NIWA
Taihoro Nukurangi

Assessment of freshwater quantity allocation and use:

analysis of current state, stocktake of data availability, and recommendations as of 2024

Prepared for Ministry for the Environment

July 2024

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NIWA CLIENT REPORT No: 2024155CH
Report date: July 2024
NIWA Project: MFE23502

Revision	Description	Date
Version 1.0	Final version sent to client	14 June 2024
Version 1.1	Final version sent to client after minor revision	9 July 2024

Quality Assurance Statement		
	Reviewed by:	Chris Daughney
	Formatting checked by:	Alex Quigley
	Approved for release by:	Phil Jellyman

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Executive summary

This report concerns water quantity accounting.

The purpose of this report is to present the results of analyses on freshwater resource quantity allocation and use to the Ministry for the Environment (MfE). Our aim was to inform environmental reporting and policy development at the national level, whilst also assisting freshwater management, planning, and consenting at the local level. Our scope covered the process of collation, analyses, and presentation of water quantity data, which we refer to as water accounting. We accessed and analysed available water quantity data, including plan limits, consent conditions, measured water abstractions, river flows, and groundwater levels from four example regions. We did not attempt to obtain all water quantity data for all regions because a nationwide analysis was outside of our scope.

Detailed data from four regions were analysed and staff from all regions were surveyed.

We obtained and analysed detailed data from Hawke's Bay Regional Council (HBRC), Marlborough District Council (MDC), Environment Canterbury (ECan), and Environment Southland (ES). These four example councils were selected by us in consultation with MfE to represent geographical areas where pressure on water resources was likely to be high due to high demand for water supply. The regions represent different settings in terms of climate, water uses, availability of water for supply, and administrative procedures. We also collated some nationwide data, and surveyed staff from all regions about the availability of their water quantity data. We set out several needs, challenges, technical advancements, and recommendations for water accounting based on our example analyses and survey results.

There are competing needs for limited supplies of fresh water.

We explain that people and livestock require water from the natural environment at particular locations and times to preserve their physical health, and activities such as irrigation require a reliable supply of water for economic viability. Water abstraction poses risks to the functioning of freshwater ecosystems because appropriate flow regimes in rivers and aquifers are essential for maintaining ecological integrity. Water supply is not adequate to meet environmental, human health, and economic needs in all locations at all times because demand and availability from rivers and aquifers both vary across the landscape due to population density, climate, topography, geology, and vegetation. Water supply also varies through time due to climate variability and temporal lags associated with water movement.

Competing needs for fresh water must be managed.

We set out the rationale for integrated water resource management, which seeks to equitably optimise economic and social well-being without compromising the sustainability of coupled water-land systems. Freshwater flow management has been recognised as being important internationally and in Aotearoa-New Zealand (NZ) through various policies, regulations, and other legal instruments. For example, the National Policy Statement for Freshwater Management 2020, amended 2023, (NPS-FM) requires environmental flows/levels and water abstraction limits to support its fundamental concept of Te Mana o te Wai, which relates to restoring and protecting the integrity of water. The overall objective of the NPS-FM is to ensure that natural resources are managed according to a hierarchy of obligations consisting of three ordered priorities: first the health and well-being of water bodies and freshwater ecosystems; second the health needs of people; and third the ability of people and communities to provide for their social, economic, and cultural well-being. We suggest that there is currently no standardised or universally accepted technical method for comparing the prioritisation of these obligations.

Water quantity data and accounting are essential.

We explain that the NPS-FM, and sustainable water governance in general, require water quantity data to quantitatively assess water allocation, availability, and consumptive use by competing freshwater needs. NZ regulations require users who abstract water above a certain rate to submit records of measured consumptive water abstraction. The need to assess freshwater allocation and use with respect to competing needs is consistent with international requirements for sustainable water governance, including achieving water security and addressing management constraints to achieve economic and environmental prosperity.

National and regional purposes for water accounting differ.

We set out potential differences in purpose between national and regional water accounting. From a national policy perspective, water quantity data and water accounting must be fit for: a) informing policy development; b) demonstrating current policies (e.g., NPS-FM) are effective and being followed; and c) national environmental reporting. From a regional perspective, water quantity data and water accounting must be fit for: a) informing evidence-based natural resource management; b) giving effect to law (e.g., Resource Management Act) in place at the time of plan development; c) compliance checking for issued consents.

There is a gap between national and regional water accounting.

We investigated the nature and completeness of existing water quantity data. We then devised, applied, and critically assessed technical methods intended to inform national-level purposes for water data and accounting. We found several challenges that inhibit the systematic nationwide analysis of water quantity data required for national environmental reporting and policy development. One challenge was inconsistencies in composition and formatting of water resource use limits in regional plans and conditions for water abstraction in consents. Inconsistencies were present through time, between regions, and between catchments within regions. Formatting inconsistencies in part occur because plans and consents can be written in free text format. Inconsistencies also reflect differences in legislation, data availability, water demand, local environmental values, institutional arrangements, and scientific methods in place when plans were development or consents were issued. Another challenge was difficulty in obtaining metered abstraction data from councils, and data quality issues associated with metered abstractions, including missing data.

Advancements in collation, analyses, and presentation of water quantity data were made.

Previous reports have outlined future directions towards aspirational water accounting systems (Bright et al. 2022) and a proposed framework for managing river flows (Booker et al. 2022). Building upon these reports, we provided conceptual advice and applied technical methods related to water quantity data and water accounting in response to seven tasks requested by MfE (Figure ES-1).

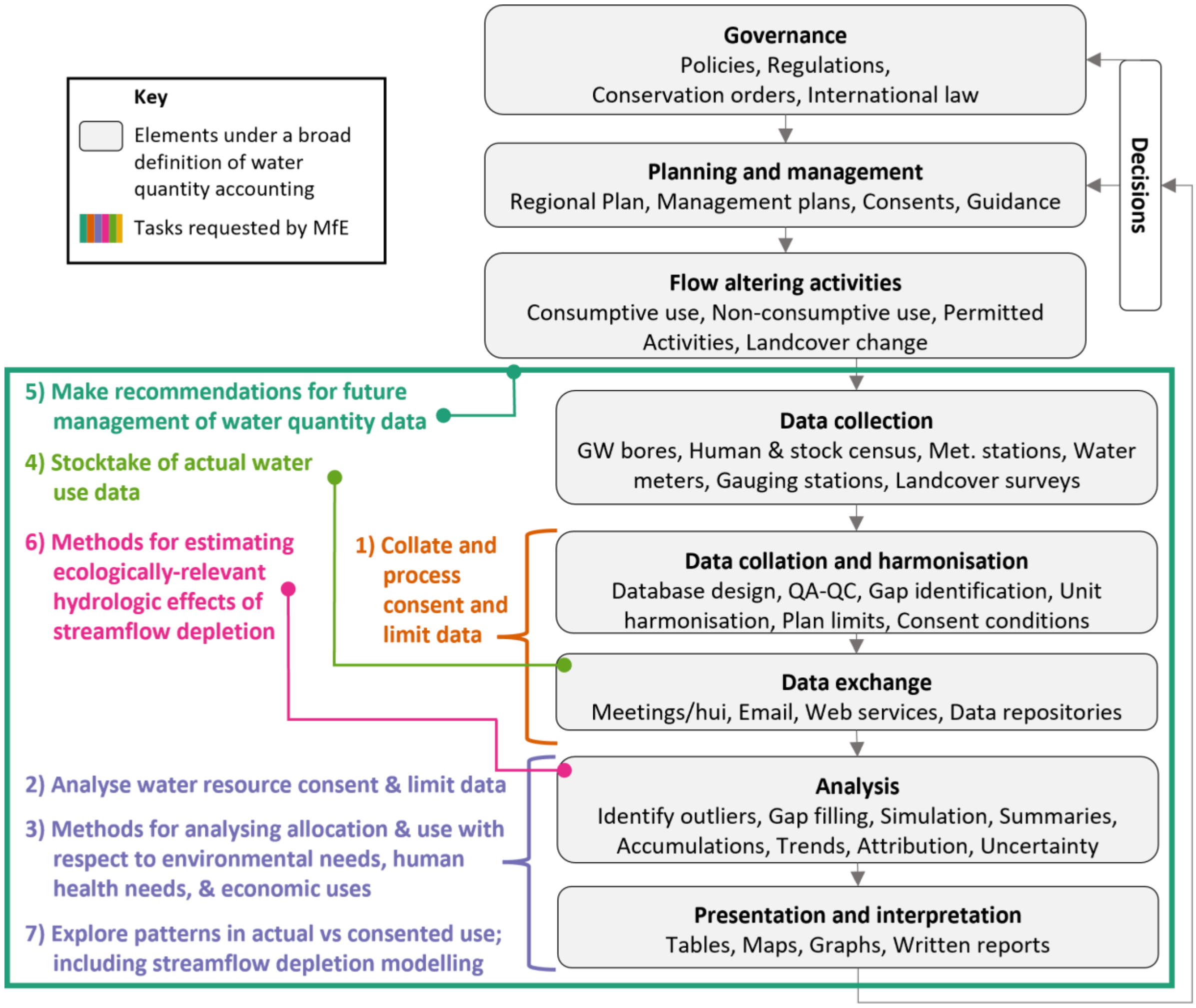

Figure ES-1: Steps in the water accounting process. Coloured text describes seven tasks requested by MfE.

Our main findings and some key results were as follows.

- We presented important context for assessing and prioritising competing freshwater needs, including definitions, theoretical considerations, and practical complications. We found that prioritisation of water use between environmental, human health, and economic uses is challenged by overlaps in the definitions of these aspects of water use. For example, water needed to support ecosystem services (e.g., natural filtering by groundwater systems) is an environmental water use that also supports human health and holds economic value equivalent to the cost of restoring or replacing the service.

- We found that water quantity data describing water resource use limits in regional plans, conditions for water abstraction in consents, and recorded rates of abstraction by meters are not held in standardised formats. For example, conditions in many consents restricted water abstraction by specifying maximum allowable instantaneous rate of take, but we also found restrictions on the maximum allowable volume to be taken over a day, a week, a month, a season, a year, and any 28-day period.

- We found that availability of water quantity data varied between regions, and that technical infrastructure allowing transfer of water quantity data is not in place across councils. For example, we queried servers to obtain data stored in standardised formats, but we also obtained bespoke excel spreadsheets or text files via email and file transfer.

- We requested water quantity data from four selected regional councils using a generalised rather than prescriptive request. We devised and applied a procedure for subsequently harmonising data from diverse sources. For example, we devised a standard method for storing restrictions that are: a) based on observations of an environmental variable (e.g., a cease-to-take river flow); and b) predetermined from rules that are independent of environmental conditions (e.g., maximum allowable annual volume).
- We accessed, collated, harmonised, and analysed regional plan provisions, water resource consents, measured abstractions, population estimates associated with permitted activities, and river flows and groundwater levels used to apply restrictions on water use. We found that minimum flows (trigger values for restricting abstraction) in consents were related to estimated naturalised 7-day Mean Annual Low Flow (MALF) but there was considerable spread in this relationship.
- We developed algorithms to automatically identify some data quality issues within measured abstraction data, including spikes and flat lines. The percentage reduction in total metered volume for daily meter records from removing flagged values was 5.6% for HBRC, 88.3% for ECan and 8% for ES. The large reduction for ECan reflects removal of some very high abstraction values present in the supplied data, which would in many cases not be physically possible. Output from our algorithms agreed with ECan's flagging of data for 99.2% of meter values.
- We found that time-series of metered data associated with consented abstractions can exhibit missing data. We devised, applied, and assessed methods for infilling of incomplete records. Abstraction could be predicted from time of year and weather within many sites with sufficient training data. Predictive performance was stronger when assessed at monthly resolution compared to daily resolution. When assessed at monthly resolution, cross-validated variance explained was greater than 0.5 for 97% of meters and the models showed little signs of bias.
- We discovered that some abstraction time-series were entirely missing, as indicated by a consent (or a known abstraction location) with no associated meter data. Missing time-series led to uncertainty about whether the absence of metered data reflects the absence of abstraction despite the presence of a consent to abstract water.
- We devised methods to account for abstractions which are not measured because water is taken for permitted activities. We devised and applied methods that used census data to estimate abstraction for permitted activities associated with people and livestock at any location on the national digital river network. We found that permitted activities could contribute a substantial amount of pressure on river flows but was less than 10% of the estimated median flow for most locations, with notable exceptions across Auckland, Waikato, Hawke's Bay, Canterbury, Otago, and Southland.
- We mapped accumulated consented maximum allowable rate of take and metered water abstraction across the national digital river network. Actual water use was

generally much lower than the overall maximum allowable rate, but exhibited similar spatial patterns. Pressure — represented by the ratio of accumulated take to estimated naturalised median flow — was generally higher in small and medium rivers than it was in larger rivers. Highest pressure values were found in rivers where upstream irrigation activities occurred.

- We conducted an integrated analysis of groundwater and surface water abstractions. We applied methods for estimating regionwide streamflow depletion from available abstraction data. This estimation includes considering the delayed effects of groundwater abstraction, which can extend over weeks, months, or even years depending on factors such as the distance between the well and the stream, the screen depth of the well, and aquifer properties. Representing these delayed responses in water resource management is crucial for achieving sustainable outcomes.
- We estimated naturalised river flows at 24 gauging stations from the Hawke's Bay region by summing measured flows with estimated streamflow depletion for demonstration purposes. We summarised differences between measured and naturalised flows to assess the effects of water abstraction on various aspects of flow regimes using a suite of environmentally-relevant hydrological metrics. We found that low flows were altered considerably at some sites but not altered at other sites, as was expected, because they had very few upstream abstractions.
- We compared measured and naturalised flows with minimum flows stated in regional plans for gauging stations in the Hawke's Bay region where relevant data were available. We found considerable differences in the percentage of time that the observed flow and the naturalised flow were below the plan minimum flow for nine of the 12 sites that we analysed.

Improvements for water quantity data and water quantity accounting are necessary.

In undertaking this work, we encountered several conceptual, technical, and institutional barriers to effective water accounting as summarised in Table 7-1 of this report. We identified four key recommendations to improve the effectiveness of future water quantity data and water accounting.

1. Water accounting must be comprehensive.

   The process of water quantity accounting should encompass the collection, collation, analyses, and presentation of water quantity data to inform freshwater management, planning, and policy development through time and across the landscape. A system-wide strategic view is needed to ensure that water accounting is fit for predefined purposes instead of being an ad-hoc analysis of whatever data are available.

2. Water accounting must be fit for specified purposes.

   Effective water accounting should quantify states and trends of: a) flows and levels in freshwater environments; b) water resource use limits in regional plans; c) allowable water use under consents and permitted activities; d) actual water use; and e) climate drivers of freshwater conditions such as precipitation and air temperature. Information describing the relationships between those entities would allow assessment of: a) the degree of hydrological alteration resulting from water abstraction; b) over-allocation versus headroom; c) water use efficiency versus wastage; and d) attribution of hydrological states between the influence of local anthropogenic effects versus climate variability or change.

3. Water accounting must explicitly quantify variability in time and space.

   Important changes in water availability and alteration of river flows can occur: a) at daily time-scales due to rapid changes in abstraction and natural river flows; and b) between reaches within catchments due to the positioning of abstractions. Water accounting should therefore be able to discern relatively fine temporal and spatial patterns in order to be informative at the local level, but these patterns need to be up-scaled to provide national coverage if results are to be used consistently for national environmental reporting or policy development.

4. Water accounting must be standardised.

   Conceptual and technical definitions should be carefully considered and agreed across institutions when assessing water allocation and actual use for competing needs. Standard definitions of water allocation and use for environmental, human health, and economic needs are not currently in place. Transparent communication of conceptual definitions of needs for fresh water is important because prioritisation of freshwater use between these needs is confounded by potentially overlapping definitions. For example, the World Health Organization (WHO) definition of human health is "the state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". Under the WHO definition, uses of water supporting human health would extend beyond just drinking water to arguably include water used to support local food production, recreation, cultural values, and possibly power production. Very narrow definitions would be needed to completely separate freshwater uses between environmental, human health, and economic needs.

   Clear technical definitions and standard technical approaches are needed to overcome several challenges to completing systematic-regionwide estimates of water allocation, water use, and streamflow depletion. These challenges include: a) distinguishing missing data from genuine absence of abstraction; b) reproduceable treatment of raw data during quality assurance/checking; c) estimating the delayed streamflow depletion effects of groundwater abstractions; d) the possibility of double counting of abstraction when there is a record of abstraction from a river by an irrigation scheme and then multiple subsequent records of water use; e) difficulty in specifying a natural baseline against which abstraction can be compared; and f) attribution of changes in river flows or groundwater levels to local anthropogenic activities versus broader-scale climate variability.

Given the regional variability that exists within the current plans, consents, and metered data, and the analytical challenges outlined above (i.e., dealing with missing data, poor data quality), it is not currently possible to undertake accurate, standardised nationwide water quantity reporting. This work has shown that analyses for some example regions is achievable, but careful communication with data providers is necessary and considerable uncertainties still exist. Nationwide water accounting for New Zealand would only be practically feasible if regional datasets are standardised and common definitions and procedures for data quality assessment are applied.

1 Introduction

1.1 Brief from the Ministry for the Environment

As the Government's primary adviser on environmental matters, the Ministry for the Environment (MfE) aims to provide effective policy advice on environmentally sustainable water resource allocation and use. In collaboration with Statistics NZ, MfE also seeks to gain insights into the status and trends of freshwater resource allocation and use. Data for assessing freshwater allocation and use are essential for both policy development and environmental reporting. It is important that data used for national environmental reporting is collected, collated, analysed, and presented using nationally consistent methods, as directed in the Environmental Reporting Act 2015.

Future environmental reporting, development of freshwater policies, and operational freshwater management, all require an understanding of how freshwater allocation and actual use impact environmental needs, human health, and economic uses. Assessments of water availability and water use are critical because people and livestock require access to water to maintain physical health, while various activities (e.g., irrigation, hydroelectric power production) require reliable access to water to maintain economic viability. Assessments of changes to freshwater environments resulting from water abstraction are critical because many freshwater values are influenced by river flows and groundwater levels.

MfE indicated that updated data and new methods associated with national water allocation statistics are required to assist three areas: a) future national environmental reporting; b) assessing the degree to which existing and previous freshwater policies have been complied with; and c) informing ongoing policy development. MfE emphasised that all three of these areas would benefit from both a clear description of the availability of water quantity data, and targeted analysis methods aimed at facilitating water resource management. However, the current status of data availability and accuracy concerning freshwater allocation, availability, and actual usage remains unclear and untested. Furthermore, systematic methods to compare actual water use, consented water use, and water resource use limits in regional plans have not been devised, applied, or assessed for their suitability for freshwater management purposes.

MfE indicated that the process of obtaining and analysing water allocation data also provides an opportunity to identify potential improvements in data collection, collation, analysis, and presentation that would assist future investigations. MfE also indicated that improved methods for assessing the technical efficiency (e.g., the proportion of abstracted water that is beneficially used) and environmental sustainability of water use would be beneficial.

The question of whether hidden capacity for further water allocation exists within current consenting frameworks is raised repeatedly when considering future policies relating to water quantity management. MfE indicated that this question necessitates comparing actual water use with allowable water use under consent conditions and plan limits to determine if there is hidden capacity to use water within current consenting and planning frameworks. Thus, a formal assessment of data availability, and methods needed to determine whether there is headroom for water use within environmental limits, is required. Comparison of actual water use against potential water use for consented and permitted activities is essential to gain a quantitative understanding of the impacts of freshwater abstraction on environmental values influenced by river flows and groundwater levels.

Spatial heterogeneity of freshwater abstractions, river flows, and groundwater levels will influence the distribution of water availability and potential environmental effects. MfE indicated that potential analyses should consider the effects on smaller tributaries as well as the effects on downstream and mainstem locations, or entire catchments lumped together as one unit of analysis.

Cultural aspects of freshwater allocation and use linked to the right to exercise kawanatanga (governance) in a manner consistent with the principle of partnership, and the duty to protect rangatiratanga (sovereignty) in relation to taonga katoa (treasures) are important issues. We (the authors of this report) acknowledge that freshwater values associated with Māori cultural, recreational, or aesthetic perspectives are important considerations for assessment of freshwater allocation and use. Whilst we acknowledge the importance of these issues, they are not explicitly dealt with here because they fall outside of the mandate of the authors and the scope of this work. However, Māori values and aspirations for fresh water have been described as being intertwined with flow-driven ecosystem health (Harmsworth et al. 2011), which is within the scope of this work.

The scope for this work covered the collection, collation, analyses, and presentation of water quantity data to inform freshwater management, planning, and policy development through time and across the landscape. This collection of actions all contribute to water quantity accounting (see Section 2.5 for further details about various definitions of water accounting).

1.2 Previous work on water allocation and use

A previous report on national water allocation statistics analysed the allowable rates of water abstraction from the natural environment under consents to take and use water (Booker and Henderson 2019). They calculated total allowable instantaneous rates of consented abstraction by administrative region, primary source (i.e., groundwater, surface water), and primary use (e.g., irrigation, industrial, drinking, etc.) for all locations across Aotearoa-New Zealand (NZ). A metric representing pressure on river flows from consented abstraction was mapped across the national river network by comparing an estimate of naturalised river flow against the downstream accumulated maximum allowable consented rate of take. The national water allocation statistics were used as part of national reporting on the state of the freshwater domain. Methodological details of this pressure calculation were published in Booker (2018).

Booker and Henderson (2019) indicated that their calculated pressure maps represented a worst-case scenario for river flow alteration due to consented abstractions. This scenario assumes that all maximum allowed abstractions are fully exercised, that water use is not supply limited, and that restrictions on water use are not applied. The pressure calculation also did not include the additional effect on river flows of water being abstracted in association with permitted activities. They identified opportunities for enhancing future analyses by obtaining information that was relevant to their calculations but was not available for analysis. For example, neither data describing restrictions on abstractions during times of low flow, nor data that would allow estimation of water use under permitted takes, were readily available for analysis. They also recommended that future analyses should incorporate data on measured water use, so that actual water use, rather than worst-case scenarios of potential water use, could be presented.

Booker et al. (2019) conducted an analysis of actual (recorded) water abstraction across the Greater Wellington and Manawatū-Whanganui regions. They developed and applied analytical methods to estimate daily time-series of streamflow depletion resulting from recorded abstractions from surface water and groundwater across two example regions. That work demonstrated that it is feasible to estimate streamflow depletion resulting from water abstraction at relatively fine spatial and temporal scales. However, they highlighted some impediments to reliable streamflow depletion calculations across multiple catchments and regions. These impediments included inconsistent methods for data formatting within and between regional councils, lack of availability of the required meta-data (e.g., aquifer characteristics), missing data, and indeterminant quality of recorded abstraction time-series data.

Bright et al. (2022) aimed to support long-term improvements to freshwater accounting systems in NZ. They stated that freshwater accounting systems should provide baseline information required for: a) setting target attribute states, environmental flow regimes, and water resource use limits; b) assessing whether a freshwater management unit (FMU) is, or is expected to be, overallocated; and c) tracking over time the cumulative effects of activities such as changes in water use. Bright et al. (2022) gave 26 recommendations aimed toward: a) providing high quality information for a wide range of local, regional, and national needs; and b) increasing public trust and confidence in the environmental management system through increased transparency, completeness, and consistency of information. Many of their recommendations are useful when setting future directions towards optimal and aspirational accounting frameworks. In keeping with their brief to be aspirational, their recommendations were not bound by ease of implementation or a set timeframe. Therefore, many of their recommendations did not contain prescriptive details or actionable instructions about methods for collection, collation, analysis, or presentation of water quantity data. Their recommendations remain untested and are yet to be systematically implemented. While applying a nationally consistent reporting framework is a rational and commendable recommendation given long-term aspirations for freshwater policies and environmental reporting, operational methods for ascertaining pressure and values have not been developed, tested, or applied.

1.3 Aims

The aim of this work was to access and analyse available water quantity allocation and use data to meet two objectives. The first objective was to collate and analyse examples of readily available water quantity data with a view to improve environmental reporting and informing policy development. The second objective was to identify potential improvements in how water quantity data is being collected, collated, analysed, and presented to help improve the effectiveness of future analyses. On initiation of this work MfE indicated that any recommendations emerging from this second objective would be relayed by MfE to councils via council representatives and the Land and Water Aotearoa (LAWA) team who were active participants during the current work. Thus, MfE requested that NIWA collect and evaluate examples of water resource consents and water use data, including associated information such as restrictions on water abstraction within consents and water resource use limits in regional plans. The work described in this report consisted of seven tasks:

1. Collate and process water resource consent and plan limit data.
2. Analyse water resource consent and plan limit data.
3. Assess methods for analysing water allocation and actual use with respect to environmental needs, human health needs, and economic uses.
4. Conduct a stocktake of actual water use data.
5. Make recommendations for future management of water quantity data.

6. Demonstrate methods for estimating ecologically-relevant hydrologic effects of streamflow depletion.

7. Explore patterns in actual versus consented water use.

The work presented in this report built upon and updated previous methods for calculating national-level water allocation statistics and modelling streamflow depletion as outlined in Section 1.2. It should be noted that the brief for the present work did not require a systematic analysis of data available for the entire country, but rather called for an in-depth analysis of data from example regions to inform on current practices and make recommendations for future practices related to water quantity data.

1.4 Structure of the report

This report is organised into the following sections.

- Section 2 provides some background information about fresh water for environmental needs, human health needs, and economic uses. The section first sets out some important contextual information in the form of definitions, theoretical considerations, and practical complications for assessing water allocation and use in relation to environmental needs, human health needs, and economic uses. Operational requirements relating to water quantity data and methods for quantifying water allocation and use are then provided.
- Section 3 provides a description of the water quantity data and related information used in this work.
- Section 4 provides a description of the methods that were devised and applied in this work.
- Results are presented in Section 5.
- Section 6 provides a summary of the work in relation to the original tasks requested by MfE.
- Section 6 provides general discussion related to the work.
- Section 7 provides a description of future recommendations relating to collection, collation, and analysis of water quantity data for effective water management, planning, and policy development necessary to deliver effective and efficient water use for economic purposes within environmentally sustainable limits.

2 Essential background on environmental needs, human health, and economic uses of fresh water

Integrated water resource management generally seeks to promote management of coupled water-land systems to equitably maximise economic and social well-being without compromising ecosystem sustainability (Candido et al. 2022). The importance of river flow management has been recognised in many countries that have incorporated environmental flow provisions into updated water resource management policies (Harwood et al. 2018). The importance of river flow management has also been recognised in various NZ policies, regulations, and other legal instruments. For example, the National Policy Statement for Freshwater Management 2020, amended 2023 (NPS-FM) includes clauses about setting environmental flows and levels (Clause 3.16) and identifying water abstraction limits (Clause 3.17). At the highest level, the NPS-FM is guided by the fundamental concept of Te Mana o te Wai (TMoTW), which relates to restoring and protecting the integrity of water. The overall objective of the NPS-FM is to ensure that natural and physical resources are managed according to a hierarchy of obligations following the concept fundamental concept. The hierarchy is set out in NPS-FM clauses 1.3 and 3.2, and consists of three ordered priorities: first the health and well-being of water bodies and freshwater ecosystems; second the health needs of people (such as drinking water); and third the ability of people and communities to provide for their social, economic, and cultural well-being. The NPS-FM therefore explicitly prioritises the needs of the environment above the needs of people. It should be noted that many parts of the NPS-FM are consistent with previous NZ freshwater policies and with international requirements for sustainable water governance, including achieving water security and addressing management constraints to achieve economic and environmental prosperity (e.g., Lele et al. 2013; Cosgrove and Loucks 2015).

The remainder of section sets out some contextual information relating to methods for analysing water allocation and use. Sections are first provided on environmental needs (Section 2.1), human health needs (Section 2.2), and economic needs (Section 2.3). A holistic perspective that acknowledges overlaps between environmental, human, and economic water uses is then discussed (Section 2.4). Definitions, theoretical considerations, and practical complications related to water quantity accounting concerning environmental needs, human health needs, and economic needs are then outlined (Section 2.5).

2.1 Environmental needs for fresh water

2.1.1 Flow regimes

"River flow regime" and "groundwater regime" are phrases often used to describe the main features of river flow and groundwater level at particular sites as they vary through time when viewed over the long-term. River flow regimes and groundwater regimes are intimately linked because water exchanges between surface water and groundwater are continually occurring across the landscape (Lewandowski et al. 2020; Winter et al. 1998). In this work we use "flow regimes" as a general phrase to encapsulate states and fluxes of water in freshwater environments, including rivers, wetlands, lakes, aquifers, and hyporheic zones. The hyporheic zone is the sediment and porous space beneath and alongside a surface water environment, where there is mixing of shallow groundwater and surface water.

The main features of flow regimes include magnitude and duration of low flows, magnitude and frequency of medium and high flows, and degree of seasonality. The features of flow regimes are driven by interactions between climate and catchment characteristics such as soil, geology, and vegetation (McMillan 2020). Under the following definitions, biodiversity, ecosystem services, ecological integrity, and human health (including cultural, recreational, and aesthetic aspects), can all be considered as environmental values (sometimes referred to as instream values in the NZ context) that are influenced by flow regimes.

- Biodiversity is defined in many dictionaries as the variety of life found in a place (e.g., Britannica definition).
- Ecosystem services is defined by the Millennium Ecosystem Assessment (MEA) as the benefits and services people obtain from ecosystems (MEA 2005; MEA definition). The notion of nature's contributions to people builds on the ecosystems service concept (Díaz et al. 2018).
- Ecological integrity is defined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as the ability of an ecosystem to support and maintain ecological processes and a diverse community of organisms (IPBES definition).
- Human health is defined by the World Health Organization (WHO) as a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity (WHO definition). See Sub-section 2.2 for further details.

2.1.2 Freshwater flows and environmental values

There is a wide body of international literature describing theoretical links between flow regimes and environmental values (e.g., Poff and Zimmerman 2010; Poff et al. 2010). Similarly, within NZ, there is also a body of literature that reinforces links between flow and environmental values. Many NZ studies have demonstrated empirical, but not necessarily causal, links between flow regimes and environmental values. Examples include the following links between surface water flows and potential environmental values.

- Links between flows and the distribution and abundance of fish because fish are influenced by several factors, particularly migration and habitat suitability, which are in turn strongly influenced by flow regimes (Crow et al. 2013). The specific effects of flow regimes on fish migration and habitat suitability are discussed in detail by Closs et al. (2016).
- Links between flows and physical disturbance that drives fish assemblages (e.g., Jellyman et al. 2013).
- Links between flows and hydraulic habitats defined in terms of availability of particular depth, velocity, and substrate conditions (e.g., Booker 2016).
- Links between flows and periphyton biomass. For example, Biggs (2000) linked periphyton biomass with nutrient concentrations and a hydrological variable defined as the frequency of high flow events exceeding three times the median flow (FRE3). Further work linking periphyton to nutrients, substrate and flows includes (Snelder et al. 2014; Neverman et al. 2018; Snelder et al. 2019).

- Links between flows and invertebrate communities. For example, Greenwood et al. (2016) described a hydrologically sensitive invertebrate community index for New Zealand rivers, and Townsend et al. (1997) calculated the frequency of events exceeding different ecologically relevant thresholds when comparing various surface flow metrics of disturbance to macroinvertebrate species traits and species richness.
- Links between flows and riverbed substrate composition (e.g., Haddadchi et al. 2018).
- Links between flows and river water temperature (Booker and Whitehead 2022).
- Links between flows and dissolved oxygen (Franklin 2014).

Links between groundwater flows/levels and various potential values have also been discussed or demonstrated empirically, including the following examples.

- Links between groundwater flows/levels and high biodiversity associated with groundwater invertebrates (stygofauna), and also ecosystem services such as water purification, bioremediation, and water infiltration (e.g., Boulton et al. 2008).
- Links between groundwater flows/levels and recharge of spring and lake systems (e.g., Morgenstern et al. 2015).
- Links between groundwater flows/levels and groundwater quality (e.g., Morgenstern and Daughney 2012).

The list of flow-ecology links shown above provides several explanations about why maintaining appropriate flow regimes in rivers and aquifers is vital for maintaining freshwater ecological integrity. Abstracting water from rivers and aquifers for irrigation, domestic supply, and hydroelectric generation can therefore result in increased risks to environmental values representing ecological integrity and/or human health (Gorelick and Zheng 2015). Impacts of abstraction on environmental values at low flows have rightly received much attention (e.g., Hayes et al. 2019) associated with high temperatures, low dissolved oxygen, and fish stranding, but it should be noted that there are also potential effects of high-flow harvesting on environmental values in New Zealand. See Hickford et al. (2023) for a literature review that relates various environmental values to mid-range and higher flows.

2.1.3 Challenges for determining and delivering environmental flow regimes

Rivers flows and aquifer levels need to be managed because water abstraction is required for economic purposes whilst the resulting flow and water level alteration may impact environmental values. In simple terms, environmental flow regimes that keep risks to flow-driven environmental values within acceptable levels need to be delivered by setting water resource use limits in regional plans that are used to control flow altering activities.

Globally, environmental flow regimes have been proposed and adapted using different approaches. Many of these approaches are based on a combination of: 1) designing and purposefully manipulating flow regimes to achieve targeted ecological and ecosystem service outcomes; and 2) limiting alterations from the natural flow baseline to maintain biodiversity and ecological integrity. See Acreman et al. (2014) for further discussion of “designer flows” (e.g., De Villiers et al. 2008) versus “deviation from natural” (e.g., Richter et al. 2012) and when each method, or their mixture, may be more appropriate. Regardless of methods, determining environmental flow regimes across entire landscapes is challenging due to several interacting factors.

- The effects of flows on environmental values are mediated by landscape settings relating to climate, vegetation, sediment supply, geology, topographic setting (altitude, slope, etc.), and ecological processes. Thus, the same change in flow regime will produce different effects on environmental values in different locations.
- Different environmental values will have different relationships with river flows and aquifer systems. The strength, magnitude, and direction of flow-ecology relationships will vary depending on the environmental value. For example, some species would benefit from more disturbed flow regimes whereas other species may prefer more benign flow regimes (Palmer and Ruhi 2019). Flow-ecology relationships will also vary depending on landscape setting (Snelder et al. 2011). For example, in highly disturbed aquatic habitats the frequency of flows above a threshold for sediment transport could be seen as important for ecosystem functioning (Jellyman et al. 2013), whereas in spring locations the threshold for sediment transport may be reached very rarely.
- Aside from cessation of flow, it is very difficult to define and isolate the influence of a single component of a flow regime as being particularly important for overall ecological integrity and/or human health. For example, higher flows relate to flushing of sediment, mid-range flows relate to cuing of fish movements, whereas low flows relate to provision of space, maintenance of temperature or dissolved oxygen etc.
- Many components of natural flow regimes are highly correlated, but these correlations can be broken under altered flow regimes. Thus, unintended consequences can arise from selecting a sub-set of statistically independent hydrological variables to represent all aspects of the flow regime when defining environmental flow regimes. For example, summer minimum flow may be statistically representative of summer flow conditions, but sole application of this variable to define environmental flow regimes will allow larger than intended changes in summer mean flow or variability. Conversely, application too many hydrological variables to define environmental flow regimes is problematic because it is not practically feasible to control flow altering activities in a way that will guarantee delivery of a flow regime defined by a multitude or hydrological variables.

The delivery of environmental flow regimes across entire catchments presents significant challenges due to the following reasons:

- River flows and groundwater levels (especially within shallow aquifers) are inherently variable due to changes in weather regardless of local human activities or management interventions. For example, even in natural catchments, different weather patterns in each year will produce different surface water flows. Thus, the influence of management actions on flow alteration could be masked by weather/climate patterns, and environmental flow regimes could not be delivered naturally, irrespective of abstraction.

- River flow alteration cannot be measured directly. River flows can be measured but this is expensive. Continuous flow time-series are usually measured at gauging stations, and spot gauging techniques provide instantaneous flow at discrete times but cannot capture flow variability. In theory, the sum of measured abstractions/manipulations can be compared to measured river flows to estimate river flow alteration. However, such a comparison can only be applied at gauging stations, and the hierarchical nature of river flows means that gauging stations are not necessarily representative of their upstream catchments or nearby catchments. More importantly, estimate of river flow alteration will be highly uncertain because many abstractions are not measured, some abstracted water may return to supplement groundwater levels or river flows, and the timing and extent of groundwater abstractions on river flows is uncertain due to temporal lags, especially if aquifer properties are unknown (Zipper et al. 2021). It is possible that uncertainty in quantifying river flow alteration may be greater than natural variability in river flows, and/or greater than the expected effect of alternative management actions.
- River flow alteration occurs over multiple temporal and spatial scales. Measurement location is particularly important when considering either the cumulative effects of multiple small abstractions distributed across the landscape (river flow alteration may be higher in tributaries and lower in main stems) or the large effects of a single large abstraction (river flow alteration may be very large just downstream of the abstraction but reduce with distance downstream as flow accumulates). See Booker et al. (2014) for demonstration of why the same rules for water take limits can lead to different outcomes across a catchment.
- River flow alteration can be expressed as relative alteration (i.e., a proportional reduction or a percentage reduction) or as absolute alteration (i.e., a reduction in litres per second). Absolute alteration is meaningful within a site, but not meaningful when comparing between sites. Furthermore, the meaning of relative alteration for various environmental values may not be constant between sites or between flows within a site.
- Determining river flow alteration necessitates defining a baseline state. This is a technically challenging task because the quality and coverage of data required is not available. It is also not clear whether a baseline state should just account for water abstractions, or also account for landcover changes, and climate changes even though all three factors combine to alter flows (see Lapides et al. 2022).
- Type and configuration on engineering infrastructure (e.g., dams, canals, bores, surface water abstraction points) and potential water uses (e.g., domestic supply, irrigation, or hydroelectric power generation) may limit the degree to which proposed environmental flow regimes can be delivered. For example, engineering infrastructure that transfers water between catchments provides greater scope for both flow alteration and delivery of environmental flow regimes.

See Booker et al. (2022) for detailed discussion on the above points and a proposed framework for managing river flows.

2.1.4 Flow naturalisation and streamflow depletion

Environmental flow regimes are often expressed after having quantified components of natural flow regime (e.g., Richter et al. 2012). Removing human influences from streamflow time-series is a process often referred to as river flow naturalisation. Estimates of naturalised river flows are essential to express river flow alteration. However, clear definition of natural river flow or natural flow regimes is needed because methodological definitions can vary. Several methods for flow naturalisation have been developed, including adding observed (and/or estimated) water abstraction data to observed river flow data, simulation by physically-based models, and substituting re-scaled observed time-series from a "natural" reference site to a site of interest. The process of estimating the cumulative effect of water abstraction is known as streamflow depletion calculation. Since missing abstraction data often have to be simulated and lags between groundwater abstractions and realised influences on streamflow are unknown, the process is sometimes known as streamflow depletion modelling. Terrier et al. (2021) provides detailed discussion of naturalisation methods and why naturalised flows should not necessarily be considered true natural flows. Methods have been applied for estimating the degree of hydrological alteration at ungauged sites across regions overseas (Sengupta et al. 2018), but not systematically across New Zealand.

2.2 Human health needs for fresh water

Water is fundamental for human survival. While this report primarily addresses the allocation and use of water resources in terms of quantity, it is crucial to consider both water quantity and quality together in the context of human health needs. Water quality issues coincide with water quantity issues particularly closes when considering domestic supply because domestic water supply should be suitable for human consumption.

2.2.1 Medical health

From an international perspective, the United Nations General Assembly has recognised the human right to safe and clean drinking water and sanitation. The United Nations Committee on Economic, Social and Cultural Rights adopted General Comment No. 15 on the right to water. Article I.1 states that "The human right to water is indispensable for leading a life in human dignity. It is a prerequisite for the realisation of other human rights" (United Nations 2002). Comment No. 15 also defined the right to water as the right of everyone to sufficient, safe, acceptable and physically accessible and affordable water for personal and domestic uses (UN website; water for life).

Water allocation policies and procedures must supply the quantities necessary for meeting basic human needs, recognising access to drinking water as a fundamental human right. The cessation or reduction of access to drinking water can lead to physical health issues such as kidney stones, urinary tract complications, and cancers due to inadequate water consumption (Yongsi 2010; Healthify 2022), as well as mental health concerns (Wutich et al. 2020; Kimutai et al. 2023). Therefore, it is crucial to ensure that the quality of water used for domestic purposes meets acceptable standards (WHO 2022). Globally, diseases resulting from the consumption of contaminated water kill millions of people annually, most of whom are children under the age of five. Microbial and chemical pollution are ongoing concerns worldwide, including in New Zealand. Exposure to microbes and chemicals in drinking water can lead to a range of diseases (Khan et al. 2007), including chronic diseases like cancer and cardiovascular disease, as well as adverse reproductive outcomes and effects on children's health, such as neurodevelopmental issues (Levallois and Villanueva 2019).

The [Water Services Act (2021)] aims to ensure people across NZ can access safe water. The act defines "drinking water" as water that is used for: human consumption; oral hygiene; preparing food, drink, or other products for human consumption; or washing utensils that are used in relation to human eating or drinking. The Act defines potable water as water that: is safe to drink; and complies with the Water Services (Drinking Water Standards for New Zealand) Regulations 2022. This means that potable water is fit for human consumption because it is safe to drink and does not contain health-threatening substances. The act defines the terms "water supplied" and "domestic self-supply". These definitions are needed in the NZ context because some dwellings abstract water from the natural environment directly whereas others obtain water that has been abstracted by a third party (e.g., water company, local institution, or collective organisation). Within the act domestic self-supply means a stand-alone domestic dwelling that has its own supply of drinking water, and a domestic dwelling means a building that is used as a single household unit (Water Services Act 2021 definition).

In this work, we define domestic water supply as water abstracted from the natural environment and then supplied to dwellings or other locations for small-scale local consumption including for drinking. Domestic water supply can be from self-supply or from reticulated supply by water companies or local institutions. Estimates of domestic water use have been made in NZ. For example, some estimates indicate that the average person in NZ uses 227 litres of water per day (Learnz website). Figure 2-1 shows an estimate of typical domestic water consumption, using an example from Auckland.

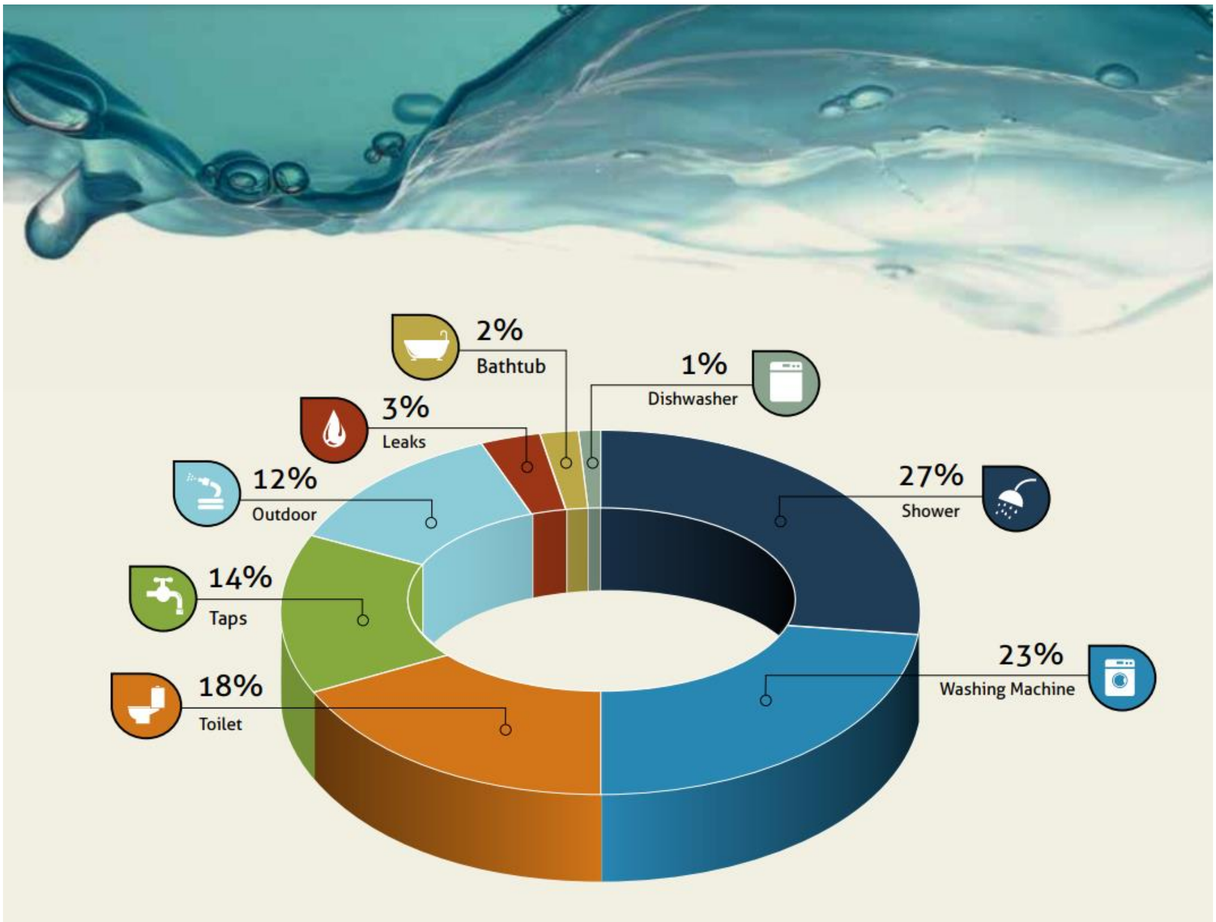

Figure 2-1: Typical domestic water use in Auckland. Source: WaterCare, Auckland.

2.2.2 Broader human health needs

Human health is connected to water in a way that extends beyond a medical perspective of water quality and quantity for basic drinking and cooking. As stated above, human health is defined by the WHO as a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity. Under the WHO definition it is inappropriate to confine links between fresh water and human health to a medical perspective because fresh water can play a role in human physical, mental, and social well-being. Assessment of water availability and use for human health needs to consider more than water for drinking.

In addition to water for drinking, cooking, and washing, domestic water supply also plays an important role in realising human rights such as the right to produce food and protect livelihoods. There is a considerable body of international literature on this topic. For example, Hall et al. (2014) applied the concept of "domestic-plus" services that provide water for domestic and productive uses around homesteads in rural and peri-urban areas where water is used to produce food for domestic consumption. They challenged the widespread public sector practice of planning and designing water infrastructure for a single (domestic only) use. From a global perspective, they argued that the human right to water for domestic uses to meet public health and gender objectives, includes the right to water for supporting livelihoods according to broader human rights frameworks.

Water also plays an important role in supporting human health outside of domestic water supply. In the international literature, there is growing recognition that functionally intact and biologically complex aquatic ecosystems provide many economically valuable services and long-term benefits to society (Baron et al. 2002). For example, freshwater flows have been linked with fisheries in large tropical systems (Sabo et al. 2017). Lynch et al. (2016) outlined 10 reasons why inland fish and fisheries from across the globe are important to individuals (food security, economic security, empowerment), society (cultural services, recreational services, human health and well-being, knowledge transfer and capacity building), and the environment (ecosystem function and biodiversity, as aquatic "canaries", the "green food" movement). Noble et al. (2016) described the importance of fisheries as keystones for freshwater management for indigenous peoples of North America, Australia, and NZ. Arlinghaus et al. (2021) indicated that recreational fishing is a valued pastime in many countries but stated that participation in recreational angling across the globe varies substantially and is directly related to societal-level developments affecting resources, time, and socialisation into fishing. Lynch et al. (2023) identified nine flow-dependent fundamental ecosystem services that biotic components of indigenous freshwater biodiversity provide to people. They organised these ecosystem services into three categories: material, non-material, and regulating, but presented the ecosystem services in an order that intermingled them between these three categories (Figure 2-2). They also stated that "If freshwater biodiversity is protected, conserved, and restored in an integrated manner, as well as more broadly appreciated by humanity, it will continue to contribute to human well-being and our sustainable future via this wide range of services and associated nature-based solutions to our sustainable future." Baron et al. (2002) stated that long-term benefits of freshwater ecosystem services include the adaptive capacity of aquatic ecosystems to respond to future environmental alterations, such as climate change.

Figure 2-2: Nine fundamental ecosystem services that biotic components of indigenous freshwater biodiversity provide to people. Green = material. Brown = non-material. Blue regulating. Source: Lynch et al. (2023).

Benefits of freshwater ecosystems for society that relate to broad human health are also well recognised within the NZ literature. Local examples include the following.

- Freshwater flows (including connectivity and magnitude of flows those in rivers, wetlands, and lakes) have been linked to food security in situations where food gathering is related to freshwater flows historically (Fyfe and Bradshaw 2020) and currently (Watson et al. 2021).
- Freshwater flows have been related to fisheries (e.g., juvenile whitebait species and adult eel species) but also in relation to plants, birds, and other animals (Tipa 2013).
- The influence of freshwater flows has been particularly related to habitat provision (Jellyman et al. 2003), migration (Jellyman et al. 2009), and fish passage (Knapp et al. 2019) for eels, which are culturally significant (Tipa and Nelson 2017).
- River flows have been recognised for their contribution to landscape-scale aesthetic quality in an NZ study which found differences between large and small rivers (Pflüger et al. 2010).

- River flows have been linked to fishing experience for NZ anglers (e.g., Hayes and Lovelock 2017) and
- River flows have been linked to cultural experience for mandated iwi undertaking mahinga kai activities (Crow et al. 2018).
- Purification, bioremediation, and water infiltration are amongst the ecosystem services provided by groundwater systems (Boulton et al. 2008; Sirisena et al. 2018).

