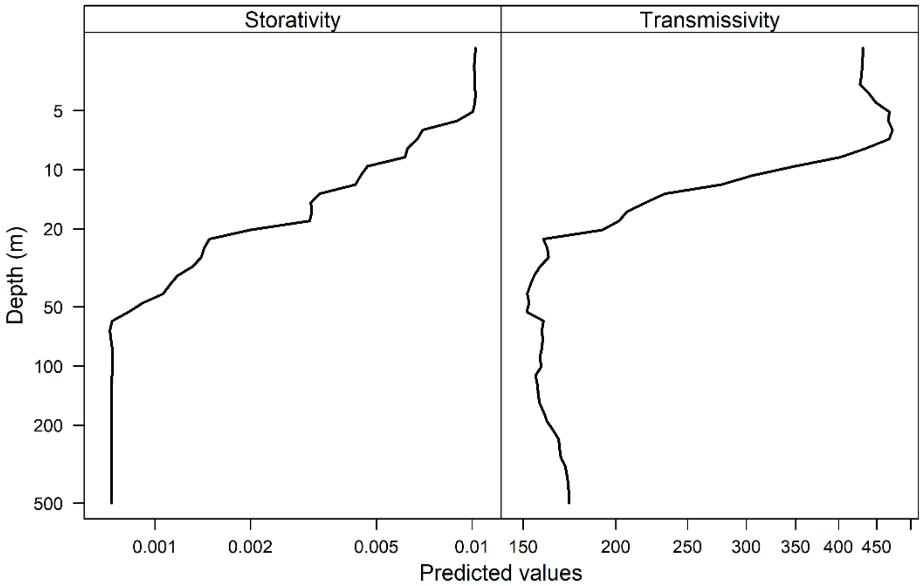

Figure 4-17: Predicted values of storativity (unitless) and transmissivity (m^2 day^{-1}) whilst all other variables are held at their mean.

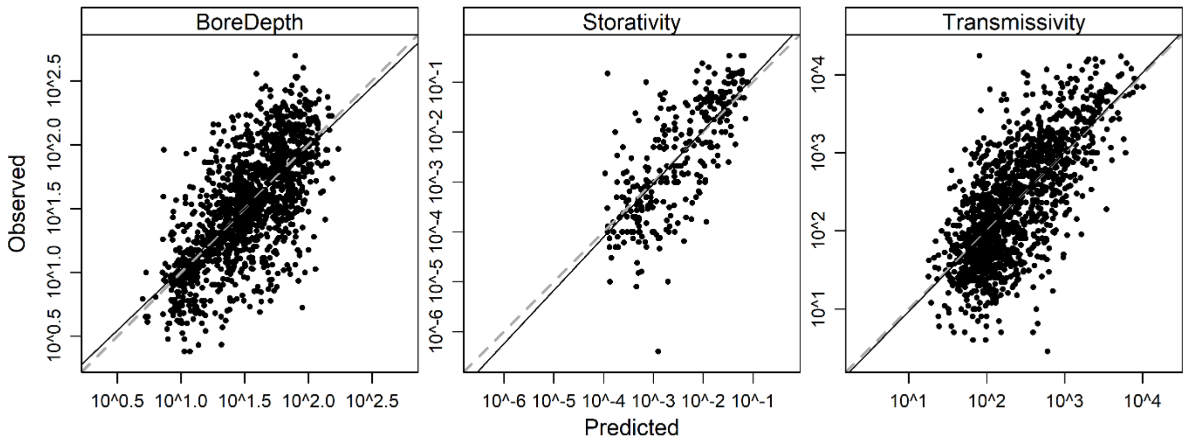

Figure 4-18: Observed against out-of-bag predicted values of bore depth (m), storativity (unitless), and transmissivity (m^2 day^{-1}). Solid line represents linear regression, dashed line represents 1:1.