2.2.3 Māori cultural values, beliefs, and practises

Freshwater flows are linked with various aspects of human health, including local customary practices (Gleick 1998; Stewart-Harawira 2020). Whilst cultural aspects of freshwater allocation are not explicitly in scope for this work, it is important to acknowledge that fresh water is intrinsic to Māori cultural values, beliefs, and practises. Māori values and aspirations for fresh water are intertwined with various aspects of flow-driven ecosystem health set out in Section 2.1.2 (Harmsworth et al. 2011). For example, explicit links between surface water flows and Māori cultural values in the form of mahinga kai-food gathering activities conducted by mandated iwi representatives have been demonstrated and quantified (e.g., Tipa and Nelson 2012; Crow et al. 2018). The introduction to a section of Hickford et al. (2023) dedicated to the topic of Māori cultural values relating to high-flow harvesting (a form of river flow management) indicated the strength of interconnection between fresh water and Māori cultural values, beliefs, and practises:

> *"Māori have an intricate, holistic and interconnected relationship with te taiao (the environment) that is based upon mātauranga Māori (generational knowledge), whakapapa (genealogy) and whānaungatanga (relationships). Wai (water) is one of the key components that supports the intricate relationships Māori have with te taiao, and the spiritual and cultural significance of fresh water can only be determined by the tangata whenua who have traditional rights over it.*
>
> *Freshwater management where iwi/hapū/whānau (mana whenua) define their cultural values is required through the duty of partnership under Te Tiriti o Waitangi. This section [Section 3 of Hickford et al. (2023)] outlines some key cultural values associated with wai that can be used to understand the cultural risks/opportunities associated with high-flow harvesting [a form of river flow management]. The purpose of this section is not to identify specific cultural values associated with (or at risk from) high-flow harvesting, but to identify themes associated with high-flow harvesting that can be used as the basis for further kōrero (conversation) with mana whenua."*

In relation to cultural values, readers are also referred to the statement of Crow et al. (2018) that:

> *"If the interests of Māori are to be weighed alongside the many other uses, and if environmental streamflow assessments and allocative decision-making are to benefit from the knowledge of whanau, hapū and iwi, new techniques are needed to assess the appropriateness of streamflows in culturally sensitive ways".*

Further information on the role of flows from a Mātauranga Māori perspective can be found in Harmsworth et al. (2011), Harmsworth et al. (2016), Tipa et al. (2016), Te Aho (2019), Taylor et al. (2021), Taylor (2022), Tadaki et al. (2022) and references therein. It should also be noted that Miller et al. (2015) presented evidence demonstrating that there is support for the management outcomes for cultural attributes by Māori and also to the wider public.

The quotes and references provided above indicate that many aspects of Māori cultural values, beliefs and practices fit within the WHO definition of human health because they relate to physical, mental, or social well-being.

2.3 Economic needs for fresh water

In New Zealand, a reliable water supply is particularly critical for economic growth due to the country's heavy reliance on the agriculture and tourism industries (Hopkins et al. 2015). Agriculture, a major sector of the NZ economy, depends on water for irrigation, livestock, and processing activities (IrrigationNZ 2019; MfE and Stats NZ 2020; Stats NZ 2020). A consistent water supply ensures that farmers can reliably produce high-quality crops and livestock, contributing significantly to the economy. The economic value to access to water for irrigation is difficult to quantify precisely, however, it has been estimated that irrigation contributes $4.8 billion (2.4% in 2014 terms) to NZ's real GDP (NZIER and AgFirst Consultants Ltd 2014). Studies have shown that access to irrigation water is particularly beneficial in drier areas, flatter areas, and poorly draining areas (Grimes and Aitken 2008).

Moreover, the manufacturing and energy sectors in NZ also require reliable water sources for their operations to be economically viable. Water is used in various processes, such as cooling systems in manufacturing plants and hydroelectric power generation. A reliable water supply ensures the continuous operation of these industries, promoting economic growth and stability. Hydropower generation, which currently provides 57% of New Zealand's electricity needs (EECA 2024), plays a crucial role in NZ's economy. It also holds strategic importance for long-term benefits, helping mitigate the impacts of climate change by reducing reliance on fossil fuels and supporting the country's commitment to achieving net-zero carbon emissions (Raihan and Tuspekova 2023).

Access to clean water is not only vital for direct economic activities but also for public health that indirectly bring long-term economic benefits. A reliable water supply, as described in Section 2.2, helps in reducing waterborne diseases (Collier et al. 2021), thereby lowering healthcare costs and improving workforce productivity. Healthy employees contribute more effectively to the economy, driving economic growth.

Additionally, NZ's tourism industry, which relies heavily on the country's natural beauty and outdoor activities, benefits from a reliable water supply. Tourists are drawn to NZ's pristine lakes, rivers, and beaches, making water quality and availability crucial for attracting visitors and supporting tourism-related businesses (Gluckman et al. 2017).

2.4 Overlapping needs within integrated human-freshwater systems

Water is a finite resource that is essential for ecosystems within the natural environment, human health, and various economic activities. Human activities, such as agriculture, industry, and urbanisation, have significant impacts on water resources. Environmental degradation resulting from human activities, such as pollution, habitat destruction, and consumptive water use, directly influence water quality and water availability for human health needs and for natural environmental needs. Environmental management therefore requires balancing the needs of the natural environment, human health, and the economy. However, these three entities are not necessarily mutually exclusive as illustrated in Figure 2-3. Only the narrowest of definitions would completely separate freshwater needs for environmental, human health, and economic needs. There are many topics that need to be considered within freshwater assessments of allocation and use that related to some combination of environmental, human health, and economic needs. For example, tourist activities are an important part of the NZ economy, yet many aspects of tourism rely on functioning ecosystems and a viable supply of clean fresh water in natural environments (e.g., angling, kayaking, rafting, tramping). At the same time, outdoor physical activities are often related to mental health and social wellbeing, which are firmly within the definition of human health. It is therefore crucial that assessments of water availability and use adopt an integrated, rather than compartmentalised, view of water needed for environmental, human health, and economic uses. It should also be noted that water management is interconnected with other aspects of sustainable development, including food security, health, and climate change adaptation. An integrated/holistic approach can identify synergies and trade-offs between these goals, leading to more effective and sustainable solutions.

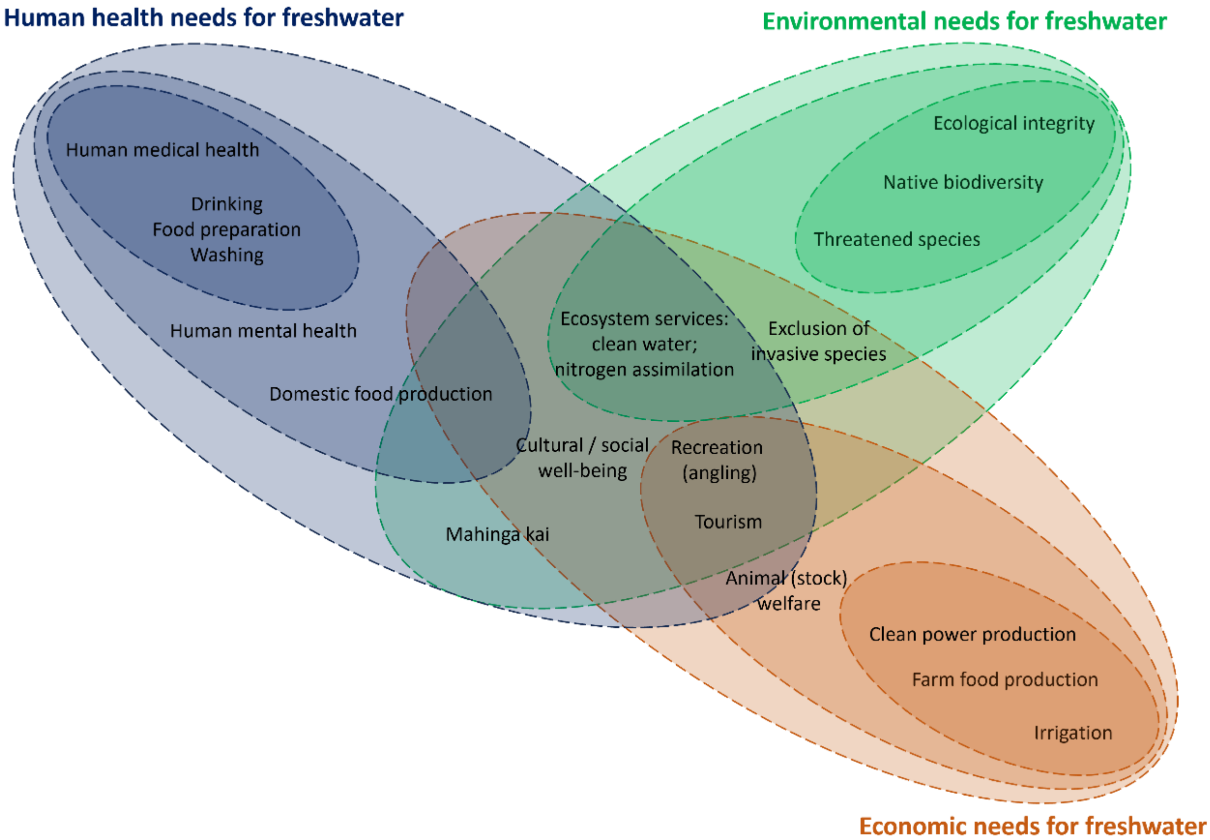

Figure 2-3: Exclusive versus overlapping definitions of human health, environmental, and economic needs for fresh water. Concentric circles represent how broader definitions encompass entities that are common to multiple needs.

2.5 Water quantity accounting for environmental, human health, and economic needs

2.5.1 Previous perspectives of water accounting

The NPS-FM did not explicitly define water accounting, but Clause 3.29 stated that:

> *"Every regional council must operate and maintain, for every FMU: a) a freshwater quality accounting system; and b) a freshwater quantity accounting system. The purpose of the accounting systems is to provide the baseline information required: a) for setting target attribute states, environmental flows and levels, and limits; and b) to assess whether an FMU is, or is expected to be, over-allocated; and c) to track over time the cumulative effects of activities (such as increases in discharges and changes in land use). The*

accounting systems must be maintained at a level of detail commensurate with the significance of the water quality or quantity issues applicable to each FMU or part of an FMU. … The freshwater quantity accounting system must record, aggregate, and regularly update, for each FMU, information on the measured, modelled, or estimated: a) amount of freshwater take; and b) the proportion of freshwater taken by each major category of use; and c) where a take limit has been set, the proportion of the take limit that has been allocated. In this clause, freshwater take refers to all takes and forms of water consumption, whether metered or not, whether subject to a consent or not, and whether authorised or not."

Bright et al. (2022) did not define water accounting beyond referring to NPS-FM Clause 3.29 (above). They did state that freshwater accounting systems provide measured and/or modelled data describing the quantity and quality of freshwater systems, and thus play a key role within a broader system of resource management by providing baseline information required for: a) setting target attribute states, environmental flows and levels, and limits; b) assessing whether a FMU is, or is expected to be, over-allocated; and c) tracking over time the cumulative effects of activities (such as increases in discharges and changes in water and land use).

It should be noted that other definitions of water accounting exist, with many definitions extending to cover water quality as well as water quantity. International definitions of water accounting can be very broad. For example, Vardon et al. (2023) stated that:

"Water accounts are a framework for assembling multiple data sources into a coherent information system. There are many types of water accounts covering the hydrological cycle, water quality, the water supply and sewerage industries, water fees and charges, defensive and restoration expenditures, and financing as well as for water-related ecosystem services, like water purification, water regulation and flood control. Through the consistent application of concepts, definitions, classifications and structures, water accounts can be linked to other types of environmental information and in particular ecosystem accounts and the System of National Accounts (SNA). The SNA is used by every country in the world for economic management and policy. Water accounting can provide the integrated information that can support water governance and management, just like the national accounts support economic management and policy.

Water accounting has evolved over more than three decades, and this experience is brought together in the System of Environmental-Economic Accounting (SEEA). Nearly 100 countries use or are developing this system, and 73 countries and regions have produced water accounts, using a range of data sources and methods, and with production growing steadily over time. The production and use of water accounting is global and is undertaken in all types of countries (e.g. low- to high-income, small to large, and at various levels of water stress)."

2.5.2 Scope of water quantity accounting

For this work, we assumed that the process of water quantity accounting would encompass the collection, collation, analyses, and presentation of water quantity data to inform freshwater management, planning, and policy development through time and across the landscape. We suggest that the primary purpose of water quantity accounting is to quantify the states of, and links between, freshwater flows and levels (e.g., river flows, groundwater levels, wetland levels, lake levels), water availability (under regional plans, consents, permitted activities, and other uses), and actual water use (measured and unmeasured) to inform on potential and actual flow-driven impacts on water-related environmental needs, human health needs, and economic uses for fresh water. Our perspective on water quantity accounting therefore aligns with the report of Bright et al. (2022), although our scope related to the water quantity aspects and did not include water quality aspects which were considered by Bright et al. (2022).

The effectiveness of water quantity accounting is influenced by the combination of available data, technical methods, and intended purposes. The process of water quantity accounting should therefore not be confined to analysis of whatever data are available but should encompass data collection and collation at one end and intended purposes at the other end (Figure 2-4).

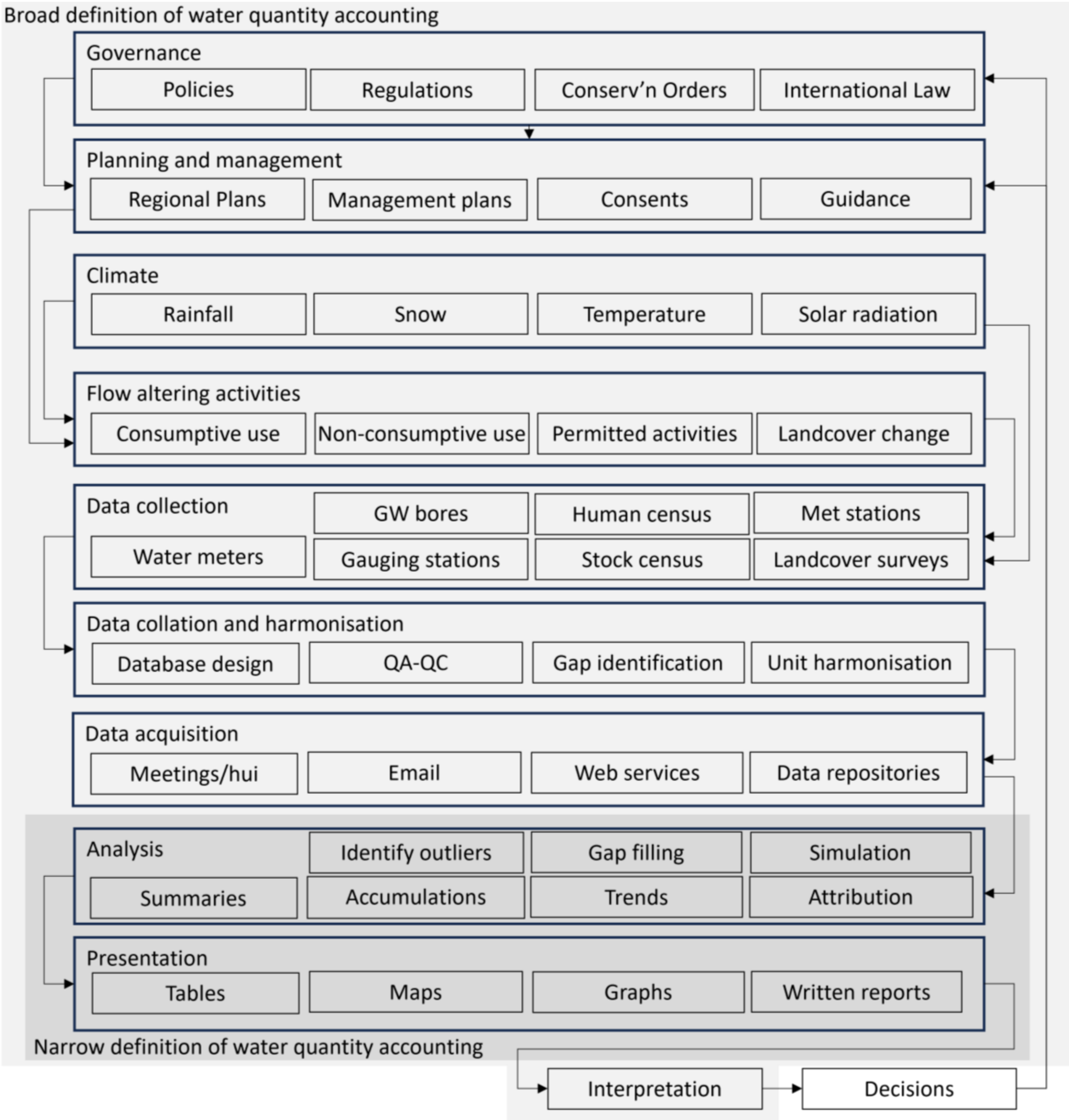

Figure 2-4: Conceptual diagram defining the scope of water quantity accounting. Note, all entities are independent of institutional arrangements.

2.5.3 Requirements for water quantity accounting

Globally, considerable scientific effort has been devoted to increasing the understanding of flow-ecosystem relationships to assist water resource managers. For example, much applied research has focused on defining environmental flow regimes recommended to sustain linked socio-cultural-ecological objectives (Arthington et al. 2018). Several approaches and methods are available for defining environmental flow regimes, although all are associated with significant uncertainties (Acreman et al. 2014; De Villiers et al. 2008). A similar situation exists for NZ.

Implementation of planning rules aimed to deliver environmental flow regimes has received relatively little attention (Dourado et al. 2023). Subsequent practical operationalisation of water allocation systems to deliver environmental flow regimes and protect environmental values is generally not well-researched except for downstream of impoundments (Poff and Schmidt 2016). In this context, water quantity accounting is needed to assess alteration of flow regimes and the degree to which environmental flows have been delivered. However, the devising, operation, and testing of water quantity accounting systems to fulfil their intended purpose has received little attention.

3 Input data and information

3.1 Data acquisition

Water quantity data were obtained from councils in two ways: a) direct provision of data by council staff; and b) by querying the LAWA water take consent data for each council using the Web Feature Service (WFS) Uniform Resource Locator (URL) provided by each council. The data requested from each council were as follows.

- Water resource consents, including information describing position, use, source, allowable rates of take etc.
- Restrictions on consent abstraction quantities, including information describing the conditions (e.g., low flow conditions) under which water could either not be taken at all (full restriction) or not be taken at the maximum consented rate (partial restriction).
- Daily recorded water meter data, daily river flows, and groundwater levels.

In addition to these data requested from councils, allocation limits were identified from active regional plans. Despite variability between councils, water resource use limits in plans are usually specified in terms of a “total allocation” (the maximum rate of abstraction summed over all abstractions), and a term often labelled as “minimum flow”. We noted that minimum flow is sometimes used to mean a flow that the council wishes to maintain, whereas the same term is also sometimes used to mean a cease-to-take trigger flow. In this work we use “cease-to-take” trigger flow to mean the river flow below which an abstraction (or group of abstractions) must cease. Inspection of regional plans revealed that various other forms of allocation limit can also be applied in addition to a total allocation and a minimum flow.

We discussed water quantity data availability with several regional authorities during the course of this work. The four councils we requested data from were: Hawke’s Bay Regional Council (HBRC); Marlborough District Council (MDC); Environment Canterbury (ECan); and Environment Southland (ES). These councils were selected by us in consultation with MfE to represent geographical areas where pressure on water resources was likely to be high due to high demand for water supply. However, the regions represent different settings in terms of water uses, climate, availability of water for supply, and administrative practices.

The process for collating water quantity data is illustrated in Figure 3-1. In response to our requests, councils provided data in two different ways. The first method was delivery of bespoke data files via email or file transfer, typically as excel spreadsheets or text files. The second method was by providing scripts to query a council server in order or obtain the data. We carried out queries and collated the data using the R programming language, and the Python programming language where it was needed to apply Python query scripts and python .pkl files provided by ES. Data were collated and harmonised according to a common schema outlined in Section 3.7. For each type of water quantity data sought (consents, restrictions, plan limits, meters, surface water flows, and ground water levels) the data that we obtained are summarised in Sections 3.2–3.6.

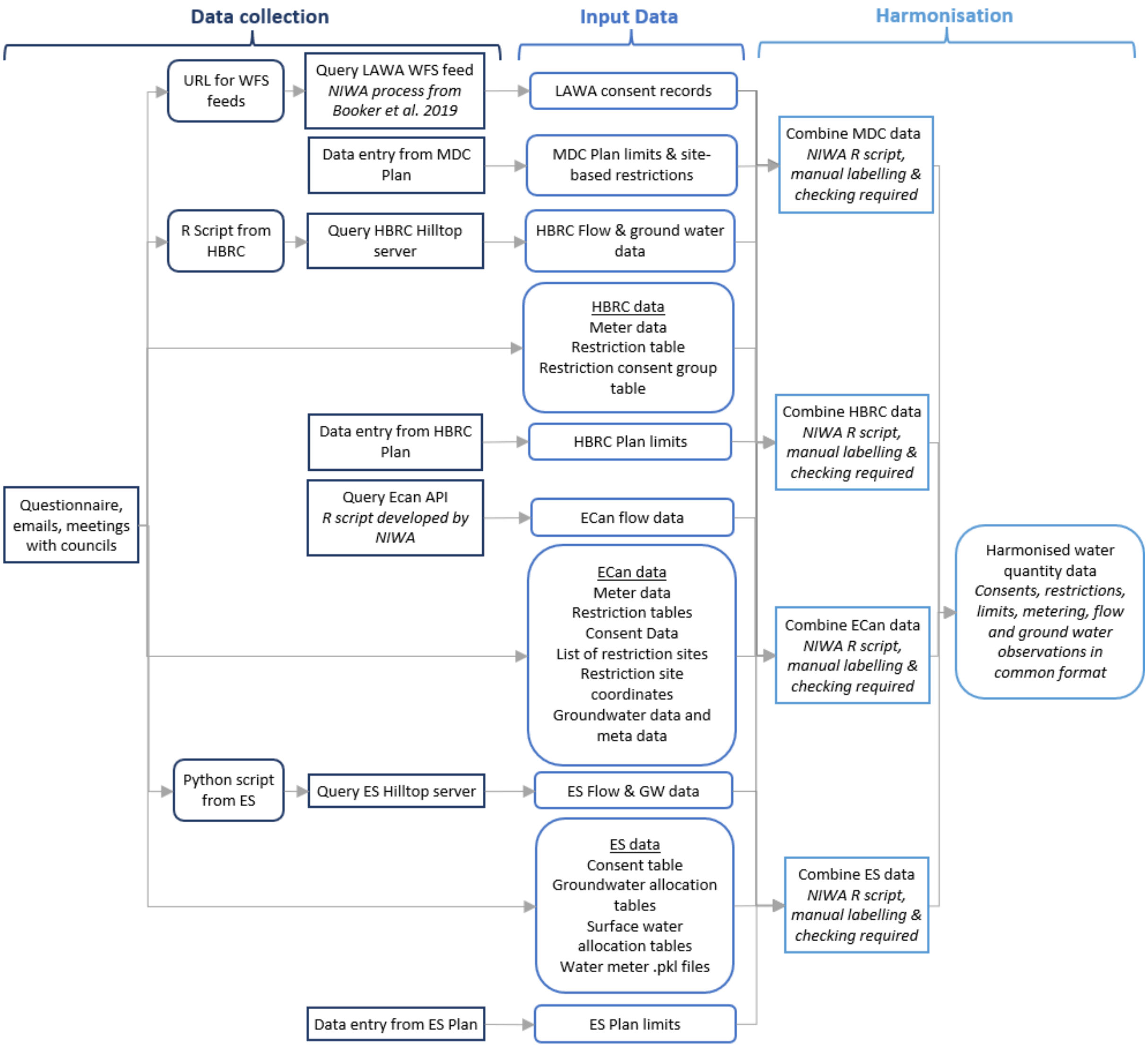

Figure 3-1: Process for collation of water quantity data from four councils.

3.2 Water resource consents

Resource consent data was successfully obtained for three of the councils by querying the council LAWA feeds on 21-Jun-2023: HBRC, MDC, and ES. As the ECan LAWA feed was non-operational at that time, a spreadsheet containing consent information was emailed to us instead. The ECan feed subsequently became operational, a new URL was provided to us, and all LAWA feeds were re-queried on 07-Mar-2024. The resource consent data provided is summarised in Table 3-1. The maximum allowable instantaneous rate of abstraction (maximum rate) and the maximum allowable volume during a water year (maximum annual volume) were important for our analysis.

Table 3-1: Summary of water resource consent data supplied by each council. * Note: HBRC included historical consents. ** These items are not exhaustive, commonly occurring features are included

		Council					
		HBRC	MDC	ECan		ES	
Source		LAWA	LAWA	LAWA	Council	LAWA	Council
Number of consent rows		11500*	1820	7002	7751	1123	1160
Qualitative Information**	Consent Identifier	✓	✓	✓	✓	✓	✓
	Primary source	✓	✓	✓	✓	✓	✓
	Primary Use	✓	✓	✓	✓	✓	✓
	Water management zone	✓	✓	✓	✓	✓	✓
	Ground water management zone	✗	✗	✓	✓	✓	✓
	Catchment	✓	✓	✓	✓	✓	✓
	Consent Status	✓	✗	✗	✗	✓	✓
	Consent description	✓	✗	✗	✗	✓	✓
	Bore identifier	✗	✗	✗	✓	✓	✓
	Creation / Publication records (e.g. date, time, creator)	✗	✗	✓	✗	✓	✗
Quantitative Information	Commencement & Expiry dates	✓	✓	✓	✓	✓	✓
	Maximum Annual	✓	✓	✓	✓	✓	✓
	Maximum Rate	✓	✓	✓	✓	✓	✓
	Coordinate	✓	✓	✓	✗	✓	✗
	Maximum Monthly	✗	✗	✓	✓	✗	✗
	Maximum Weekly	✓	✗	✗	✗	✓	✗
	Maximum Daily	✗	✗	✗	✗	✓	✓

The consent information provided was generally of a similar format, and with similar column names. However, for some councils specific pre-processing of consent information was required to harmonise data formatting. For ECan, consent data was provided from two sources. The council-provided table was used in the first instance. Any consents in the LAWA table that were missing from the council-provided table were then added. As the council-provided table was missing consent coordinates, these were obtained from the ECan map server "Resource Consents Active" layer. For ES, consent data was also provided from two sources. LAWA consents were used in the first instance as they contained consent coordinates. Consents in the council-provided table but not in the LAWA table were then added. No coordinates were obtained for these additional consents.

One limitation of the consent information we obtained is that it reflects a snapshot of the consent information at the time it was provided. Historical consents were not necessarily included, with the exception of HBRC, who provided a much higher number of consents than other councils because of the presence of many consents that have expired. Furthermore, some of the information provided for each consent is only relevant to the date of provision. For example, HBRC and ES provide a field describing “consent status” to identify surrendered consents, expired consents, and expired consents with s124 status (consents that are expired but may be exercised whilst a new consent is under application). We cannot know at what point this consent status came into effect from the available data, which means consent status cannot be considered for past time points whilst applying a historic analysis over a given period.

A further challenge for collation of the consent information provided to us was that for three of the four councils (MDC, ECan, ES), there were multiple entries for the same consent, whereas the LAWA format appears to be designed to represent each consent as a single row. In most cases of multiple entries for the same consent, it appears that replication was used to account for the same consent being linked to multiple water management zones. This may be a legitimate phenomenon in situations where a consent comprises multiple locations of take in multiple water management zones, or where abstraction affects both a surface water management zone and a ground water management zone. There also appeared to be instances of adding updated consent entries without removing the older entries for the updated consent.

Other specific considerations for the consent data for each council are given below.

Hawke’s Bay Regional Council

We noticed some HBRC consents have a maximum rate and maximum annual volume of zero. HBRC advised us that these are consents to allow future taking of water (e.g. once other consents have expired), but no abstraction is allowed until a future date, or consents where no water is allowed to be taken in a period, this could be a portion of the year where takes for certain activities are restricted (not allowed).

HBRC had some consents with a primary source labelled as “stream depleting”. HBRC advised that these are groundwater takes with some stream depleting effect, of various and potentially unknown magnitude. We treated consents with “stream depleting” as a primary source as being groundwater abstractions when calculating streamflow depletion and analysing consents. HBRC also had some consents with “storage” as a primary source. HBRC indicated that these abstractions come from a reservoir or some other form of storage. We treated consents with “storage” as a primary source as being surface water abstractions when calculating streamflow depletion.

Marlborough District Council

For MDC, 1% of consents had two rows (N=20). The two rows were identical except for the water management zone and catchment, each having a row for “Rarangi Shallow” and “Wairau” water management zone & catchment. To not account for these consents twice in the region-scale sums of this analysis, we only used the “Rarangi Shallow” rows.

Environment Canterbury

For ECan LAWA consent data, for 14% of consents (N=851) there appeared to be older consent information (creation date 12-06-2018) updated with some change to the consent information (creation date 06-03-2024). However, as the LAWA data were used only where there was no overlap with the council-provided data, none of the LAWA-provided consent data with this duplication issue were used in our analysis.

Additionally, the ECan data contained 792 consents (12%) where a single consent identifier was used for multiple rows for different primary sources and water management zones. In these cases, there was a maximum rate of abstraction for each primary source type, and a maximum annual volume for only one source type. Following communication with ECan staff, we understood that consents with their primary source labelled as "streamflow depleting" represented the part of each groundwater consent that should be considered as depleting surface water. We assumed that maximum rate for the region can be obtained by summing surface water rows and groundwater rows. We assumed that stream depleting rows should not be summed with groundwater rows because this would double-count their maximum rate. We noted that ECan's use of "streamflow depleting" contrast with HBRC use of the same term.

We noticed that all rows in the consent data provided by ECan whose primary source was stream depleting had a primary use labelled as industrial. Rows labelled stream depleting with another row with the same consentID were given the primary use from these matching rows.

Inspection of ECan consent data revealed that no consents had their primary use labelled as "hydroelectric", and many consents with large maximum allowable rates of take had their primary use labelled as "industrial". We used the ECan website to inspect the text in the written consent conditions for consents with maximum allowable rates of take greater than 1 m^3s^{-1}. We left one of these consents as "industrial" because it was described as "for the purposes of flushing and filling Lake Hood when the flow in the Ashburton River is at or above 15 cubic metres per second". However, we relabelled the primary use for several consents based on the written consent conditions as indicated in Table 3-2. This exercise demonstrated that there is ambiguity in definitions of primary use, and that some consents with high rates of abstraction are issued for mixed uses.

Table 3-2: Consents whose primary use was amended from industrial based on inspection of text in the actual consent.

ConsentID	Primary use	Written consent conditions from the ECan website
CRC233859	Irrigation	Stockwater and irrigation
CRC012006	Irrigation	for stockwater and irrigation supply
CRC052056.5	Irrigation	Glenroy Community Irrigation Company
CRC155937	Irrigation	Irrigation
CRC169499	Irrigation	To dam, divert, take and use surface water to supply the Montalto-Hinds Stockwater Scheme.
CRC172958	Hydroelectric	Lake Coleridge Power Station, WILBERFORCE RIVER
CRC173064	Hydroelectric	Lake Coleridge Power Station, HARPER RIVER
CRC173079	Hydroelectric	Lake Coleridge Power Station, HARPER RIVER
CRC173115	Hydroelectric	Lake Coleridge Power Station, LAKE COLERIDGE
CRC173172	Hydroelectric	Lake Coleridge Power Station, ACHERON RIVER

ConsentID	Primary use	Written consent conditions from the ECan website
CRC182542	Irrigation	to use water for irrigation and stockwater purposes, and to generate electricity at Montalto and Highbank Power Stations
CRC204470	Drinking	drinking water supply, and also Institutional, industrial, processing, stock water, amenity, irrigation use and fire-fighting activities.
CRC213528	Stock	Stockwater Race Network, Ashburton District
CRC905302.3	Hydroelectric	POWER GENERATION (Tekapo A Power Station).
CRC905308.2	Hydroelectric	TEKAPO-PUKAKI CANAL
CRC905324.1	Hydroelectric	Pukaki-Ohau canal
CRC905331.1	Hydroelectric	Ohau Canal from LAKE OHAU
CRC905338.1	Hydroelectric	into Ohau B Canal from Lake Ruataniwha

Environment Southland

For ES, there were five cases of consents (<0.5% of consents) with two distinct rows in the consent database. In each of these cases there were two consents that were identical except for primary source (one ground water, one surface water), water management zone, and location. We assumed that duplicates are intended to allow accounting for abstraction from different multiple water management zones. For our analysis, a single consent was chosen for each of these five cases, based on the apparent "primary source" from the written consent descriptions. If the primary source was unclear, we selected the groundwater option.

Some examples of the written consent conditions for these cases are as follows.

- "To take and use a total of 25,000 L/day of groundwater from Bore E46/1048 and surface water from Hedgehope Stream for a dairy operation at 2237 Winton Hedgehope Highway, Hedgehope".
- "To take and use up to 150,000 L/day of groundwater & 87,500 L/day of surface water for the purpose of a dairy operation at 1039 Five Rivers Lumsden Highway".
- "To take and use 135,000 L/day of groundwater/surface water for a dairy operation at Orepuki-Riverton Highway".

For ES there were also two consents (<0.5% of consents) labelled as "Non-consumptive surface water" under the primary source column. The consent description stated these were for gravel washing, and dredging. The maximum rate and maximum annual values in these two cases were changed to zero, to reflect the non-consumptive nature of these consents.

The coordinates of two consents (<0.5% of consents) supplied by ES were incorrect because they were located outside of New Zealand. These coordinates were set to NA.

Consent information about the Manapouri Power Scheme which abstracts water from the Southland Waiau at a very high rate, was provided to us by ES.

3.3 Restrictions on consented abstraction

Restrictions on consented abstraction were provided as tables from each council. The restriction information provided is summarised in Table 3-3. These data differed substantially in format between councils, and specific processing was required in each case. Further detail of restrictions for each council and specific processing is explained below.

Restrictions were categorised into two main groups: a) Restrictions that we labelled as "observation-based restrictions" because allowable abstraction on each day was restricted based on an observation of a specified environmental variable (e.g., flow) at a specified place (e.g., gauging station), and at a specified time (e.g., the day before); or b) Restrictions that we labelled as "predetermined restrictions" because allowable abstraction was predetermined from specified rules (e.g., seasonal volume, total allowable abstraction rate for a group of consents), which are independent from observed environmental conditions.

Table 3-3: Summary of data for restrictions on consented abstraction supplied by each council. Italics indicates why data were not obtained.

	Council			
	HBRC	**MDC**	**ECan**	**ES**
Source	Tables provided by council	Proposed Marlborough Environment Plan (version 15th Nov 2023)	Tables provided by council	Consent table provided by council
Description	A table of both predetermined restrictions and observation-based restrictions	A table of observation-based restrictions	A series of different tables for observation-based restrictions with links to consents	A table of consent information with a list of conditions for each consent in free text format
Number of observation-based restrictions × consents	4889	*Link between restrictions and consents not established*	33503	*Restrictions not readily extracted into a table for analysis*
Observation-based restriction site information	Site identifiers Site measurement type (e.g., Daily average flow) Coordinate	"Purpose" site identifier "Method" site identifier FMU	Site identifiers Catchment, Area Coordinate Whether active	
Observation-based restriction information	Upper limit Lower limit Restriction type (cease/normal/reduce)	Consent class that restriction applies to "Purpose" measurement type & minimum value "Method" measurement type & minimum value "Method" management action	Limit identifier Limit description Trigger quantity Restriction type (low flow / residual)	

	Council			
	HBRC	MDC	ECan	ES
Number of predetermined restriction limits	10592	*None provided*	*None provided*	*Restrictions not readily extracted into a table for analysis*
Predetermined restriction information	Consent identifier Consent Status Rule Scope Identifier for consent or consent group for restriction Restriction maxima Take season start & end	*None provided*	*None provided*	

Hawke's Bay Regional Council

For HBRC, a single table was provided containing restrictions. Some of these restrictions represented observation-based restrictions with a rule (either cease, normal, or reduce) which is enforced when a site flow is within a certain range. The remaining restrictions were rules that apply to consents/abstraction points/meters, or groups of consents/abstraction points/meters. HBRC advised us on provision of the data that only rules pertaining to consents or groups of consents are relevant to our water allocation analysis, so only these consent restrictions were used. Restrictions include rules that apply to consents or groups of consents for maximum instantaneous rates and periodic rates which are rates applied over various time periods (daily, weekly, per 28-days, monthly, seasonally, annually). Consent groups were identified from a separate table provided by HBRC.

Marlborough District Council

For MDC, the Proposed Marlborough Environment Plan contains a table of observation-based restrictions and plan minimum flows/levels. An excerpt of this table is shown in Table 3-4 as an example. Restriction rules are applied using "management method" flows/levels which are imposed upon consents, to attain a target flow regime, part of which is a minimum "management purpose" level. This plan information alone is not sufficient to apply these restrictions to consents, as consent classes are not known. MDC also have a table specifying observation-based restrictions designed to keep monitored aquifer conductivity levels within a specified range.

MDC provided data for linking consents to relevant restrictions for the Wairau Valley and Riverlands aquifers. However, due to time constraints on the project, it was jointly decided with MfE not to undertake the analysis.

Table 3-4: Excerpt from the proposed Marlborough environment plan Appendix 6, Schedule 3.

Freshwater Management Unit (FMU) *	Class	Minimum Flow or Level (Management Purpose)	Monitoring site or Method **	Management Flow or Level *** (Management Method)
Awatere	A	Minimum of 2.000 m^3/s at outlet to sea	Awapiri	Rationed below 2.300 m^3/s Fully restricted below 1.450 m^3/s
	B			Rationed below 5.600 m^3/s Fully restricted below 2.300 m^3/s
	C			Rationed below 9.500 m^3/s Fully restricted below 5.600 m^3/s

Environment Canterbury

ECan provided a series of tables: Low flow sites; Low flow sites × bands; Low flow sites × bands × consents; Active low flow sites × bands; Active Low flow sites × bands × consents. These tables contained overlapping combinations of the same restriction information. Additionally, a separate table for low flow site locations was also provided. The suitable table of active low flow sites × bands × consents was selected and used to obtain observation-based restrictions. Coordinates for sites were added from matching to the separate coordinate tables.

No further information was provided by ECan regarding predetermined restrictions, beyond the maximum rate, maximum annual, and water use consented monthly fields of the consent data. However, there were some cases of consent restrictions present in written consents which the consent database did not capture. We inspected 30 randomly selected consents, plus the 10 consents with the largest rates of allowable instantaneous rates of take to check consistency between wording of written consents issued to water users and the database delivered to us from ECan. We found that the database largely represented written consents well, but some details from written consents were inconsistent or absent from the ECan database. For example, many consents contained a type of “secondary restriction” in addition to the instantaneous rate of take. These secondary restrictions all took the form of a maximum volume of take that was allowable over a period, but that period varied between consents. For example, consents are restricted to a maximum allowable volume over periods of 7 days, 21 days, one month, etc.

Environment Southland

The restriction information provided by ES was a detailed consent database with consent conditions listed in free text format. These conditions included not just water quantity restrictions but also other conditions (e.g., monitoring requirements, administrative fees). Quantitative consent conditions included both observation-based restrictions and predetermined restrictions. However, converting this information to a data format suitable for a regional scale quantitative analysis would be highly labour intensive. It may be possible to use machine learning to text scrape numeric details from free text consents, but this would require a large controlled numeric dataset for training and testing. Some examples of consent conditions, expressed in various ways, are:

- “The rate of abstraction shall not exceed: 1. 1,200,000 litres per day; and 2. 7,000,000 litres per week.”

- "The rate of abstraction shall not exceed the abstraction rate specified in the following table, for the corresponding range of flow in the Makarewa River, as measured at the Councils river monitoring site at Counsell Road: Abstraction Rate Makarewa River Flow (m^3/second) m^3/day Litres/second > 2.0 6500 75 2.0 - 1.5 4333 50 1.5 - 1.0 2166 25 < 1.0 0 0 ". Note that the numbers given are intended to appear as a table in a pdf consent format.
- "No abstraction shall occur when flow in the Oreti River, as measured at Environment Southland's Lumsden Cableway monitoring site, is at or below 4.9 cubic metres per second."
- "Abstraction from bore F44/0075 shall cease when flow in the Mataura River at the Environment Southland monitoring site at Gore is less than 9m^3. "
- "Abstraction, other than for reasonable domestic use and for the reasonable needs of the consent holder's animals for drinking water, shall not occur when flow in the Otapiri Stream, as measured at the Environment Southland monitoring site at Otapiri Gorge, is less than 272 litres per second."

3.4 Metered abstractions

We refer to water abstraction meter time-series as "meter data". Meter data were directly provided to us by councils. Following our requests, councils were generally hesitant to provide meter data. Several councils noted that presence of gaps and noise in meter data might confound our analysis. Meter data that was provided is summarised in Table 3-5. Some councils provided specific information on the preprocessing of meter data, which is outlined below.

Table 3-5: Summary of water abstraction data supplied by each council. Italics indicates why data were not obtained.

	Council			
	HBRC	**MDC**	**ECan**	**ES**
Source	Table provided by council	*None used for analysis*	Table provided by council	Python .pkl files provided for each meter
Number of meters	2904		6598	84
Measurement frequency	Daily		Daily	Some sub-daily, some daily, some monthly or sporadic

Hawke's Bay Regional Council

Meter data were supplied by HBRC. This data was described as "semi processed" with data quality issues resolved by HBRC staff as they are identified. HBRC indicated to us that the data are checked for compliance, consistency with previous data, unexpected gaps (if there are no results where they are expected), spikes, negatives and some checks with meter readings where these are provided. HBRC indicated that gap filling hasn't been applied. They indicated that where telemetry fails there is an expectation (and consent requirement) that daily records are kept, and these get recorded on a different data source.

During our analyses, we noticed that the meter data contained no missing values. From the description of the meter data checking process provided by HBRC, we understand that this reflects that the data genuinely does not have gaps after they have been semi-processed by HBRC to resolve issues as they are found.

Marlborough District Council

MDC conducted quality checks on water meter data for the Riverlands aquifer FMU and Wairau Valley Wairau River takes, to supply data for this study. However, in consultation with MfE, the NIWA project team decided not to include MDC's water meter data analysis in this work due to time constraints.

Environment Canterbury

We received meter data from ECan, and also a description of how raw meter data is processed by ECan. This description is summarised below:

- Data from meters are received as either an instantaneous volume, incremental volume, or flow. Negative abstractions are filtered out, then all measurements ≥ zero are converted to a daily volume (m^3). Where multiple measurement types are available for the same user, instantaneous volumes are used in preference, followed by incremental volume, followed by flow. There are some single abstraction points with multiple meters that send in individual datasets, which are summed to make a single time-series of total daily abstraction.

- For some sites, data is received from multiple sources/service providers. When on a given day one meter reads zero and the other non-zero, the non-zero value is used. Where the meters both have non-zero measurements, then one of the two potentially valid values must be selected. The percent difference between the options is used: if the percent difference is ≥100% then the smallest daily volume is used. If the percent difference is ≤100% then the maximum daily volume used.

- In the case of gaps in meter data time-series, these are filled with zeros, and flagged as a gap. Meters are then matched to the water abstraction point dataset (and thus to consents). Those that cannot be matched are excluded. The maximum rate for that abstraction point is then used to flag erroneous data by flagging values >10 times the maximum rate.

- One limitation of this data is that due to the same water abstraction points being used for different activities (e.g., measuring river flow, discharges) it is possible that non-abstraction data has been linked to a valid water abstraction point, and has not been filtered from the source. Additionally, abstraction data where there is no "active" consent can occur where the abstraction data starts before the start of the consent (or before the consent was "given effect to").

- Meter data from the most recent year is incomplete because some meter data is received as manually downloaded abstraction data from some consent holders. These missing data does not get received by ECan until the end of the water year (end of June).

For our analysis, missing data filled with zeros by ECan's internal processing were removed, so that they were treated as missing rather than zero.

Environment Southland

ES noted that they are still in the process of establishing a procedure for processing metered data. Currently, negative spikes are removed, and positive spikes are flagged where it is known that an error/misread/instrument failure has occurred, sometimes after making contact with the consent holder.

For ES, some meter records were sub-daily, in which case they were summed to represent daily values.

We note that meter data was received for only 84 meters for ES. Fewer meter data would be expected for ES than HBRC or ECan due to differences in climate, but it is also possible the lack of meter data from ES reflects a technical issue such as incomplete data upload/transfer of the requested data.

3.5 Plan limits

Plan water allocation limits were identified from publicly available regional council plans. We inspected the plans for tables where water allocation quantities are explicitly stated. For ES, surface water limits are not tabulated but the method to calculate them is stated. ES provided water allocation excel spreadsheets, containing groundwater and surface water limits, and allocated totals relative to the limits. This council-provided data was used in preference as it contained more detail. The plan limit information identified for each council is summarised in Table 3-6.

Table 3-6: Summary of plan limits for each council. Italics indicates why data were not obtained.

	Council				
	HBRC	**MDC**	**ECan**	**ES**	
Sources	Hawke's Bay Region Resource Management Plan (RRMP)	Proposed Marlborough Environment Plan (pMEP, version 15th Nov 2023)	Canterbury Land and Water Regional Plan (LWRP)	Proposed Southland Water and Land Plan (pSLWP)	Council-provided water allocation tables
Groundwater limit area	3 Ground water allocation zones & 1 zone pair	21 ground water sites	Groundwater zones, groundwater sites *(not counted)*	32 Groundwater allocation zones	32 Groundwater allocation zones
Groundwater limit quantities	Maximum annual volume	Ground water level	Maximum annual volume Minimum levels	Maximum annual volume	Maximum annual volume, actual allocation volume, volume under application
Surface water limit area	38 flow sites 3 Surface water allocation zones & sum of all zones	21 surface water sites	Surface water zones *(not counted)* Flow sites *(not counted)*	*None explicitly listed in plan*	18 Rivers
Surface water quantities	Site minimum flow, maximum weekly volume , maximum allocatable rate, maximum daily direct take Zone direct take maximum rate, stream-depleting maximum rate, combined maximum rate	Flow	Minimum flows Maximum allocatable instantaneous rate	*None explicitly listed in plan, method for calculation provided*	Maximum allocatable rate (Q_95*0.3) for rivers with a flow gauge, and currently allocated rate
Combined limit areas	*None*	49 Catchment/FMUs	Combined surface water and groundwater allocation zones	*None*	*None*
Combined limit quantities	*None*	Max daily volume Max annual volume	Maximum annual volume	*None*	*None*

Generally, the plan limit information took different formats between councils, and tables required manual work to interpret, harmonise, and populate into a harmonised database, including applying unit conversions, reading free entry information, and restructuring limits tables to represent a single limit in each row.

For ECan, there were more than 35 different tables in the LWRP pertaining to water allocation, split across different sub-regions. Tables specifying plan limits had different formats and content, and therefore not easily entered into a database for regional-scale analysis. ECan plan limits typically included annual volumes for ground water allocation zones, instantaneous allocation rates for rivers, and minimum flows for rivers. Plan limit minimum flows were sometimes tiered for different permit levels or defined seasonally. An example of the complexity of plan minimum flows if demonstrated in Table 3-7.

Table 3-7: Example of water allocation table from LWRP.

Table 14(za): Pareora Freshwater Management Unit Environmental Flow and Allocation Regimes

River or Stream (see Planning Maps)	Location of recorder site, or site where flow is measured	NZTM Map Reference	Minimum flow and restrictions for A permits (L/s)	Minimum flows for takes to storge from the A permit Allocation Block (L/s)	Allocation Limit for A permits (L/s)	Minimum flow for B permits (L/s)	Allocation limit for B permits (L/s)
Pareora River (including all tributaries)	The Huts flow recorder	5080683N 1445353E	When Timaru District Council is discharging additional water: **Oct-Nov** 540 L/s – 50% restriction in maximum rate of take 440 L/s – total cessation of take **Dec-Sep** 470 L/s – 50% restriction in maximum rate of take 400 L/s – total cessation of take When Timaru District Council is **not** discharging additional water: **All months** 470 L/s – 50% restriction in maximum rate of take 400 L/s – total cessation of take	1,600 L/s Note: only that portion of the A Block available above the A Permit minimum flow for takes to storage may be abstracted	198 L/s	5,00 L/s Note: only that portion of the B block available above the B Permit minimum flow may be abstracted	2,500 L/s (of which no more then 500 L/s can be allocated upstream of the recorder)

Not all planned limits are stated in regional plans. For example, for HBRC, the TANK plan change (Tūtaekurī, Ahuriri, Ngaruroro, and Karamū catchments) is not in the RRMP. For another example, our discussion with ECan indicated that there are six additional catchment plans and four water conservation orders specifying further plan limits. For ES, the Mataura and Oreti water conservation orders specify additional limits for the Mataura and Oreti catchments, respectively. We did not consider limits in additional catchment plans and water conservation orders for this regional-scale analysis, due to the labour-intensive nature of collating this information.

HBRC has a water allocation tool displaying consented allocation against plan limits. A snapshot of the data from this tool was provided to us. Each of 37821 rows in this snapshot contained consent information, the associated plan and catchment, stream depletion effects, and how the consent contributes to the planned allocation limits. On provision of this tool, HBRC indicated that “there is complexity in comparing consented totals to allocation limits as we have numerous allocation frameworks operating and each plan has different criteria."

3.6 Flow and Groundwater level data

Flow and groundwater level time-series were obtained from each council. Councils had a process for querying their server to obtain this data, except for groundwater data for ECan which was transferred by email. The data obtained are summarised in Table 3-8 and Table 3-9.

Table 3-8: Summary of groundwater data supplied by each council. Italics indicates why data were not obtained.

	Council			
	HBRC	**MDC**	**ECan**	**ES**
Source	Server query, script provided by council. All sites queried.	*None used in analysis*	Tables provided by council	Server query, script provided by council with list of sites
Number of sites	104		613	21
Specific pre-processing	None		None	Sub-daily records averaged to mean daily

Table 3-9: Summary of flow data supplied by each council. Italics indicates why data were not obtained.

	Council			
	HBRC	**MDC**	**ECan**	**ES**
Source	Server query, script provided by council. All sites queries.	*None used in analysis*	Server query via API	Server query, script provided by council with list of sites
Number of sites	85		90	32
Specific pre-processing	Unit conversions applied as relevant		Only restriction sites queried QC 400 excluded Sub-daily records averaged to mean daily	Unit conversions applied as relevant Sub-daily records averaged to mean daily

MDC prepared river flows and groundwater levels for the Riverlands aquifer FMU and Wairau Valley Wairau River to supply data for this study. However, in consultation with MfE, the NIWA project team decided not to include MDC data analysis in this work due to time constraints.

3.7 Common water quantity data structure

The data provided by each council were sorted into a common format shown in Table 3-10. This format was based on the information that was present, how this somewhat disparate information could be unified, and what data were necessary for analysis of allocation, restrictions, and limits. The format we applied for data harmonisation was much less extensive that of Booker et al. (2015), reflecting that not all data required for the schema in Booker et al. (2015) were provided.

Table 3-10: Common format for water quantity data.

Table	Data label
Consents Contains information for each consent	consentID, identifier for each resource consent PrimarySource, primary source of consented water take PrimaryUse, primary use of consented water take WaterManagementZone, water management zone for consent Catchment, catchment for consent CommencementDate, ExpiryDate, start and end date of consent MaxRate, maximum consented rate of take (L/s) MaxAnnual, maximum annual take volume (m^3/year) Latitude, longitude, WGS84 coordinate
Meter data Contains time series from each water meter	meterID, identifier for each meter Date, day of observation Value, volume of water abstracted that day (m^3/day)
Meters to consents Links meters with a consent	meterID, links to a meter in the meter database consentID, links to a consent in the consent database. One or more consents may be associated with each meter, and vice versa
Groundwater /Surface water data Contains time series from each groundwater site/ surface water site	siteID, identifier for each bore/ flow gauge Date, day of observation Value, mean daily value for groundwater level (m) / flow (m^3/s)
Ground water /Surface water sites Contains coordinate for each site	siteID, identifier for each bore/ flow gauge Latitude, longitude, WGS84 coordinate
Site limits Contains limits associated with a certain groundwater or flow site	siteID, identifier for each bore/ flow gauge associated with limit bandID, Identifier of limit band for a site limitLower, limitUpper, band lower and upper bounds, in same units as groundwater/surface water values

Table	Data label
	Rule, rule to be applied when within limit bounds e.g., “Cease” or “Restrict” Latitude, longitude, coordinate for site
Site limits to consents Links consents to site-based limits	siteID, matches to siteID in site limits database bandID, matches to bandID in site limits database consentID, matches to consentID in consents database
Consent limits Contains additional limits associated with consents or groups of consents	consentID, matches to consentID in consent database RuleQuantity, name of physical quantity restricted by the rule e.g., Max Daily Volume RuleValue, quantity of restriction RuleScope, specifies what the rule applied to e.g., a single consent, a group of consents, consents that cannot be used together RuleSeasonFrom, RuleSeasonTo, specify days of year that the rule applies ScopeConsents, lists consentID (or multiple consentIDs for groups) that the rule applies to
Plan limits Contains limit quantities specified in plan	limitAreaID, identifier for limit area limitAreaType, whether limit is associated with catchment, water management zone, siteID etc. limitValueType, whether limit is a rate, annual allocation, minimum flow etc. limitValue, quantity of limit commencementDate, expiryDate, for which limit applies OR start & end month for seasonal limits

3.8 Data related to permitted abstractions

In addition to water takes under resource consents, Section 14(3)(b) of the RMA permits the take and use of water for certain activities without the need to obtain a resource consent. These are known as 'permitted takes.' This allows for water to be taken for an individual's reasonable domestic needs and stock water, provided that the use does not, or is not likely to, have an adverse effect on the environment. To implement the RMA statutory requirements, regional councils often specify in a regional plan the quantity of water that can be taken without a resource consent.

These unconsented water take types are:

- Permitted takes under RMA S14(3)(b).
- Permitted takes under regional/district plans.

Section 3.29 of the NPSFM 2020 requires every regional council to operate and maintain a freshwater quantity accounting system. Clause S3.29(7) states that "In this clause, freshwater take refers to all takes and forms of water consumption, whether metered or not, whether subject to a consent or not, and whether authorised or not."

Water use under permitted and S14(3)(b) activities is often not measured due to the absence of reporting requirements. Nonetheless, the proportionate water usage in permitted activities can be substantial, particularly in rural areas, as observed in regions such as parts of Waikato (WRC 2007) and Banks Peninsula, Canterbury (LAWA 2021). Consequently, these water abstractions need to be estimated to comply with water accounting requirements under the NPSFM 2020. Several regional councils have developed methods to estimate water use under permitted activities. For example, Waikato Regional Council has developed a model for predicting the peak summer permitted and S14(3)(b) surface water use.

In this work, we develop a nationally applicable model to estimate water abstraction under permitted takes. We use the following datasets and information:

- 2018 population census by meshblocks from Statistics NZ (Stats NZ).
- Reticulated water supply area data from 67 district and city councils. These data were collected and modified to improve spatial accuracy using auxiliary data such as building footprints by Puente-Sierra et al. (2023).
- Daily water for human requirement based on a national study on water use in New Zealand (LEARNZ 2024).
- Livestock numbers for four stock types representing the majority of stock water use (sheep, dairy cows, beef cows, and deer) comprising 960 hexagonal grid cells (35,000 ha) from Stats NZ's 2017 Agricultural Production Census (APC; Stats NZ 2024). We use the dataset developed by Snelder et al. (2021) by combining the low-resolution APC stock numbers with high-resolution grazed grassland (combining high- and low-producing subcategories) from the Land Use and Carbon Analysis System (Newsome et al. 2018) to assign the likely spatial distribution of stocks.
- Livestock water demands including daily shed needs from Stewart and Rout (2007), who reviewed the scientific literature and established standard estimates of stock water requirements of a range of farm animals.

In this work, we do not estimate the permitted water abstractions for emergency purposes such as firefighting.

4 Methods

4.1 Analysis dates and periods

Some of our consent and water use analysis was conducted for a given date (e.g., what consents were active on a particular date), whereas other consent and water use analysis was conducted for a given period of time (e.g., what abstraction occurred over a particular two-year period). Where results are presented for the status on a given day, the analysis date of "14-Feb-2023" was used. This date is consistent with the day of the year used by Booker et al. (2018). Where results are presented for a given period of time, the analysis period was 1-Jul-2021 to 30-Jun-2023. We chose this analysis period after having considered four points raised by regional council staff during the course of our work: 1) consent information was only available for a recent snap-shot in time for some councils; 2) not all water meter data are instantly available, therefore any analysis must lag behind the date of data acquisition; 3) more water quantity data of better quality should be available for recent times compared to historical times; 4) analysis of more than one year is preferable due to year-to-year variability in the data. We judged that 1-Jul-2021 to 30-Jun-2023 was: 1) sufficiently recent to the acquired consent data; 2) not too near to the date of data acquisition to be problematic due to lags in acquiring water meter data; 3) not too long ago to be unrepresentative of current plans and water use practices; and 4) covered two years that might have contrasting weather and water user behaviour.

Data were filtered to remove consents not active at any point within the analysis period. Subsequently, meter data, consent restrictions, observation-based restrictions and the linking databases were filtered to include only items associated with active consents. Meter and flow time-series were trimmed to include only data within the analysis period.

For the streamflow depletion analysis, we utilised a period from 2013 to 2023 to accommodate longer response times resulting from groundwater abstractions. Our analysis of model outputs focused on the period from 2018 to 2023. We excluded the first five years modelled (2013-17) because that period was considered to be influenced by abstractions from previous periods (i.e., prior to 2013).

4.2 Water resource consents

Consent data was processed using a similar procedure as Booker and Henderson (2019).

Primary uses were grouped into one of seven categories: Hydroelectric, Industrial, Irrigation, Frost Protection, Drinking, Stock and Mixed/Other. The categories expand on those for Booker and Henderson (2019) to include frost protection and stock water, each of which were included as categories for three of the four councils. The category definitions used are shown in Table 4-1.

Table 4-1: Groups used to define consent primary use.

Primary Use	Raw primary use			
	HBRC	MDC	ECan	ES
Hydroelectric	Hydro	Electricity generation	Hydro	Hydro
Industrial	Industrial	Industrial	Industrial	Industrial, meat works, mining works, gravel wash, dredging
Irrigation	Irrigation	Irrigation Winery	Irrigation	Irrigation, pasture irrigation, horticulture irrigation
Frost protection	Frost Protection	Frost Protection	Frost Protection	*None present*
Drinking	Drinking	Domestic Municipal	Drinking	Drinking, water supply – rural, water supply - town
Stock	Stock	*None present*	Stock	Stock
Mixed / other	Combined / mixed, other, not specified	Monitoring, communal scheme, ancillary use Various combinations of the following uses: ancillary use, domestic, irrigation, vineyard spraying, commercial, winery, industrial, electricity generation, frost protection, storage, stock water	Not Specified	Not specified, dairying – cows, stockwater & pasture irrigation, recreational, pump test, stockwater & domestic

Whilst checking consent maximum rates and maximum annual values, we found that 3.3% (475/14376) of consent rows had a maximum rate and maximum annual volume of NA or zero. These cases could be consents where these values are meant to be zero, because the consent is non-consumptive, or they could be cases where there is missing data. The consents are included in analysis and counted toward numbers of consents, but not towards accumulated maximum rates or maximum annual volumes.

Maximum rate and maximum annual volumes associated with consents were checked. Where one of Maximum rate and maximum annual volume is zero or missing, and the other is non-zero, they were filled by conversion of the maximum annual into an instantaneous rate, or vice versa. This was the case for 22.7% of consent rows (3270/14376).

We analysed consents by plotting and mapping consent quantities (maximum annual volume, maximum rate), primary source, primary use and expiry and commencement dates.

4.3 Restrictions on consented abstraction

We checked observation-based restrictions, and then calculated whether these restrictions were active for each day of the analysis period. Restriction upper limit values are a trigger flow necessary for calculating if the restriction is active, and any restrictions with a missing upper limit were removed. Restriction lower limit values allow a restriction to be inactive if flow falls below a low trigger value. Where missing, restriction lower limit values are assumed to be zero i.e., the restriction is active at any flow below the trigger flow. We note that upper and lower limit values can be used to apply different levels of restriction over a wide range of flows.

A time-series of whether a restriction is active was calculated for each restriction at each site with associated gauge observations. The restrictions for a given day were calculated using flow on that day. In practice, restrictions may be based on flows averaged over a sliding window, or with a lag period beforehand e.g., average of the last seven days, the day prior. In the absence of detailed information of how observed flows are used to obtain trigger values, we opted to use a simple assumption of flows on that day. On days where observation values are missing, it is assumed that this lack-of-data reflects an actual lack of valid monitoring data, and that the restriction cannot be enforced. The result is a time-series for each observation-based restriction of when it is active.

We compared restriction trigger values to actual river flows by considering the observed median flow during the analysis period for each limit with an associated flow time-series. We also compared restriction trigger values to naturalised 7-day mean annual low flow (MALF), by associating each restriction coordinate with a segment of the digital network (using the process described in Section 4.5.1). We then used the estimated MALF for that segment from Booker and Woods (2014). During inspection of the sites we noticed that site “SW_266401 / Waimakariri River” was incorrectly located on a smaller side stream by our automated procedure and this error was amended.

We checked predetermined restrictions where possible by comparing them to the consent database maximum rate and maximum annual volume. These values were not always identical, and where different, the strictest rule has been applied.

We applied observation-based and predetermined restrictions to consents, with the goal of calculating the maximum instantaneous rate of abstraction for each consent on each day.

For each consent, a time-series was created containing values for each day of the analysis period that the consent is active. On days the consent is active, the consent limit is first assumed to be its maximum rate from the consent database. Next, if the consent is associated with any active observation-based restrictions, an adjusted instantaneous rate is calculated according to the rule for that restriction. Rules are assumed to act as follows:

- Cease, Low flow: No water may be taken,
- Normal: No change to the maximum rate,
- Reduce: Half the maximum rate may be taken. This is an approximation as explained below.

The "Reduce” rule is used by HBRC to stepdown allowable consented rate to avoid flows reaching the cease flow, or to allow permitted use but ban irrigation. Rules for stepping down consents are written into consents but were not available to us in quantitative form, thus, we have approximated it as allowing half the consent maximum rate.

If the consent has any predetermined restrictions that apply to its maximum rate or daily allowable volume, these restrictions are imposed. Some predetermined restrictions are a seasonal restriction or set of seasonal restrictions. In these cases, it is assumed outside the specified seasons, the allowable abstraction is zero. For restrictions that apply to groups of consents, the allowable rate for any given consent is the maximum rate of the rule. Thus, each consent is restricted to the maximum it could abstract, even if not all consents can simultaneously use the full abstraction rate. This is an example of a rule that is challenging to impose in a real-time water quantity accounting system because allowable abstraction depends on abstraction from other consents/consent-holders.

Of the calculated allowable rates from: a) the consent maximum rate; b) observation-based restrictions; and c) predetermined restrictions, the most restricted option is chosen for each day resulting in a time-series for each consent with the instantaneous rate of abstraction for each day.

Our approach to calculating restriction obtained the allowable instantaneous rate for each consent on each day. This is useful for assessing maximum potential abstraction on a given day, or for compliance checking. However, actual allowed water abstraction may be less because of periodic restrictions. These are restrictions where a maximum abstracted volume is defined for a period of time, such as maximum annual volumes and maximum weekly volumes. Such rules cannot be included in daily restrictions because it is impossible to calculate what should be allocated on any given day without knowing historic use and predicting future use. The situation is further complicated where restrictions are linked to multiple consents, and it is unclear how much allocation should be attributed to each consent.

4.4 Metered abstractions

4.4.1 Identifying potential errors in abstraction time-series

The time interval of meter readings was checked. Daily meter data was requested, and any sub-daily meter data was merged into daily values during pre-processing. However, some records had a greater-than-daily sampling interval. A meter's records were removed if there was not at a daily interval for at least 50% of the measurements.

Meter time-series were checked and potential erroneous data were flagged. Flagged values included negative values, periods of three or more days with an identical non-zero value ("flatline"), periods of three or more days with a constant gradient ("ramp"), and high values greater than 10 times the maximum allowable rate. Where multiple consents are associated with one meter, the maximum allowable rate was the sum of the maximum rates of all associated consents. If the maximum allowable rate for a meter was zero or NA, high values could not be flagged. All flagged meter values were set to NA.

4.4.2 Infilling of incomplete abstraction time-series

To infill meter timeseries, we required meters to have an associated site and less than 50% of their daily values missing for the period 1 July 2021 to 30 June 2023. We used the centroid of the locations of associated consents as the site for each abstraction meter. If no site was identified, the meter time-series was not infilled.

For each abstraction time-series, we fitted a statistical model to describe patterns of daily abstraction as a function of concomitant (present) and antecedent (past) rainfall and temperature from the virtual climate station network (VCSN) (Tait and Woods 2007; Tait et al. 2012; Tait and Macara 2014). We surmised that abstractions may be influenced by concomitant and antecedent weather conditions, therefore we derived several variables representing antecedent weather conditions to use as predictors. We applied a weighted interpolation to obtain daily rainfall and temperature time-series for each meter site from the nearest four VCSN grid points. Mean daily temperature was calculated as the average of minimum and maximum daily temperature. We subsequently calculated the local rainfall and temperature averaged over the preceding 7 and 30 days for each site.

We fitted statistical models to predict missing daily abstraction as a percentage of maximum allowable rate for that site after having applied our automated procedure to filter out values identified as being possibly erroneous. We used concomitant, 7-day-averaged and 30-day-averaged values of both rainfall and temperature as predictors. The output from each statistical model represented expected daily abstraction at a specified site given weather conditions present during the modelled period.

The random forest method that we applied uses machine-learning by combining many regression trees into an ensemble to produce more accurate regressions. It does this 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). Independent predictions (i.e., independent of the model fitting procedure) are made for each random forest 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 can be used to subsequently derive estimates of the predictive performance of the model for new cases (Breiman 2001). For example, predictive performance metrics are often calculated from the OOB predictions to provide an estimate of generalization error (i.e., the predictive accuracy of the model for cases that are independent of the model-fitting procedure; 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 as has been applied in previous studies (e.g., Booker 2013; Booker and Woods 2014; Booker and Whitehead 2018).

We compared measured daily values with their OOB predicted equivalents within each site to test ability of the models to predict within-site daily patterns of take.

We calculated the coefficient of variation (r-squared), Nash-Sutcliffe Efficiency (NSE), model bias (bias), root-mean-square-deviation (RMSD), and number of samples (n) for each site to evaluate OOB predictive performance of the models. R-squared is the proportion of variance in the dependent variable that is predictable from the independent variables as processed by the statistical model (Anderson-Sprecher 1994). R-squared of zero indicates that predictions explain no variation in the observed data whereas r-squared of one indicates predictions that explain all variation in the observed data. 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 can vary between one and negative infinity with zero representing a model that is no better than a constant prediction at the mean flow value, and one representing perfect predictions. Bias is the tendency of the simulated data to be larger (negative bias) or smaller (positive bias) than their observed counterparts on-average (Gupta et al. 1999). Bias values of zero represents a model performance that is unbiased. RMSD is the square root of the average of the squared errors (Hyndman and Koehler 2006). RMSD represents the difference between observations and predictions on-average across a dataset. See Moriasi et al. (2007) for further discussion of various model performance metrics.

We obtained complete time-series for the period 1 July 2021 to 30 June 2023 by replacing missing or flagged abstraction values with those predicted by our models for each take time-series. We labelled the complete times-series as the "filled" time-series.

4.4.3 Linking metered abstraction to consents

To estimated metered abstraction for each consent on each day we needed to add up metered abstraction where multiple meters are related to a single consent, and then divide metered abstraction where multiple consents are related to a single meter. A given consent may be linked to multiple meters, and some of those meters may also be linked to other consents.

For each meter, the quantity abstracted was divided amongst the linked consents. Abstraction was assigned to consents proportional to the maximum annual volume for each linked consent. If a consent was linked to multiple meters, the annual volume for that consent was divided by the number of meters for than consent. Last, if any of the consents linked to the meter had a zero or missing maximum annual volume, the abstraction was divided evenly between consent holders.

There are considerable limitations to our approach for apportioning metered abstraction:

- We assume each consent holder on each day abstracts water from shared metered abstraction points in a manner proportional to their maximum annual volume. Our method did not recognise that maximum annual volumes may have different headroom for different consents, and that abstraction requirements each day will differ to for different water uses and management practices. Our method did not recognise that not all associated consents are necessarily active on each day.
- We assume multiple meters linked to a consent represent different measured abstractions. Were this assumption to be incorrect, the effect would be to overestimate abstracted volume. ECan indicated that our assumption would be inappropriate where multiple meters report the same abstraction record, but also stated that such cases, where known, had been merged during preprocessing.
- We assume each consent uses each metered abstraction point evenly. This does not recognise that consent holders may have a preferred abstraction point, rather than operating multiple abstraction points evenly.
- We assume meters use can be assigned to a consent only if a consent is active. This does not recognise the consents may continue to operate under s124.

Given these limitations, per-consent analysis of abstraction is approximate and should be treated with caution. However, aggregate analysis of abstraction should represent overall consent-holder abstraction behaviour.

4.5 Mapping accumulated pressure

The total upstream accumulated allowable rate of take standardised by naturalised median flow for of each segment in the New Zealand river network was calculated and mapped to provide an indicator of pressure on stream flows (hereafter we refer to this metric as "accumulated pressure"). Maps of accumulated pressure reflect the likely proportional reduction in flow that would result from abstraction. The accumulated pressure on the river network associated with consent quantities (e.g., maximum allocated rate, metered abstraction) was mapped using the same method as Booker et al.

(2019). We accumulated several different quantities using the accumulated pressure method from Booker et al. (2019). Booker et al. (2019) mapped accumulated consent maximum rate of abstraction, which represents a worst-case scenario in which all consents are exercised simultaneously at their maximum instantaneous rates. We included further scenarios to account for the role consent restrictions, and differences between actual and allowable abstraction:

- Consent instantaneous allowable rate (accounting for restrictions)
  - a) On average across the analysis period (1 July 2021–30 June 2023)
  - b) On the "lowest-flow" day for each region
- Metered abstraction rate
  - c) On average across the analysis period (1 July 2021–30 June 2023)
  - d) On the "lowest-flow" day for each region

The "lowest-flow" day was defined separately for each region as the day for which the highest number of surface water restrictions were active. Whilst the timing of lowest flows differs between rivers, this criterion aims to identify on a region-wide basis the day where surface water availability is most limited.

For mapping accumulated pressure, consents have been analysed excluding hydropower use, which is of a much larger magnitude that other uses. For an analysis of pressure from hydropower, see Booker and Henderson (2019).

A summary of the methods from Booker et al. (2019) for accumulating consent quantities onto the river network is described in the remainder of this section.

4.5.1 Mapping consents onto the river network

Co-ordinates describing a location were supplied for each consent. Each non-hydropower consent was assigned to one (for surface water abstraction) or many (for groundwater abstraction) segments of the Digital Network version 2.4 (DN2.4) using an automated procedure.

Each consent with a primary source of "groundwater" was associated with all segments on DN2.4 whose centroid was within a 2000 m radius of the coordinates for the consent. This method assumes groundwater abstraction would deplete river flows within the specified radius (Figure 4-1).

Each non-hydropower consents with a primary source of "surface water" was assigned to a single segment on DN2.4 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 seven-day mean annual low flow (MALF) from Booker and Woods (2014) was assigned to the consent (Figure 4-1). This method was used in an attempt to avoid incorrectly associating surface water takes with very small streams, and therefore overestimating the effect of abstraction. Booker et al. (2019) manually assigned hydropower consents to a segment of DN2.4, and the same assignments were used for this analysis.

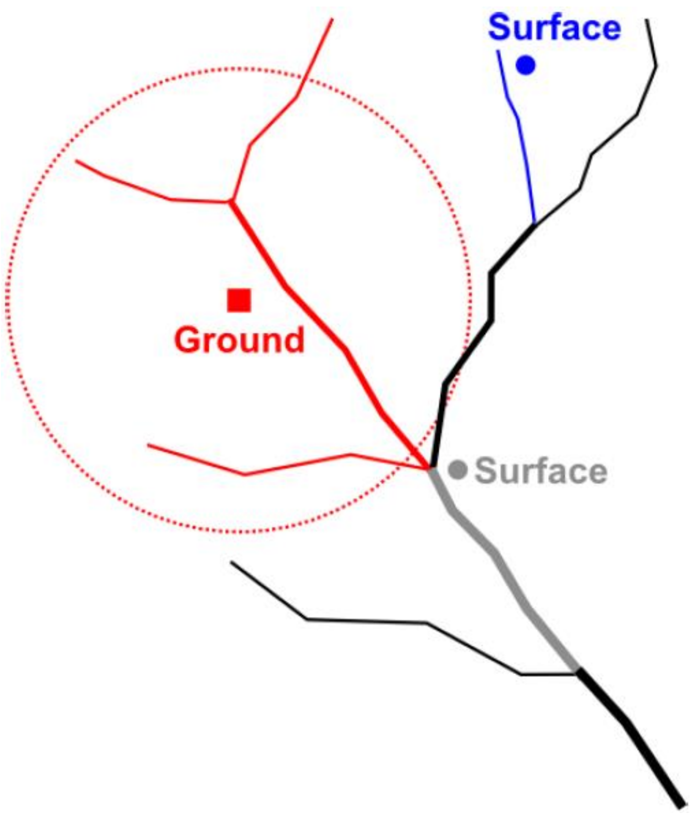

Figure 4-1: A schematic diagram showing the segment assignment for groundwater and surface water consents. The colour of the segment depicts the consent it has been assigned to. For groundwater consents, all segments within 2000 m were assigned to a given consent (red), while surface water consents were 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 mean annual low flow (MALF) (grey). Note that this assignment of consent locations to segments cannot account for multiple meter locations for a single consent.

4.5.2 Apportioning groundwater abstractions between segments

We apportioned each groundwater abstraction between its assigned river network segments as a function of distance to the segment and river low flow. The inverse distance squared was used to represent distance from groundwater consent location 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 take, 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 $Q_i = \Sigma_j Q_{ij}$. River depletion from each groundwater take was proportional to the MALF of segments multiplying by inverse squared distance as follows:

$$w_{ij} = \frac{\frac{MALF_i}{d_{ij}^2}}{\sum_i \left(\frac{MALF_i}{d_{ij}^2}\right)} \quad (1)$$

$$Q_{ij} = \begin{cases} w_{ij} T_{ij} & d_{ij} < 2\ km \\ 0 & otherwise \end{cases} \quad (2)$$

4.5.3 Upstream accumulation

Consent quantities (e.g., maximum allocated rate) were accumulated for each segment in DN2.4. After assigning each consent (or a proportion of each consent in the case of groundwater consent) to a segment, we routed each of these values downstream to calculate the cumulative effects of all upstream consents. This procedure was repeated separately for each category of use (e.g., irrigation consents, industrial consents) and separately for each category of source (e.g., all groundwater consents, all surface water consents). This allowed the cumulative effects of any category of either use or source as well as the total effects to be expressed.

Accumulated quantities for each segment were divided by the estimated naturalised median flow of each segment, to account for the relative size (or flow rate) of rivers being depleted. These standardised accumulated quantities represent the proportion of the median flow that is impacted upstream for each segment.

Naturalised estimates of various hydrological indices were available following the work of Booker and Woods (2014). These represent the best available estimates of flow indices such as the seven-day MALF, mean flow and median flow in the absence of major abstractions. See Booker and Woods (2014) for details of how these hydrological indices were calculated and tested. We chose to standardise by the median flow rather than MALF to be consistent with previous analysis, and because during low flow abstractions may be restricted and because some rivers can experience extremely low flows for limited periods, but still exhibit large flows at other times.

4.6 Plan limits

To analyse allocation with respect to plan limits, we first identified the data required to calculate allocation or observed state compared to the limits. In the majority of cases, plan limits could not readily and accurately be calculated with the data that were available to us. Difficulties in quantitatively representing and then assessing plan limits were reflected in our communications with regional council staff. For example, one regional council staff member commented that:

> *"We have this [comparison of consented to planned allocation in order to assess headroom versus overallocation] as we have an Allocation monitoring tool, but there is complexity in comparing consented totals to allocation limits as we have numerous allocation frameworks operating and each plan has different criteria. We spent a lot of time getting this working and right and are confident in it's output. With the info you have available I don't think you'll be able to recreate it and I'm wary of mixed messaging"*

For many plan limits, we did not have the information required to assess the level of flow alteration that was allowable within the limit. We did have the required information to assess some plan limits for HBRC. To demonstrate methods for assessing allowable flow alteration associated with a plan limit, we assessed plan limits by comparing minimum flow thresholds (also known as cease-to-take thresholds) against both measured flows and estimated naturalised flow. We compared the percentage of the time that observed and naturalised flows were below minimum flows limits. Naturalised flows were calculated using the methods from Section 4.9 of this report.

4.7 Permitted abstractions

To estimate the permitted water use by humans across NZ, the population residing outside of the reticulated water supply areas (i.e., no council or community water supplies, as defined by Puente-Sierra et al. 2023) was identified using Stats NZ's 2018 population census. In this work, we assumed that the population within a meshblock is uniformly distributed over its spatial area. For example, for meshblocks where only a part of the area has reticulated supply, the meshblock population was divided into reticulated and non-reticulated parts based on the area. The population was further distributed to river catchments to implement streamflow depletion resulting from water abstractions (see Section 4.8). A daily water consumption rate of 227 L/day/person was used (LEARNZ 2024).

Based on the approach developed by Snelder et al. (2021), Stats NZ's livestock numbers for 2017 were assigned to grazed grasslands within APC hexagonal grid cells (see Section 3.8) and then to river catchments. Similar to the human population distribution, it was assumed that livestock numbers are uniformly distributed within a grazed grassland. The following average livestock water demands, including daily shed needs (Stewart and Rout 2007), were utilised:

- Stockwater drinking demand (L/d/animal):
  - Sheep: 3
  - Dairy cows: 45
  - Beef cows: 30
  - Deer: 6.

Dairy shed water demand (milk cooling and plant washing) over the milking season of July to April: 50 L/d/cow.

4.8 Streamflow depletion model

As noted in Section 1.3, one of the aims of this work is to demonstrate methods for estimating ecologically-relevant hydrologic effects of streamflow depletion. Abstractions from both surface water and groundwater deplete natural flows. Surface water abstractions directly deplete the rivers from which water is drawn. However, streamflow depletion due to groundwater abstraction is difficult to determine due to the complex diffusive effects of the aquifer system, which influence the response pattern of pumping (Barlow and Leake, 2012; Zipper et al., 2021). A single groundwater abstraction can deplete many nearby streams, and response times for depletion can extend over weeks, months, or even years following the abstractions. The response times vary depending on local hydrogeological conditions, such as aquifer properties (e.g., transmissivity and storativity), surface water and groundwater interactions, depth of the well screen, and the distance from the well to nearby streams (Bredehoeft and Durbin 2009; Konikow and Leake 2014).

In this work, we adapted the streamflow depletion modelling methods developed by Booker et al. (2019). Please refer to Booker et al. (2019) for details of the modelling approach. A summary of the approach is as follows:

- The spatial framework of the streamflow depletion model is New Zealand's national river network, as defined in the River Environment Classification (REC; Snelder and Biggs 2002).
- Depletion from each groundwater take is associated with all segments on the REC within a 2 km radius of the coordinates describing the groundwater take point.

- The proportion of depletion from each river segment due to a groundwater take depends on the distance between the well and the segment, flow (based on the naturalised 7-day MALF), and the length of the segment within a 2 km radius of the well.
- The model consists of two different approaches to estimate streamflow depletion:
    1. One-layer model: This model assumes the aquifer from which groundwater is abstracted is essentially a single unconfined aquifer. Therefore, the well screen is hydraulically connected (homogeneously through the aquifer material) to the stream(s) that deplete due to groundwater pumping. Streamflow depletion due to pumping from the unconfined aquifer is estimated using an analytical approach developed by Jenkins (1968).
    2. Two-layer model: This model uses a two-layer approach based on the screen depth of the groundwater well. For groundwater abstractions within 0–30 m below ground level, the approach described in (1) is used (assuming the aquifer system up to 30 m depth is unconfined, which is generally the average thickness of the unconfined aquifer, e.g., Ministry of Health, 2010). For takes below 30 m, it is assumed the water is pumped from a semi-confined aquifer overlain by an aquitard and an upper aquifer. Streamflow depletion due to pumping from the bottom aquifer is estimated using an analytical model developed by Hunt (2009).

In this current work, we utilised the two-layer model.

Two aquifer parameters (transmissivity and storativity) are used for calculating streamflow depletion. These parameters, estimated using aquifer tests, were obtained from regional councils. However, these parameters are not available for all necessary locations. We used the Random Forest statistical technique to estimate the aquifer parameters at unmeasured locations (Booker et al. 2019).

4.9 Ecologically-relevant hydrologic metrics

Hydrologic metrics considered in this study are listed and defined in Table 4-2 along with a brief rationale for their environmental and ecological relevance. We used a selection of hydrologic metrics from Richter et al. (1996) and the three seasonality of metrics of Colwell (1974) because these metrics have routinely been used to assess flow regimes and flow alteration (e.g., Puckridge et al. 1998; Olden and Poff 2003; Mostafazadeh et al. 2024). We included FRE3 count and duration because it has previously been applied in the analysis of NZ flow-ecology relationships (Clausen and Biggs 2000). For all indices except for Colwell's indices, we calculated annual values. Colwell's indices are designed to be calculated over the whole flow record. Colwell's Predictability is the sum of Constancy and Contingency, and reflects the likelihood of being able to predict a flow occurrence. Predictability is maximized when the flow is constant throughout the year (Constancy Maximised), or if the pattern of high or low flow occurrence is repeated across all years (Contingency maximized).

Table 4-2: Ecologically relevant hydrologic metrics used in this analysis. Following methods by Richter et al. (1996), Colwell (1974), and Clausen and Biggs (2000).

Group	Hydrological metric	Description	Ecological-environmental significance
Monthly magnitude	Mean flow for each calendar month	Indicates seasonal high and low flows.	Associated with general seasonality of flow when averaged across years. Changes indicate whether flows have been altered during particular seasons (e.g., summer).
Magnitude and duration of annual extremes	1-day mean minimum flow	Daily low flow	Associated with stress during extreme low flows. Reduction indicates loss of aquatic habitat area and quality, higher water temperatures, and low dissolved oxygen in some locations.
	7-day mean minimum flow	Weekly low flow	See above but indicates intermediate duration low flow stress.
	90-day mean minimum flow	Seasonal low flow	See above but indicates prolonged low flow stress.
	1-day mean maximum flow	Daily high flow	Associated with magnitude of disturbance. Reduction indicates reduced propensity of for geomorphological re-setting, which drives physical habitat templates.
	7-day mean maximum flow	Weekly high flow	See above but for intermediate duration of high flow disturbance.
	90-day mean maximum flow	Seasonal high flow	See above but for prolonged duration of higher flows.
Timing of annual extremes	Day of minimum	Timing of lowest flow after having shifted start day of year to reduce the chance of a single low flow event being counted in consecutive years	Associated with the timing of lowest flow. Change indicates a delay in timing of low flows.
Frequency and duration of pulses	FRE3 count	Number of events exceeding three times the (naturalised) median flow	Associated with mean days of periphyton accrual (Snelder et al., 2014) and physical disturbance (Jellyman et al. 2013), although see complications explained in (Neverman et al. 2018) and (Haddadchi et al. 2020).
	FRE3 maximum duration between	Maximum duration between events exceeding three times the (naturalised) median flow	See row above. Associated with riparian and emergent vegetation growth.
Rate and frequency of change in conditions	Number of days which flow is rising	-	A proxy indicator of hydrological disturbance versus stability because sites with fewer days of rising flow have rapid responses to rainfall events. Reduction indicates that some small events have been removed due to abstraction, but increases could result from pulses in abstraction.
	Number of days which flow is decreasing	-	See row above.

Group	Hydrological metric	Description	Ecological-environmental significance
	Number of reversals	Number of times flow switches in direction of rate of change	A proxy indicator of hydrological disturbance versus stability because sites with frequent reversals have many hydrograph peaks. Reduction indicates that some small events have been removed due to abstraction, but increases could result from pulses in abstraction.
Colwell's Indices	Predictability	Predictability measures how tightly an event is linked to a season	Indicates whether lower flows (and also higher flows) always happen in the same month of the year. Changes can be associated with changes to cues for fish migration, invertebrate movement, and vegetation growth.
	Constancy	Constancy measures how uniformly the event occurs through all seasons	Indicates weakness versus strength of seasonal patterns. See above for interpretation of changes.
	Contingency	Contingency measures the repeatability of season patterns	Indicates strength of between-year patterns. See above for interpretation of changes.

All hydrologic metrics can be calculated from a daily flow time-series. However, some metrics invoke the notion of a baseline against which values are compared. We applied methods that took account of the need to compare a naturalised state against an altered state. We used naturalised flows for calculation of baseline medians flows when calculating counts and durations relating to FRE3, and for calculation mean flow to standardize flow quantities.

We used 5 years of HBRC observed flows from 1 July 2018 to 30-Jun-2023 for demonstration purposes. We included only sites for which at least 75% of values were not missing. These sites were linked to segments of the river network using the same method as for linking surface water consent locations to the river network in Section 4.5.1. We produced an estimate of naturalised flows using modelled streamflow depletion (see methods described in Section 4.8). We excluded sites where stream flow depletion was zero or negligible (<1% of naturalised flow on each day from 1 July 2018 to 30-Jun-2023). Hydrologic indices were calculated for the remaining sites.

We compared hydrologic indices from observed and estimated naturalised flows in terms of their absolute value and percent change. For most metrics, the percentage change in a metric (x) for observed (obs) compared to naturalised (nat) was calculated as:

$$Percentage\ change\ (\%) = \frac{x_{obs} - x_{nat}}{x_{nat}} \times 100 \quad (3)$$

The calculation of percentage change in the day of minimum flow was modified to:

$$Percentage\ change\ (\%) = \frac{change\ in\ day}{(182.5)} \times\ 100 \quad (4)$$

where change in day is calculated from the day of minimum flow (d) as:

$$change\ in\ day = \begin{cases} d_{obs} - d_{nat} + 365 & if\ d_{obs} - d_{nat} < -182.5 \\ d_{obs} - d_{nat} -\ 365 & if\ d_{obs} - d_{nat} > 182.5 \\ d_{obs} - d_{nat} & otherwise \end{cases} \quad (5)$$

This modified calculate acknowledges that a change of greater than half-a-year in span is equivalent to a smaller change in the opposite direction. It also acknowledges that the magnitude of d_{nat} is not important, and a 100% change should be the maximum change of half a year (182.5 days).

5 Results

5.1 Data selection for analysis

Water quantity data were filtered to contain only information linked to consents active during the analysis period of 1-Jul-2021 to 30-Jun-2023. The number of consents, abstraction meters, restrictions, limits, and river flow or groundwater level time-series varied between regions (Table 5-1).

Table 5-1: Amount of water quantity data for each agency for the analysis period. "-" indicates no data were obtained and/or analysed.

	HBRC	MDC	ECan	ES
Number of consents	3336	1686	6402	1103
Number of abstraction meters	1275	-	5514	48
Number of restriction sites	31	-	234	-
Number of consents with observation-based restrictions	650	-	1296	-
Number of restriction sites x bands x consents	1535	-	7076	-
Number of consents with predetermined restrictions	2518	-	-	-
Number of rules used to calculate predetermined restrictions	5907	-	-	-
Number of flow time-series associated with a restriction or limit	20	-	66	11
Number of groundwater time-series associated with a restriction or limit	0	-	0	0

Whilst filtering the data based on the analysis period, consents with an invalid date were removed (N=16, 0.1%). Limits which could not be successfully matched to any consents were also removed (Consent-based limits: N=436, 7.4%; Site-based limits: N=131, 1.5%). It is possible that the removed limits pertain to historic consents excluded from the analysis. It is also possible that the removed limits represent active or proposed limits that are so new that they have not been reflected in any consents included in our analysis.

Table 5-2 indicates the level of missing data within consent, restriction, and limit tables. Note that items with no missing data are not listed, and there were no missing values in the predetermined restrictions table. Generally, completeness of the data was reasonably high, except for missing maximum instantaneous rates for 84% of MDC consents, missing coordinates for 24% HBRC restriction sites, and missing MaxAnnual for 23% of ECan consents. Note that these missing MaxAnnual values for ECan are from “stream flow depleting” consent rows which we understand are not intended to contribute to annual sums.

Table 5-2: Percentage of values with NA values for consent, restriction, and limit data for the analysis period. Plan limits do not typically have commencement and expiry dates, so it is unsurprising that many of these are missing.

		Percentage of NA values			
Table	Data label	HBRC	MDC	ECan	ES
Consents	PrimaryUse	0	0.2	0	8.1
	WaterManagementZone	8.3	0	0	3.5
	Catchment	0.1	0.1	0	0.3
	MaxRate	6.3	84.0	0.01	1.7
	MaxAnnual	6.6	6.0	23.4	1.5
	Latitude, longitude	0	0	1.6	4.0
Observation-based restrictions	limitUpper	0	-	0.4	-
	Latitude, longitude	32.2	-	1.2	-
Plan limits	limitValue	5.1	0	-	12
	commencementDate, expiryDate	86.6	100	-	100

The amount of missing data in time-series (flows and abstraction meters) was assessed by counting the number of active gauges and meters for each day of the analysis period, and the number of non-missing values (Figure 5-1). For HBRC and ECan, time-series records are reasonably complete with more than the 80% of gauges/meters active each day. The exception to this is a higher number of missing flow readings in early 2023 for HBRC coinciding with the aftereffects of Cyclone Gabrielle on 14 February 2023. HBRC meter data had no gaps at all. For ES, meter data was often not at a daily frequency meaning the number of meter readings on any given day is fewer than the number of meters.

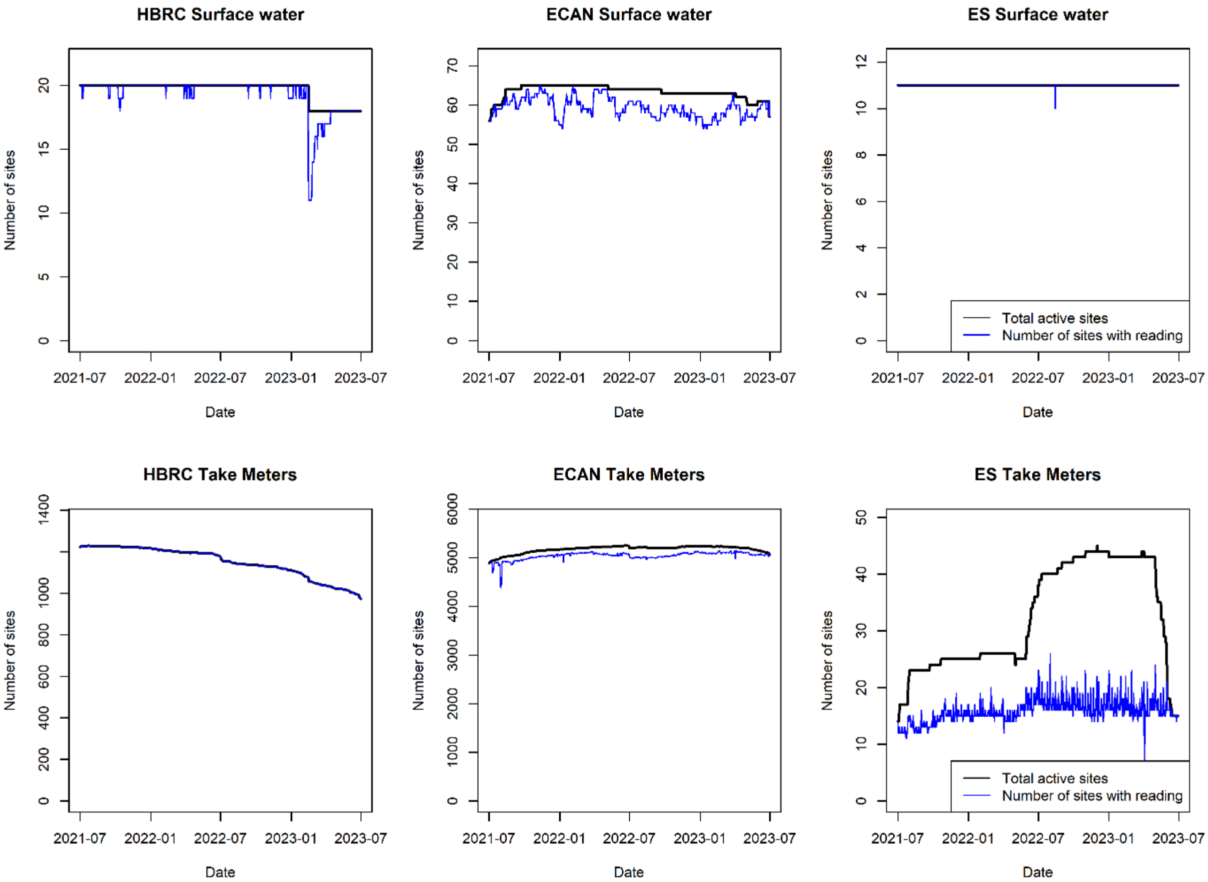

Figure 5-1: Number of time-series records active, and with a valid reading, for each day of the analysis period.

Not all consents were linked to restrictions, or meters, or both restrictions and meters (Figure 5-2). There was great between-region variability in the proportion of consents that were linked to meters and restrictions.

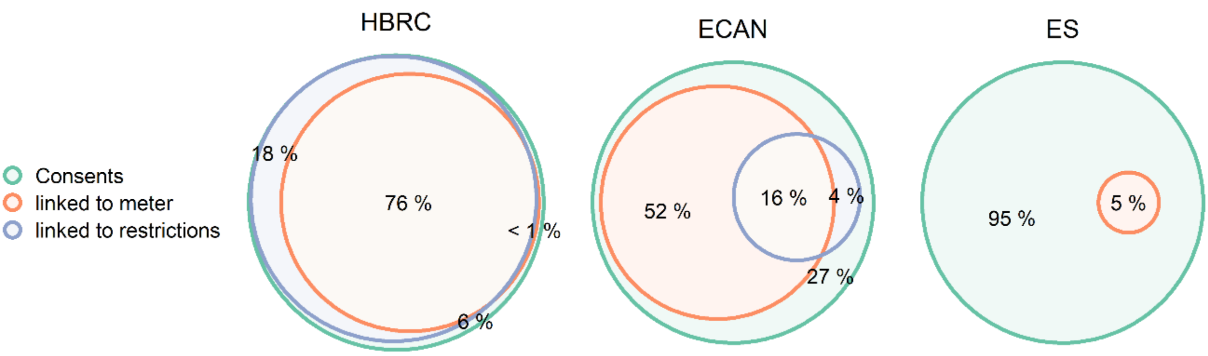

Figure 5-2: Percentage of consents for the analysis period linked to meters and restrictions (observation-based or predetermined). White indicates overlap for consents linked to restrictions and meters.

Not all written consents contain observation-based restrictions, thus we would not expect all consents to be linked to restrictions in this database. The number of consents linked to restrictions is higher for HBRC (94%) than for ECan (20%) because of the presence of predetermined restrictions. For ES, no quantitative site-based restriction data was obtained. Of the restriction sites for each council, not all were linked to a flow time-series. For HBRC, 17 of 31 restriction sites (55%) had an active flow time-series. For ECan, 65 of 233 restriction sites had an active flow time-series (28%). This indicates that many restrictions could not be updated on a daily basis because the dependent variable was not being continuously monitored (or was not obtained for this analysis).

One would expect all consents to be linked to predetermined restrictions in the case of HBRC. All consents in the consent database which did not have any predetermined restrictions meet one or both of the following two criteria: a) the consent maximum rate of take and maximum annual volume are both zero i.e. the consent is non-consumptive; b) the consent status is either “Expired”, “Surrendered”, or “Expired – s124.” Some of these expired consents were inactive at the time of provision of the consent-restriction data but are active during our analysis period. “Surrendered” consents have been included for our historic analysis because we cannot know at what point they were surrendered. We included them to capture all possible consent water abstraction but acknowledge this may be an overestimate.

Table 5-3 shows the proportion of meters for consents according to their maximum rate, which is of interest because consents with rates of less than 5 L s^{-1} are not required to be metered. For those consents requiring metering, HBRC and ECan each had >80% of consents with meters, and ES had 9.4%. Note that these values may underestimate the true percentage of metered consents due to the inclusion of “surrendered” consents.

Table 5-3: Percentage of consents for the analysis period with a meter (% metered), and number of meters (N meter) for councils which supplied meter data. Consents are divided into three categories according to their maximum rate of abstraction.

	HBRC		ECan		ES	
	% metered	N meters	% metered	N meters	% metered	N meters
Max Rate ≥ 5 L s^{-1}	88.5% 2341/2645	1514	84.0% 4159/4962	5771	9.4% 19/201	23
Max Rate < 5 L s^{-1}	40.2% 193/480	173	11.7% 157/1346	527	3.6% 32/883	34
Max Rate Unspecified	7.1% 15/211	13	0	0	0	0

Consents may be associated with multiple meters and vice versa. For HBRC 2540 consents (76%) of consents were linked to one meter, and 9 consents (<0.5%) were linked to two meters. 1037 meters (61%) were linked to just one consent, 320 meters (26%) to 2 consents, and the most consents linked to any one meter was 7. For ECan, 3333 consents (52%) were associated with just one meter, 667 (10%) with two meters, and one consent was associated with 143 meters. 93%t meters (N=5143 were associated with a single consent, 302 meters (5%) were associated with 2 consents, and the most consents linked to any one meter was 11.

Locations of included consents, and restriction sites are mapped in Figure 5-3. Across all councils, 12% of consents (N=1481) were missing coordinates, and 6% of restriction sites (N=17) were missing coordinates. For ECan restrictions sites (e.g., gauging sites) tended to be located towards the foothills as well as in lowland areas whereas consents were much denser in lowland areas than hilly and mountainous areas.