4.5 Estimated streamflow depletion using the one-layer model

Estimated streamflow depletion resulting from both surface water and groundwater abstraction calculated using the one-layer model was mapped across the studied regions (Figure 4-19). Inspection of these maps indicated that estimated streamflow depletion varied spatially and between dates. Several findings could be drawn from inspecting Figure 4-19.

3. Mapping estimated streamflow depletion could aid identification of possibly erroneous recorded values. For example, suspiciously high groundwater abstractions causing very high estimates of streamflow depletion in the Manawatu River on 14/02/2017 and the Rangitikei River 14/02/2018.

4. For any particular day, streamflow depletion was estimated to be constant along long lengths of river in some catchments. This occurred in catchments containing abstraction points located towards the headwaters but no abstraction points in their middle reaches (e.g., Wanganui River located towards the north of the Manawatu-Wanganui region).

5. Catchments containing many evenly distributed abstraction points were estimated to have steady increases in streamflow depletion with distance downstream (e.g., the Ruamahanga River in south Wairarapa in the Wellington region).

6. Between-year differences in abstraction were present. For example, some catchments experienced abstraction on the same day of the year across years, but other catchments did not experience abstraction on the same day of the year across years (e.g., The Wainuioru River on the east coast of the Wellington region).

7. River segments near groundwater abstractions often routed streamflow depletion to the same downstream location, but in some cases a single groundwater abstraction was estimated to deplete streamflow in more than one catchment.

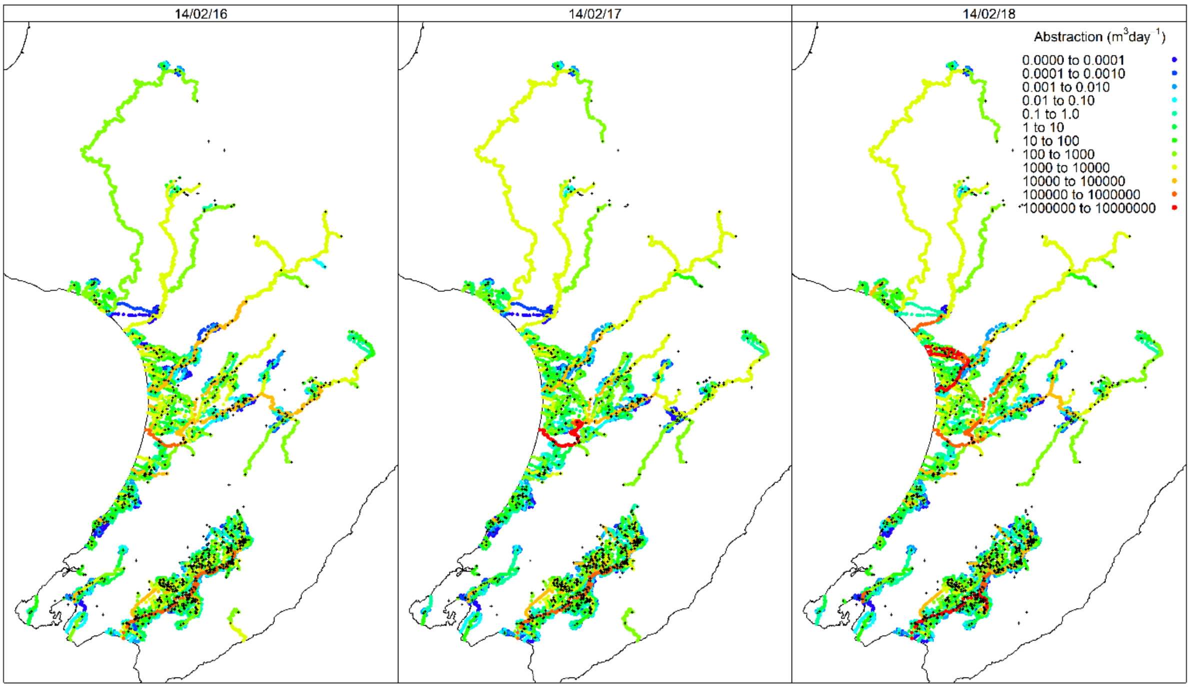

Figure 4-19: Maps of estimated streamflow depletion on the 14th of February 2016, 2017 and 2018 calculated using the one-layer model.

4.6 Estimated streamflow depletion using the two-layer model

In addition to our one-layer approach, we also applied a two-layer approach to calculate streamflow depletion resulting from groundwater abstraction. When applying the two-layer streamflow depletion model (Ward and Lough, 2011), required parameters include transmissivity (*T1*) and specific yield (*S1*) of the upper aquifer, and transmissivity (*T2*) and storativity (*S2*) of the lower aquifer as well as the thickness (*B′*) and hydraulic conductivity (*K′*) for the aquitard. Due to data availability, we only applied this two-layer model to boreholes with depth greater than 30 m, *S1* and *T1* were estimated at depth 30 m, *S2* and *T2* were estimated at the borehole depth, *B'* was set to 30 m, *K'* was given by *T1/B'*, and stream depletion parameter (lambda) was set to 0.05. Figure 4-20 shows a comparison of *S1* and *S2*, and *T1* and *T2* used in the two-layer stream depletion model. Generally, *S2* is less than *S1*, and *T2* is larger than *T1*. However, there are some exceptions, i.e., points above the 1:1 line in left plot and below the 1:1 line in the right plot of Figure 4-20. These patterns arose partly because some *S2* and *T2* were estimated due to their missingness. All *S1* and *T1* values applied within the two-layer model were estimated based on predictions from the random forest models described in Section3.3.

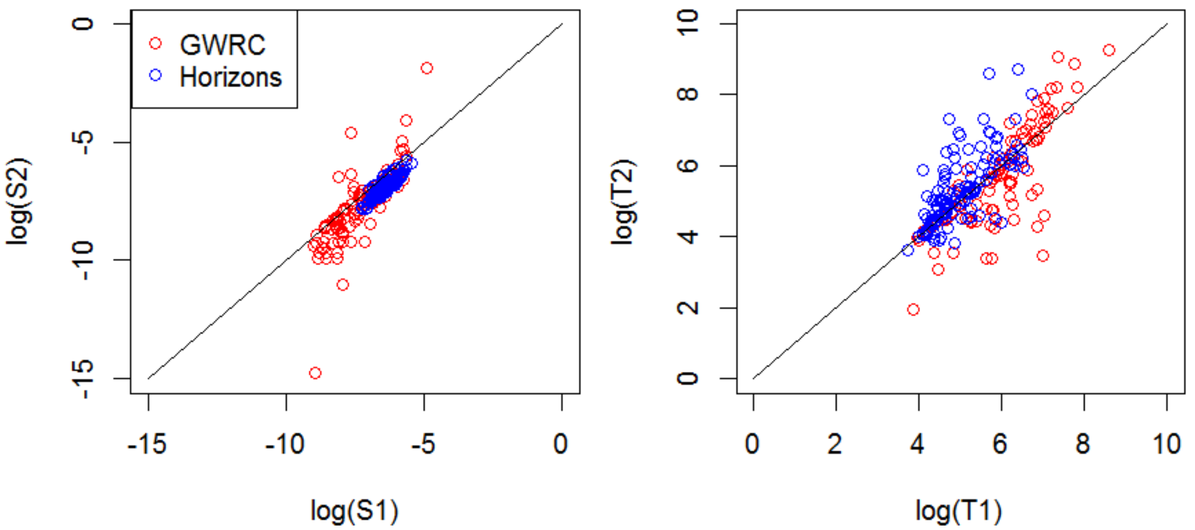

Figure 4-20: Comparison of S1 and S2, T1 and T2 used for two-layer stream depletion model.