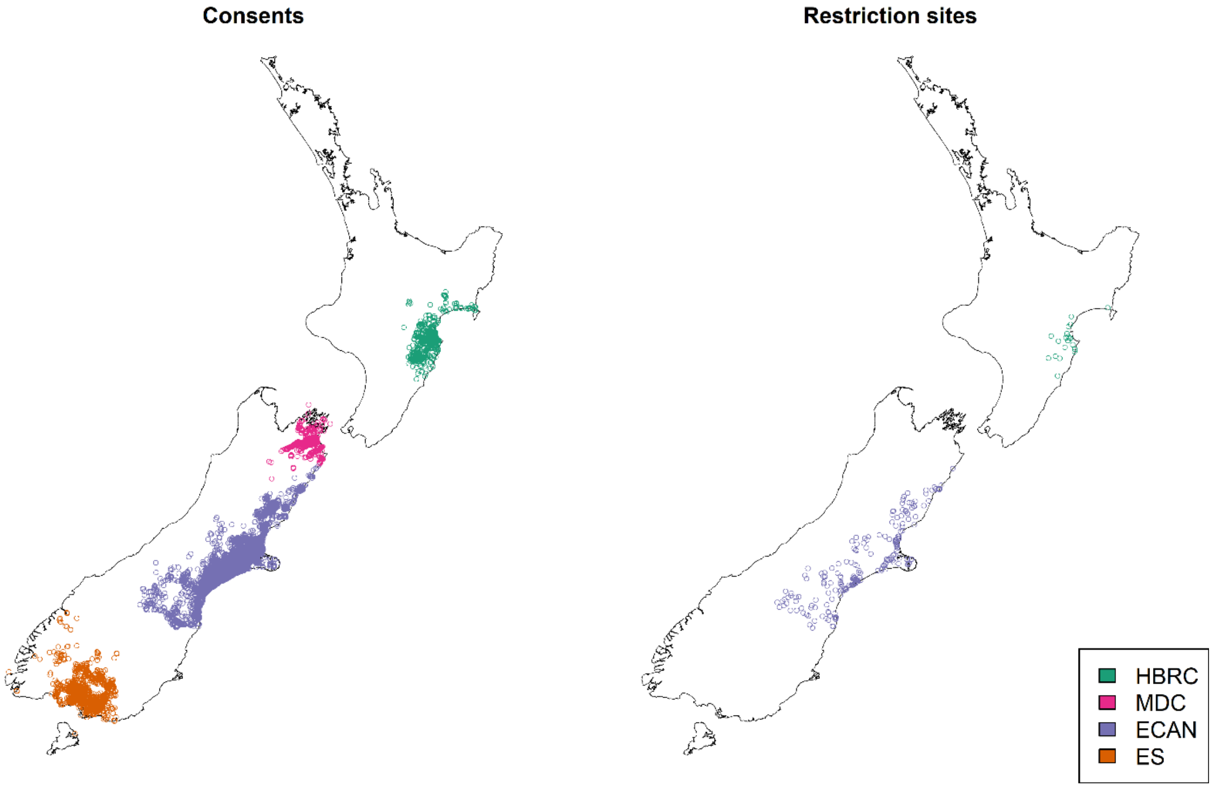

Figure 5-3: Location of consents for the analysis period, and restriction sites linked to these consents.

Given the incompleteness in some of the provided data, not all aspects of the quantitative analysis could be completed for each council (Table 5-4). Consents were analysed for all councils. Restrictions and metered abstractions were analysed for only some of the councils, due to data gaps. Accumulated pressure was mapped for all councils, though parts of this analysis were limited by data gaps for some councils. Most plan limits could not readily be assessed for any council with the data obtained. The streamflow depletion model, and analysis of ecologically relevant hydrologic effects from these model outputs were calculated only for HBRC, which has the most complete abstraction records. ECan and ES meter abstraction data had substantial data gaps, limiting the usefulness of streamflow depletion analysis.

Table 5-4: Parts of analysis completed for each council.

Analysis	HBRC	MDC	ECan	ES
5.2 Water resource consents	✓	✓	✓	✓
5.3 Restrictions on consented abstraction	✓	✗	✓	✗
5.4 Metered abstractions	✓	✗	✓	✓
5.5 Mapping accumulated	✓	partial	✓	partial
5.6 Plan limits	partial	✗	✗	✗

Analysis	HBRC	MDC	ECan	ES
5.8 Streamflow depletion model	✓	✗	✗	✗
5.9 Ecologically-relevant hydrologic metrics	✓	✗	✗	✗

5.2 Water resource consents

Results for water resource consents are shown Figure 5-4 to Figure 5-23 in Sections 5.2.1, 5.2.2, 5.2.3, and 5.2.4 for HBRC, MDC, ECan, and ES respectively. In general, results indicated the following patterns.

- Irrigation was the largest non-hydroelectric consented water use for all regions.
- There were a small number of hydroelectric consents with very high maximum rates.
- Consent locations were not uniformly spread across each region. Consents were often grouped in some areas, likely related to irrigable land or near to population centres.
- Groundwater consents were often located in discrete areas, likely associated with aquifers.
- Consent durations typically spanned tens of years. In some cases, consents appear to expire on a rolling basis and in some cases many consents expire the same date.
- It is typical for the maximum instantaneous rate of irrigation consents to be higher than the corresponding maximum annual rate. This reflects an expectation to not be irrigating year-round, and the provision to irrigate at a higher rate when needed without allowing the consent holder to irrigate constantly at this higher rate.

5.2.1 HBRC

Results for water resource consents for HBRC are shown Figure 5-4 to Figure 5-8. Some points of note from analysis of the data that we obtained include the following.

- The location of HBRC consents is concentrated around the Hastings/Napier area for all water use types except hydroelectric and stock.
- The main uses of abstracted water, outside of hydroelectricity, are irrigation and drinking water, based on sum of consent maximum rate.
- HBRC has an additional primary source category "Storage” which HBRC have advised us represents water abstraction from a reservoir or some other form of storage. There are few consents with storage as a primary source.
- Surface water consents appear to expire at different times whereas groundwater consents expiry dates line up on common dates.
- The maximum rate for frost protection consents appears to be a fixed proportion of the maximum annual volume.

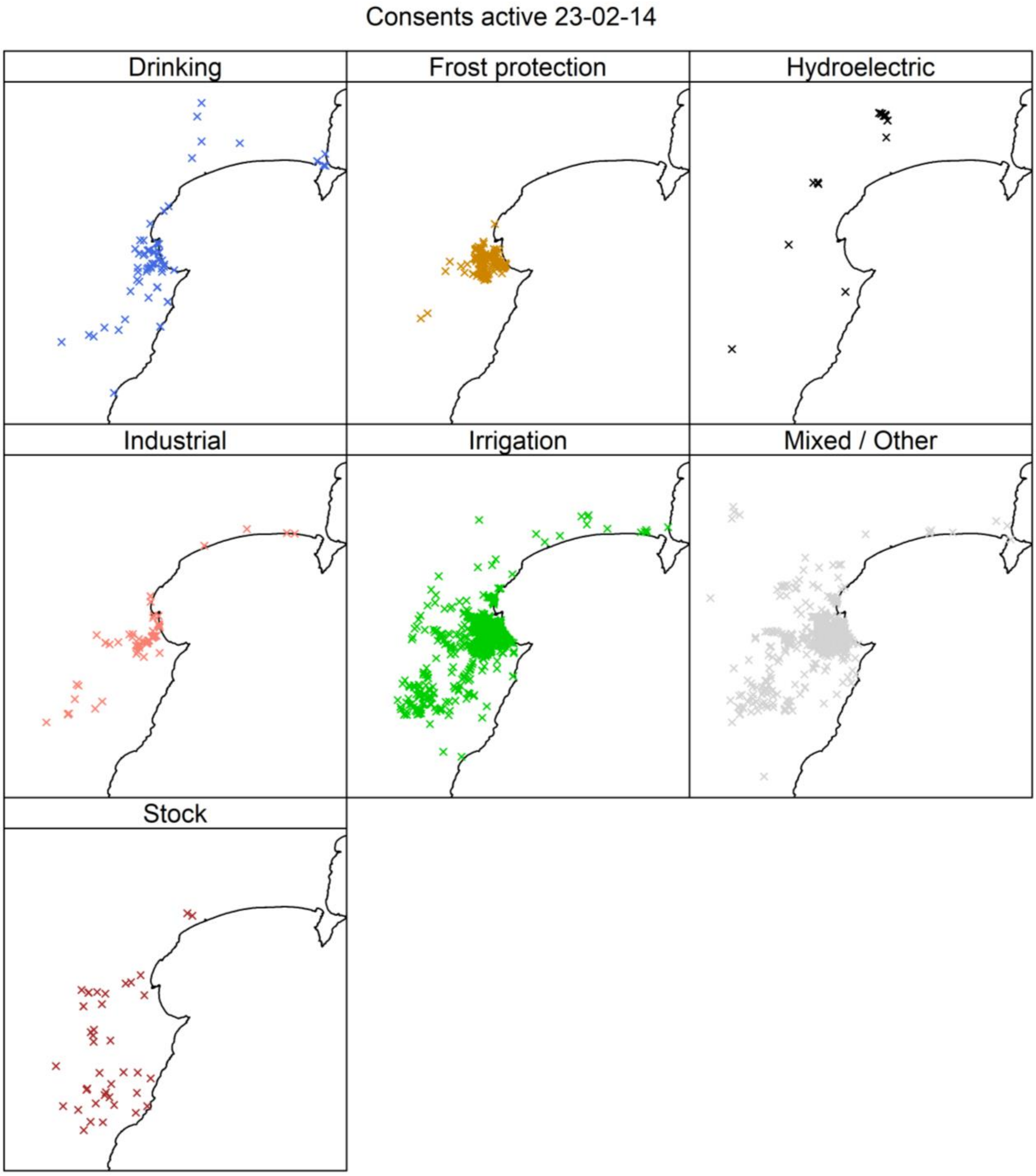

Figure 5-4: Map of location of HBRC consents active 14/02/2023, showing primary use types.

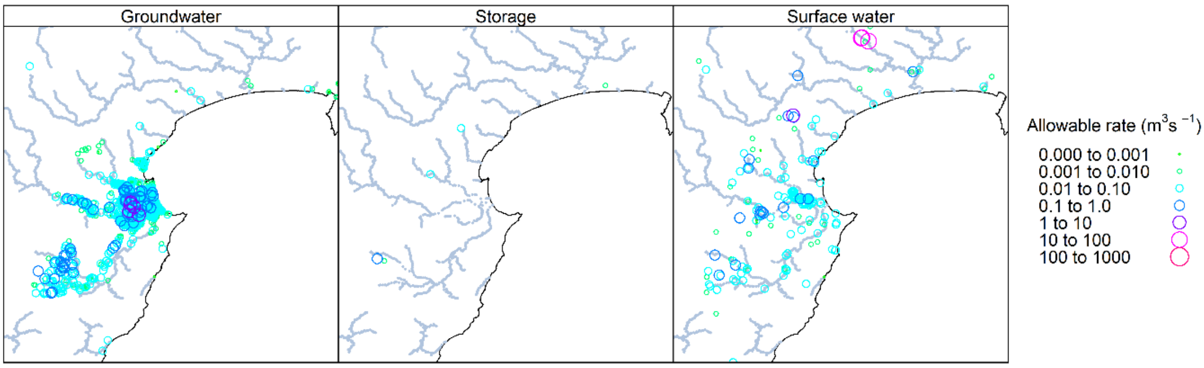

Figure 5-5: Map of location of HBRC consents active 14/02/2023, showing consent maximum rate.

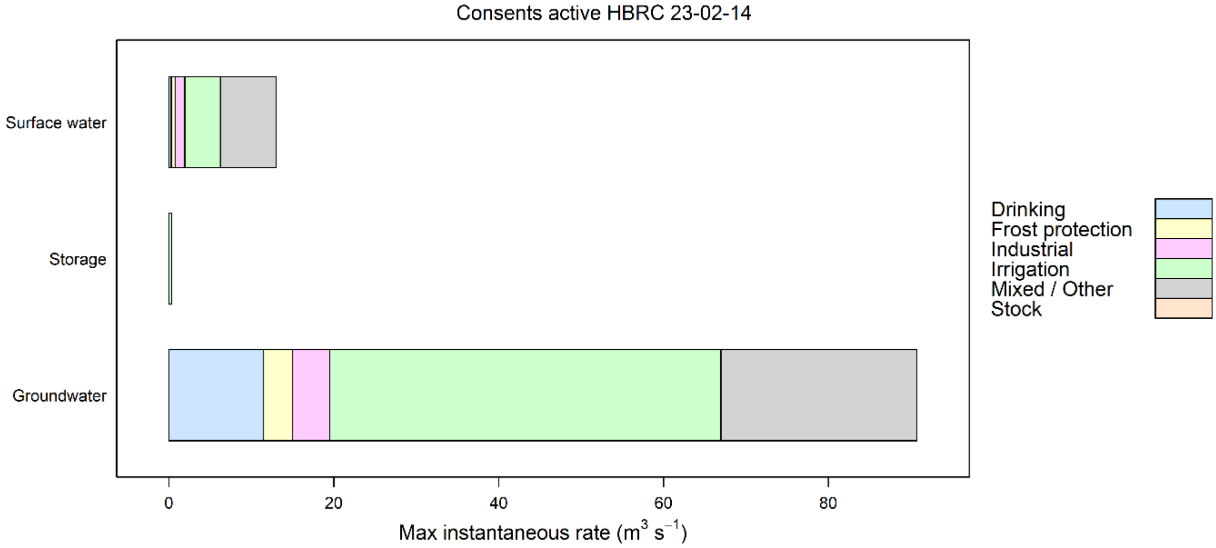

Figure 5-6: Barchart of sum of consent maximum instantaneous rate for HBRC consents active 14/02/2023, showing primary source and use types.

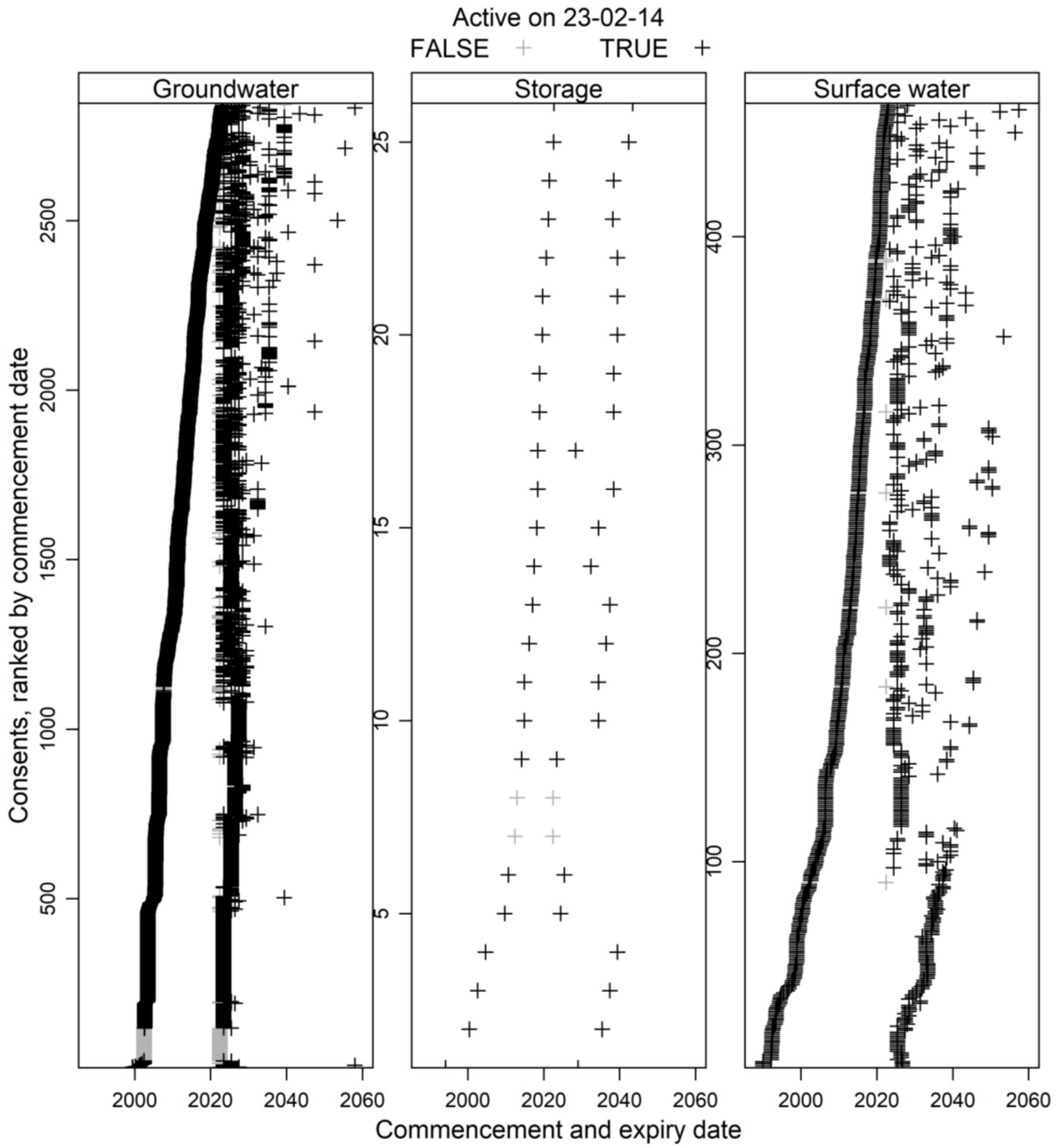

Figure 5-7: Plot of consent expiry and commencement date for HBRC, for consents active at any point in time for the analysis period. Commencement and expiry date for each consents plot parallel to the x-axis.

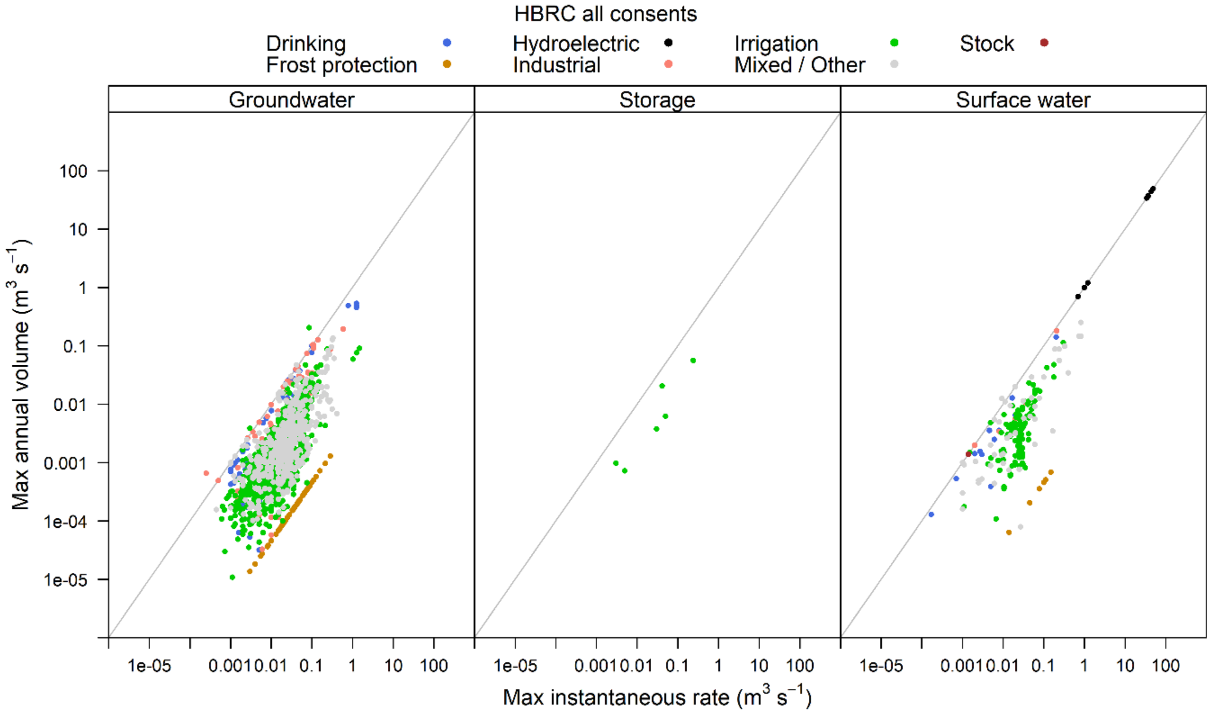

Figure 5-8: Plot of consent maximum rate and maximum annual volume for HBRC consents active 14/02/23.

5.2.2 MDC

Results for water resource consents for MDC are shown in Figure 5-9 to Figure 5-13. Some points of note from analysis of the data that we obtained include the following.

- The location of consents was concentrated in the Wairau and Awatere valleys.
- The main uses of abstracted water, outside of hydroelectricity, was irrigation and "Mixed/Other", based sum of on consent maximum rate. Note that this occurs because MDC often specify consent primary use as a combination of uses (e.g. "Irrigation and stock", or "Frost protection and domestic").
- Many MDC consents did not have a maximum rate specified. The maximum rate was assumed to be the equivalent rate to the maximum annual volume, causing them to line up in Figure 5-13.

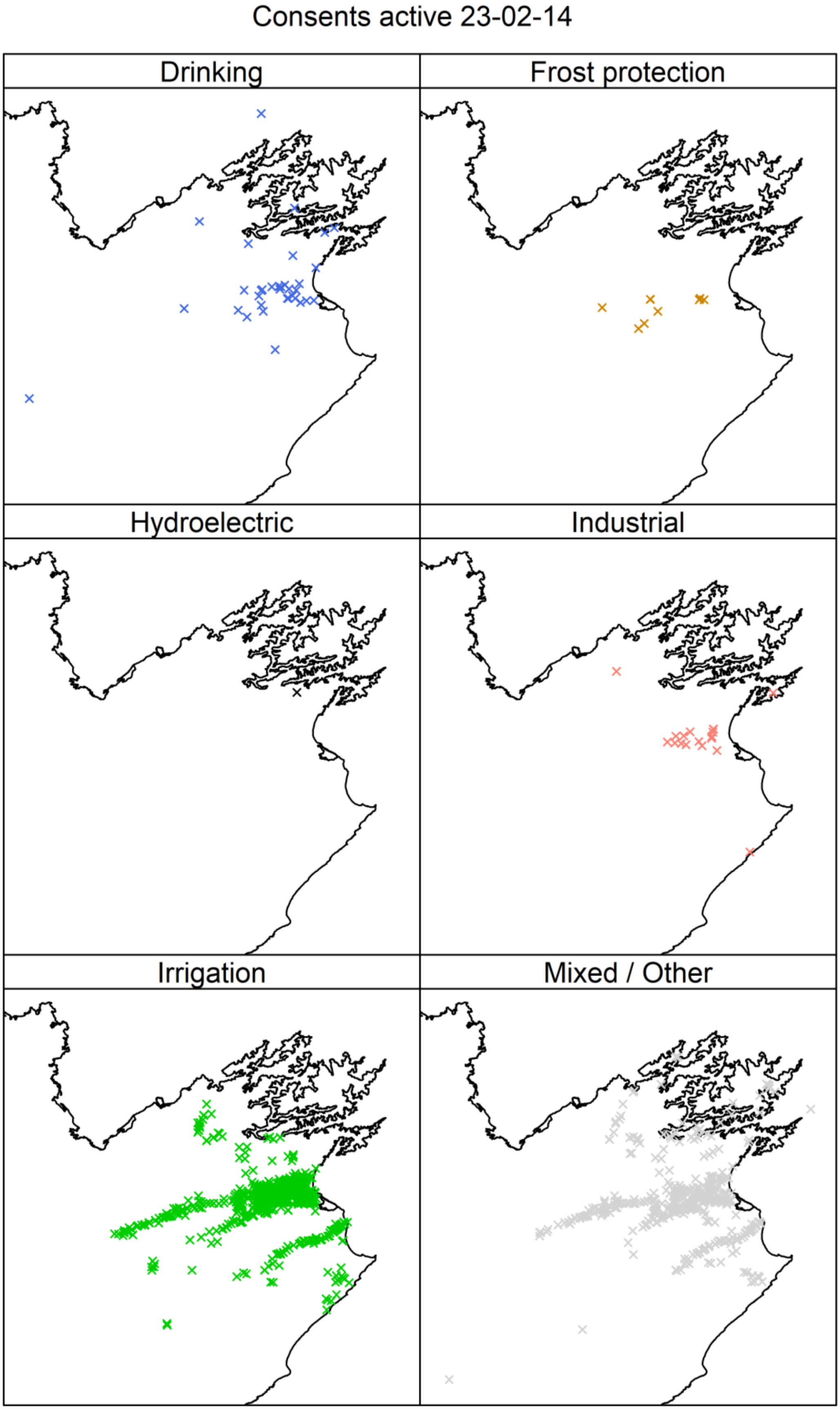

Figure 5-9: Map of location of MDC consents active 14/02/2023, showing non-hydroelectric primary use types.

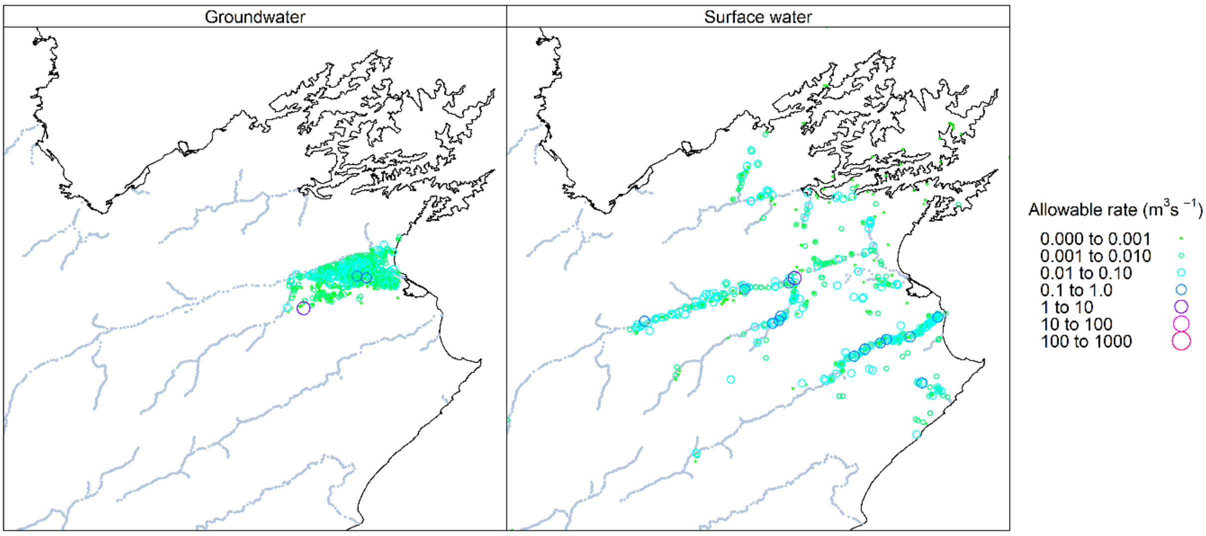

Figure 5-10: Map of location of MDC consents active 14/02/2023, showing consent maximum rate.

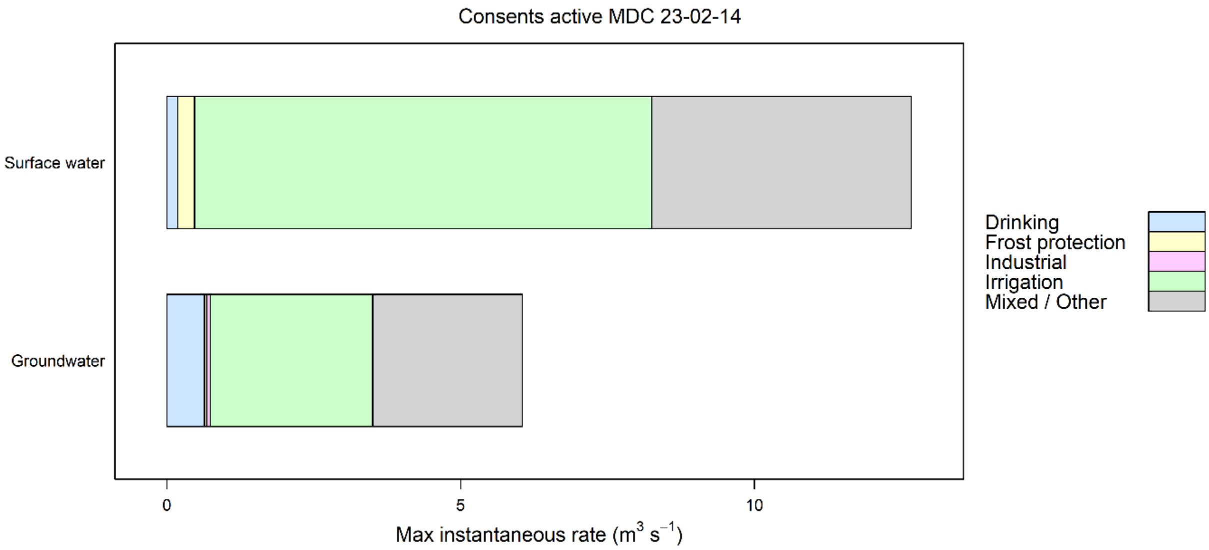

Figure 5-11: Barchart of sum of consent maximum instantaneous rate for MDC consents active 14/02/2023, showing primary source and use types.

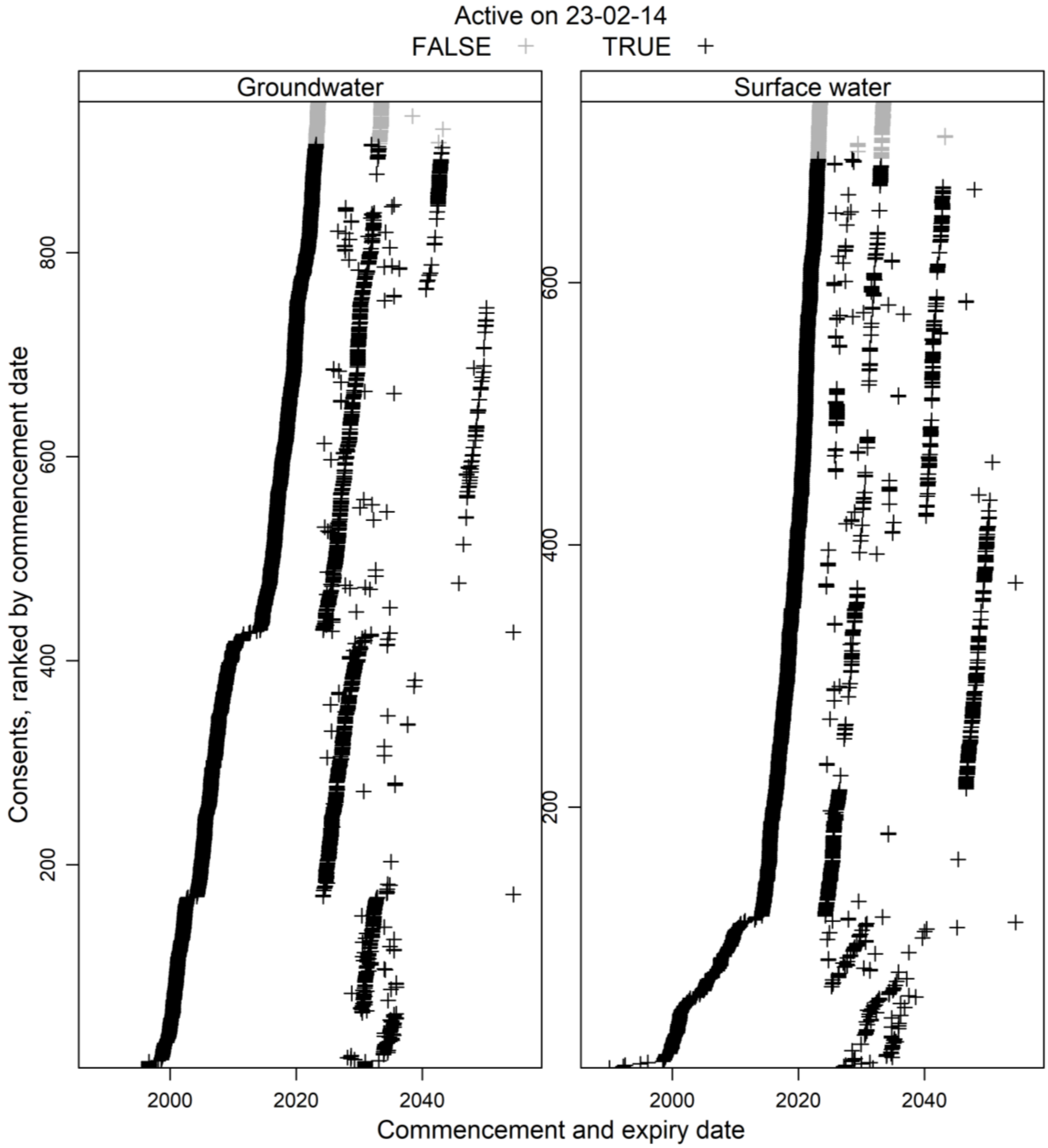

Figure 5-12: Plot of consent expiry and commencement date for MDC for consents active at any point in the analysis period. Commencement and expiry date for each consents plot parallel to the x-axis.

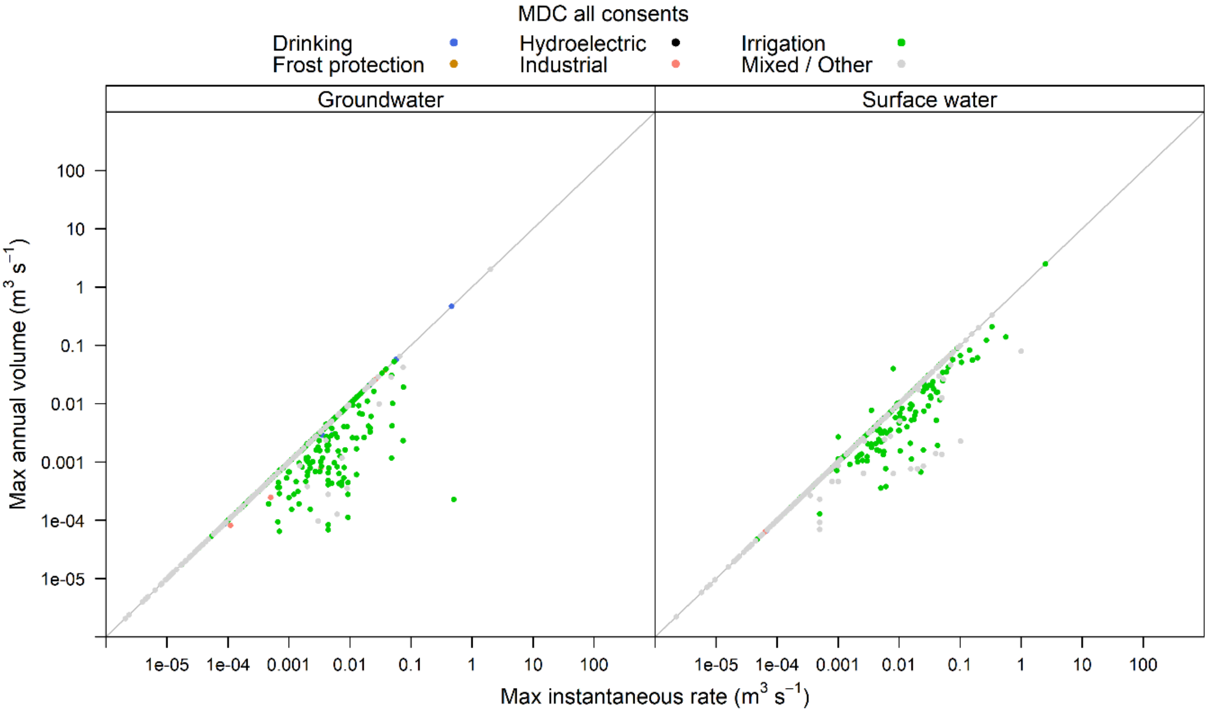

Figure 5-13: Plot of consent maximum rate and maximum annual volume for MDC consents active 14/02/2023.

5.2.3 ECan

Results for water resource consents for ECan are shown Figure 5-14 to Figure 5-18. Some points of note from analysis of the data that we obtained include:

- The location of consents was spread mainly throughout lowland Canterbury.
- Consents with the largest allowable rates are all surface water abstractions.
- The main use of abstracted water, outside of hydroelectricity, was irrigation, based on sum of consent maximum rate.
- ECan has an additional primary source category "Stream depleting." Consents rows in this category always shared a consent ID with another consent in the groundwater category.
- We understood that consents with their primary source labelled as "streamflow depleting" represented the part of each groundwater consent that should be considered as depleting surface water. We understood that stream depleting rows should not be summed with groundwater rows because this would double-count their maximum rate.

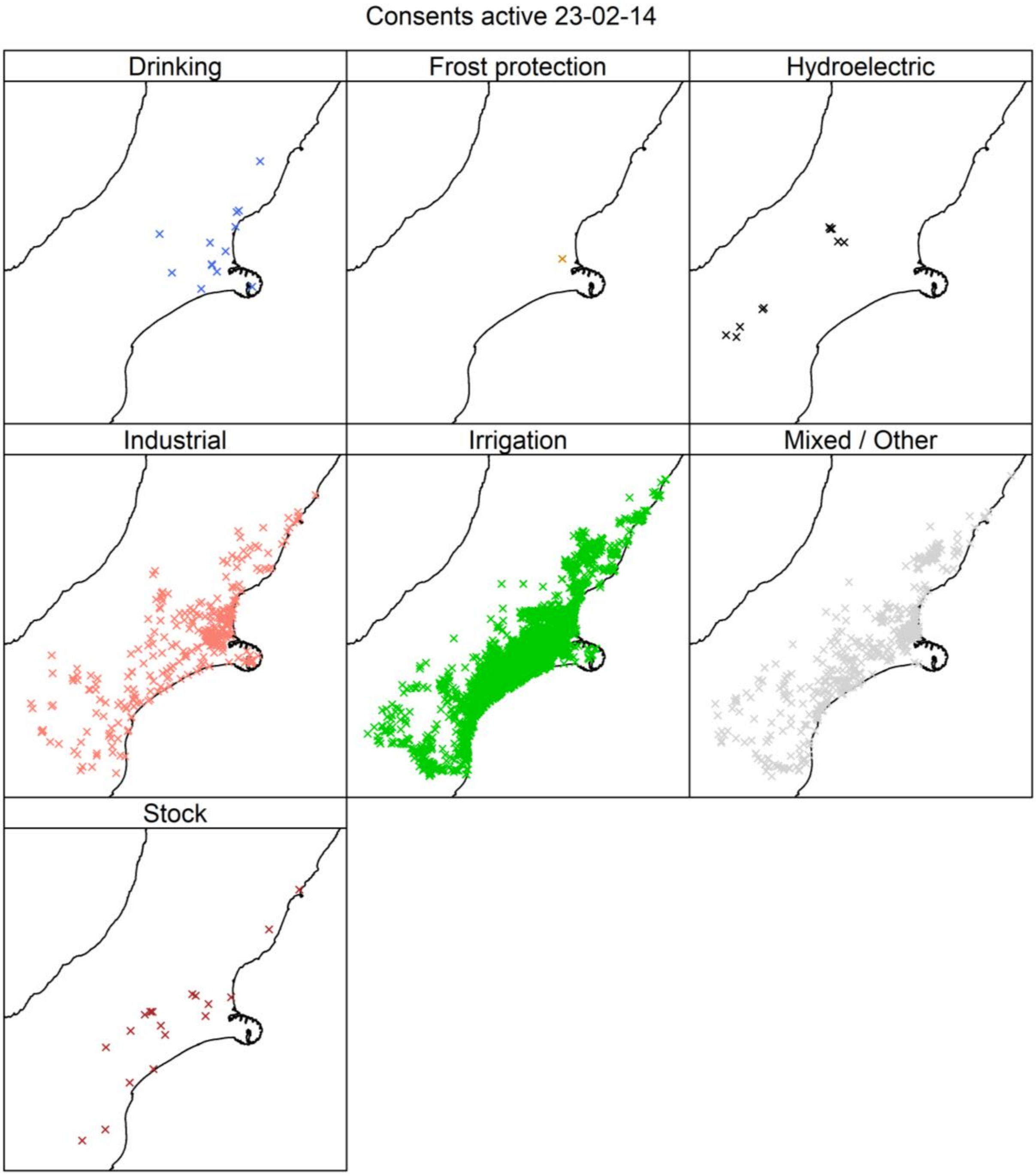

Figure 5-14: Map of location of ECan consents active 14/02/2023, showing primary use types.

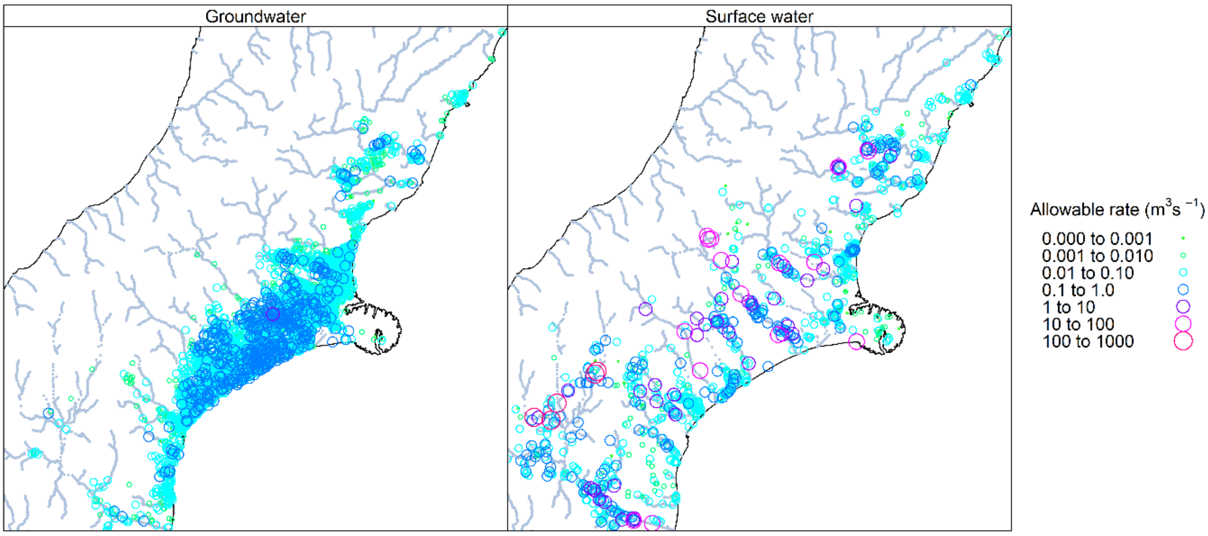

Figure 5-15: Map of location of ECan consents active 14/02/2023, showing consent maximum rate.

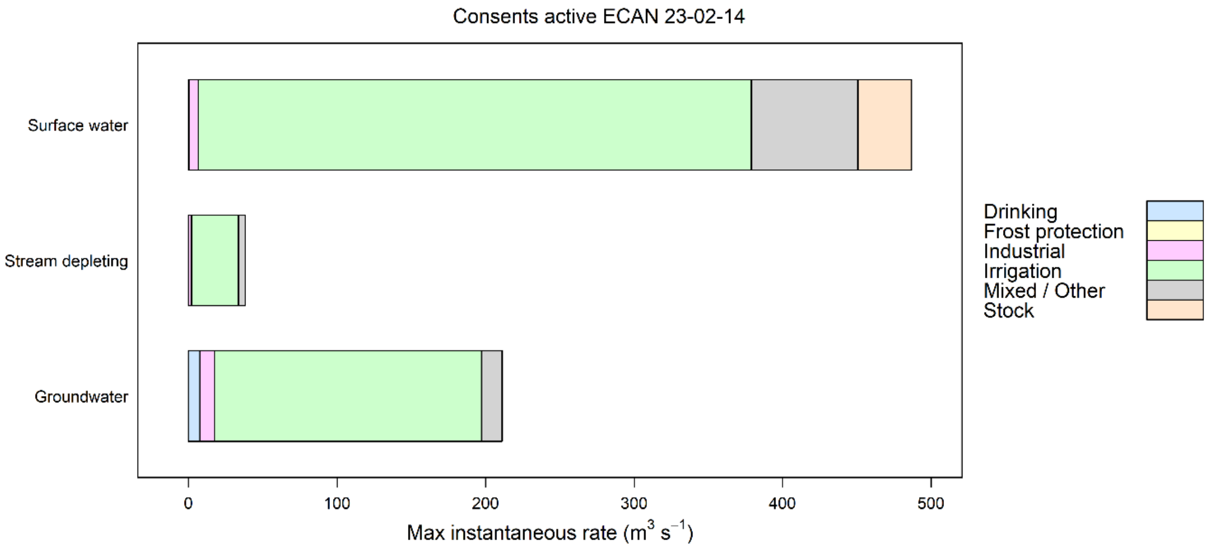

Figure 5-16: Barchart of sum of consent maximum instantaneous rate for ECan consents active 14/02/2023, showing primary source and use types.

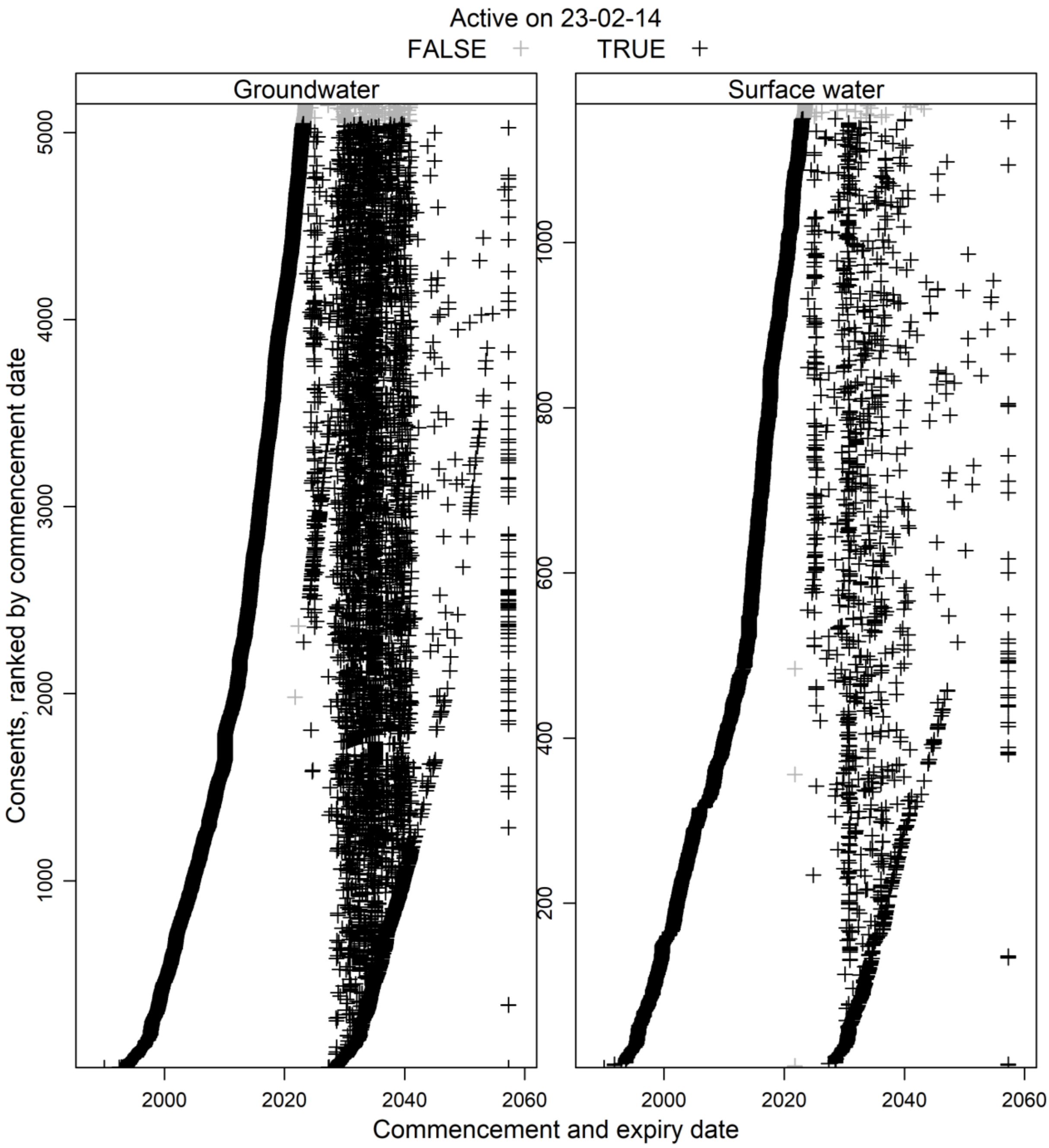

Figure 5-17: Plot of consent expiry and commencement date for ECan for consents active at any point in the analysis period. Commencement and expiry date for each consents plot parallel to the x-axis.

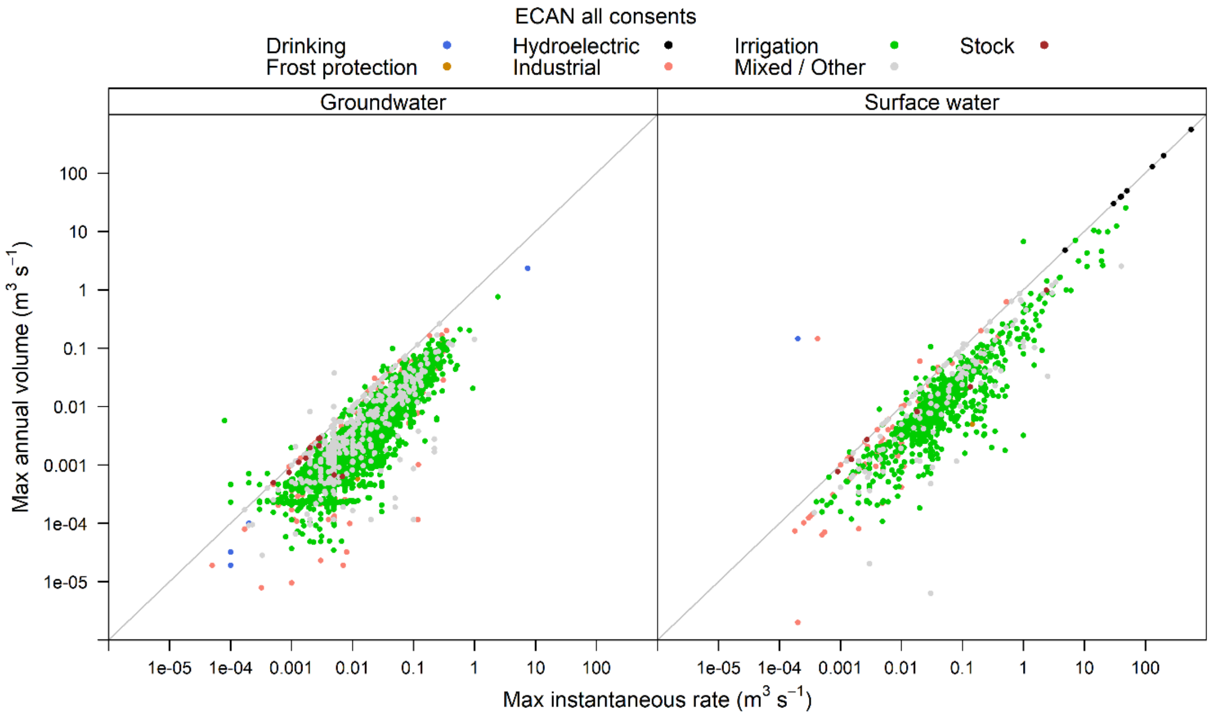

Figure 5-18: Plot of consent maximum rate and maximum annual volume for ECan consents active 14/02/2023.

5.2.4 ES

Results for water resource consents for ES are shown in Figure 5-19 to Figure 5-23. Some points of note from analysis of the data that we obtained include:

- The location of consents was concentrated around Southland Plains.
- ES had a large number of stock water consents, but MaxRate and MaxAnnual for these was relatively low, meaning these consents comprise a small portion total allocation volume.

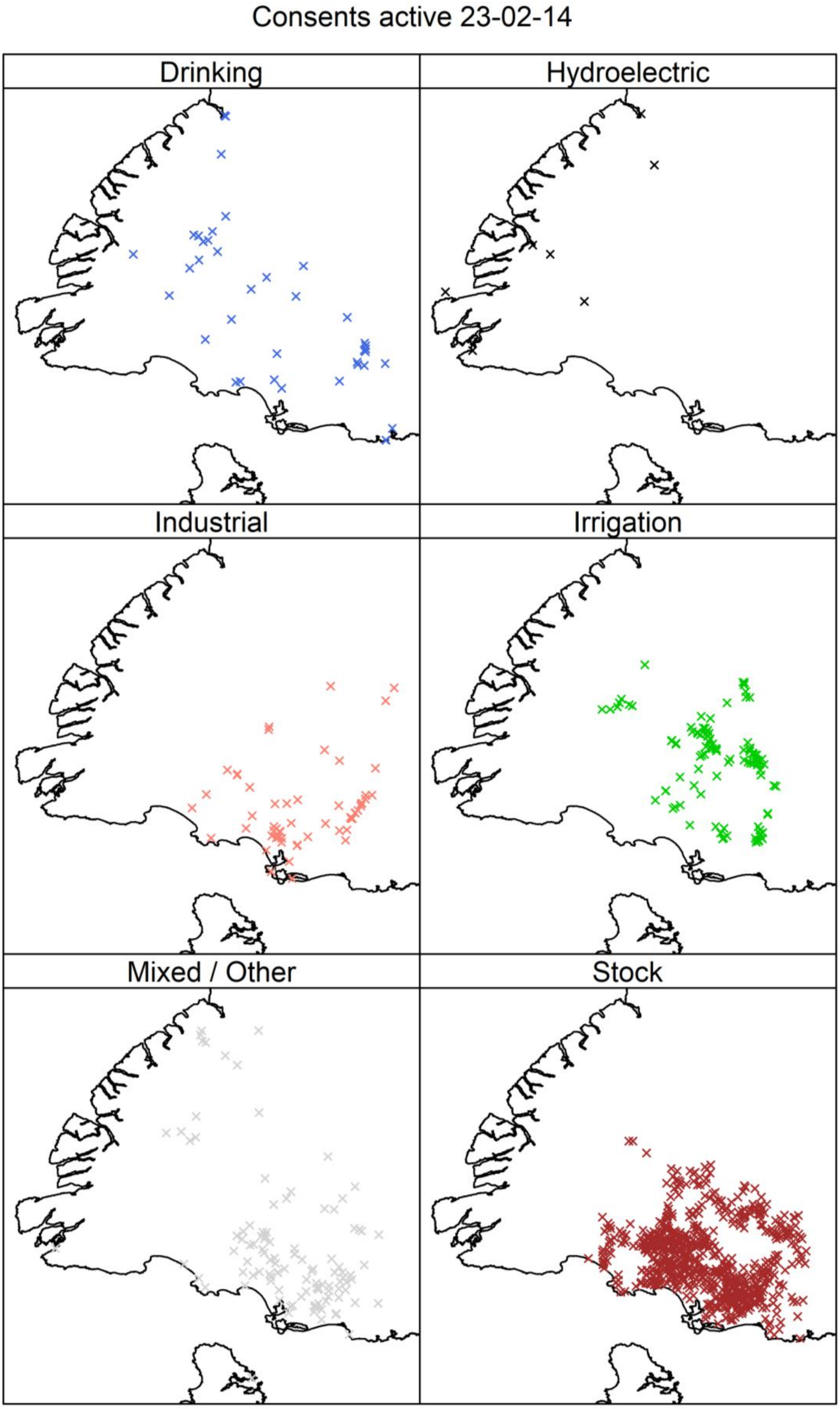

Figure 5-19: Map of location of ES consents active 14/02/2023, showing primary use.

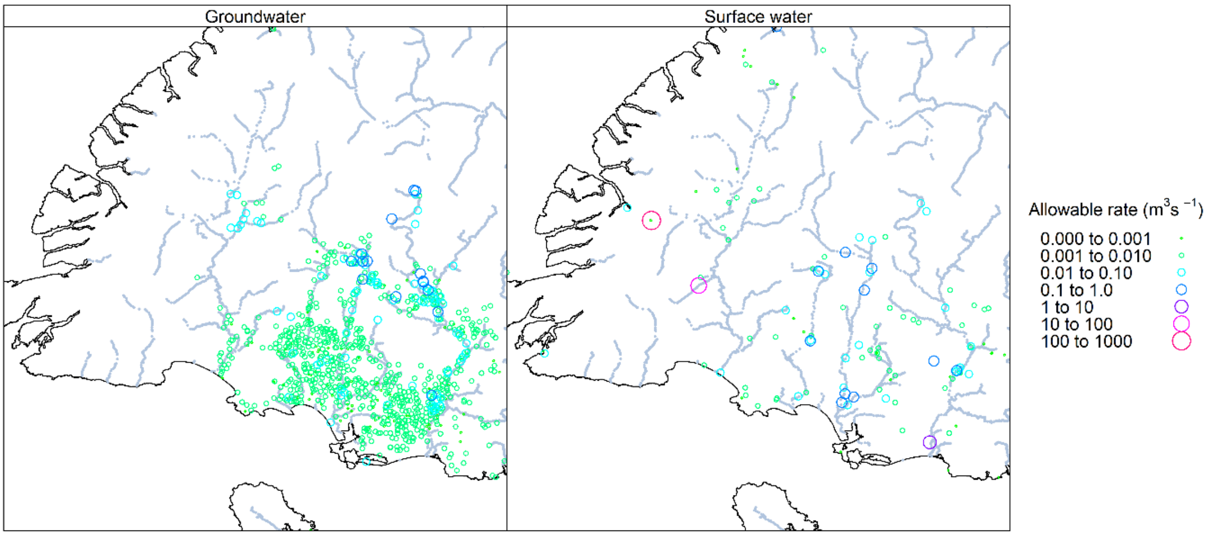

Figure 5-20: Map of location of ES consents active 14/02/2023, showing consent maximum rate.

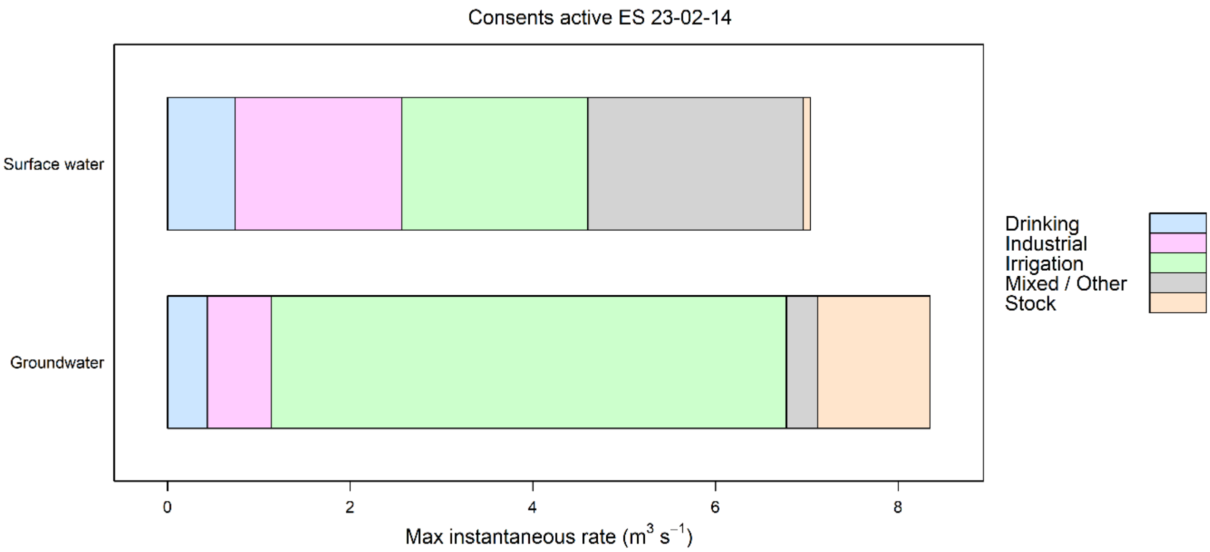

Figure 5-21: Barchart of sum of non-hydropower consent maximum instantaneous rate for ES consents active 14/02/2023, showing primary source and uses.

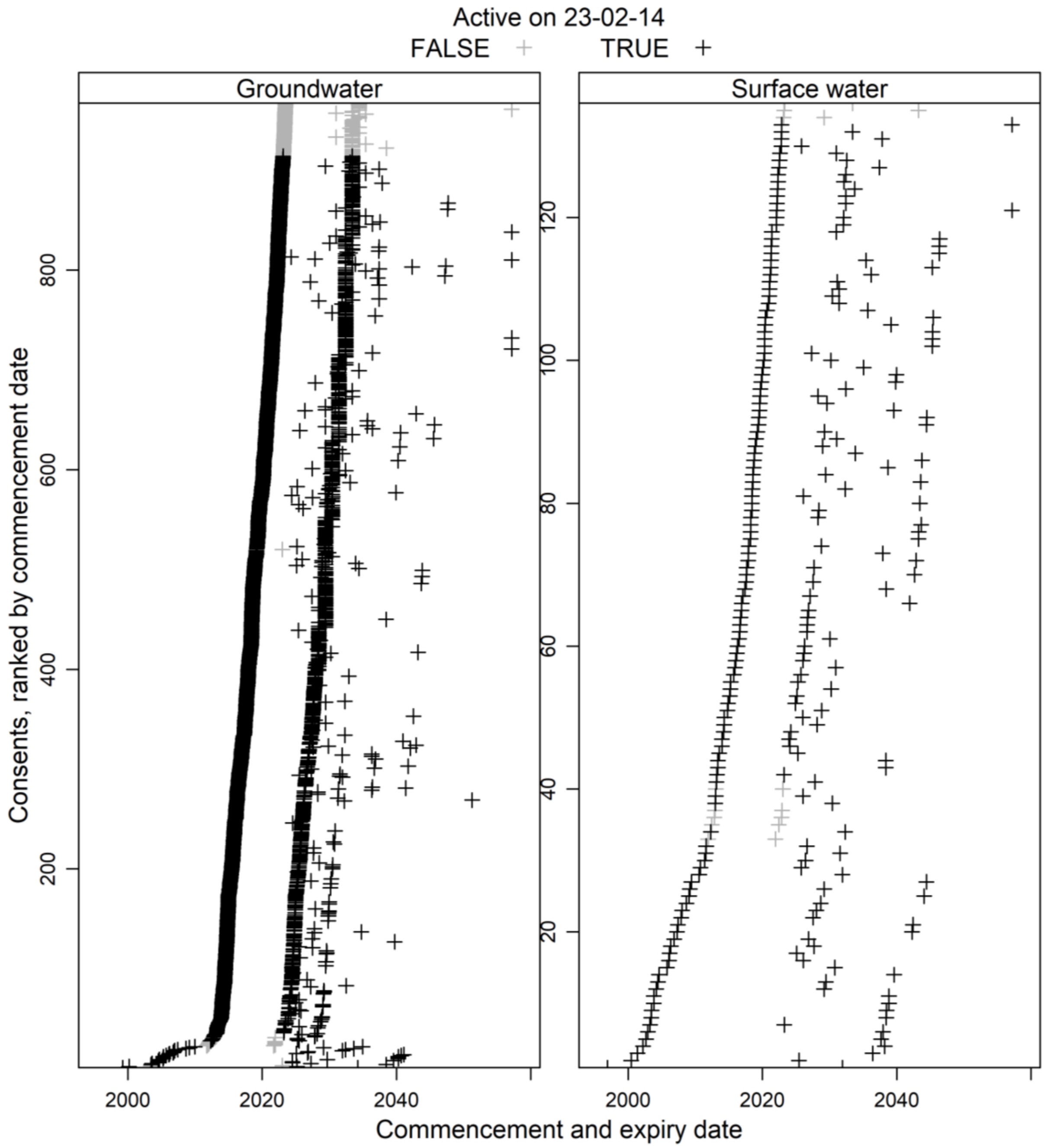

Figure 5-22: Plot of consent expiry and commencement date for ES for consents active at any point in the analysis period.

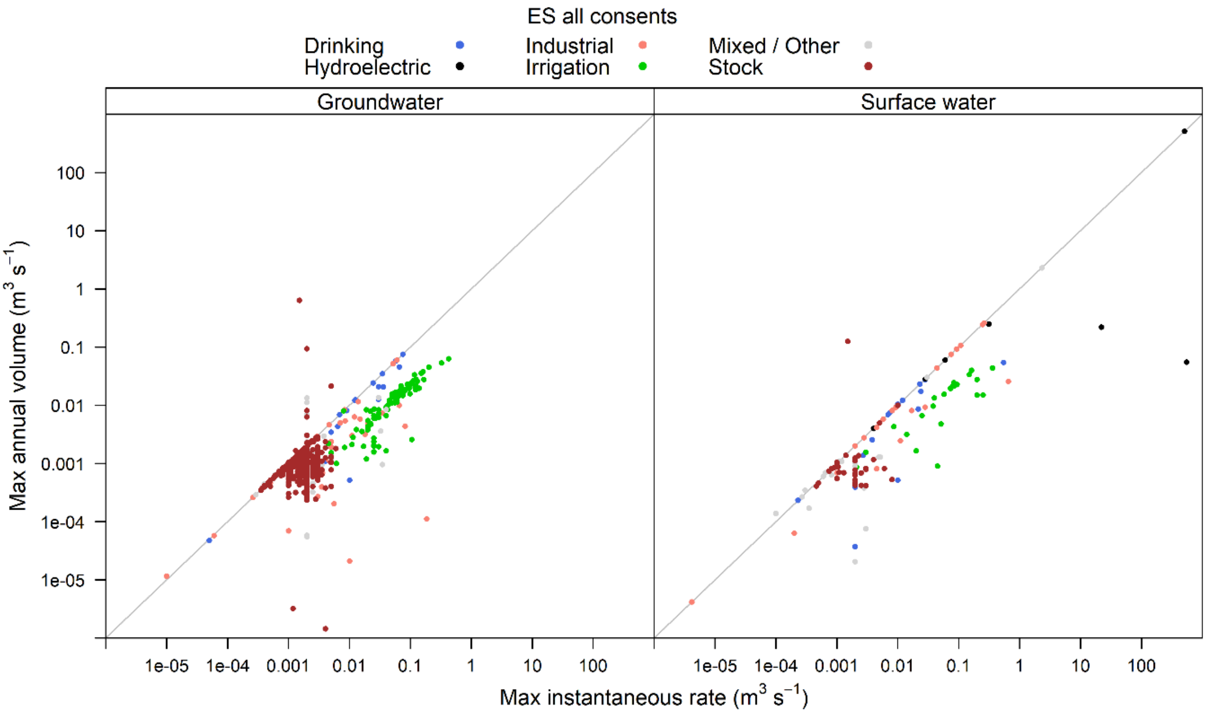

Figure 5-23: Plot of consent maximum rate and maximum annual volume for ES consents active.

5.3 Restrictions on consented abstraction

5.3.1 Observation-based restrictions

While checking observation-based restrictions, we identified that the upper limit was missing for 8 restrictions (<0.5%) from ECan, and that a further 3 low-flow restrictions (<0.5%) had a negative upper limit value. These restrictions were ignored. For restrictions with a corresponding flow time-series, some examples of hydrographs and flow duration curves with restriction ranges indicated are shown in Figure 5-24.

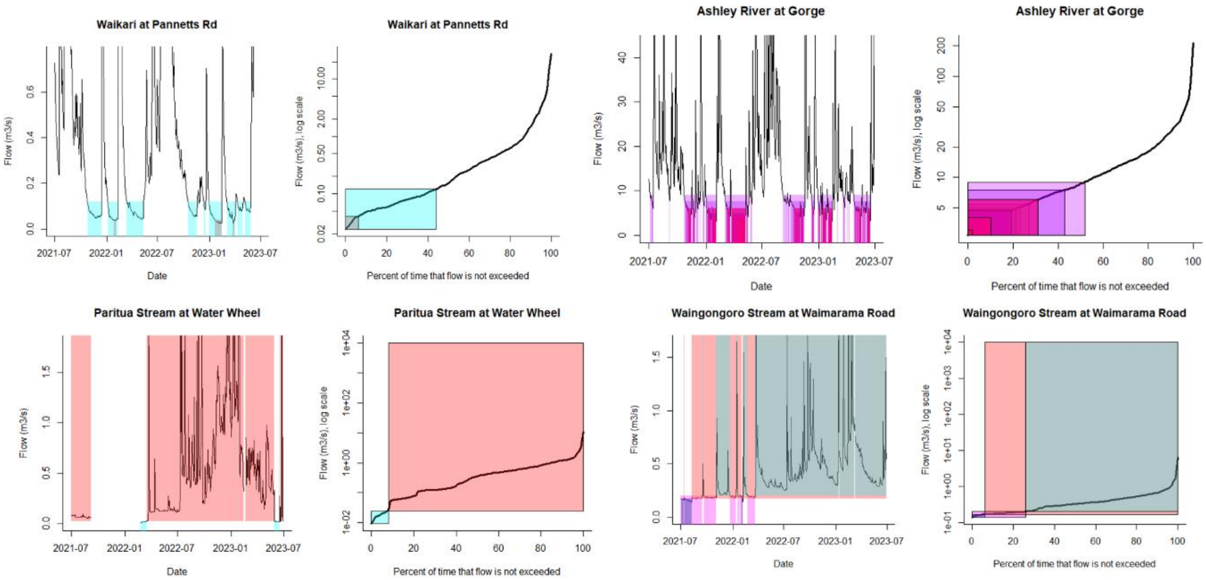

Figure 5-24: Example hydrographs and flow duration curves, with active restrictions indicated by coloured boxes. Each colour represents a different restriction.

For HBRC, restrictions are defined as a lower and upper value, with three rule types: cease, reduce and normal. 48% of sites (N=15) have just two restrictions (cease and normal) and some sites have more bands and more restrictions, with two sites having 17 restrictions. For HBRC, the explicitly defined “Normal” restriction level means that some restriction rule is always active.

For ECan, restrictions are defined by an upper “trigger value” below which the restriction is active. The only restriction rule present, “low flow” causes a cease in abstraction. 30% of sites (N=71/234) have just one restriction, but some have a very high number of restrictions e.g., 359 restriction rules at “Rakaia River / SW_6852602”, and 101 restriction rules at “Waitaki river at Kurow.” For ECan, the absence of a “Normal” rule means that restrictions are only active at low flows.

Figure 5-25 shows restriction trigger values compared to observed flows during the analysis period. Restriction triggers are typically much lower than median flows. Figure 5-26 shows these same restriction trigger values compared to estimated naturalised MALF from Booker and Woods (2014). Restriction triggers are scattered around estimated naturalised MALF, but there is considerable spread in the relationship. Some spread way from the diagonal line in Figure 5-26 will be associated with uncertainty in estimated naturalised MALF for ungauged sites, which are considerable as explained in Booker and Woods (2014). Another reason for spread way from the diagonal line in Figure 5-26 could include misspecification of the site location on the national river network onto which estimated naturalised MALF has been mapped (e.g. in flat areas where the river network does not represent artificial channels which might be described as drains).

We inspected points plotting in the top-left of Figure 5-26 to understand other reasons for spread way from the diagonal line. We expected values being plotted on the y-axis of Figure 5-26 to be trigger flows (cease-to-take) expressed as flow rate at a flow observation site, as indicated by the data being labelled “low flow”. Inspection of raw data led us to suspect that some of the points plotting in the extreme top-left of Figure 5-26 were not river flows but were actually lake levels as indicated by their site names (e.g., Lake Opuha at Metres above sea level; Lake Coleridge at Intake). This situation is an example of confusion that can result from the challenge of populating a database with data from non-standardised consent conditions.

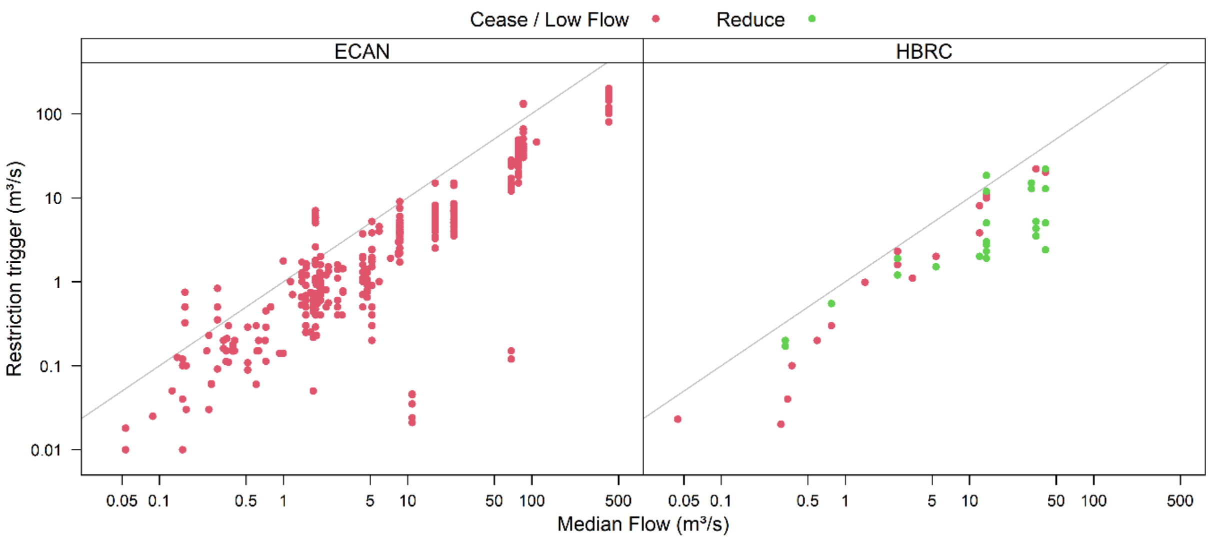

Figure 5-25: Restriction trigger flows compared to the observed median flow during the analysis period. Note that the "Cease" rule for HBRC and "Low Flow" rule for ECan have an equivalent meaning.

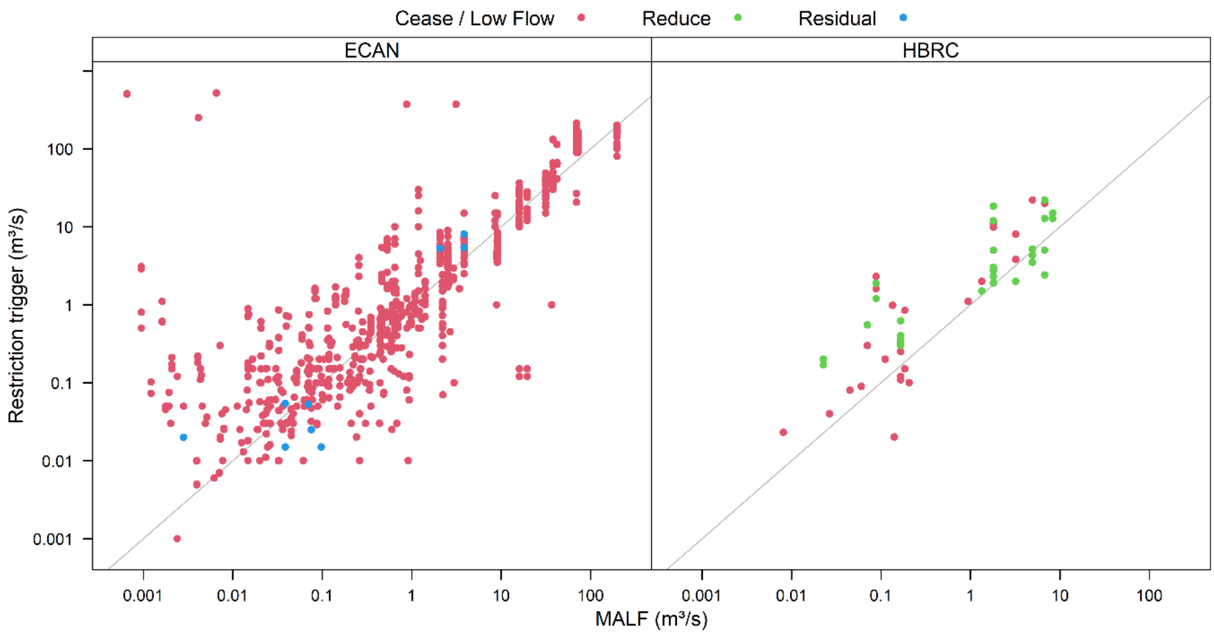

Figure 5-26: Restriction trigger values plotted against estimated naturalised MALF from Booker and Woods (2014). Note that the "Cease" rule for HBRC and "Low Flow" rule for ECan have an equivalent meaning.

Figure 5-27 shows the total number of restrictions with a gauge reading, and with an active restriction for each day of the analysis. HBRC “Normal” restrictions, which cause no change to consent abstraction, were excluded from this count. For HBRC, the number of restrictions active was highest in February 2022, and few restrictions were active in the Jul-2022 to Jun-2023 year. For ECan, the number of restrictions active peaked in autumn of each year.

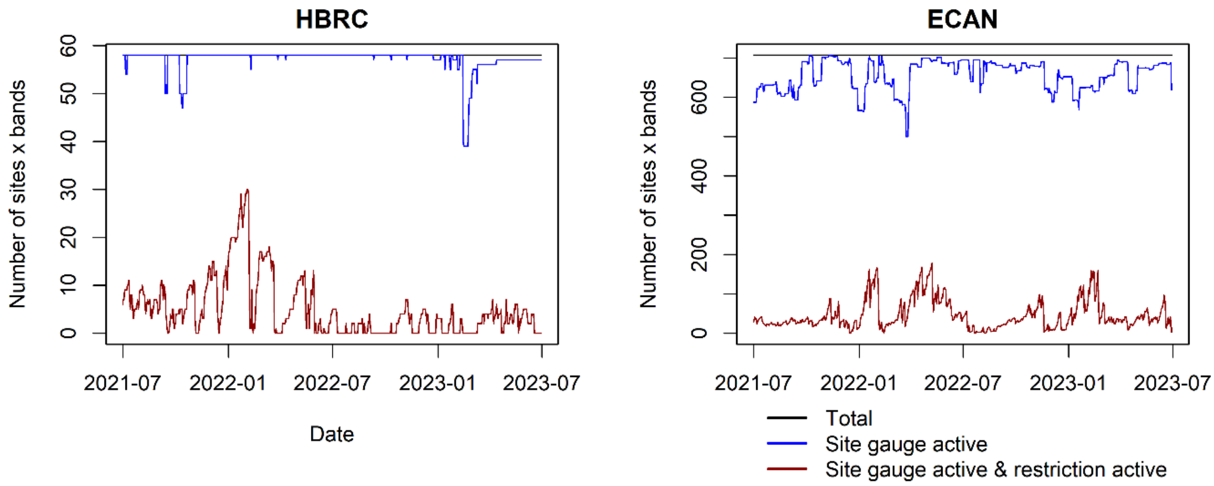

Figure 5-27: Number restrictions bands with an active gauge and active for each day of the analysis period.

5.3.2 Predetermined restrictions

The types of predetermined restrictions active for the analysis period (01-Jul-21 to 30-Jun-23) are shown in Table 5-5. Most restrictions are maximum rates of abstraction and maximum weekly volumes, and apply to a single consent. Rules were usually for an annual period, but some were also for shorter, seasonal periods.

Table 5-5: Summary consent-based restriction information for HBRC for consents active during the analysis period.

Rule item	Types present	Number of instances
Rule Quantity	Maximum rate	2541
	Maximum weekly volume	1767
	Maximum annual volume	1003
	Maximum 28-day volume	577
	Maximum monthly volume, Maximum daily volume, or Maximum season volume	19
Rule Scope	Apply to a single consent	5770
	Apply to a group of consents	121
	"Low flow special" (applies to a single consent for notification but not for compliance checking)	16
Rule Season	01 Jul - 30 Jun	5714
	01 Jun - 31 May	83
	01 Nov – 30 Jun	36
	01 Jul – 31 Oct	15
	All other periods (28 different periods each containing N<10 rules)	59

The consent-based restriction rules for maximum rate of abstraction and maximum annual volume of individual consents (as opposed to consent groups) overlapped with information from the consent database obtained through LAWA. The consent restriction database contains more detailed information as it also contained consent seasons. In most cases (94%), the values in each database were identical.

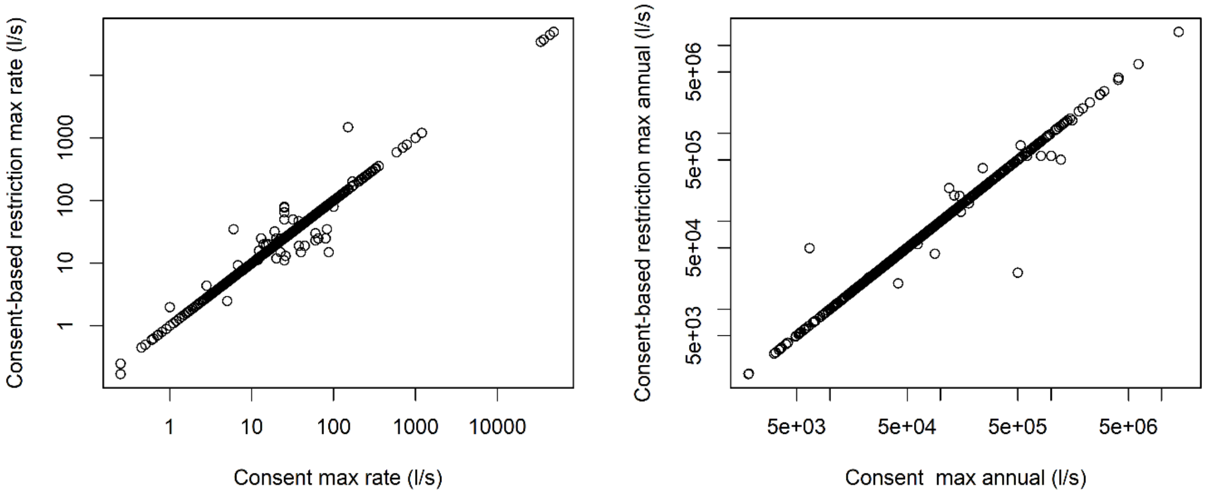

Figure 5-28: Maximum rate and maximum annual values from the consent database and consent-based restriction database for consents active during the analysis period.

5.3.3 Restricted consent allocation

Figure 5-29 shows the allowed abstraction in terms of the number of consents, and total instantaneous rate of consents for each day of the analysis period. The upper pair of lines on each plot indicates the total allocation (if consent restrictions are disregarded), and how much this is reduced by when restrictions are considered. Restrictions impact a very small number of consents, but have a somewhat larger impact on the allowable instantaneous rate, suggesting restrictions are targeted at larger consents. The lower pair of lines show consents with observation-based restrictions, and those that have an active gauge. This shows that approximately 20% of consents (by number of consents) are controlled by observation-based restrictions for each council. For HBRC, flow time-series were able to be obtained and were active more of the time, except for a period in autumn 2023. For ECan, the flow time-series was not obtained / active for a large proportion of restrictions abstraction.

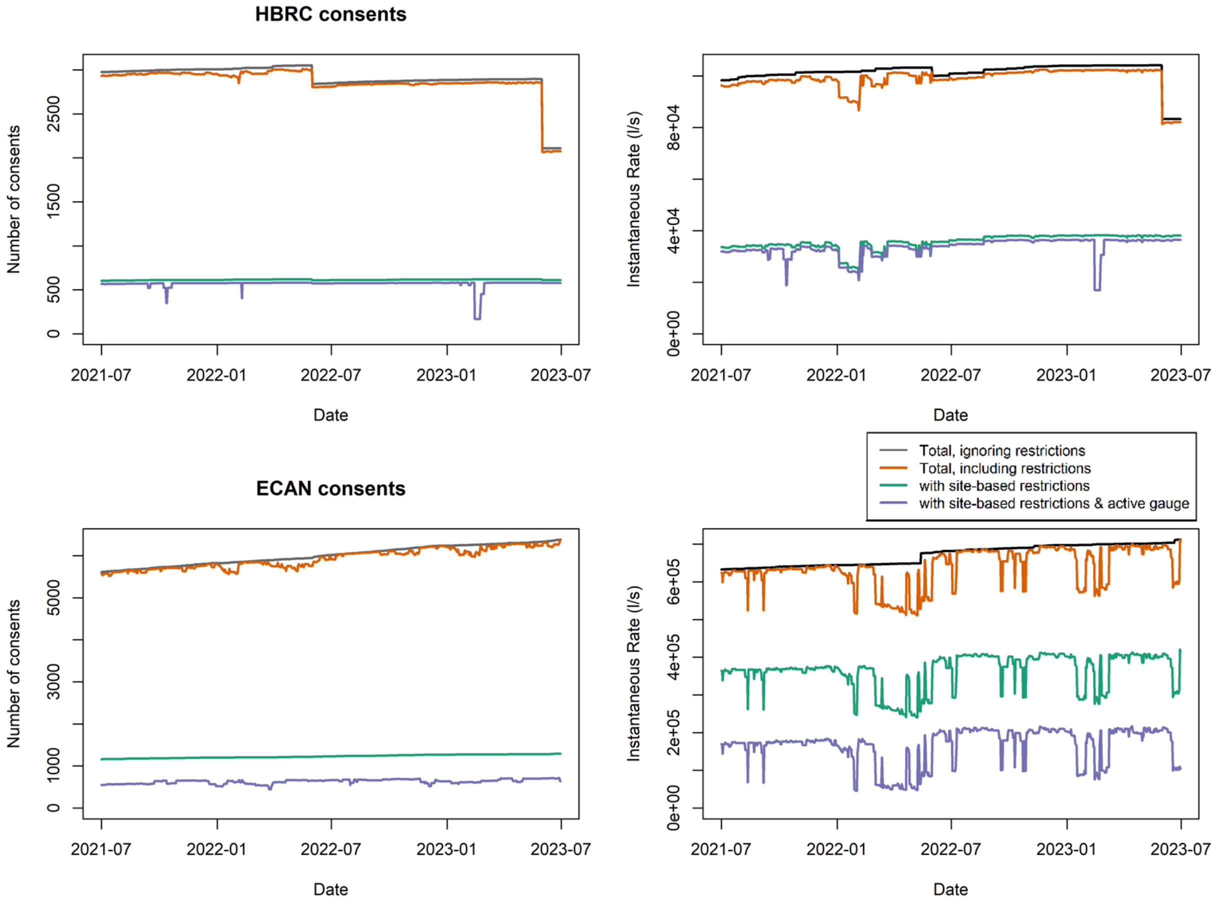

Figure 5-29: Number of consents and consent allowable instantaneous rate of take for each day of the analysis period for HBRC and ECan. Note: Hydroelectric consents are excluded.

Figure 5-29 indicates a steady increase in number of consents throughout the analysis period for ECan. This result may be a consequence of a real increase in issued consents, or may be an artifact of being supplied with a dataset that only contained active consents at the time the data was supplied. Consents that were active at the start of our analysis period may have been removed from a dataset that only contained active consents for a date towards the end of our analysis period.

5.4 Metered abstractions

Removal of non-daily time-series resulted in the removal of zero out of 1275 meters for HBRC (0%), three out of 5514 meters for ECan (<0.5%), and 29 out of 48 meters for ES (60%). Flagging of meter values resulted in flagging 745 out of 1275 meters for HBRC (58%), 1373 out of 5514 meters for ECan (25%), and 29 out of 48 meters for ES (60%). For HBRC 13.6% of meter observations were flagged, 0.6% of observations for ECan, and 14.8% flagged for ES. HBRC has 897 meters with some gaps requiring filling (70%), ECan had 3378 meters requiring gap filling (61%), and ES had 19 meters (40%). Gap filling was required either because of flagged values or because the meter record did not span the full duration of the analysis period.

The percentage reduction in total metered volume for daily meter records from removing flagged values was 5.6% for HBRC, 88.3% for ECan and 8% for ES. The large reduction for ECan reflects removal of some very high abstraction values present in the supplied data, which would in many cases not be physically possible. Note that these high values were flagged by ECan in the data supplied. We compared our high value flag to the equivalently calculated flag in the ECan data. The two flags agree for 99.2% of meter values.

5.4.1 Infilling of incomplete abstraction time-series

Of 6837 meters, we identified 5959 meters (87%) for which we could model daily abstraction rates. To be included, meters needed to be linked to a consent with a non-missing coordinate and have at least 50% of values non-missing and non-flagged for the 2-year period.

Random forest models predicted daily take well for many sites. For example, out-of-bag (OOB) r-squared calculated at daily resolution was greater than 0.5 for 54% of meters (Figure 5-30). This indicates that the model explained over half the variance for most meters. However, models performed less well for some meters; OOB r-squared calculated at daily resolution was less than 0.2 for 16% of meters. Further inspection showed that in some cases this apparent poor performance was common for meters with very few positive values of take.

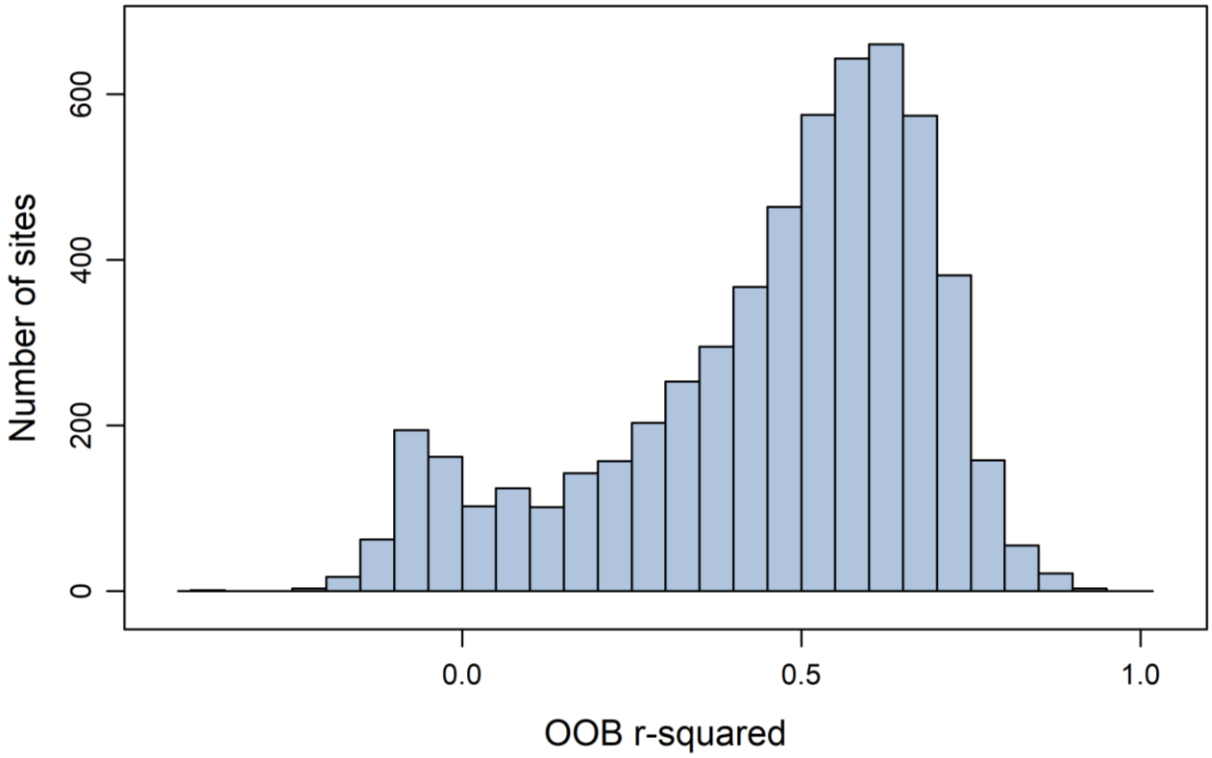

Figure 5-30: Out-of-bag (OOB) r-squared for predicted daily water abstraction divided by maximum allowable rate (in log base 10 space) for each of 5743 meters.

Performance metrics in Figure 5-31 show model predictive performance was stronger when assessed at monthly resolution compared to daily resolution. OOB r-squared was greater than 0.5 for 97% of meters, NSE was very high for nearly all meters, and the models showed little signs of systematic bias when assessed at monthly resolution. Model-predicted and measured values for each month are shown in Figure 5-32.

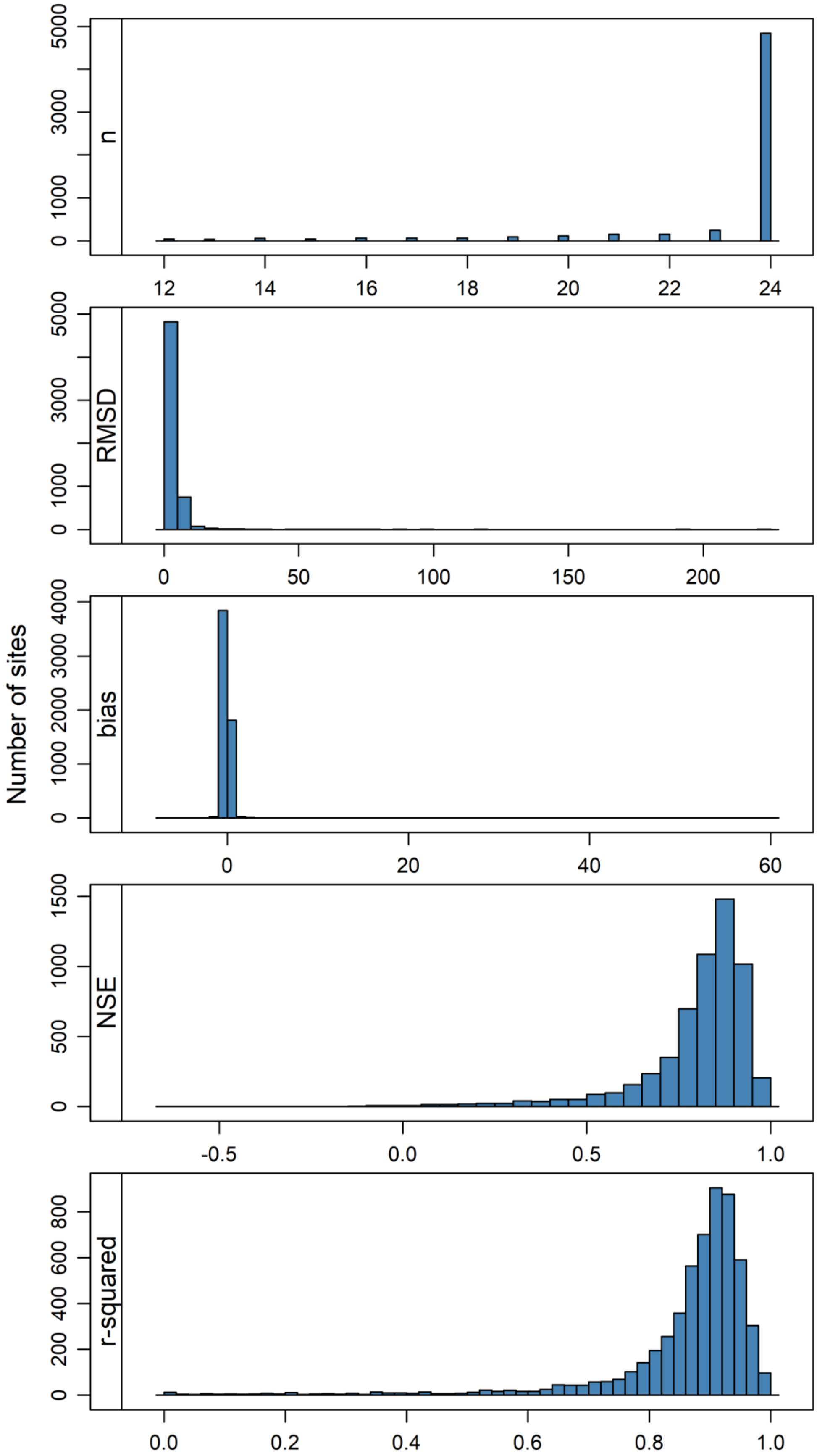

Figure 5-31: Various performance metrics for out-of-bag (OOB) predicted monthly water abstraction (modelled as a percentage of maximum allowable rate) for each of 5743 meters.

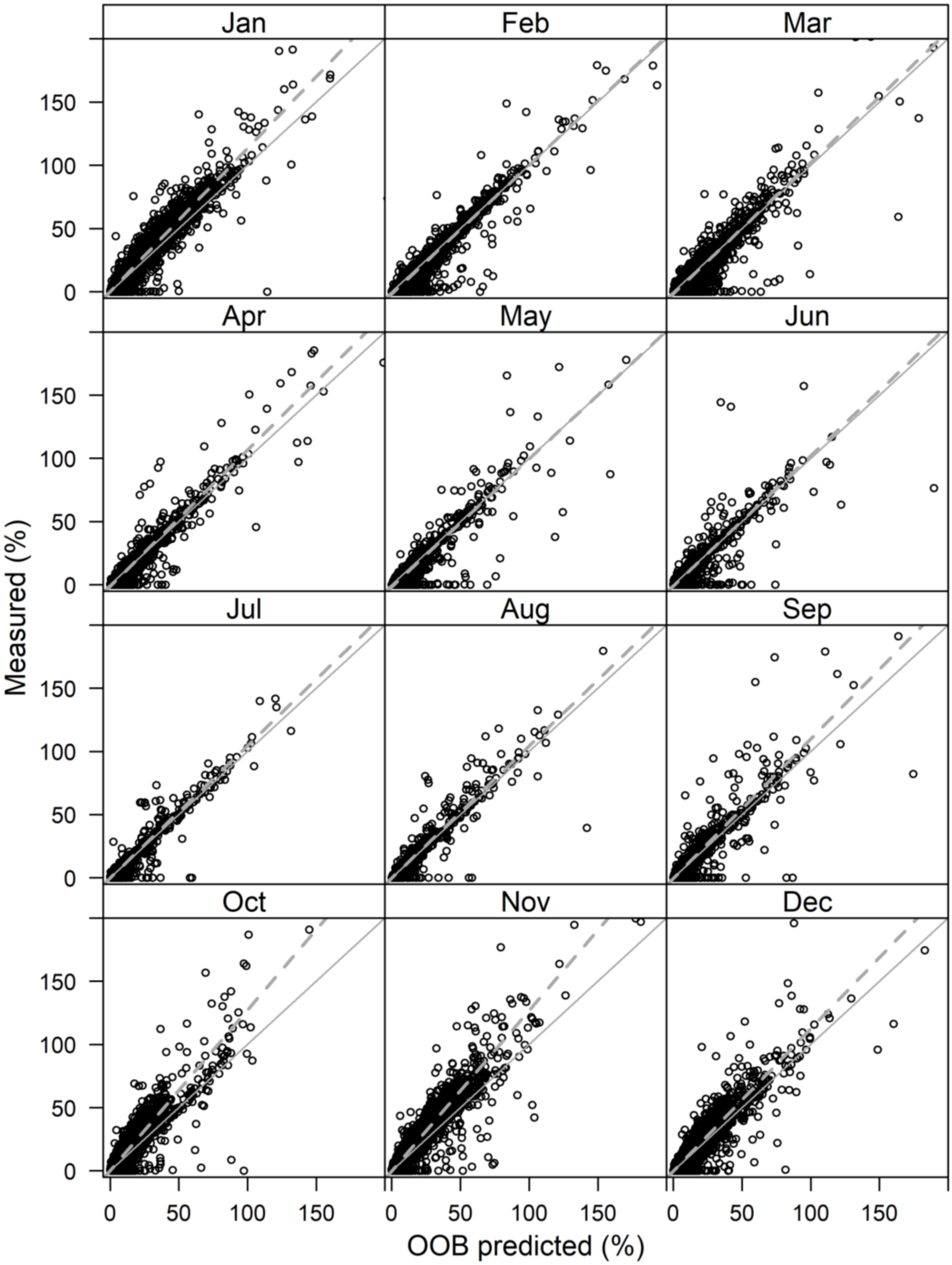

Figure 5-32: For each calendar month, measured versus out-of-bag (OOB) predicted mean water take as a percentage of maximum allowable rate, during the analysis period. Each panel contains a data point for each year at each site. Note, sites with very high values are not shown.