Figure 4-21 gives the estimated stream depletion for two regions calculated using the two-layer streamflow depletion model. Visual inspection shows that results are very similar to those gained by the one-layer model shown in Figure 4-19. This similarity results from strong relationships between *S1* and *S2*, and between *T1* against *T2*. Regressions of *S1* against *S2* in log-log space showed strong relationships (r^2 = 0.68, p = <0.001, f = 547.1 on 1 and 254 d.f.). Regressions of *T1* against *T2* in log-log space also showed strong relationships (r^2 = 0.54, p = <0.001, f = 301.1 on 1 and 254 d.f.).

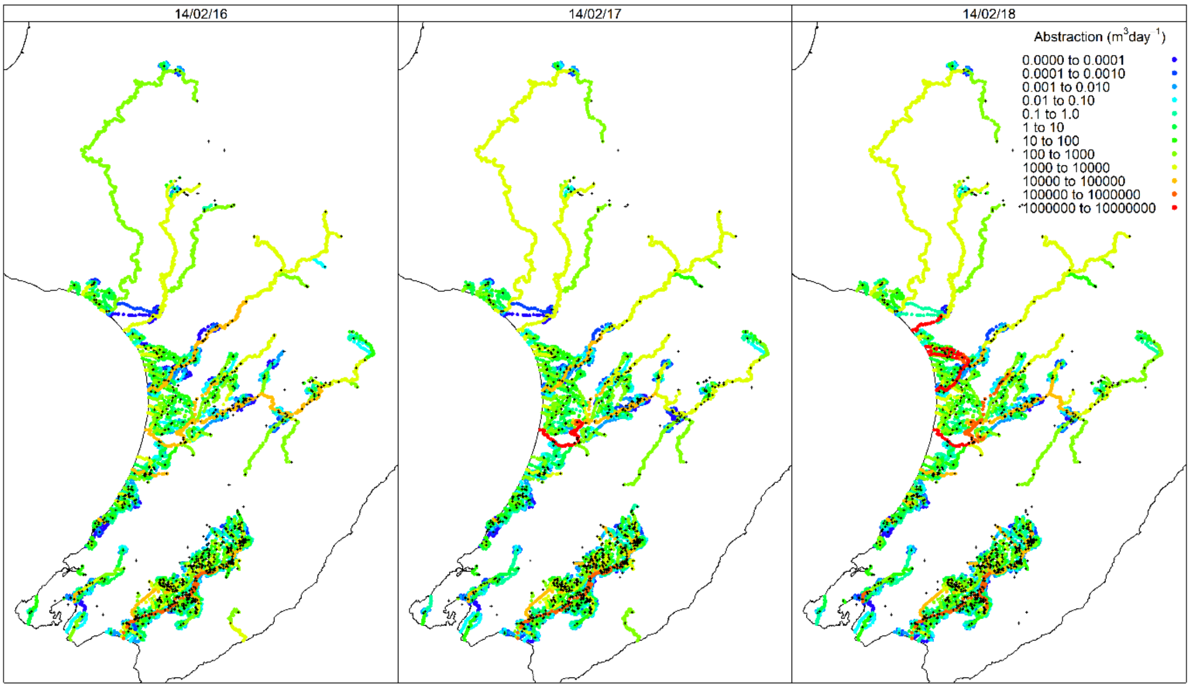

Figure 4-21: Maps of estimated stream depletion on the 14th of February 2016, 2017 and 2018 based on the two-layer model.

5 Discussion

5.1 Regional variations in data conventions

We successfully applied the same basic functions to download time-series data from GWRC and Horizons Hilltop servers. We found many similarities in database structure between the two regional councils. We were able to obtain time-series in WML2 format for both councils. However, despite these similarities, the same procedure could not be applied for these two councils because they did not use exactly the same database conventions. For example, Horizons recorded abstraction records were nested within Hilltop collections, whereas GWRCs recorded abstraction records were not nested within collections. These differences occurred despite the two councils using the same software in respect of database provision. This indicates that considerable effort would be required to obtain the same type of data from all regions across New Zealand.