Overall, the results indicated that our models were able to predict patterns of take through time within each take site. Consequently, modelled predictions were used to fill gaps within recorded take time-series to provide a valid representation of the real (but unknown) missing values. For the 4294 meters with some gaps or flagged values, 81% could be filled by the model, having meter criteria of a) having a coordinate, and b) having at least 50% of values non-missing or non-flagged for the 2-year period. Infilling gaps in these meters increased total abstraction during the analysis period by 0.04% for HBRC, 0.01% for ECan and 0.3% for ES. Some examples of raw, flagged, and filled time-series are given in Figure 5-33.

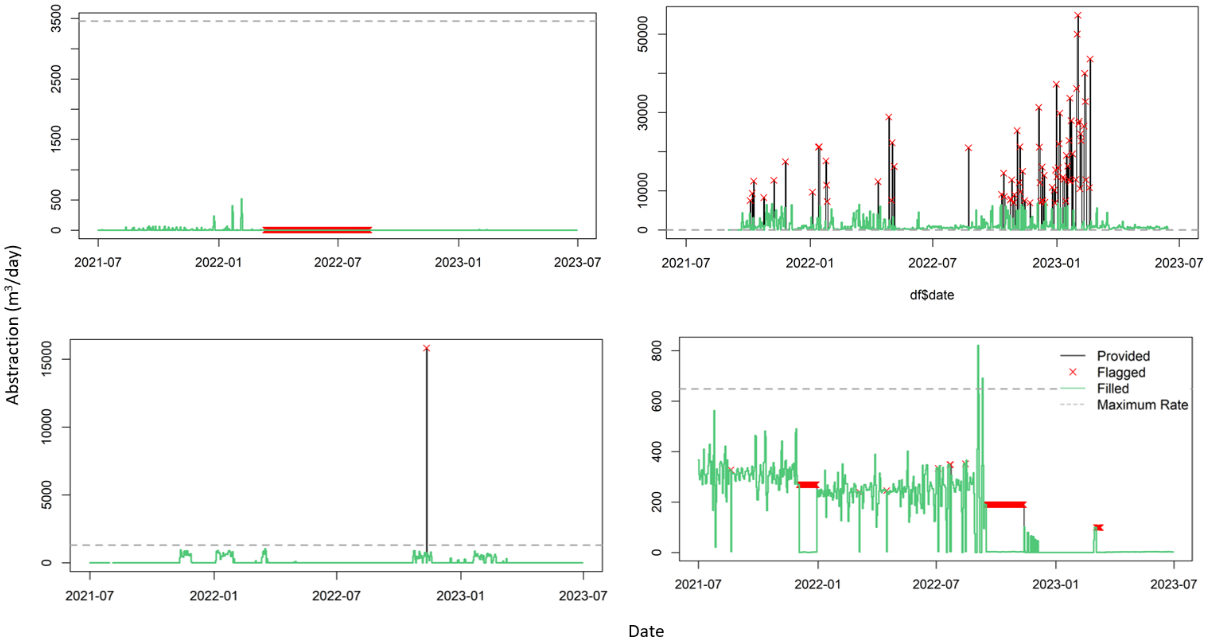

Figure 5-33: Examples of council-provided, flagged, and filled meter time-series for the analysis period. Maximum rate for a meter is the sum of the maximum rates of all associated consents.

5.4.2 Linking metered abstraction to consents

Some examples of meter time-series plotted alongside daily consent allocation for each day of the analysis are shown in Figure 5-34, after apportioning filled metered abstraction to each consent.

After filling and apportioning metered abstraction to consents, the percentage of consented water abstraction (by total maximum rate) with a non-missing take was assessed, for all non-hydroelectric uses (Table 5-6). For HBRC and ECan, 70–75% of total consented maximum rate was metered.

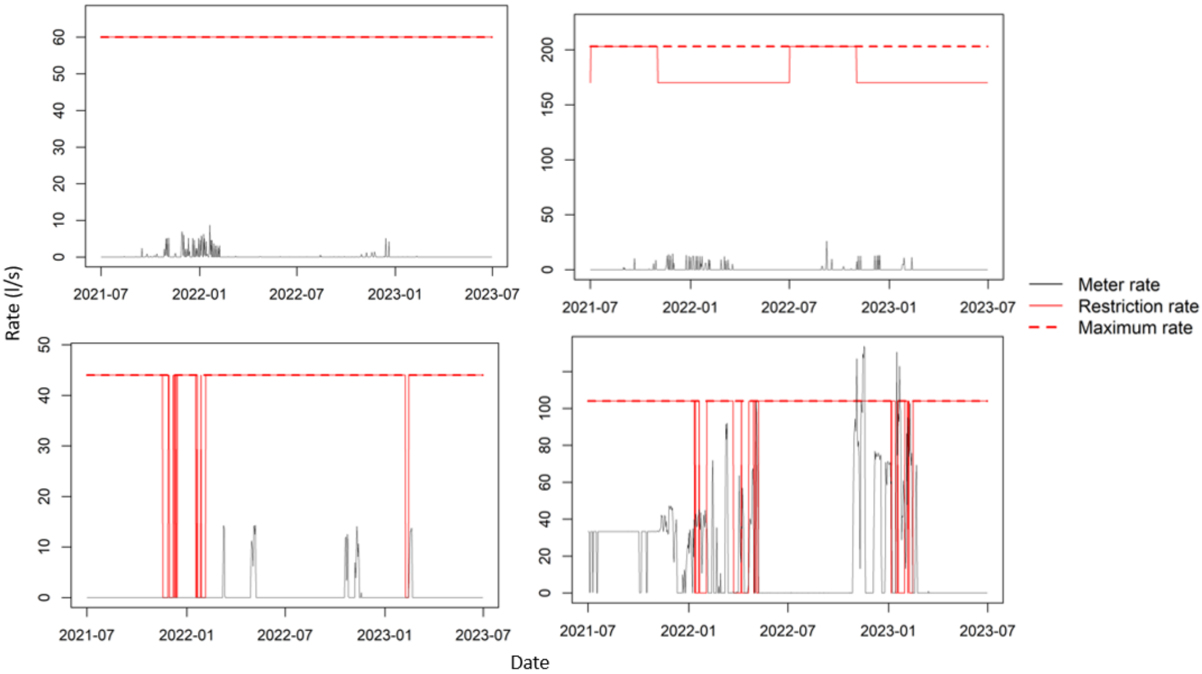

Figure 5-34: Examples of consent metered abstraction, maximum rate, and restricted daily rate.

Table 5-6: Percentage of consented maximum rate with a meter reading on each day of the analysis period, totalled for all days. Consents are divided into three categories according to their maximum rate of abstraction.

	HBRC	ECan	ES
	% metered	% metered	% metered
Max Rate ≥ 5 L s^{-1}	74%	73%	3%
Max Rate < 5L s^{-1}	17%	8%	<1%
Overall	74%	72%	3%

Abstraction compliance per-consent for each council is shown in Figure 5-35 to Figure 5-37. Unfilled meter data was used, after removal of flagged values.

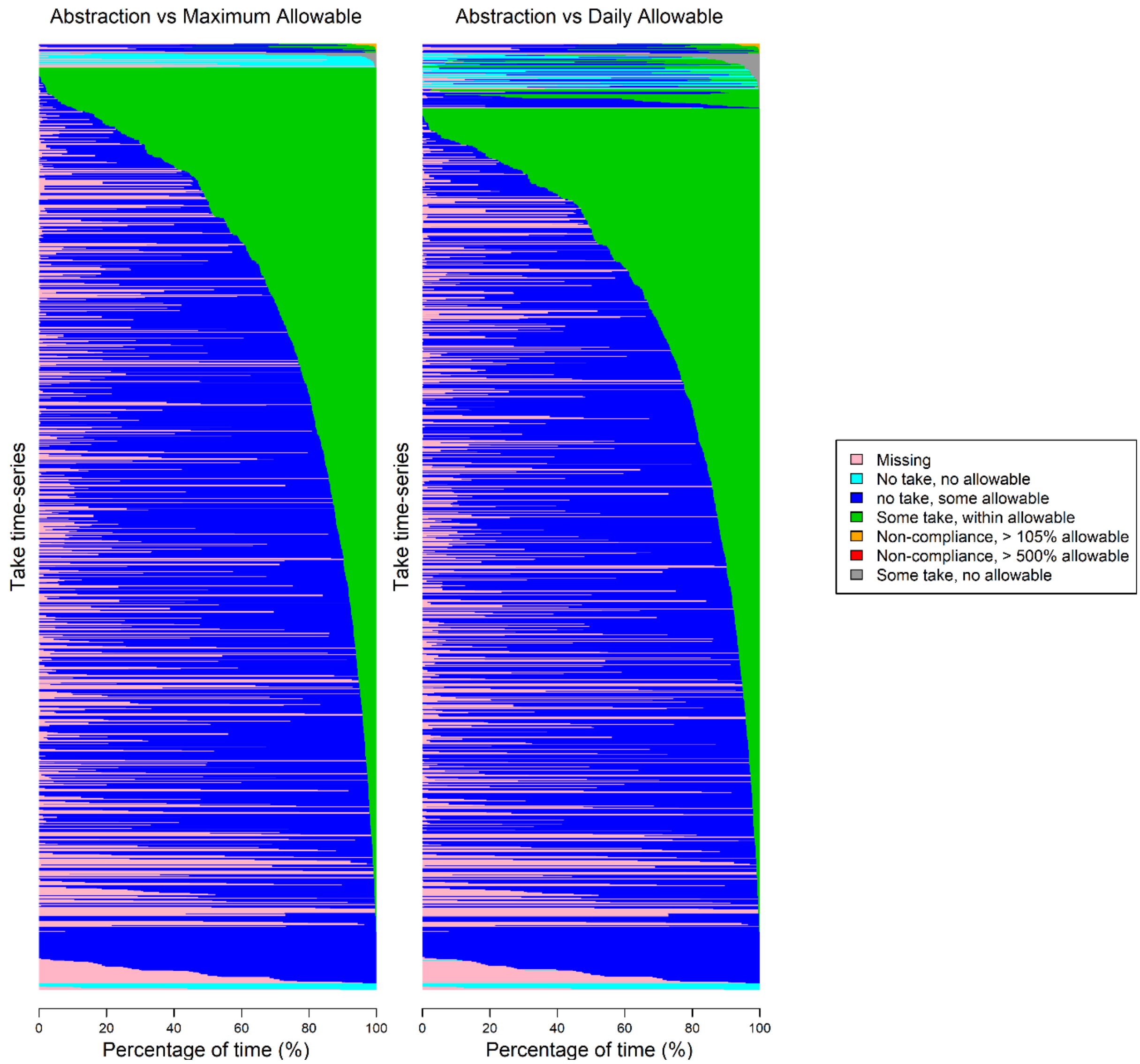

Figure 5-35: Comparison of consent abstraction with allowable rates during the analysis period for HBRC. Each horizontal bar represents a consent, and colour indicates whether time-series data is missing, or how much is taken compared to allowable. The allowable rate is the fixed consent maximum allowable rate (left) and daily allowable rate which accounts for restrictions (right).

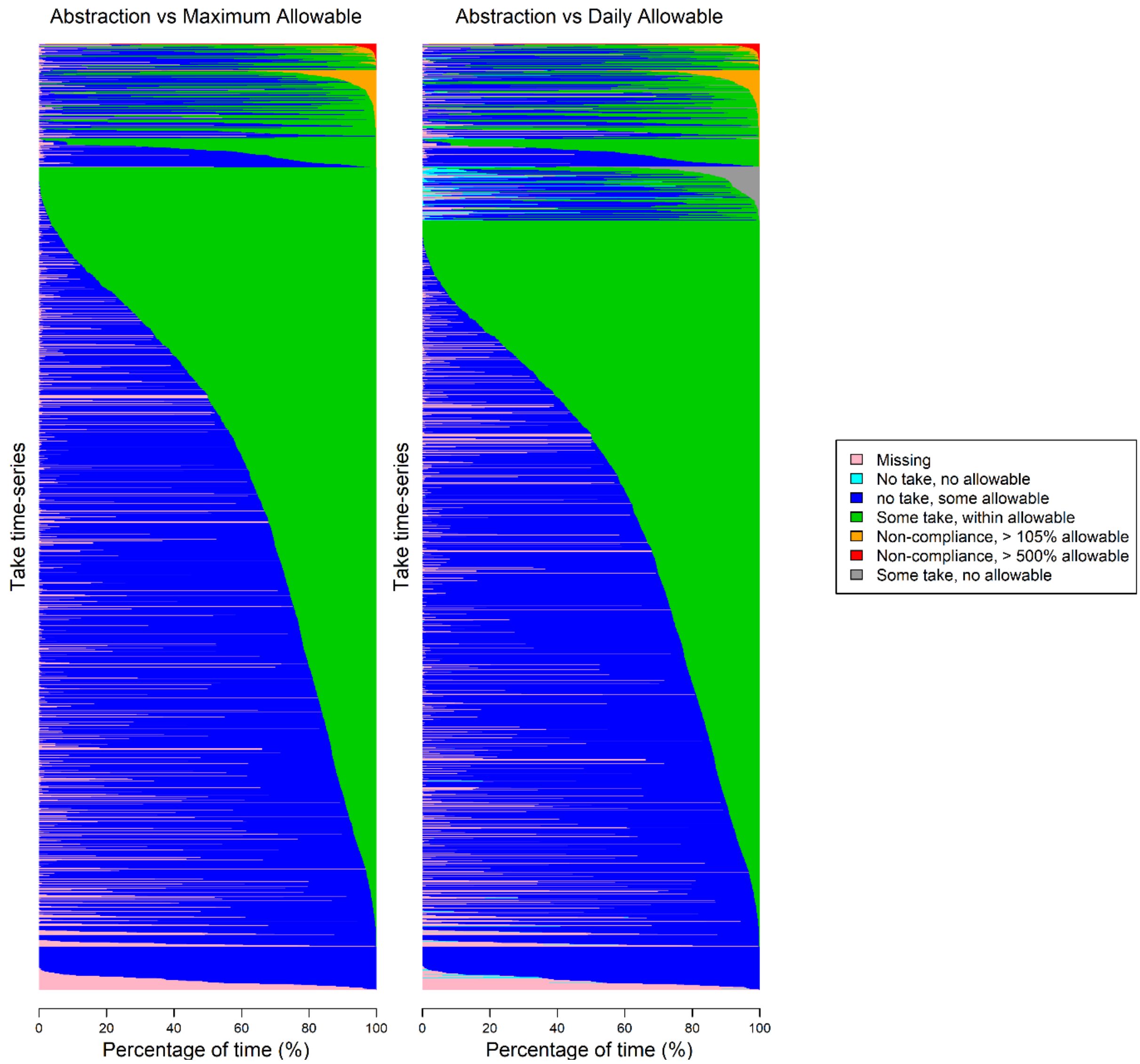

Figure 5-36: Comparison of consent abstraction with allowable rates during the analysis period for ECan. Each horizontal bar represents a consent, and colour indicates whether time-series data is missing, or how much is taken compared to allowable. The allowable rate is the fixed consent maximum allowable rate (left) and daily allowable rate which accounts for restrictions (right).

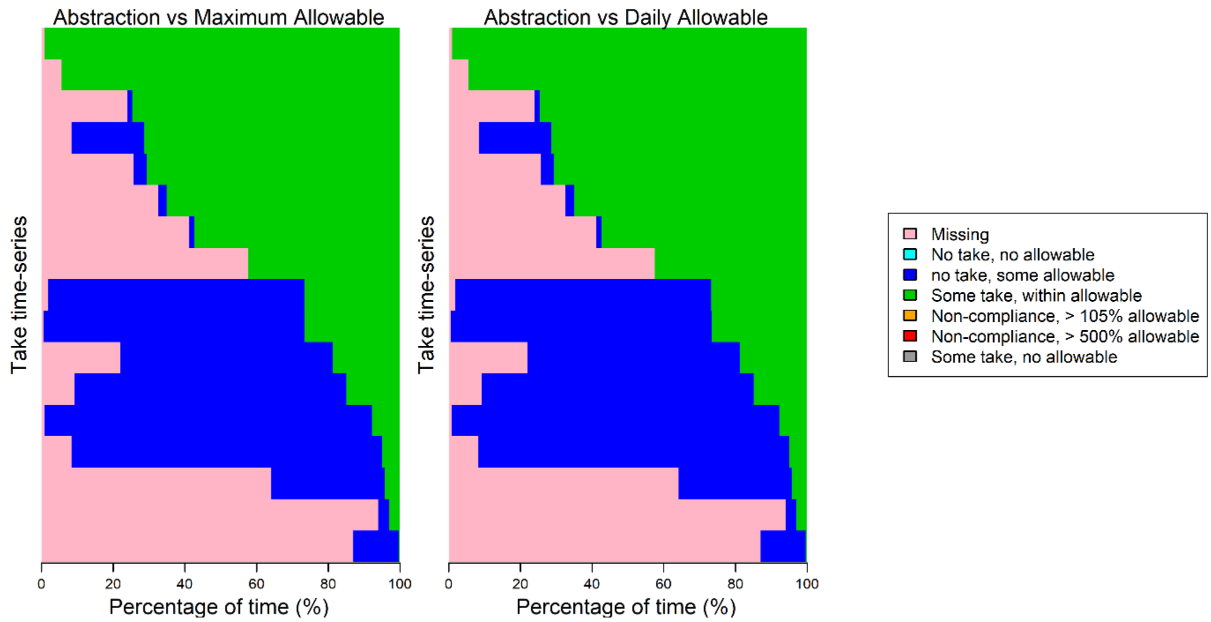

Figure 5-37: Comparison of consent abstraction with allowable rates during the analysis period for ES. Each horizontal bar represents a consent, and colour indicates whether time-series data is missing, or how much is taken compared to allowable. The allowable rate is the fixed consent maximum allowable rate (left) and daily allowable rate which accounts for restrictions (right).

For HBRC and ECan, the most prevalent case on any given day is “No take, some allowable” showing that most of the time, consents are not exercised. Where abstraction does occur it is most often “Some take, within allowable”. There were some instances of take beyond allowable, and these instances are greater when restrictions are taken into account. For ES, there are few metered consents. Of these consents, there is some take most of the time, and there are no instances of take beyond the allocated limit.

The total metered allocation and abstraction for each day of the analysis is shown in Figure 5-38. Our results demonstrate that, for metered consents, a low portion of the maximum take rate is actually taken on any given day. This result indicates that either there is considerable headroom for more abstraction, or that restrictions are overly generous. Typically, maximum annual volumes or other period restrictions in consents have the consequence that the instantaneous allowable rate cannot be exercised all of the time. It should be noted that the limiting effect of period restrictions is not reflected in the values of allowable instantaneous take shown in Figure 5-38.

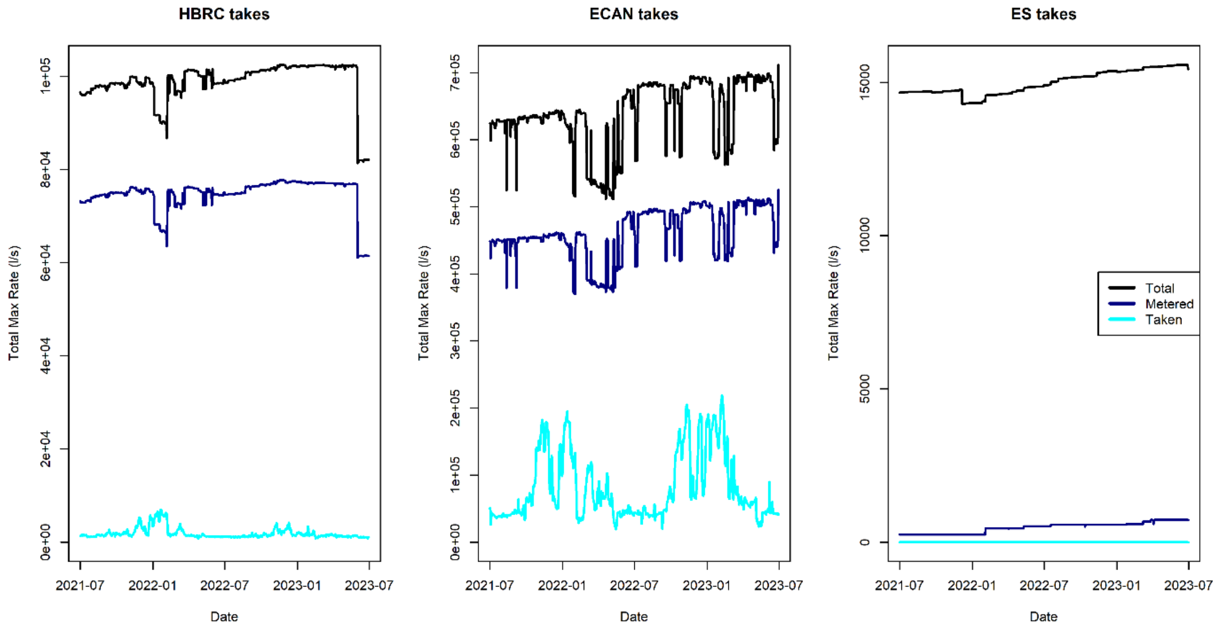

Figure 5-38: Total metered allocation and abstraction during the analysis period. Total is total allowable instantaneous take regardless of whether takes are metered or unmetered. Metered is total allowable instantaneous take for metered takes. Taken is total take measured by meters.

Figure 5-39 compares metered abstraction to consented rates. Most consented annual abstractions are within the maximum annual volume, and some are well below. Maximum rates of consented abstraction can be well below the maximum allowable, or well above. This result indicates that some abstractors never broke their consent conditions, whereas others did break their consent conditions on at least one day during the analysis period. It should be noted that taking a maximum abstraction rate is largely affected by sensor noise. In general, average abstraction rates are below the maximum allowable abstraction rate, and below the rate which is equivalent to taking the maximum allowable annual volume.

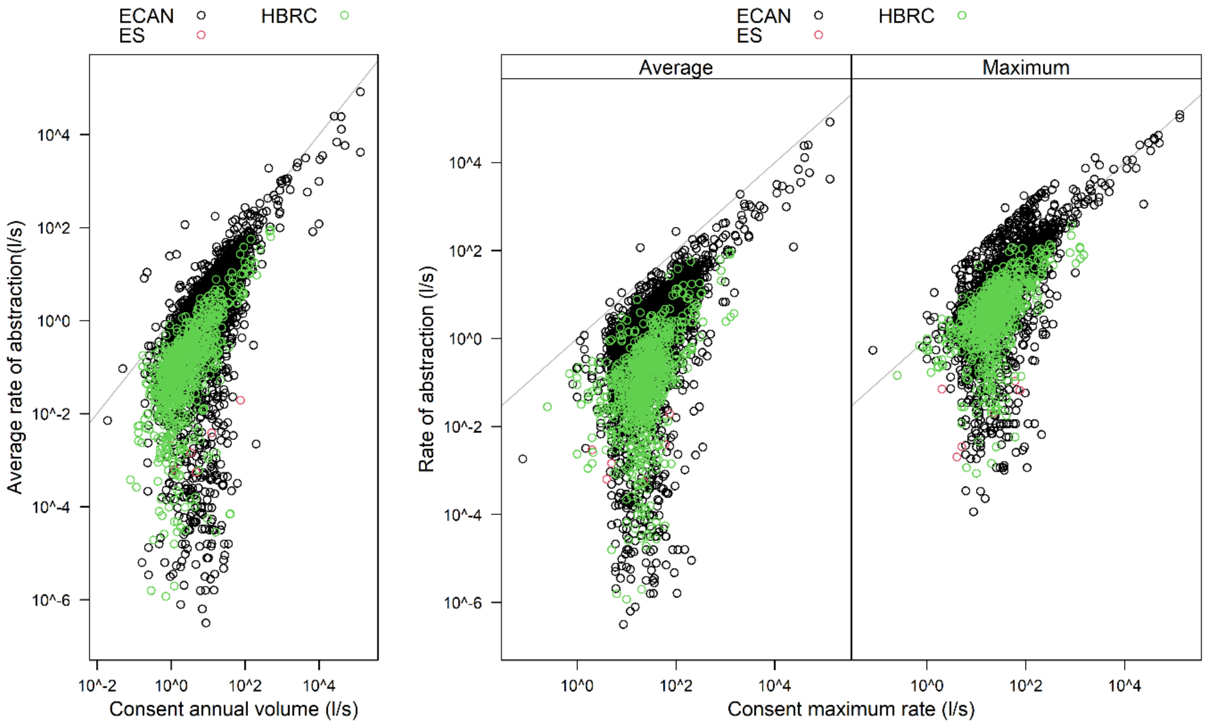

Figure 5-39: Metered rate of take compared to consent maximum rate and annual volume for all consents active during the analysis period. Average rate of abstraction is the average metered abstraction for a given consent during the analysis period. Maximum rate of abstraction is the is the rate on the day of highest take for a given consent during the analysis period. Each circle represents a single consent. Note that the consent annual volume has been converted to a corresponding rate of take (L/s).

5.5 Mapping accumulated pressure

Consented accumulated pressure, which assumes the worst-case scenario of all consents being exercised simultaneously at their maximum rate is shown in Figure 5-40 and Figure 5-41. Figure 5-40 demonstrates the highest pressure on flow regimes is likely to occur in smaller rivers, where proportionally more water is consented. Irrigation uses resulted in the highest rates of stream depletion across the country, although takes for industrial and drinking uses are important in some catchments (Figure 5-41).

Metered accumulated pressure is shown in Figure 5-42 and Figure 5-43. This represents known accumulated pressure arising from the average abstraction rate during the period 1-July-2021 to 30-June-2023. Metered accumulated pressure is likely to be lower than actual accumulated pressure given the presence of non-metered activities, including consents without a meter and permitted water abstractions. Metered accumulated pressure exhibits similar patterns to consented accumulated pressure with the highest pressure on flow regimes arising in small rivers (Figure 5-42) and mostly for irrigation uses (Figure 5-43).

Accumulated pressure for the consent and abstraction scenarios is compared in Figure 5-44. Compared to the worst-case maximum consented rate scenario, the scenario considering average instantaneous consented rate shows the relatively small impact of restrictions on reducing consented instantaneous rate for the 2-year period. The small role of restrictions could arise for various reasons including weather patterns, or successful management of flow regimes such that minimum flows are seldom reached and thus restrictions seldom enforced. To investigate the role of restrictions further, we compared accumulated pressure on the lowest flow day for each region (the which most restrictions are active) in Figure 5-44. On the lowest flow day, the impact of restrictions is also challenging to discern. This may reflect that many consents were not linked to restrictions.

Compared to the worst-case maximum consented rate scenario, metered abstraction is much lower (Figure 5-44). This metered abstraction does not account for unmetered consents. Furthermore, there are many factors reducing actual abstraction to below maximum rates (e.g. not irrigating off-season), and maximum annual volumes which enforce less water use than the maximum rate. The abstraction rate on the "lowest flow" day was higher than the average for the analysis period for HBRC, and lower than the average for the analysis period for ECan.

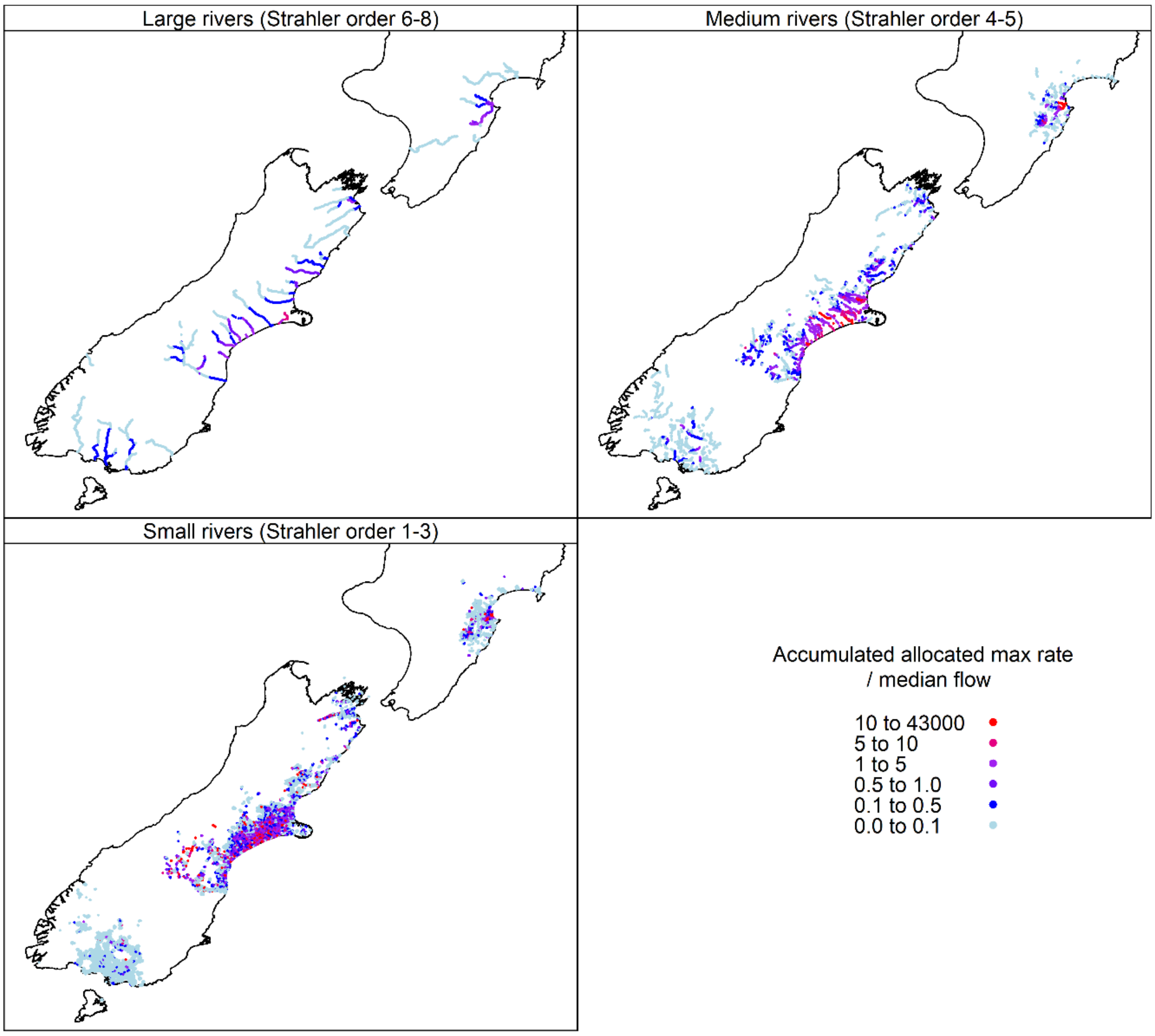

Figure 5-40: Map of accumulated upstream non-hydropower consented maximum allocated rate relative to median flow, grouped by river size, for consents active 14/02/2023.

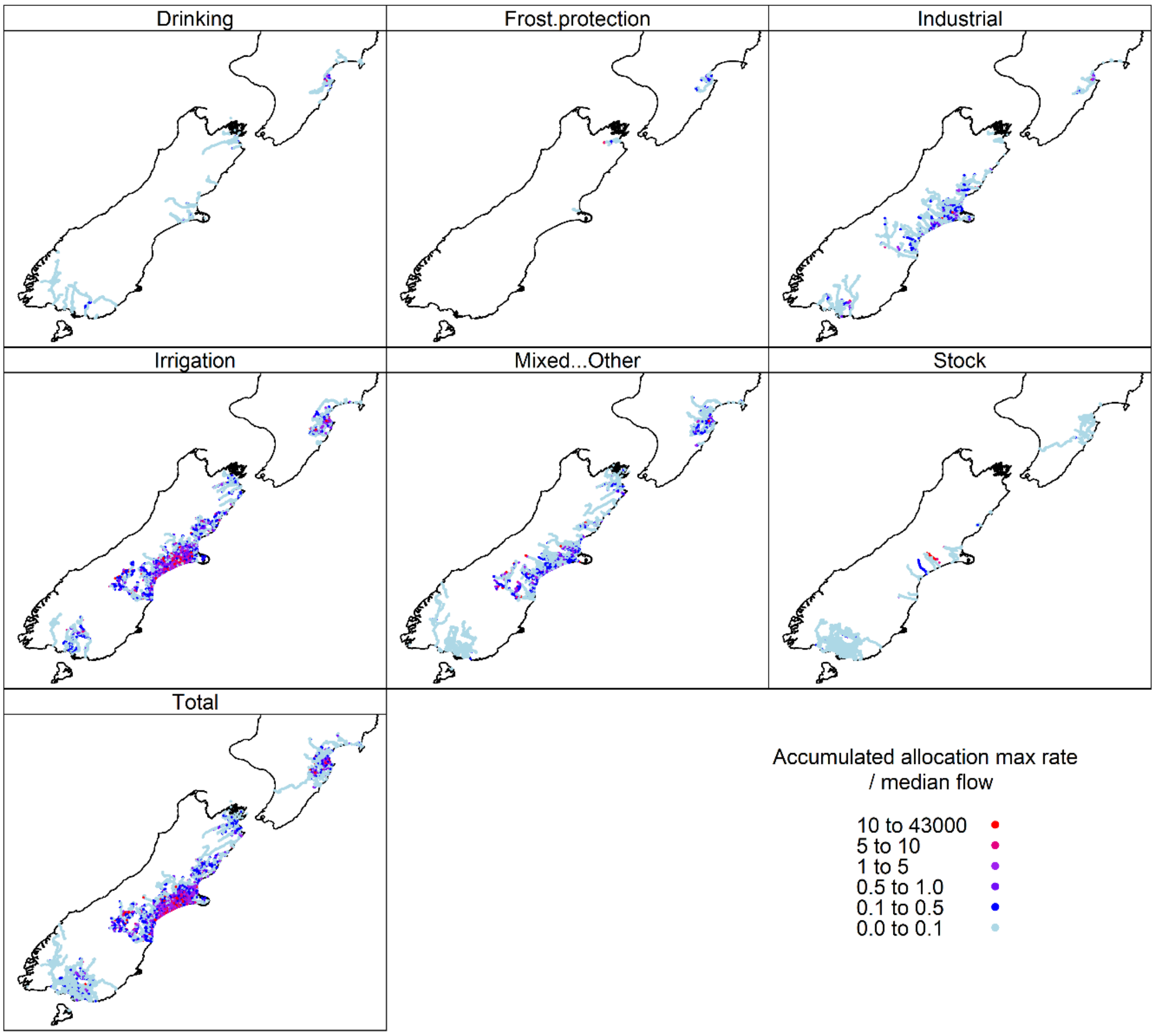

Figure 5-41: Map of accumulated upstream non-hydropower consented maximum allocated rate relative to median flow, grouped by primary use, for consents active 14/02/2023.

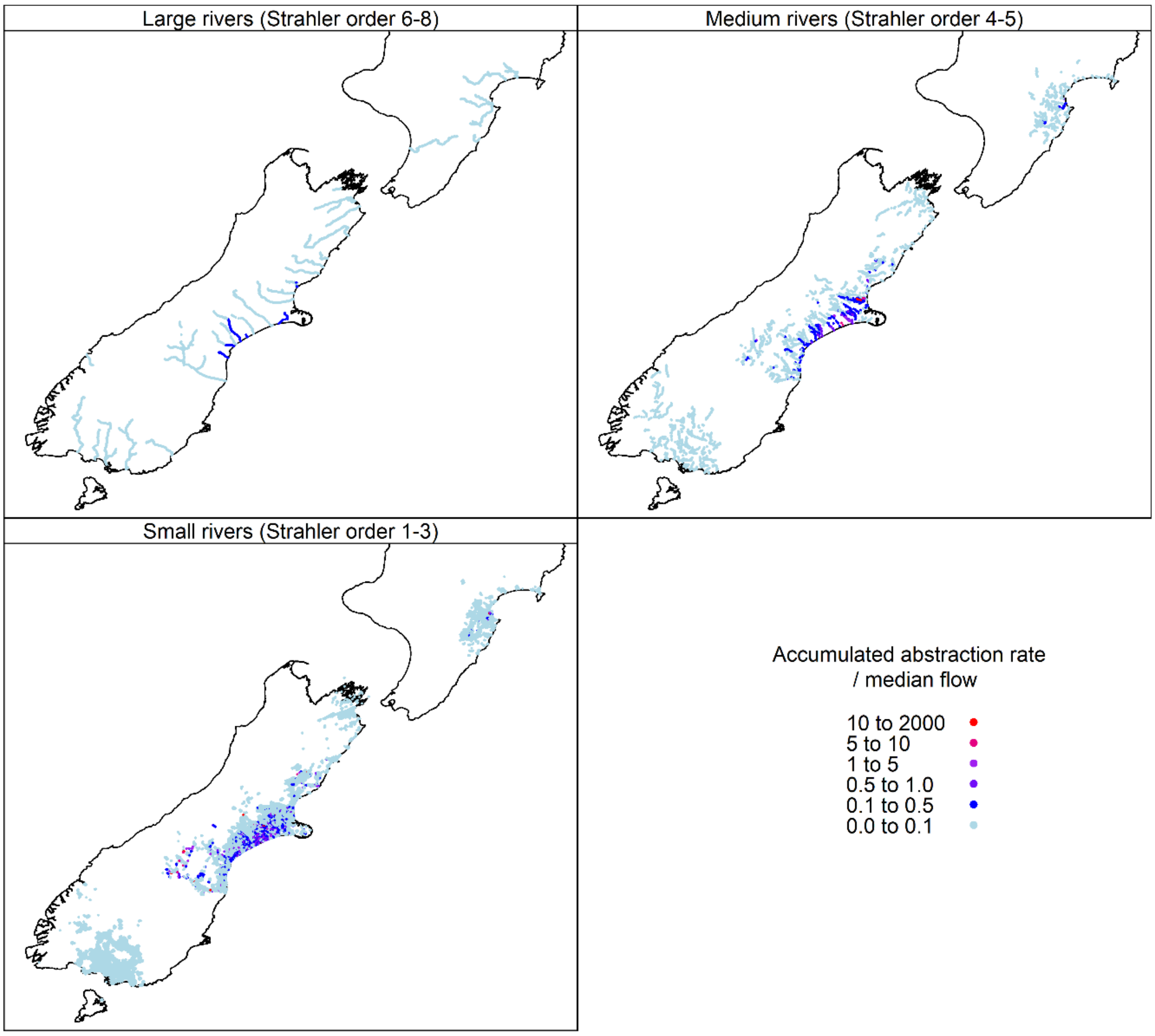

Figure 5-42 Map of accumulated upstream non-hydropower average metered abstraction rate (from 1-July-2021 to 30-June-2023) relative to median flow, grouped by river size, for consents active 14/02/2023.

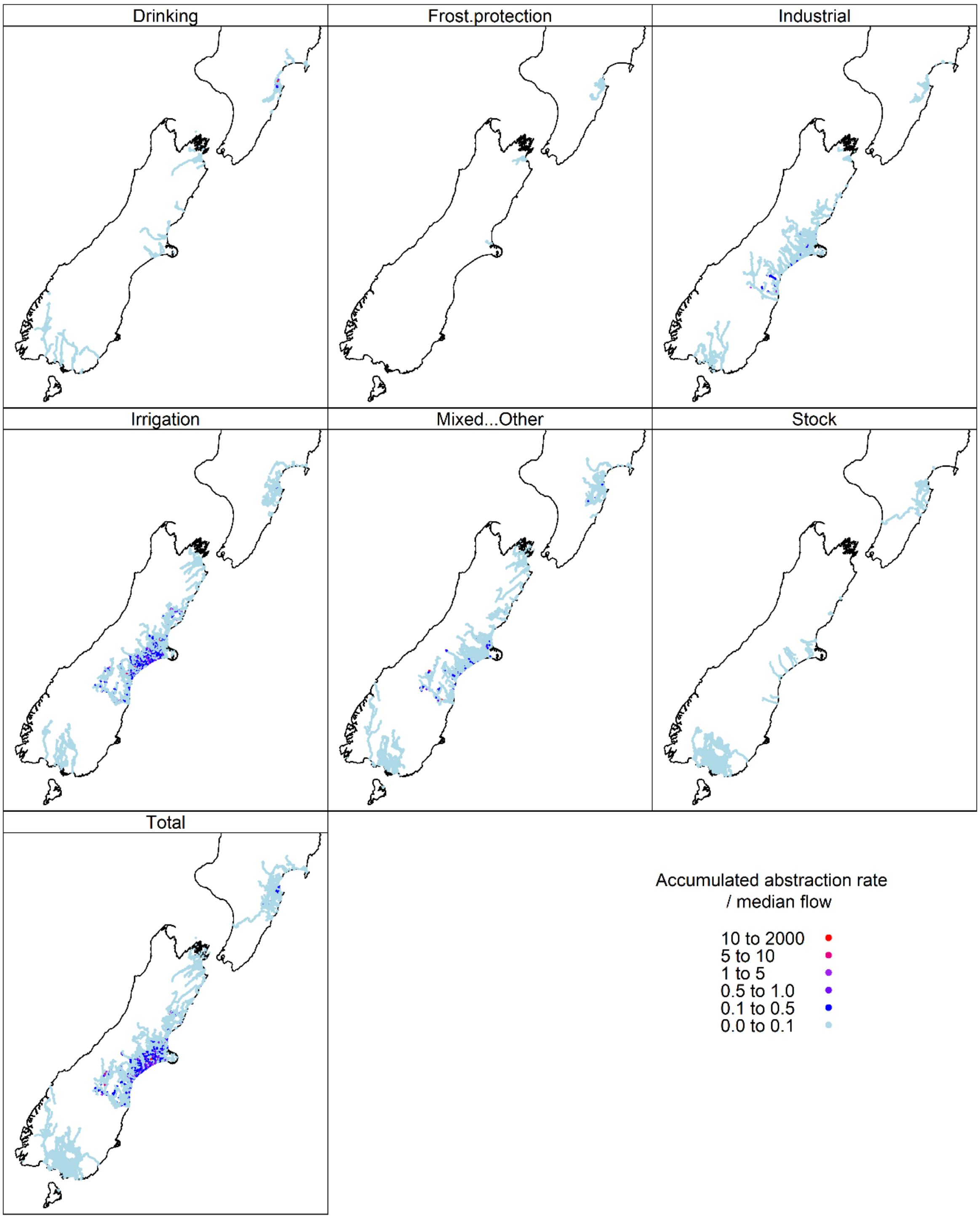

Figure 5-43 Map of accumulated upstream non-hydropower average metered abstraction rate (from 1-July-2021 to 30-June-2023) relative to median flow, grouped by primary use, for consents active 14/02/2023.

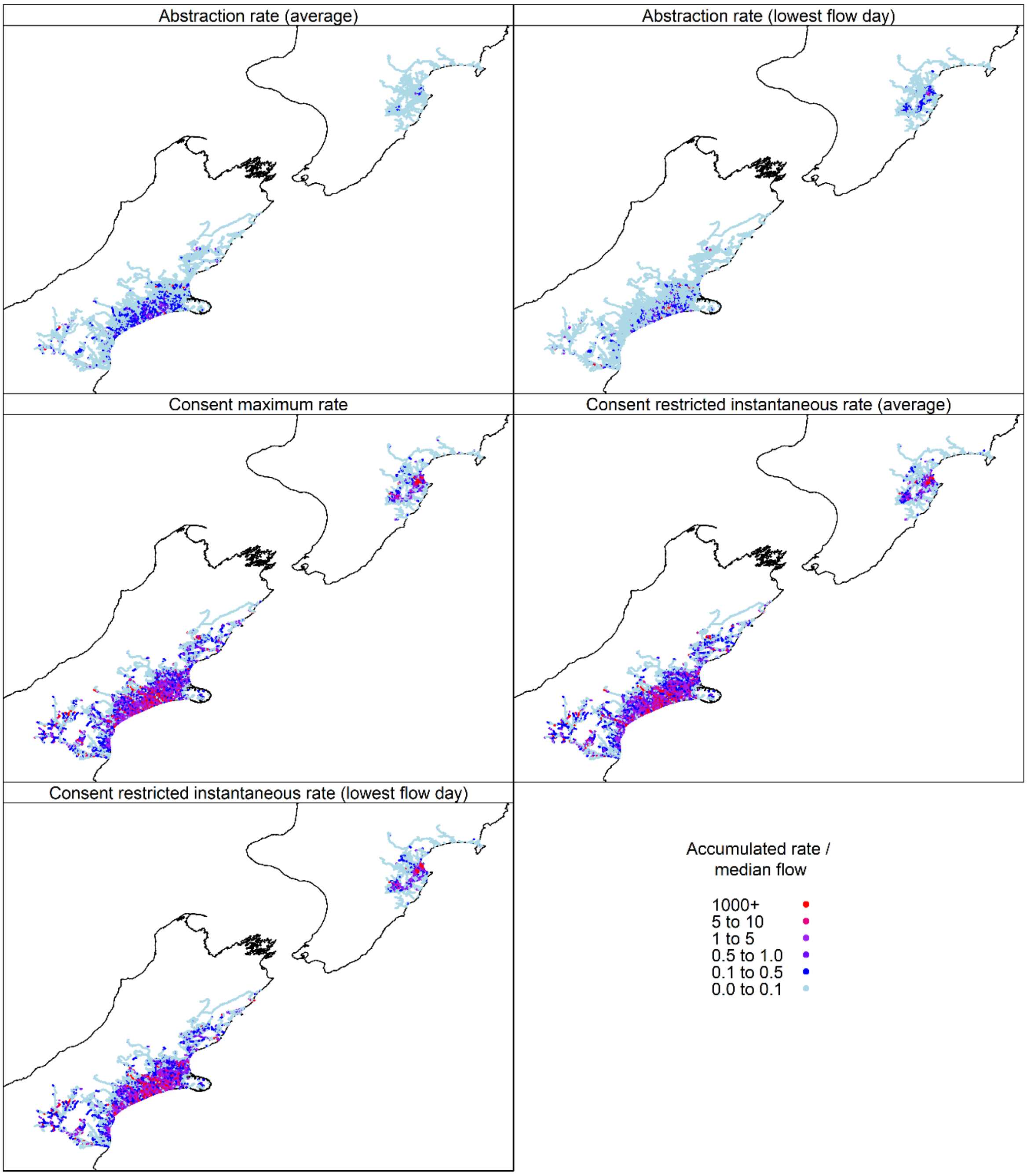

Figure 5-44: Map of accumulated upstream non-hydropower maximum consented rate, and instantaneous allowable rate, and metered abstraction on the driest day, relative to median flow, for consents active 14/02/2023.

5.6 Plan limits

Types of plan limits and data supplied for each council varied. For each type of limit for each council, we assessed the data required to calculate consented allocation or observed flows/levels with respect to the plan limits. For plan limits where sufficient data was available, we compared consented allocation to plan limits.

5.6.1 HBRC

Table 5-7 shows most types of limits for HBRC could not be assessed from the data obtained. For limits associated with a given zone, consent zones were not present in the consent data obtained from LAWA. For limits where consent quantities are summed for a river gauge site, no way to link consents to these sites was available. One could potentially use observation-based restrictions to link consents and flows sites but there are several potential issues: 1) 80% of HBRC consents did not have observation-based restrictions linked to them, and it was unclear how these should be dealt with; 2) a consent may involve several abstraction points in different locations; 3) sites used for restriction may be a gauged site used as point-of-reference where abstraction actually occurs on another ungauged river; and 4) some sites may be upstream of other sites and it is unclear whether consents should be counted and both upstream and further downstream sites.

Table 5-7: Summary of plan limit types identified for HBRC, and whether we could assess these with the data collected. ✗ indicates missing data, incomplete or unclear data, and ✓ data that is present.

Limit area type	Limit value type	Able to assess limits?	Data requirements
River gauge site	Minimum instantaneous flow, High flow minimum instantaneous flow	Yes	✓ River gauge time-series
River gauge site	Maximum weekly volume	No	✓ Consent maximum weekly · Consent link to gauge site(s)
River gauge site	High flow maximum rate	No	✓ Consent maximum rate · Consent link to gauge site(s)
River gauge site	High flow maximum daily	No	· Consent maximum daily · Consent link to gauge site(s)
Ground water allocation zone	Maximum annual volume	No	✓ Consent maximum annual volume ✗ Consent ground water allocation zone
Surface water allocation zone	Maximum instantaneous rate (Direct/Stream Depleting/Total)	No	✓ Consent maximum instantaneous rate ✗ Consent surface water allocation zone ✗ Consent stream depleting portions and zoning

Per the regional plan for HBRC, minimum flows aim to provide adequate habitat for ecosystem:

> *"The prescribed minimum flow is the flow at which adequate habitat is available for existing aquatic ecosystems under natural conditions. Controlling takes so that flow is not reduced artificially below minimum flow ensures habitat availability is maintained while acknowledging that habitat availability will reduce as a river naturally falls below the minimum flow."*

Given the intent of these minimum flows as ecologically-relevant (or environmentally-relevant), we compared minimum flows against the observed and estimated naturalised flows (Figure 5-45 and Figure 5-46). We used the streamflow depletion model analysis period of 1 July 2018 to 30 June 2023 because these model outputs are needed to calculate naturalised flows. Naturalised flows are an estimate of what flow would have been without streamflow depletion associated with permitted activities and metered abstractions. Of the 32 sites identified with a minimum flow limit, 12 sites were analysed because they had a daily flow record that was at least 75% complete. For these 12 sites, we found naturalised flows were below the minimum flow for 0 to 5.5% of the time across rivers, and observed flows were below the minimum flow for 0 to 23% of the time (Figure 5-46).

In identifying minimum flow levels for each site, we noted that for some sites (Tukituki River at Red bridge, Tukituki river at Taiparu road, Waipawa river at RDS/SH2) there were multiple minimum flows in the regional plan for different time periods. We chose the flows associated with the correct time period (1 July 2018 to 30 June 2023) but note that these minimum flows had changed from different prior limits.

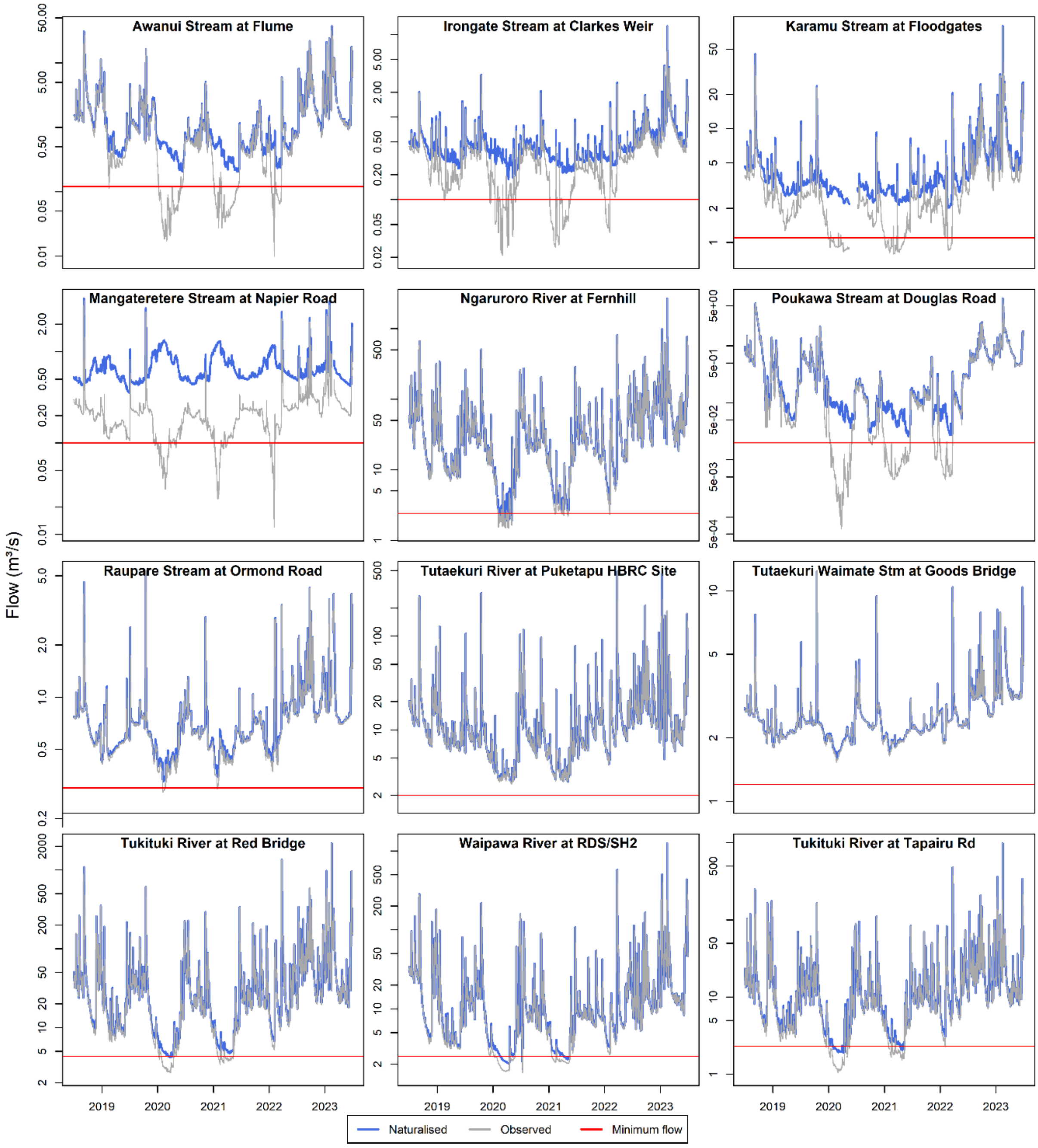

Figure 5-45: Observed flows and estimated naturalised flows compared to minimum flows at 12 flow gauge sites. Naturalised flows are an estimate of flow without the estimated influence of metered abstractions and abstractions for permitted activities.

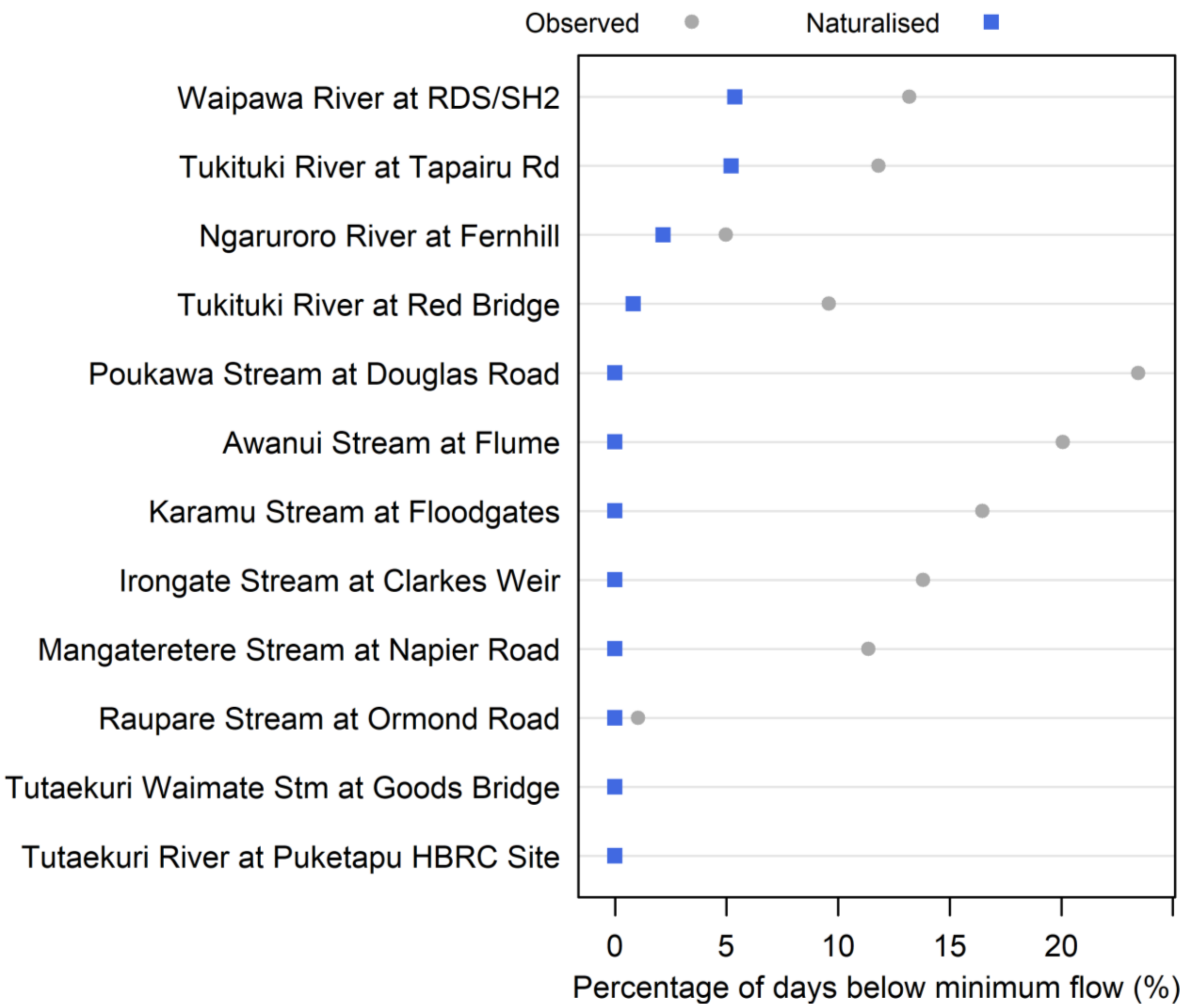

Figure 5-46: Percentage of days which observed and estimated naturalised flows are below minimum. Naturalised flows are an estimate of flow without the estimated influence of metered abstractions and abstractions for permitted activities.

Our findings indicated that the relationship between minimum flows and both observed flows and naturalised flows was not uniform across sites. Observed flows fell below minimum flows for several sites, whereas minimum flows were much lower than both observed flows and naturalised flows for several sites. This finding indicates that minimum flows did not afford the same level of protection to naturalised flows across sites, assuming that there were no systematic differences in climate between the sites.

For five of the 12 sites, observed flow was less than the minimum flow for more than 10% of the time and the naturalised flow was less than the minimum flow 0% of the time. Discrepancies between blue points and grey points in Figure 5-46 suggest that flow dropped below the minimum flow as a consequence of abstraction rather than as a consequence of naturally occurring low flow conditions at several sites. This indicates that the minimum flow was not effective at maintaining low flows to not drop below the minimum flow. There are several possible reasons to explain this finding: a) permitted activities are not controlled by the minimum flow; b) some consents are not controlled by a minimum flow; c) some consents may be being controlled by a lower minimum flow than is shown in Figure 5-45; d) changes in minimum flow values through time due to plan changes; e) flow may be being reduced as a consequence of groundwater abstraction that occurred at an earlier time when the minimum flow restriction was not being exercised; and f) our streamflow depletion estimated could be overestimating the streamflow depleting effect of groundwater abstraction on river flows.

5.6.2 MDC

For MDC, we were unable to compare allocation against limits from the regional data obtained (Table 5-8). MDC did provide additional water quantity data for Wairau Valley and Riverlands aquifers. However, due to time constraints for this project, it was jointly decided with MfE not to undertake the analysis of these data.

Table 5-8: Summary of plan limit types identified for MDC, and whether we could assess these. (✗) indicates data missing, (·) data present but incomplete or unclear and (✓) data we have.

Limit area type	Limit value type	Could we readily assess limits?	Data requirements
River gauge site	Minimum instantaneous flow	No	✗ River gauge time-series
Groundwater gauge site	Minimum level	No	✗ Groundwater gauge time-series
FMU	Maximum daily volume Maximum daily volume for a season	No	✗ Consent maximum daily ✗ Seasonal restrictions · Consent FMU
FMU	Maximum annual volume	No	✓ Consent maximum annual · Consent FMU

For consent information, the data from LAWA did not contain all the required fields. For example, there was no maximum daily rate specified, and the maximum instantaneous rate was empty for 84% of MDC consents (Table 5-2). The "Catchment" field did not match the FMU areas on the MDC plan in all cases. For example, LAWA catchments have short names, that match the plan limit catchment names approximately a third of the time e.g., Are Are, Awatere, Brancott. However, some plan limits had detailed catchment specifications that were not readily identified for each consent as exemplified below.

- "Wairau River downstream Of the Hamilton River confluence Excluding Goulter River, Goulter significant Wetland W35, Lake Chalice and Possum Swamp Stream Significant Wetland W116."
- "Wairau Aquifer Excluding Gibsons Creek (Waihopai intake to the Omaha River confluence), Opaoa River (including Roses Overflow and Opaoa Loop Wairau Lagoons and the Pipitea Significant Wetland W55 and Chaytor Significant Wetlands WI 27, W128 and W129."
- "Opaoa (from Mills and Ford Road to the confluence Of the Opaoa Taylor Rivers)."

Overall, it was unclear whether catchments in the LAWA database matched those in the plans completely, and whether it would be suitable to compare to plan limits in this manner.

Flow and groundwater time-series were not obtained. Had those data been available, the actual time-series would be readily compared to plan minimum flow values. "Management purpose" targets are distinguished from the "management method" restriction rules in MDC plans, so it is meaningful to assess observed flows against these target values.

5.6.3 ECan

No quantitative database of plan limits was obtained for ECan. See Section 3.5 for further information.

5.6.4 ES

ES plan limits could not readily be analysed with the data we collated (Table 5-9).

Table 5-9: Summary of plan limit types identified for ES, and whether we could assess these with the data collected. ✗ indicates missing data, · incomplete or unclear data, and ✓ data that is present.

Limit area type	Limit value type	Could we readily assess limits?	Data requirements
Water management zone	Annual volume	No	✓ Consent maximum annual volume ✓ Consent water management zone · Consent stream depletion effects
River gauge site	Maximum instantaneous rate at gauge site	No	✓ Consent max rate · Consent link to gauge site(s) · Consent stream depletion effects

Limits for groundwater management zones are represented as an annual volume for each zone, where annual volumes and zones are provided in the LAWA water take consent data. However, streamflow depletion effects need to be considered. ES did provide excel tables with calculated streamflow depletion effects using two methodologies, but they did not provide the means to readily calculate such depletion effects. We noticed different methodologies were used to calculate streamflow depletion effects for different consents, perhaps due to data availability. Overall, the stream depletion effects represented in the provided data were not readily able to be assessed by us.

Surface water limits are represented as a total maximum rate at a flow site. However, the consents were not readily linked to relevant downstream gauge site(s) from the consent databases provided. The ES surface water allocation summary had tabs for each catchment, from which consent gauge site(s) could be identified, given some manual data input. However, calculation of streamflow depletion effects is also required, but was not readily achievable.

5.7 Permitted water use

Table 5-10 and Figure 5-47 show the human populations residing outside reticulated water supply areas, categorised by region. These populations are likely to rely on water access through permitted activities. Among these regions, Auckland has the highest number of people associated with permitted activity water usage, estimated at 40,353,204 m^3/yr, while West Coast region has the lowest, estimated at 892,188 m^3/yr.

Figure 5-47 also displays livestock numbers categorised by region. As explained in Section 3.8, our study used sheep, dairy cows, beef cows, and deer to estimate livestock water usage, assuming that the water use by other livestock is negligible. Additionally, it is probable that stock water is abstracted through resource consents for mixed uses such as irrigation and stock water. Due to a lack of detailed data, especially at fine resolutions like farm level, we assume that all stock water supply is obtained through permitted activities. The Whanganui-Manawatū region had the highest number of animals, totalling around 6.2 million, with 82% being sheep. The largest number of dairy cows is in Waikato, at around 1.8 million.

At the national level, our estimate of permitted water use for human and livestock needs totals approximately 380 million cubic meters per year (Mm^3/year), with over 60% (approximately 240 Mm^3/year) is used by livestock. The largest permitted water use is in Waikato (approximately 80 Mm^3/year), followed by Canterbury (approximately 55 Mm^3/year) and Auckland (approximately 45 Mm^3/year).

In many regions, the majority of permitted water is for livestock, except in Auckland, Wellington, and Nelson-Tasman. Additionally, the comparison between permitted water use and consented (metered) water use reveals, the permitted water use accounts to a significant proportion of total water use in some regions. For instance, permitted water use in Hawke's Bay accounts for approximately 18% of the consented water use.

Figure 5-49 shows the estimated pressure on rivers from permitted activities. Permitted activities are less than 10% of the estimated median flow for most locations, with notable exceptions of higher pressure across Auckland, Waikato, Hawke’s Bay, Canterbury, Otago, and Southland. Higher pressure also occurred in some smaller rivers in various locations were animal and people populations were relatively high and river flow were relatively low.

Table 5-10: Estimated number of different livestock classes and human populations that utilise permitted water by region.

Region	Dairy	Beef	Sheep	Deer	Human
Northland	376,106	378,448	322,095	5,415	56,861
Auckland	125,942	107,365	245,153	10,284	486,714
Waikato	1,833,209	492,769	1,518,669	66,249	191,697
Bay of Plenty	321,618	109,170	316,482	26,901	133,012
Gisborne	7,273	175,442	962,333	6,138	16,544
Taranaki	579,559	117,284	502,752	3,974	60,892
Whanganui-Manawatū	467,352	569,966	5,071,156	56,840	83,353
Hawke's Bay	94,563	453,867	2,996,166	57,939	66,400
Wellington	12,884	52,536	658,327	6,727	175,241
Nelson-Tasman	49,062	31,828	246,725	6,161	43,133
Marlborough	22,926	43,816	373,701	5,485	12,836
West Coast	165,224	35,229	72,124	32,892	10,761
Canterbury	837,696	318,098	3,120,433	141,048	253,089
Otago	142,161	118,577	1,796,008	36,201	103,718
Southland	687,503	175,412	4,009,014	189,912	26,755

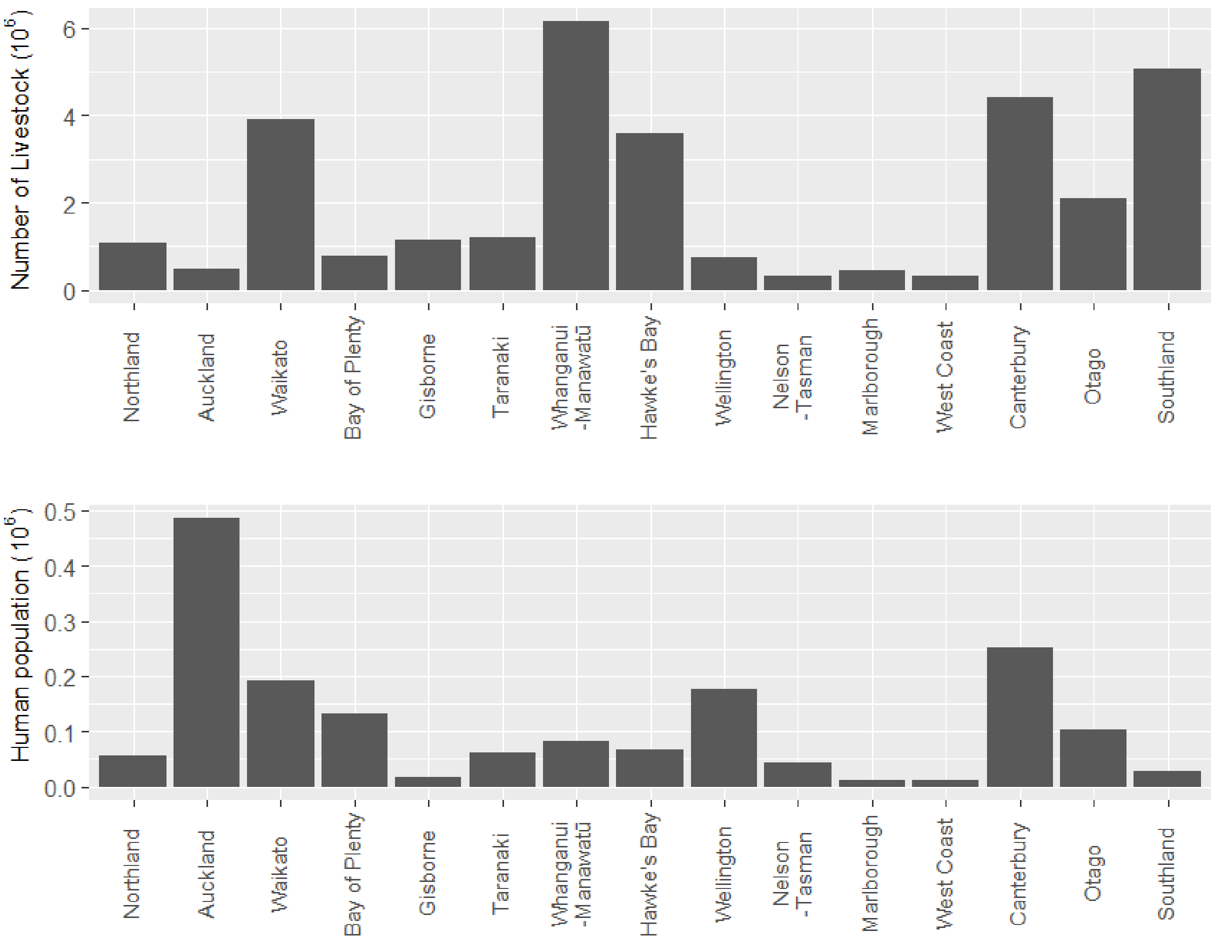

Figure 5-47: Estimated number of humans and livestock that utilise water abstracted under permitted activities by region. Unit: numbers in millions.

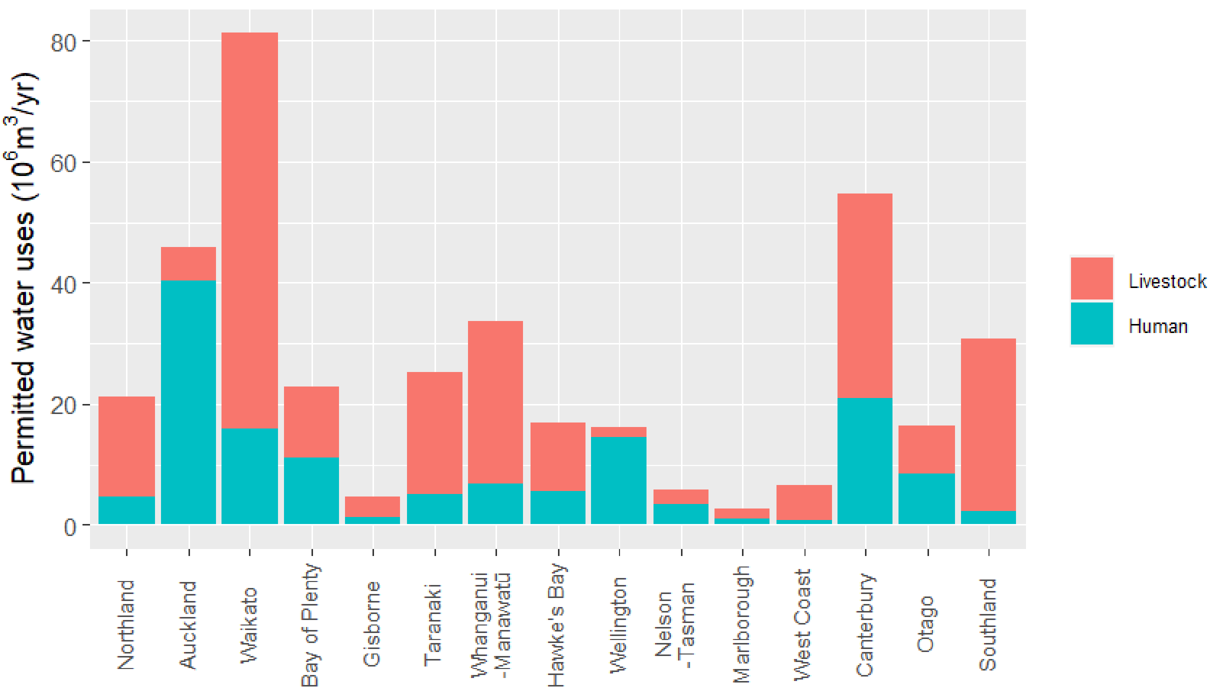

Figure 5-48: Estimated mean annual permitted water use by humans and livestock. Unit: million m^3/year.

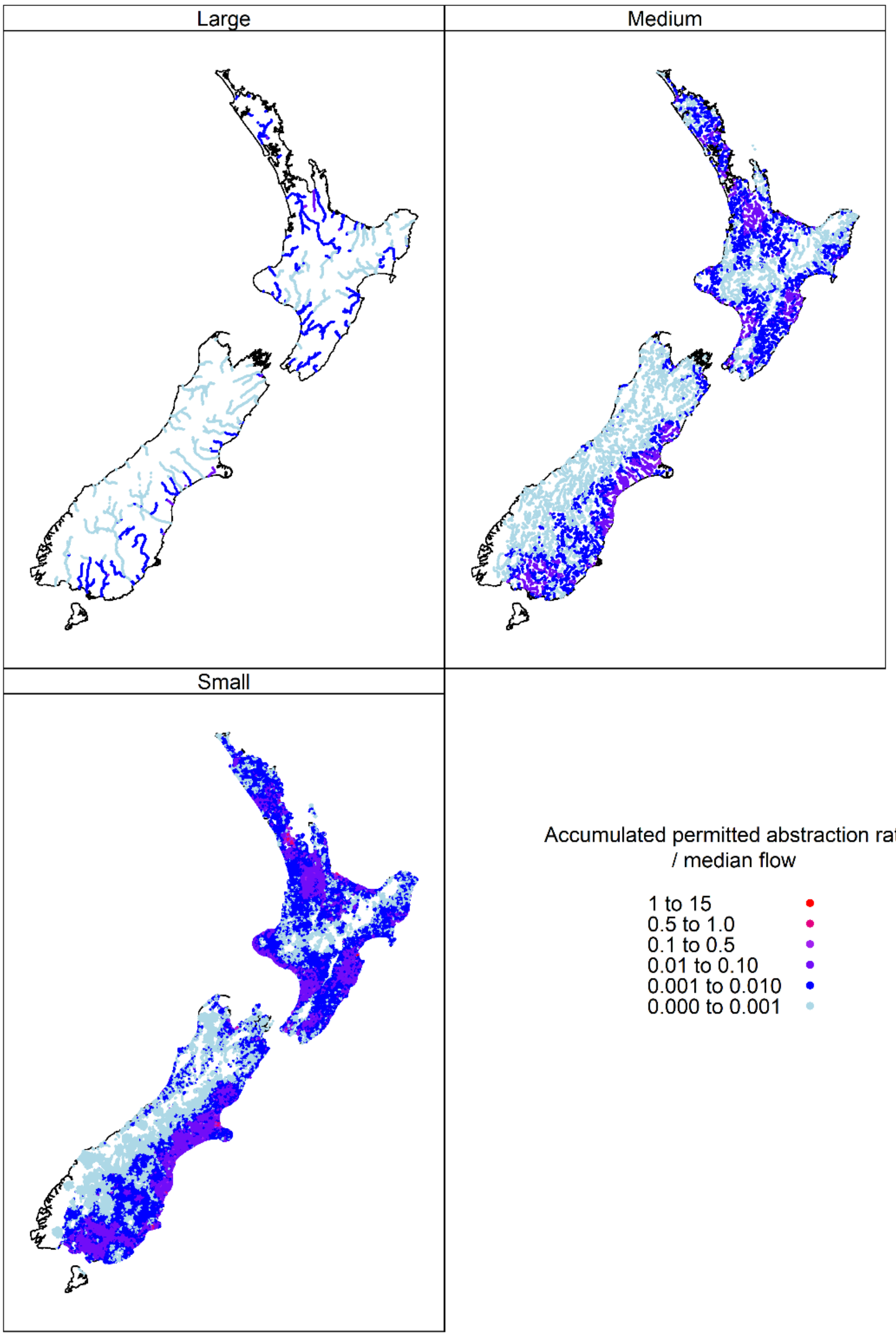

Figure 5-49: Map of accumulated upstream estimated permitted abstraction rate relative to median flow. Small = Strahler orders 1–3. Medium = Strahler orders 4–5. Large = Strahler orders 6–8. Note that for small rivers, areas of white occur where there are no permitted abstractions.

5.8 Streamflow depletion model

We applied methods to estimate streamflow depletion for the Hawke's Bay region. Streamflow depletion was calculated at the river reach level, and routed down from upstream to downstream until streams reach the sea. In Figure 5-50, we present the mean annual streamflow depletion resulting from different types of water abstractions: consented surface and groundwater, and permitted use. Our analysis revealed that nearly three-quarters of the streamflow depletion is attributed to groundwater abstractions.

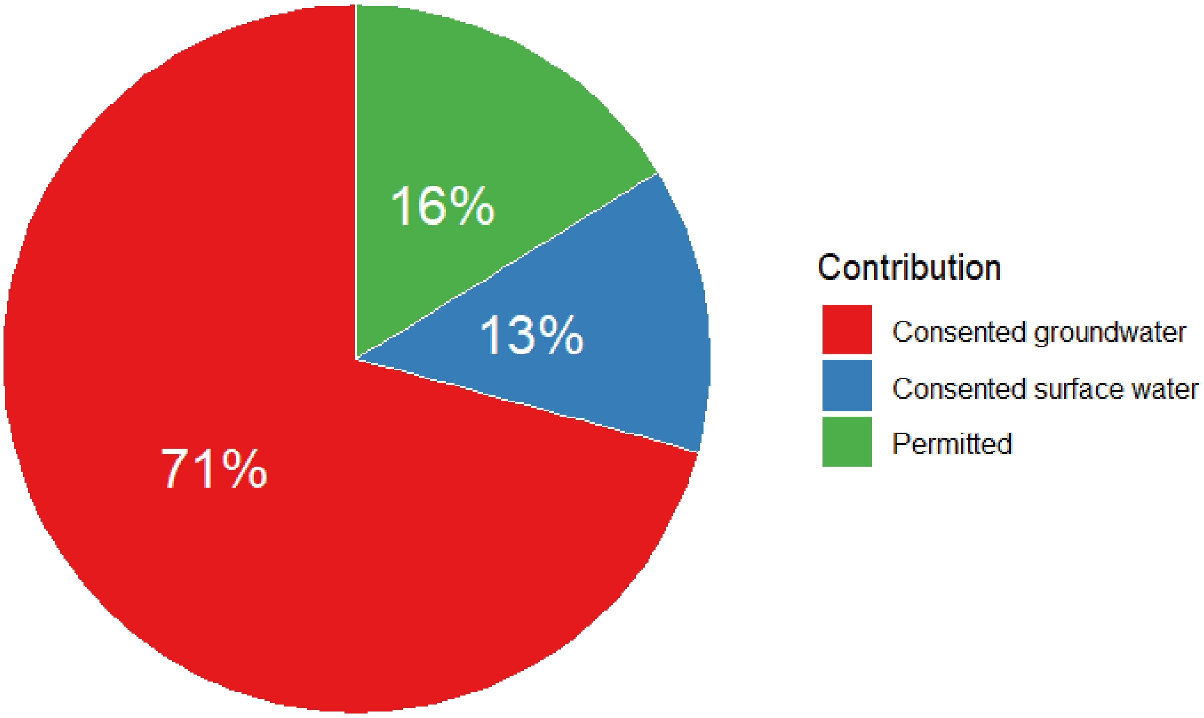

Figure 5-50: Contributions of mean annual stream depletion from different abstractions in Hawke's Bay region during the modelled period 2018–2023.

Figure 5-51 illustrates the spatial distribution of mean annual stream depletion from various abstractions in the Hawke's Bay region during the modelled period from 2018 to 2023. Once again, we observed that the greatest impact of streamflow depletion arises from groundwater abstractions, particularly along the Tukituki and Ngaruroro rivers.

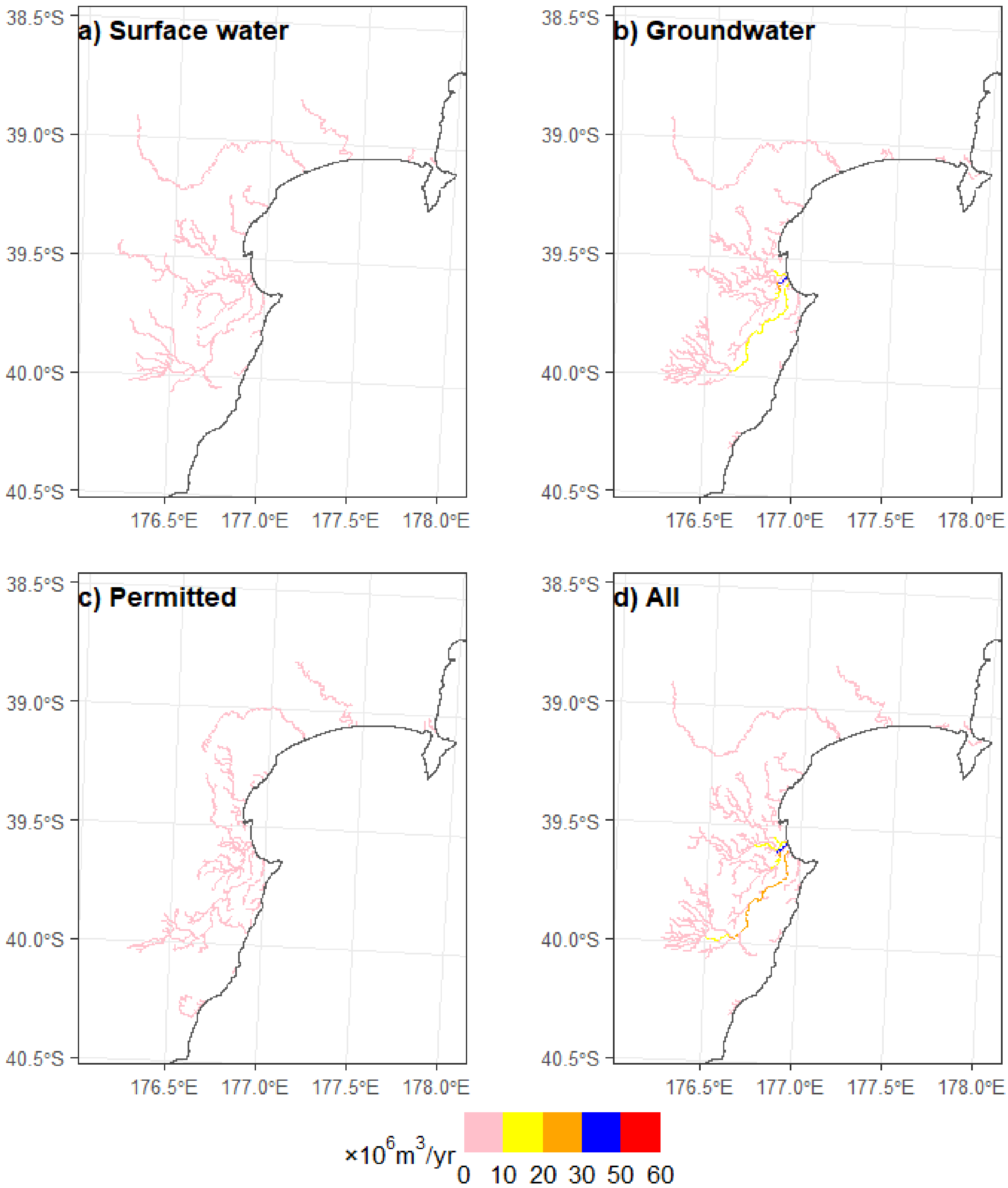

Figure 5-51: Estimated spatial distribution of mean annual stream depletion from different abstractions in Hawke's Bay region during the modelled period 2018-2023.

In Figure 5-52, we illustrate the mean daily cumulative streamflow depletion outputs over two summer months, from 1 January to 28 February 2020, at three sites (refer to Figure 5-53 for the locations). We selected these months to highlight streamflow depletion because they coincide with the lowest river flows, groundwater levels, and highest water demand in Hawke's Bay. We found that streamflow depletion is greatest due to consented groundwater abstractions at these sites. Streamflow depletion due to consented surface water abstractions from the Ngaruroro River was relatively higher than from the other two rivers.

Furthermore, our analysis shows that streamflow depletion due to consented surface water abstractions, along with consented groundwater abstractions, significantly decreases in February for the Ngaruroro River potentially due to water abstraction restrictions. Notably, streamflow depletion due to permitted water use was comparable to that of consented surface water abstractions for the Tukituki and Tūtaekurī rivers during summer, and in February for the Ngaruroro River.

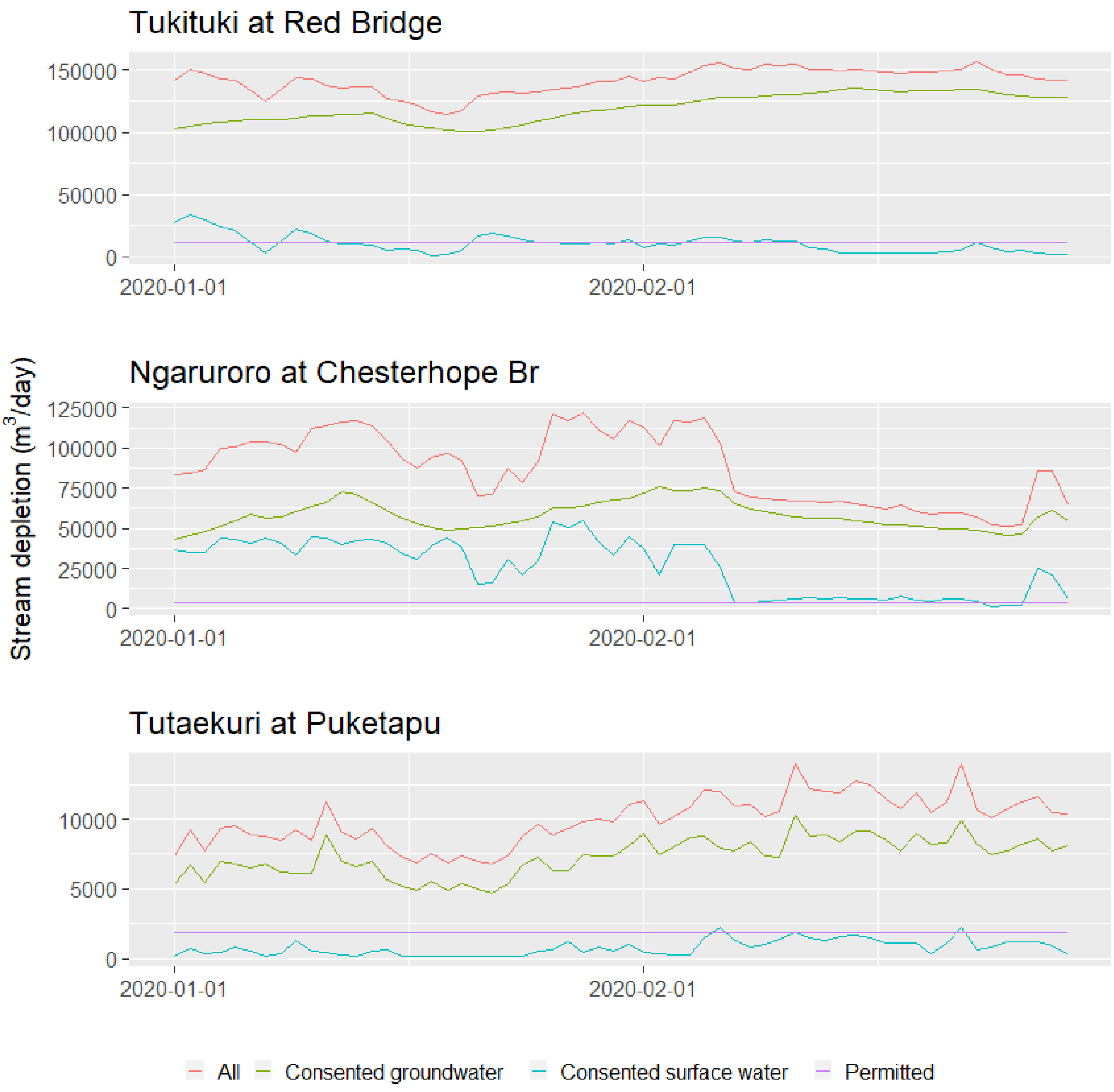

Figure 5-52: Estimated cumulative daily stream depletion due to consented surface and groundwater abstractions, permitted takes along with the total at three locations in Hawke's Bay. Refer to Figure 5-53 for the locations.

5.9 Ecologically-relevant hydrologic metrics

The flow gauge sites used for calculation of ecologically-relevant hydrologic metrics are shown in Figure 5-53. Most of these sites are in the Napier-Hastings area. Some gauge sites are near the coast, and therefore likely to be downstream of abstractions, whereas many gauge sites are further inland, and therefore less likely to be downstream of abstractions.

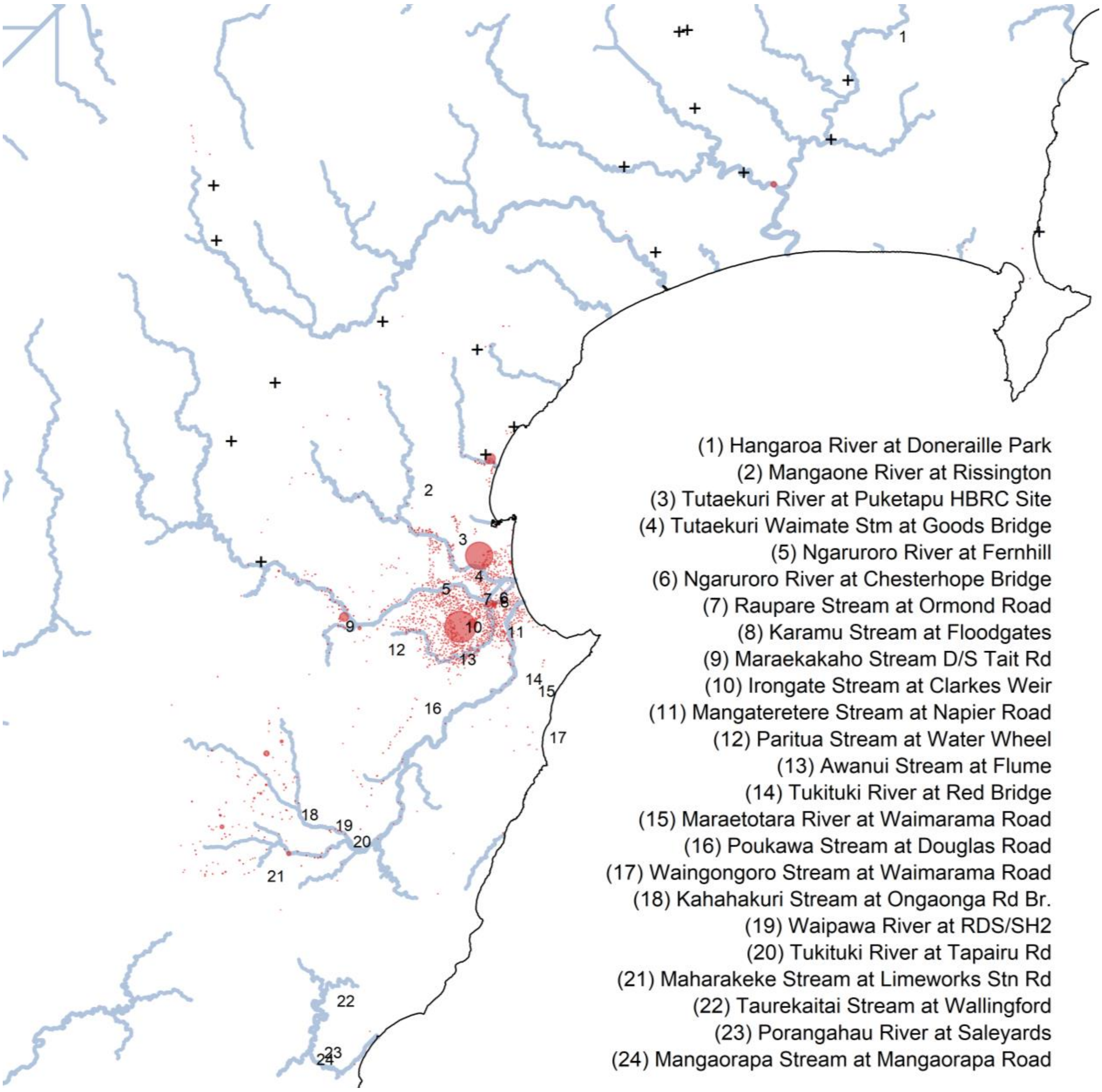

Figure 5-53: Map of flow gauge sites included for analysis of ecologically relevant hydrologic effects. Red dots indicate approximate locations where metered abstraction occurs, with dot size being representative of abstraction total magnitude during the 10-year streamflow depletion modelling period (1 July 2013 to 30 Jun 2023). Note that streamflow is also depleted by permitted activities which are not shown on this map. Black + symbols indicate gauge sites where streamflow depletion in negligible (<1%).

Of the 102 flow gauge records provided by HBRC (which includes historic sites), 42 had sufficient data during the 5-year analysis period (1-July 2018 to 30-Jun-2023). Of these 42 sites, 18 had no streamflow depletion predicted by the streamflow depletion model (because they had no upstream abstraction), or streamflow depletion of less than 1% of naturalised flow on any given day during the period. The remaining 24 sites with some predicted streamflow depletion were used for this analysis.

Figure 5-54 shows observed and estimated naturalised flows for three example sites. The sites represent a range of river flows, and differing proportions of streamflow depletion. Figure 5-54 demonstrates the general pattern of little flow alteration at high flows, and proportionally larger alteration at lower flows.

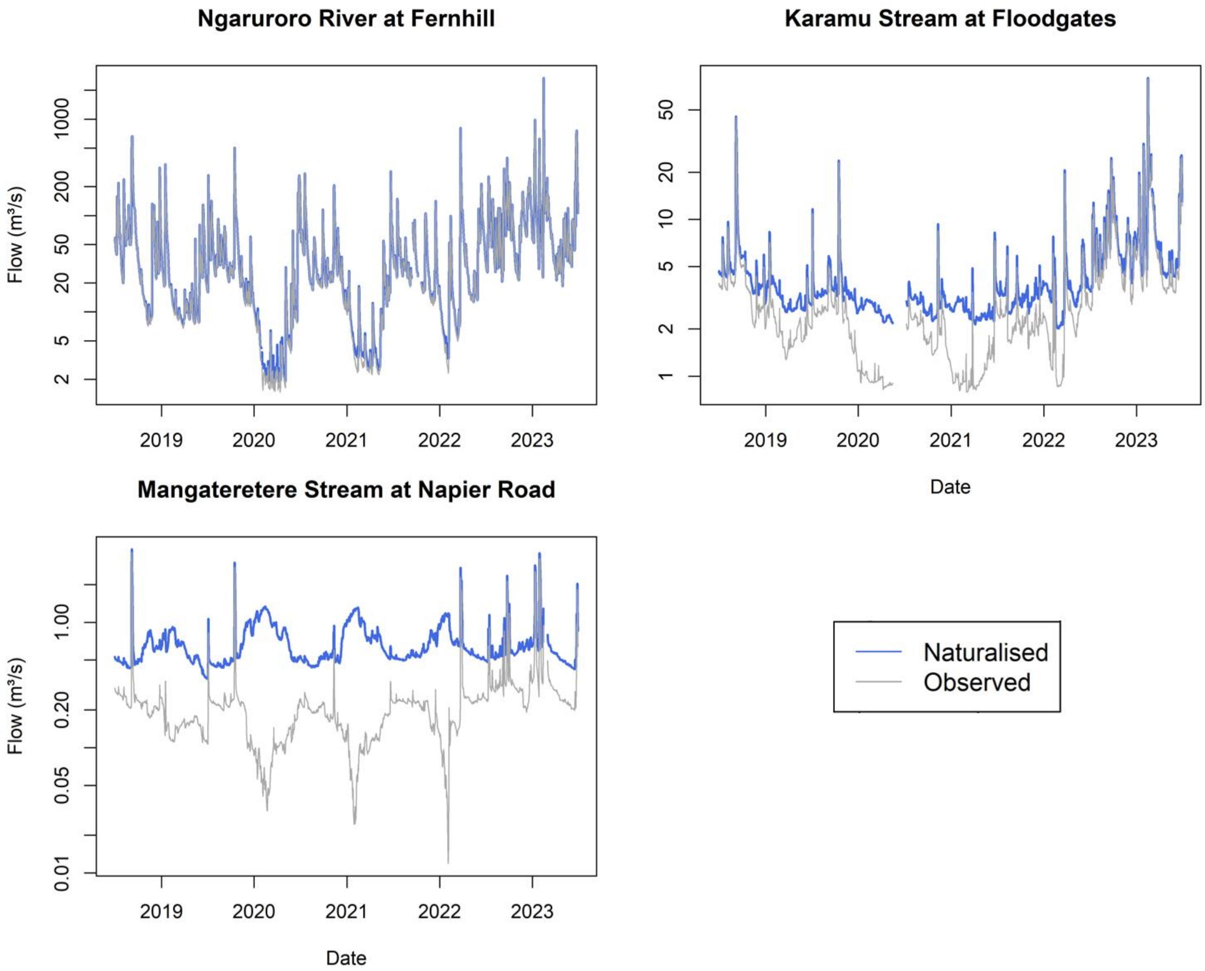

Figure 5-54: Examples of observed and estimated naturalised flows for three example sites. Note the log-scale y-axis emphasises alteration at low flows.

Mean annual hydrological metrics for each example site in the case of observed and estimated naturalised flows are given in Figure 5-55. The percentage change in hydrological metrics for observed flows compared to naturalised is given in Figure 5-56 for the three example sites, and Figure 5-57 for all sites. These figures demonstrate high alteration for Mangateretere Stream and low alteration for the Ngaruroro River. Across all sites, metrics representing flow magnitude are most altered, particularly extreme low flows. Changes to frequency and timing variables are less altered. It should be noted that high alteration of flow for some sites align with investigations and planning decisions put in place by HBRC. For example, a Tūtaekuri, Ahuriri, Ngaruroro and Karamū (TANK) Plan Change decision released in September 2022 introduced new water allocation provisions that recognised that the Heretaunga Plains Aquifer is an over-allocated resource, and that HBRC must consider actual and reasonable water use when assessing applications to replace existing consents (HBRC web link).