5.2 In filling of missing periods of abstraction

We found that several records contained periods of missing data (Figure 4-4). Some missingness was likely to have occurred as records commenced or expired during the period of interest. Other periods of missingness occurred intermittently throughout the period of interest. We did not attempt to fill in any missing periods. Missing data could potentially be in-filled provided that strong correlations between air temperature or potential evaporation and recorded abstractions, or between pairs of nearby recorded abstractions could be established.

5.3 Comparison of one-layer and two-layer stream depletion models

We applied two methodologies to model streamflow depletion resulting from groundwater abstraction; a one-layer approach and a two-layer approach. Our two-layer approach attempted to improve upon our one-layer approach by incorporating influences of an aquitard, and greater delays in streamflow depletion from deeper groundwater abstractions. However, we found little differences in results when these two methods were applied.

5.4 Negative flow data

Our methodology was designed to incorporate potential flow augmentation caused by flow diversions when estimating streamflow depletion. The methodology relied on use of negative streamflow depletion values to represent streamflow augmentation resulting from diversions. We did not utilise this methodology; there were no negative numbers applied within our streamflow depletion model. This was because we were not able to ascertain associations between records and diversions to represent flow augmentations. Consequently, some records that were in reality augmentations may have been entered into our model as abstractions, and some records that were in reality diversions may have been entered into our model as abstractions without an accompanying augmentation record.

5.5 Recommendations

Our method could be applied to any region, but several types of data are required as described in Section 2.2. We were able to gain these data by manually requesting data from GWRC and Horizons staff, from Horizons environmental monitoring data service, from Hilltop servers hosted by GWRC and Horizons, and by cross-referencing with the previous study of Booker et al. (2016b).

We found there were some additional information that may have proved beneficial.

- An indication of when a newly commenced record is intended to replace a recently ceased record.
- An indication of whether each record contains observations of:
  - a) abstraction from groundwater or surface water;
  - b) discharge to groundwater or surface water; or
  - c) diversion between locations.

In the situation where a record represents a diversion between locations (e.g., two rivers), our method would require information describing the direction of diversion and the two locations.

6 Conclusion

We demonstrated that calculation of streamflow depletion time-series resulting from recorded abstractions from surface water and groundwater is possible.

In this project we demonstrated that:

- continuous (i.e., daily time-series) records of water abstraction are available from at least two regional councils;
- records of water abstraction can be obtained from regional councils using automated methods to access data via web-service-feeds;
- the format of the currently available data was appropriate for the task of estimating streamflow depletion;
- some meta-data relating to records of water abstraction are necessary to estimate spatially distributed time-series of streamflow depletion, specifically locations of takes, source, record type (abstraction vs discharge) and information relating to groundwater bore characteristics are ideally required;
- replicable and transparent methods of estimating daily time-series of streamflow depletion could be applied across two regions; and
- an interactive app displaying calculated streamflow depletion across the regions, and through time, aided interpretation of the results.

Streamflow depletion estimates can be used for both improved environmental reporting and streamflow management. To date, national environmental reporting in New Zealand has included estimates of maximal potential pressure on river flows resulting from water consents (e.g., Booker et al., 2016b), but not actual pressure on river flows resulting from recorded abstractions. Streamflow depletion calculations would allow estimates of actual reductions in river flows to be incorporated into environmental reporting. These streamflow depletion calculations would reflect changes in water use resulting from changes in a combination of: a) water management planning or policy; b) adherence to water use restrictions; c) efficiency of water use; and d) weather or climatic patterns. Streamflow depletion calculations are also required for calculation of naturalised river flows (i.e., flows that would have occurred in the absence of abstraction). Estimates of naturalised river flows would be beneficial for streamflow management planning processes because it is insightful to compared water resource use limits (minimum flows and total allocations as required by the NPS-FM) with naturalised rather than altered flows when assessing potential effects on in-stream values. Calculating streamflow depletion can also be useful in identifying data quality issues (large spikes in recorded abstractions, or errors in recorded units).

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