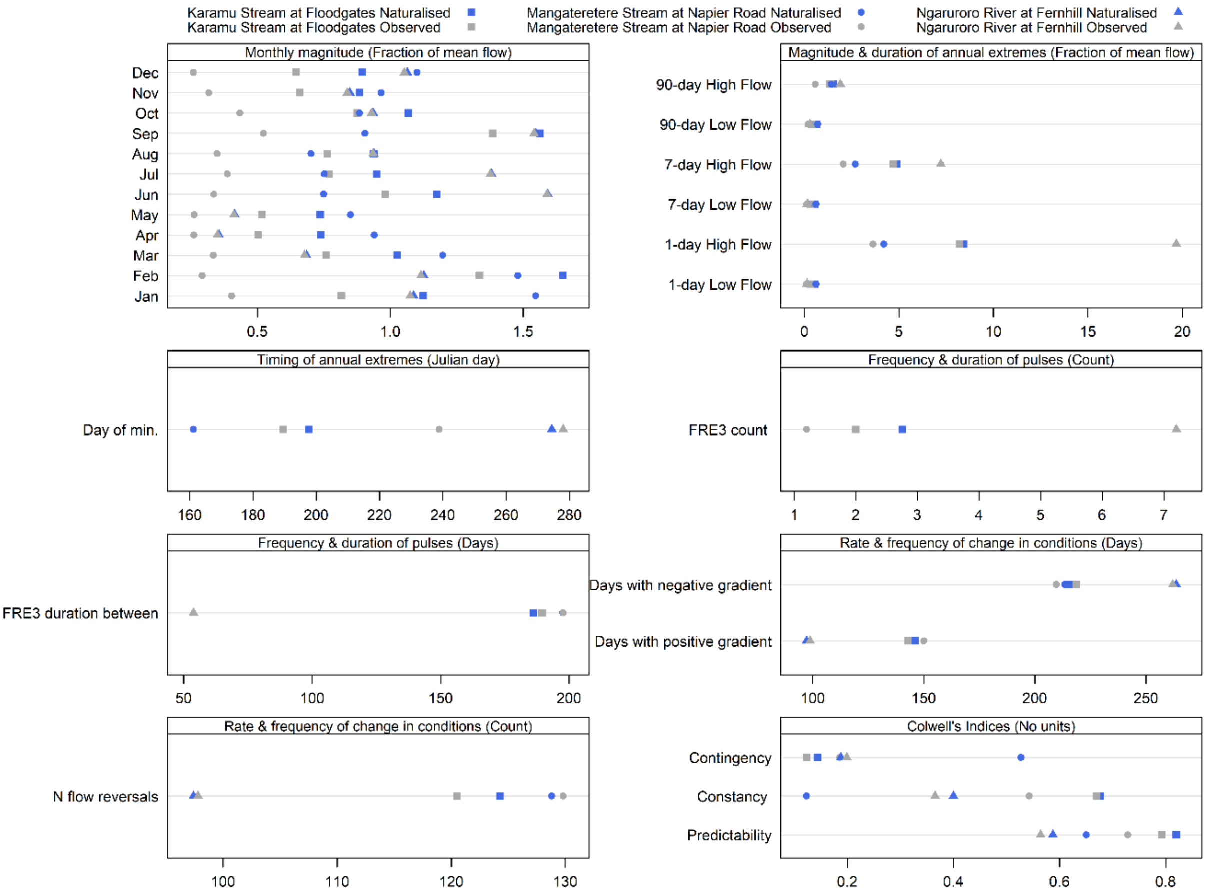

Figure 5-55: Mean annual hydrological metrics for the three example sites, for observed and estimated naturalised flows. Note that flow metrics are arranged by group and by units, due to the differing scales of variables with different units.

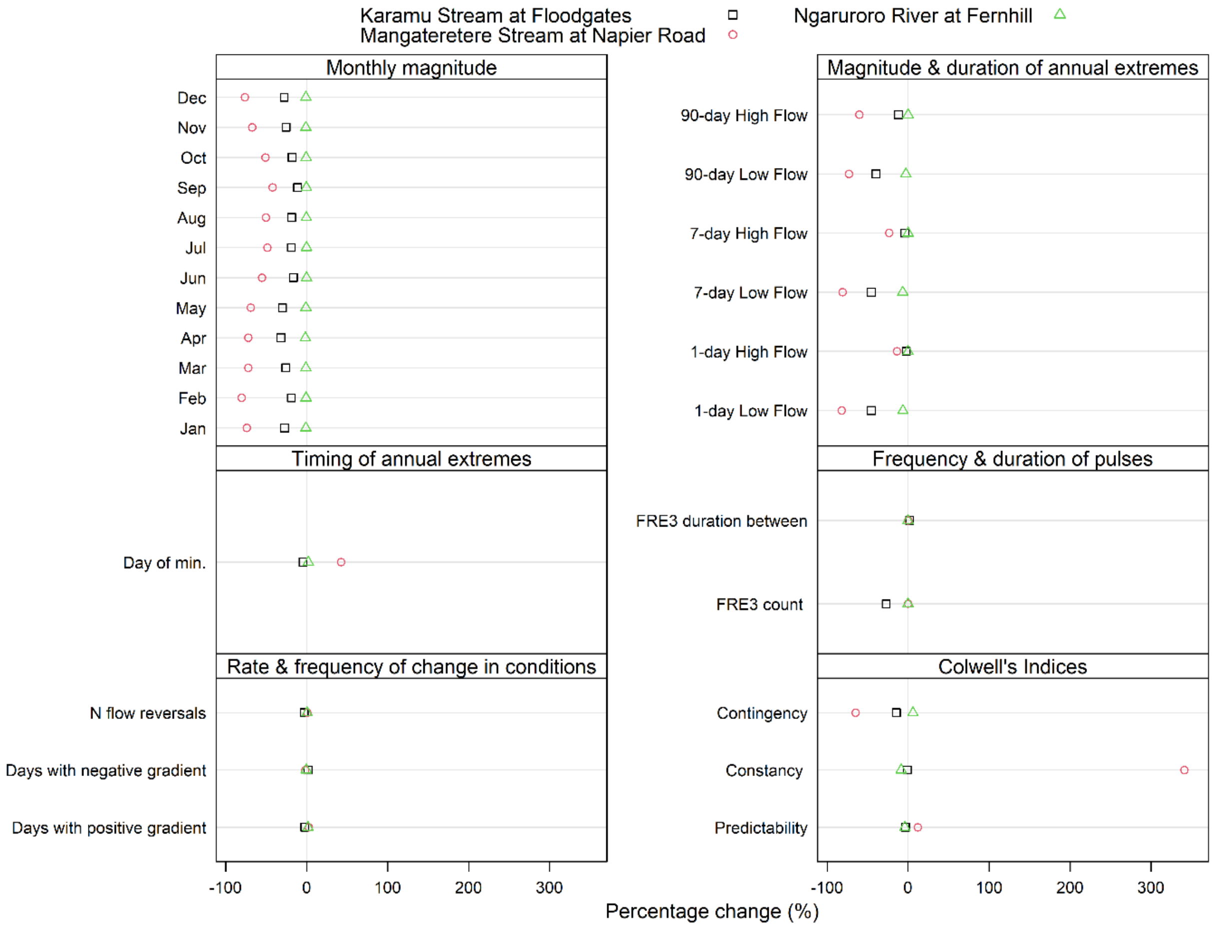

Figure 5-56: Percentage change in observed vs estimated naturalised mean annual hydrological metrics for the three example sites. Note that changes for timing of annual extremes are calculated as a percentage of 183 days (half a year duration) rather than a true percentage change, per Section 4.9.

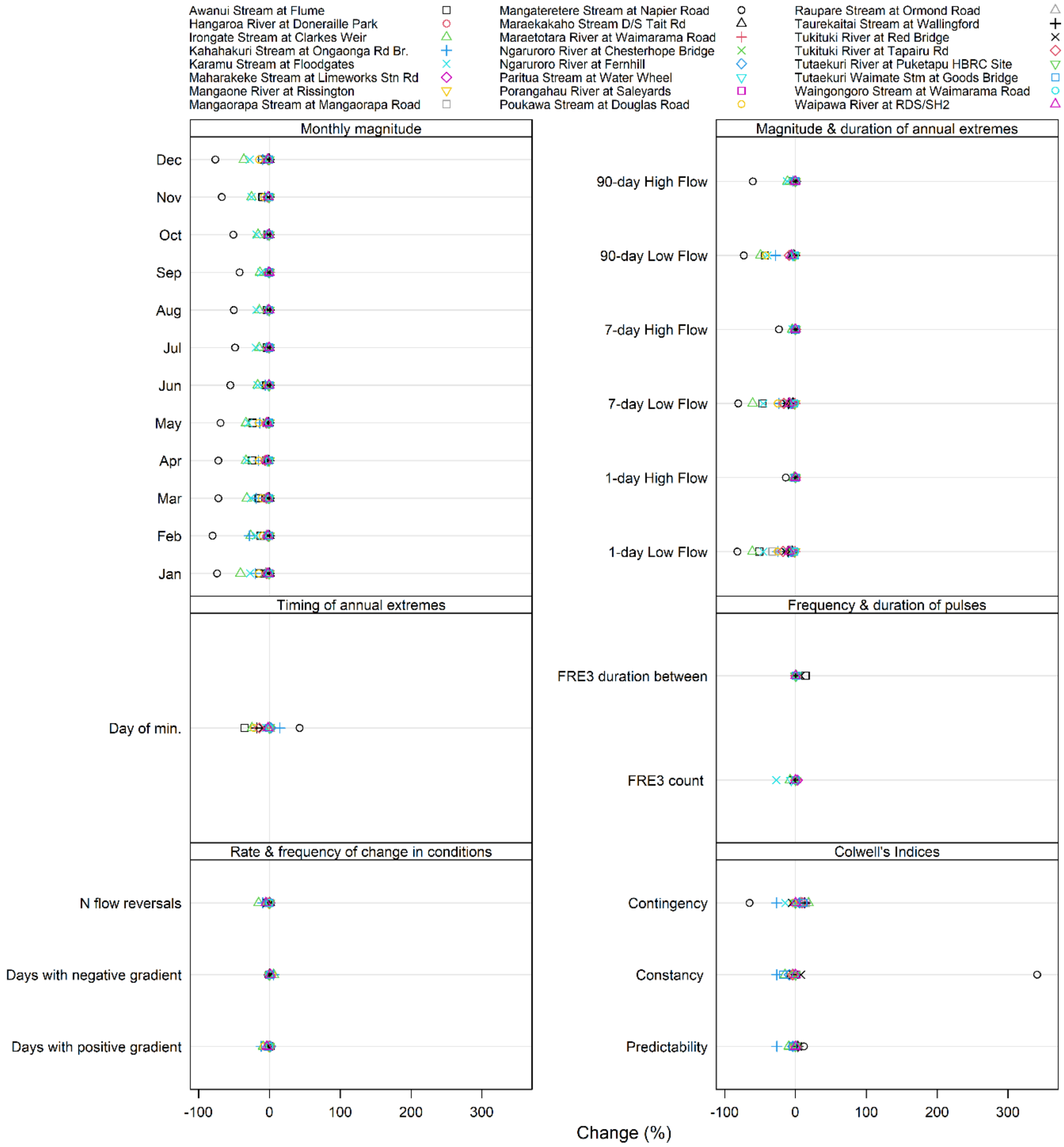

Figure 5-57: Percentage change in mean annual hydrological metrics for all sites.

Percentage change in hydrological metrics for each year for each of the three example sites is given in Figure 5-58 to Figure 5-60. These figures demonstrate the higher alteration in 2020, 2021, and less alteration 2023 for all three rivers.

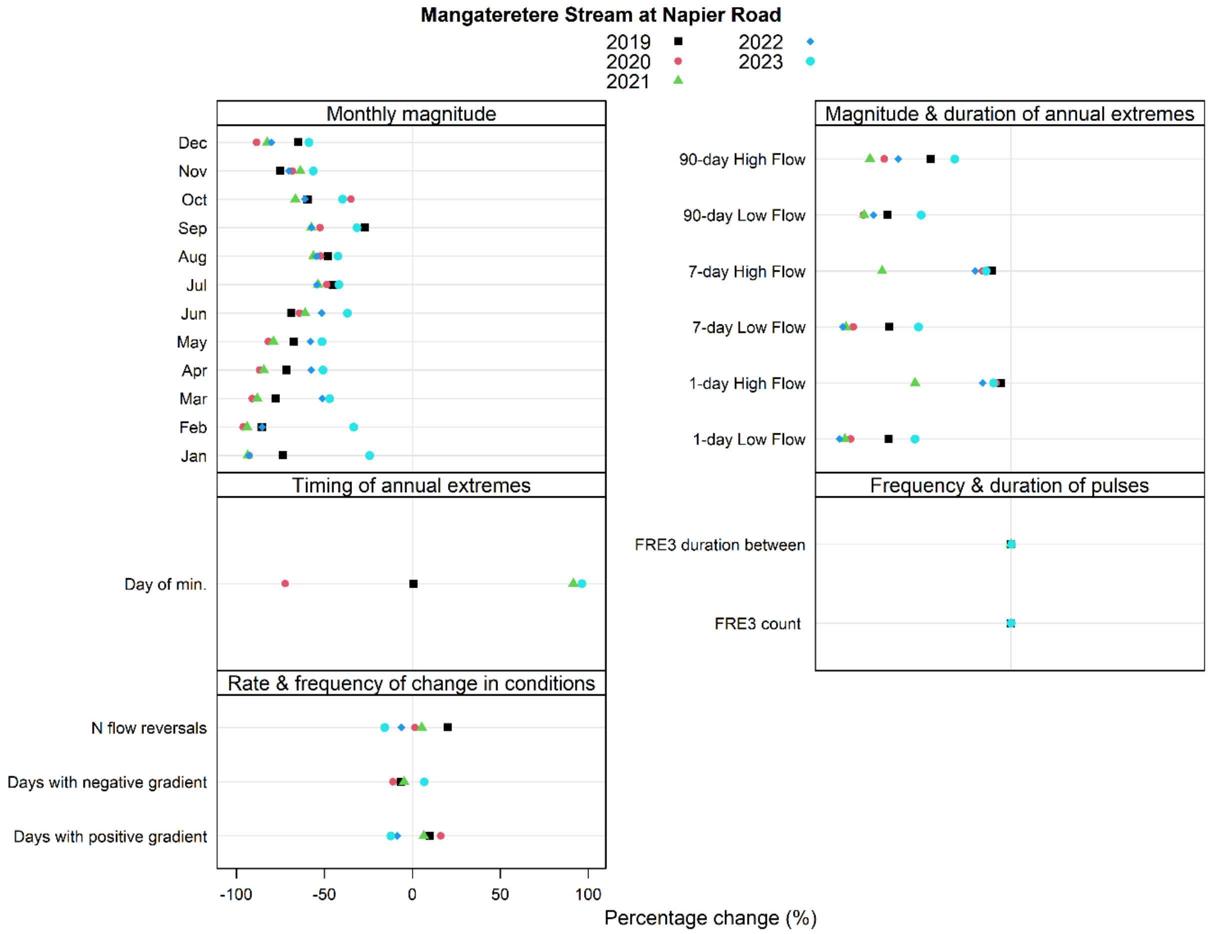

Figure 5-58: Percentage change in observed vs estimated natural flows each year for Mangateretere Stream at Napier Road. Years are water years starting 1 July.

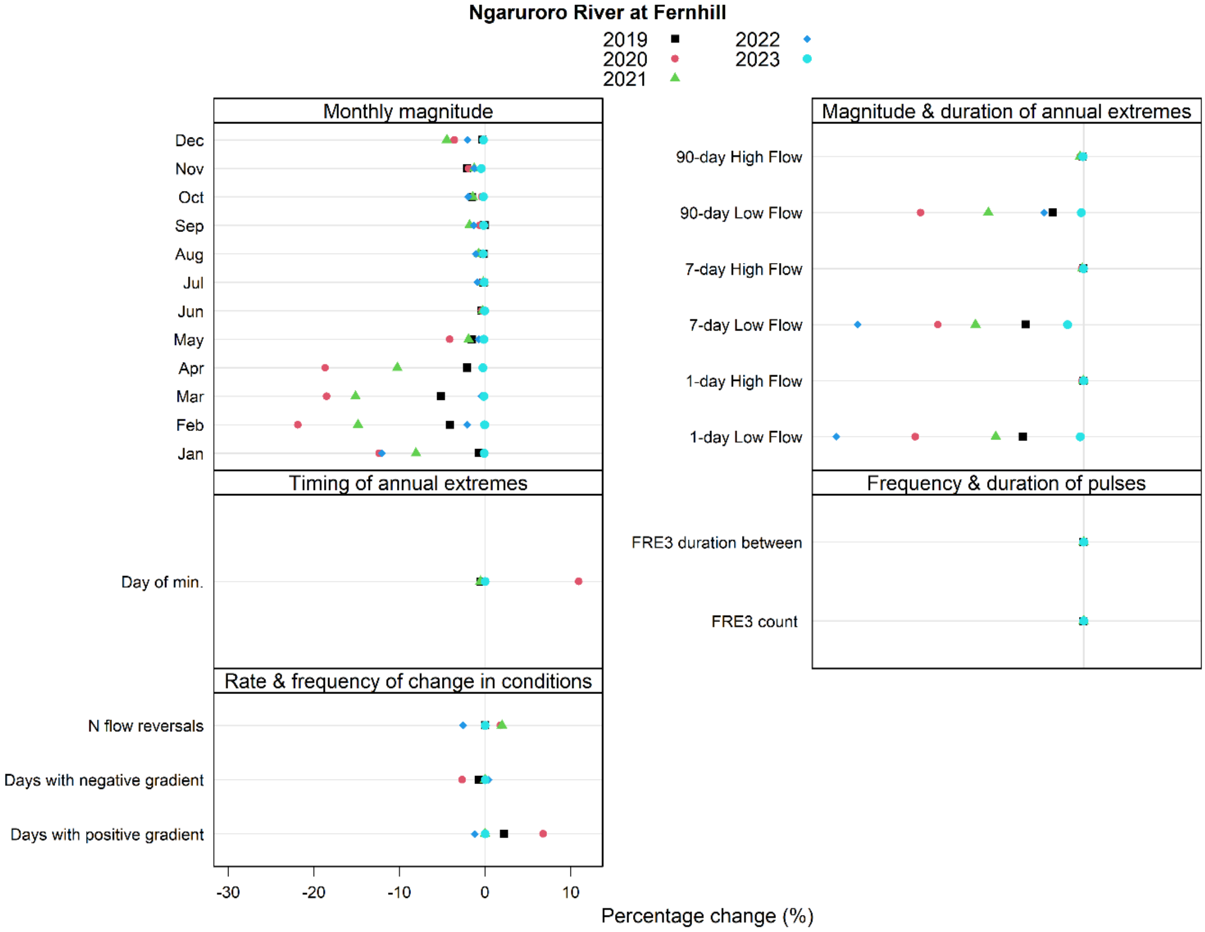

Figure 5-59: Percentage change in observed vs estimated natural flows each year for Ngaruroro River at Fernhill. Years are water years starting 1 July.

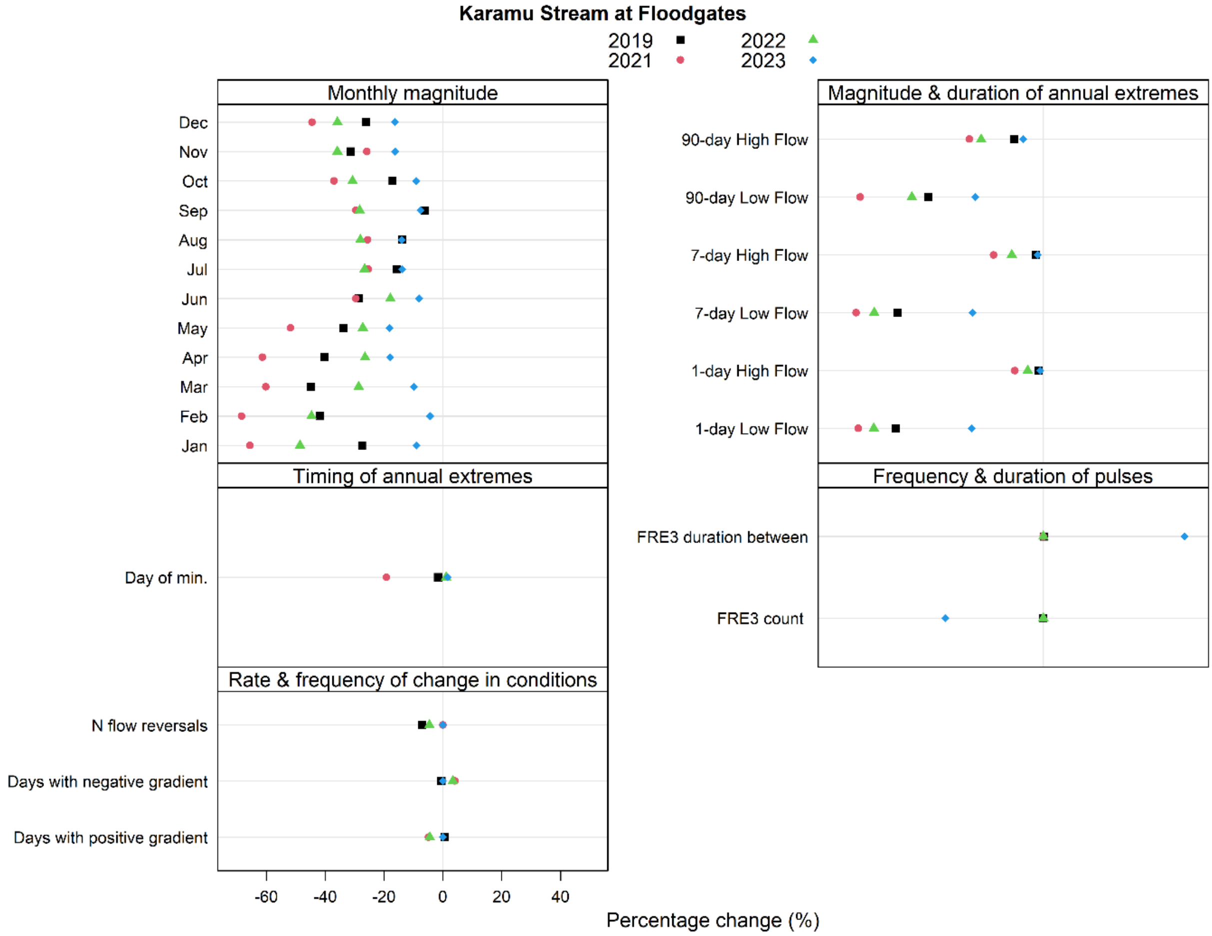

Figure 5-60: Percentage change in observed vs estimated natural flows each year for Karamu Stream at Floodgates. Years are water years starting 1 July. Note, the year 2020 is excluded due to missing flow data for a portion of that year.

Hydrological metrics are compared across sites in Figure 5-61. Results demonstrate the following patterns.

- January flows are lower than the overall average flow for half of the sites, but higher than average flow for the other half. For most sites January alteration is low.
- Low flows occur between late November and mid-March, this timing is altered for only a handful of sites, and in both directions.
- 7-day mean annual low flows which are a higher proportion of mean flow are most altered, whereas 7-day mean annual low flows which are very small compared to mean flow are less altered.
- Changes are small in frequency related variables FRE3 and Number of flow reversals.

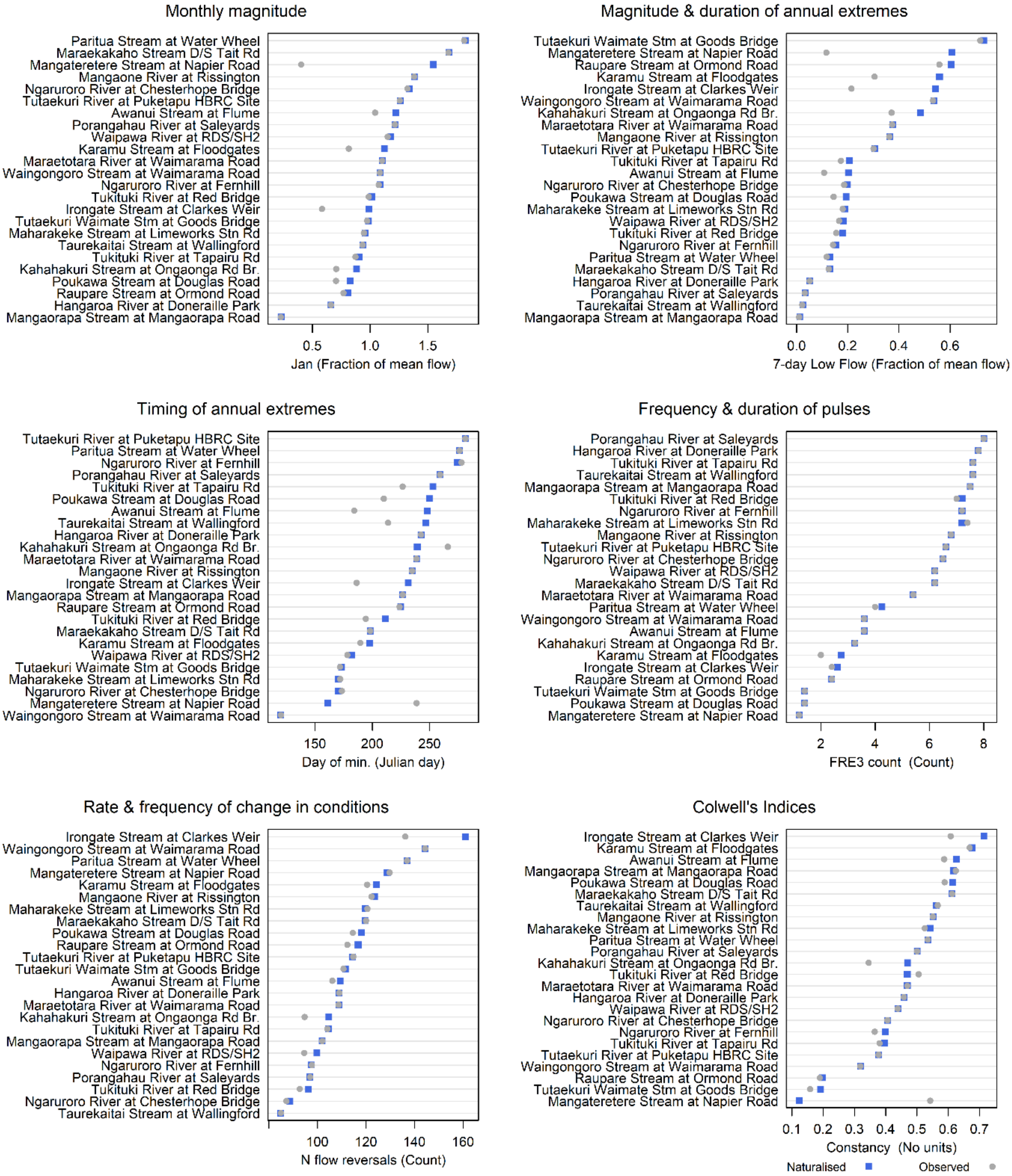

Figure 5-61: Hydrological metrics for each sites. One metric from each group has been selected. Sites are ranked by the estimated naturalised metric value.

6 Discussion

6.1 Conceptual points

6.1.1 Uncertainty in specifying flow-ecology relationships

There are relatively few easily applied methods or tools that provide quantitative predictive relationships between flow regimes and ecological integrity and/or human health. There are at least three main challenges to developing predictive models of environmental values as a function of river flows.

- The first main challenge is disentangling the influence of flow variability or flow alteration on environmental values from the influence of climate, nutrient, or biological (e.g., invasive species) processes when developing predictive flow-ecology models.
- The second main challenge is recognition of spatial patterns and processes that are often active within river systems that are considered as nested hierarchical systems because each segment of river is influenced by upstream conditions. Spatial issues become extra complicated when considering environmental values that can move through river catchments (e.g., fish, sediment).
- The third main challenge is recognition of temporal patterns and processes that are often active with respect to environmental values that are influenced by antecedent conditions as well as current conditions (e.g., algae growth occurs over long periods of steady flow rather than lower flows on just one day).

The consequence of these challenges is that there is no single best set of hydrological metrics that can be uniformly applied across locations to assess environmental risk resulting from water abstraction because different environmental, ecological, and cultural values will be linked to different hydrological metrics. However, a standard set of ecologically-relevant and environmentally-relevant hydrological metrics can be devised from which relevant hydrological metrics can be selected. Therefore, a flexible approach is required for selecting which hydrological metrics are most appropriate in which circumstances because different ecological, environmental, and cultural values will be most closely associated with different hydrological metrics.

6.1.2 Overlapping definitions of environmental, human health, and economic needs for fresh water

Methods for analysing water allocation and use with respect to human health needs and economic uses includes splitting water quantity data by primary use, but this approach assumes that water used for human health is solely represented by consents labelled as “drinking”. This approach may be technically misleading because the drinking label was not intended for this purpose, and methodologically flawed if a broad definition of human health is applied.

6.2 Technical points relating to our methods

6.2.1 Prescriptive versus general requests during data acquisition

We did not issue a prescriptive data request for this work. We issued general requests for data that would be needed to complete our stated study aims. This approach was taken following conversations with staff from MfE and regional councils (including the LAWA co-ordinator). The approach was taken based on two points. The first point was that a standardised data format was already in place for LAWA water take consent data. We decided not to issue a prescriptive data request that would clash with the existing LAWA water take consent format. The second point was the assumption that a general request would prompt a more effective response than a prescriptive request because prescriptive requests can be confusing to interpret and overly burdensome for regional councils to respond to. The general approach to requesting data had the advantage that we received large volumes of data, but also had the disadvantage that these data were not always well described, were not necessarily designed for our purposes, and there was scope for inconsistencies in formatting and definitions between datasets supplied by different organisations.

We noticed that different councils supplied consent data in different formats. Different data formats are likely to emerge within each council to suit the consent format that they have been applying. There is no reason to expect various councils to supply data in the same format following a general request for water quantity data.

We had to exert considerable effort developing a set of bespoke processes for this work as a consequence of using a general data request (see Figure 3-1). Our processes could be reused for future work if the format of the input data remains unchanged. However, the relevance of our data harmonisation processes for future work is unknown because a constant format of input data cannot be guaranteed. Our conversations with regional council staff during the course of this work indicated that future changes to the format of water quantity data are likely given changes in national policy, regional planning, regional councils processes, and water measurement technology.

Consent data was most readily able to be used to complete an analysis for all councils, due to receiving consent information in a standard format through LAWA. However, the forcing of consent information into this standardised LAWA format resulted in some possible loss of information which meant that it was not possible to assess consented allocation against plan limits. The most prevalent shortfalls were a lack of clarity in how to attribute consent quantities to relevant plan flow sites or zones, and a lack of clarity in how to handle streamflow depletion effects for groundwater abstractions.

Data that was provided was generally suitable for carrying out the required analysis. However, collating the data was time consuming due to the need to deal with data gaps, and difference in representation of data. Differences in representation of consent data may represent differences in the underlying consenting framework for different councils.

One example of inconsistencies between regions was that the representation of restrictions for HBRC and ECan was different. ECan used a single trigger value, and HBRC using an upper and lower trigger range. The reason for this is likely because HBRC enforces multiple restriction bands for a single consent (Cease and Reduce) whereas ECan enforces a single "LowFlow" cease band. The most effective way to represent these two restriction systems is different, so it is unsurprising the councils use different conventions.

Another example of inconsistencies between regions was contrasting use of the label “streamflow depleting”. ECan and HBRC both used the label “streamflow depleting” under the “primary source” column of their consent databases. Both councils are evoking the notion that “streamflow depleting” indicates the possibility that some groundwater abstractions are more closely linked to surface flows than others. We understand that consents are labelled as streamflow depleting because: a) they should be tallied with surface consents to produce a sum that will be compared with a plan limit for surface water total allocation; and/or b) their streamflow depleting effects is immediate enough and local enough to justify for the consent having restrictions that are linked to river flows. However, ECan and HBRC used different methodologies to incorporate this notion into their databases. Following conversations with these two councils, and to the best of our knowledge, the situation for each council is as follows.

- For HBRC, there is one row per consent. Each consent's primary source is labelled as either surface water, groundwater, or streamflow depleting. Communication from HBRC indicated that "stream depleting labels indicate that they are groundwater consents with an effect on surface water, the amount of the effect is variable and not always known". We interpreted HBRC's labelling system as indicating that a groundwater abstraction has been judged to have a more immediate, and more local influence on surface water flows compared to other groundwater abstractions. Since the distinction between HBRC consents labelled as groundwater versus stream depleting was not definitive, we treated stream depleting consents the same as groundwater consents in our methods.
- For ECan, for each row whose primary source is labelled as streamflow depleting, there is another row with the same consent identifier but whose primary source is labelled as groundwater. For each row labelled as groundwater, the maxRate represents the full consented maximum allowable rate of abstraction. For each row labelled as streamflow depleting, the maxRate represents the part of each groundwater consent that should be considered as depleting surface water. We interpreted ECan's labelling system as indicating that a groundwater abstraction has been judged to have some part of its flow-altering effect as having a more immediate, and more local influence on surface water flows compared to other groundwater abstractions.

Our interpretation of these labelling systems led us to a methodological dilemma: should we apply a consistent methodology across the datasets from the two regions, or should we apply different methods to the two councils' datasets based on our understanding of how they were representing consents based on different methodologies for data entry? Our methodological dilemma exemplified the broader advantages and disadvantages of using general versus prescriptive data requests for national-scale water quantity accounting. In theory, a prescriptive request should yield standardised data to which standardised methods can be applied. However, our experience indicated that standardised data were not received even though the LAWA water take consent data should have been standardised following prescriptive instructions. Our experience demonstrates the importance of several issues: a) clear prescriptive descriptions (e.g., definitions of technical terms) should accompany standardised data requests; b) organisations fulfilling the requests need to have time and resources to fulfil the request; c) organisations fulfilling the requests should understand the intended purpose for the requested data; d) methods may have to be adapted to accommodate non-standard data.

6.2.2 Workflow for Water account data and reporting

In the study, we followed the "orange arrows" depicted in Figure 6-1, which involved a time-intensive process to collate the data from different councils into a common structure to carry out analysis. One advantage of this approach is that it allows for identical analyses to be conducted on all data.

However, a challenge arises from differences in the data from each council, making it is challenging to accurately represent all information within a common structure.

Alternatively, the “green arrow” pathway involves creating and storing water account-associated data in a consistent format. While this approach has benefits, such as ensuring uniformity, a challenge lies in developing a data format and acquisition process that meets the diverse requirements of all councils and various uses of the data, such as water quantity accounting, environmental monitoring, and compliance checking.

The “purple arrow” pathway, where each council directly reports water account outputs, is also used currently, as each council reports against its plan limits. However, these findings may not be easily compared nationwide or unified into a single nationwide analysis due to the unique nature of plans for each region/FMU.

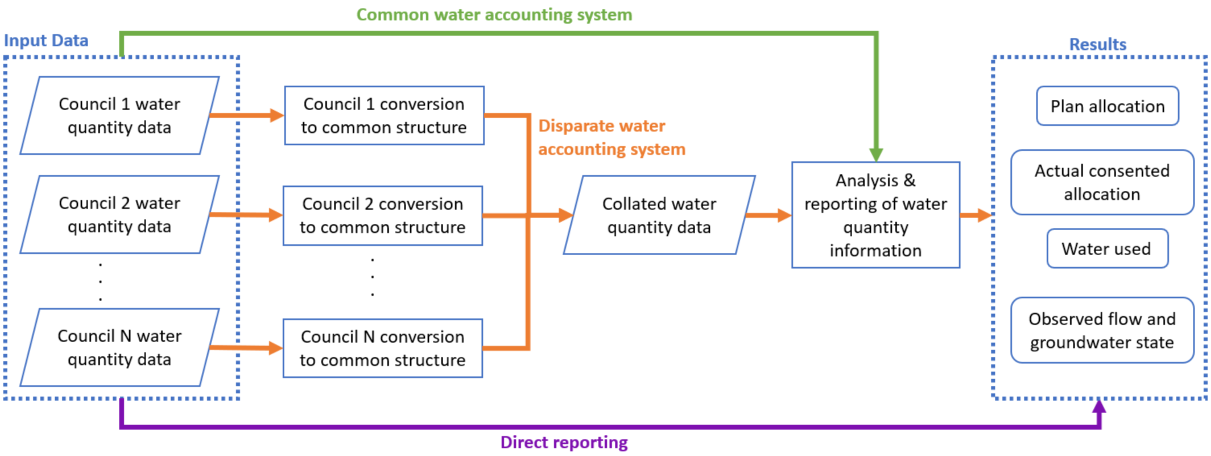

Figure 6-1: Example of pipelines for water quantity accounting and reporting.

6.2.3 Analysis period

We applied different analysis periods for different analysis due to different purposes and levels of data availability. We opted for a two-year analysis period that spanned from mid-2021 to mid-2023 for our analyses of consents, restrictions, and meter data. This period featured relatively high river flows and minimal influence from consent restrictions. Ideally, we would have preferred a broader analysis period, but we encountered limitations due to the unavailability of coincident consent data across all councils.

For the streamflow depletion analysis, we utilised a longer period from 2013 to 2023 to accommodate longer response times resulting from groundwater abstractions. However, our analysis focused on the period from 2018 to 2023. We excluded the first five years modelled (2013–17) because that period was considered to be influenced by abstractions from previous periods (i.e., prior to 2013).

One aspect not addressed in this study is the assessment of historic data availability and the development of water accounting workflows with strong backward compatibility to incorporate historic data as would be required to assess long-term trends in water use.

6.3 Consequences for water accounting

6.3.1 Requirements for water quantity accounting

Given the complexities explained in the preceding sections, freshwater managers and regional planners are faced with difficult decisions relating to water quantity accounting associated with the following sequence of topics and questions. Table 6-1 presents a list of requirements and associated questions that we suggest would logically be asked of water quantity accounting procedures given the needs for water accounting set out in Sections 1.3 and 2.5.

Table 6-1: Anticipated questions from freshwater planners and managers that logically lead to requirements for water accounting given the need to determine and deliver environmental flow regimes.

Number	Requirement	Anticipated question for water quantity accounting from planners and managers	Possible requirements for water quantity accounting that follow from questions
	Identify and limit risks to environmental values in line with legislative requirements and following engagement with local communities and tangata whenua.		
1		What environmental values can be affected by flows?	The water quantity accounting results should provide necessary flow information to evaluate the relationship between various aspects of flow regimes and environmental values at relevant spatial locations.
2		What level of flow-driven risk to environmental values is acceptable?	See Answer to 1.
	Identify environmental flows relevant to environmental values.		
3		What characteristics of flow regimes are relevant to environmental values?	See Answer to 1.
4		What degree of relative flow alteration is needed and/or what absolute level of flow regime characteristics must be maintained to define an environmental flow regime that ensures risks to flow-driven environmental values remain within acceptable levels?	See Answer to 1.
	Identify water resource use limits to deliver environmental flow regimes.		
5		What is the maximum pattern of water abstraction in time and space (or water discharged downstream of dams) required to deliver an environmental flow regime across a catchment?	See Answer to 1.

Number	Requirement	Anticipated question for water quantity accounting from planners and managers	Possible requirements for water quantity accounting that follow from questions
6		What water resource use limits in regional plans need to be in place to restrict abstractions in order to deliver an environmental flow regime by controlling flow altering human activities across time and space, bearing in mind Points 7-11?	The water quantity accounting procedure must be able to operate in hindcast (past) and forecast (future scenarios) modes as recommended by Bright et al. (2022). Both modes must explicitly consider how limits in plans are delivered within consents that control activities, including the influence of legacy consents that were granted prior to development of the current/future plan.
7		How do water resource use limits in regional plans relate to efficient water use?	The water quantity accounting procedure must be able to estimate reasonable water demand assuming efficient water use (as recommended by Bright et al. (2022)), and then compare this estimate with water that would be available under water resource use limits.
	Identify relationships between water resource use limits and delivered flow regimes.		
8		Are consented activities (and possibly permitted activities) that alter flow regimes aligned with water resource use limits in regional plans (e.g., by applying a cease-to-take threshold and/or a maximum allowable rate of take)?	The water quantity accounting procedure must be able to assess whether consented activities (and possibly permitted activities) that alter flow regimes have conditions that align with water resource use limits in regional plans. Bright et al. (2022) noted that data for permitted activity water uses currently must be estimated (modelled).
9		What factors may be altering flows that are not controlled by water resource use limits in regional plans (e.g., afforestation-deforestation, climate variability/change, permitted activities)?	The water quantity accounting procedure must be able to attribute changes in river flows and groundwater levels to climate variability and landcover change as well as water use. Bright et al. (2022) stated that the Stock Account and the Flows Account could be used to assess the extent to which these changes were driven by variations in climate (for example) and by within-catchment anthropogenic activity.
10		To what degree are controls on consented activities (e.g., restrictions on water use stated in consents) and permitted activities (restrictions on permitted activities in regional plans) controlling water use? In other words, are consents being fully utilised or are some consents only partially utilised some of the time?	The water quantity accounting procedure must be able to compare allowable water use (including any temporal restrictions), and reasonable water use (e.g., irrigation water use adjusted for weather conditions) with actual water use to calculate water utilisation.

Number	Requirement	Anticipated question for water quantity accounting from planners and managers	Possible requirements for water quantity accounting that follow from questions
11		What does the naturalised flow regime (flow under present landcover and climate but if no abstraction was occurring) and its associated uncertainties look like?	The water quantity accounting procedure must be able to estimate the naturalised flow regime (or at least the aspects that are relevant to environmental values) and their uncertainties.
12		How much year-to-year variability in naturalised flow is expected due to changes in weather?	The water quantity accounting procedure must be able to estimate spatiotemporal variability in naturalised flows.
	Assess delivery of environmental flows.		
13		How much water was allowed to be used under the water resource use limits set in regional plans?	The water quantity accounting procedure must be able to calculate maximum allowable water use if plan limits were enforced, in order to estimate the worst-case scenario for environmental impact in situations where water demand exceeds water availability.
14		How much water was allowable to be used under consented activities and permitted activities?	The water quantity accounting procedure must be able to calculate maximum allowable water use if all consents were being fully exercised and also estimate water use under permitted activities such as stock drinking and small domestic supply.
15		How much water was used under consented activities and permitted activities?	The water quantity accounting procedure must be able to calculate actual use and also estimate water use under permitted activities such as stock drinking and small domestic supply.
	Assess water use influences on flow-driven environmental values.		
16		What is the state and trend of flow-driven environmental values?	The water quantity accounting procedure does not have to answer this question directly, but must be able to estimate time-series of hydrological variables that are likely to be related to flow-driven environmental values.
17		What changes in environmental values can be attributed to flow regimes and water abstraction?	The water quantity accounting procedure does not have to answer this question directly, but must be able to attribute changes in hydrological variables that are relevant to environmental values to water abstraction versus other driving factors such as climate variability.

6.3.2 Discussion of previous work on water accounting for MfE

In many respects, our analysis and recommendations agree with previous work on water accounting in NZ such as those mentioned in Booker et al. (2015), Booker et al. (2022), and Bright et al. (2022). Common topics include the clear need for water accounting to support freshwater management, the needs for standardisation in technical methods and terminology, need to recognise spatial and temporal patterns, and the need for a common spatial framework for accounting. However, we suggest reassessment of some aspects mentioned in Bright et al. (2022) in light of our analysis, which concentrated on river flows, as follows.

- Bright et al. (2022) stated that "the presence of uncertainty should be clearly recognised in both observational and modelled data and reported in any accounting system, and considered when freshwater quantity accounting information is used in policy effectiveness reviews" and "Recommendation 4: Uncertainty should be quantified and reported for each line item in the Stock and Flows Accounts.". We fully agree with the intent of this recommendation. However, our analysis indicates that there are significant technical challenges in recognising and quantifying uncertainty within an accounting system under the current level of water quantity management, data collection, and analysis. Beyond acknowledging the presence of uncertainties, it is crucial to reduce this uncertainty to improve the accuracy of water accounting so that it is fit for specified purposes. We recognise that quantifying and reducing uncertainty is resource-intensive, as it primarily involves enhancing observations through more extensive spatio-temporal data collection and improvements to procedures for applying QA-QC. Well-designed, targeted monitoring plans, combined with rigorous scientific approaches, can effectively reduce overall uncertainty. For example, focusing monitoring and quality checks on larger water takes and/or sensitive locations, developing real-time QA-QC procedures, applying scientific methods to transfer findings to other water takes, real-time assessments for estimating naturalised flows, and assessing compliance can all improve the overall accuracy of water accounting. Uncertainty can be quantified where models are used for water accounting (e.g., Liu and Gupta 2007; Abbas et al. 2024), but standardised approaches to uncertainty representation are required across regions.

- Bright et al. (2022) suggested that "there should be a nationally consistent reporting framework that can be applied with a level of detail that is commensurate to the level of pressure on, and value of, the water resource in any particular part of the country". Our analysis indicates that quantifying the level of pressure on river flows and the significance of freshwater values are extremely challenging, these entities and can alter rapidly in both space and time. Thus, it is difficult to envision a practically-implementable method to assess level of pressure and significance of freshwater values in order to specify the level of detail for water accounting. Application of a nationally consistent reporting framework is a rational recommendation given freshwater and environmental reporting policies. Spatially varying level of detail is theoretically commendable but practically unimplementable, subjective to define, and subjective to judge in terms of the commensurate level of detail required.

- Bright et al. (2022) stated that "Integrated Freshwater Accounting (IFA) reports quantify all water stocks (masses) and flows within and between catchments… to monitor actual environmental outcomes and compare these to desired outcomes, standards and objectives." We suggest that there is a clear need to account stocks (masses) with respect to groundwater, lakes/reservoirs, and water quality, but there is little benefit to accounting stocks with respect to river flows. The mass of water stored in river channels or catchments at various points in time is: a) difficult to estimate; b) likely to change over short timeframes due to the flashy nature of river flows; and c) not pertinent to river management because river flow rates are the primary indicator of water availability and flow-driven environmental values. High resolution (i.e., at least daily) flow time-series convey far more useful information about conditions in rivers relating to environmental values and water availability than information on stocks (i.e., volume of water in rivers on the last day of each season).

- Bright et al. (2022) suggested that "The freshwater accounting framework is based on two types of tables: a Stock Account and a Flows Account. A Stock Account provides a snapshot of water and contaminant mass for a specified area and point in time. A Flows Account reports changes in water mass over a specified time period by itemising the additions and removals of water mass to/from the area for which the accounts are being produced." We suggest that this recommendation is somewhat more appropriate to groundwater and water quality than river flows where stock accounts are less relevant (except for lakes and reservoirs) and flows accounts would have to be very high frequency to be relevant to environmental values. There would be a great deal of equifinality in results if flows accounts were too coarse in time (e.g., monthly, or annual). Therefore, we recommend designing data collection processes to reflect the characteristics of the resource (e.g., groundwater generally flows slower than surface water) for pragmatic reasons and economic efficiency. Consequently, methods should be developed to aggregate or disaggregate groundwater and surface water data spatially and/or temporally at the scale necessary for meaningful and efficient decision-making in water accounting. Furthermore, clear recommendations for appropriate levels of aggregation/disaggregation in space and time needs to be devised, accepted, and applied (e.g., monthly per aquifer unit for groundwater, daily per segment of a river network for surface water). A method for aggregating up or down in spatial and/or temporal scale must be developed and applied to ensure that river flow accounts can be compared to groundwater flow accounts, and vice versa. This recommendation should be considered in conjunction with the first recommendation above.
- Bright et al. (2022) suggested that "the area for which freshwater accounts are being produced as an Input-Output Unit (IOU). It is a scalable, specific, real-world hydrological system that has been delineated for freshwater accounting purposes. The most readily identifiable IOU is a catchment". We suggest that this recommendation is somewhat more appropriate to groundwater and water quality than river flows due to the importance of high-resolution spatial information (e.g., drying reaches and streamflow depletion in small tributaries) as was suggested by the request from MfE to investigate this issue.

7 Task completion, recommendations, and conclusions

This report contains a large body of work that spans a range of topics relevant to water quantity accounting and water resource management. We obtained data from four example regions and communicated with staff from several additional regions about their water quantity data and accounting. However, we did not analysis all water quantity data from all regions because a nationwide analysis was beyond the scope of our project.

The process of water accounting could mean many different things to different people working on different regions/catchment due to differences in legislation, data availability, water demand, local environmental values, institutional arrangements, and scientific methods in place when plans were development or consents were issued. This situation presents several challenges for water accounting to produce consistent results at the national level, but also to be effective and efficient at the local level. The overall conclusion to this work is that, in order for water accounting to be nationally consistent, local water accounting and water quantity data must be comprehensive, fit for specified purposes, explicitly quantify variability in time and space, and be standardised.

Generally, our analysis indicated that the data available for water quantity accounting purposes is much more complicated than one might expect. It would be inappropriate to assume that each abstraction has a single time-series of take, easily interpreted consent conditions that only apply to that abstraction, a single set of known coordinates, and relates to a single clause in a plan etc. Furthermore, achieving water accounting at a spatially varying level of detail is technically challenging and costly due to: a) exhaustive data needs for characterising pressure; b) lack of transparent and prescriptive methods to define and characterise freshwater values; and c) subjectivity in trading-off levels of pressure against significance of freshwater values.

Comprehensive water accounting is needed to ensure that water accounting is fit for predefined purposes rather than being an ad-hoc analysis of whatever data are available. A system-wide strategic view is required that encompasses the collection, collation, analyses, and presentation of water quantity data to inform freshwater management, planning, and policy development through time and across the landscape. Specifically, effective water accounting should quantify states and trends of: a) flows and levels in freshwater environments; b) water resource use limits in regional plans; c) allowable water use under consents and permitted activities; d) actual water use; and e) climate drivers of freshwater conditions such as precipitation and air temperature. Information describing the relationships between those entities would allow assessment of: a) the degree of hydrological alteration resulting from water abstraction; b) over-allocation versus headroom; c) water allocation and use efficiency versus wastage; and d) attribution of hydrological states between the influence of local anthropogenic effects versus climate variability or change.

Water accounting could conceivably be applied over several time-scales depending on purpose (over all time, annually, seasonally, monthly, weekly, daily). Water accounting could also conceivably be applied over several spatial-scales (nationally, regionally, per-catchment, per-segment of a river network). Our results indicate that important changes in water availability and alteration of river flows can occur: a) at daily time-scales due to rapid changes in abstraction; and b) between reaches within catchments due to the positioning of abstractions. Water accounting therefore needs to be able to discern relatively fine temporal and spatial patterns at the local level in order to be informative, but these patterns need to be up-scaled to provide national coverage if results are to be used consistently for national environmental reporting or policy development.

Clear technical definitions and standard technical approaches are needed to overcome several challenges to completing systematic-regionwide estimates of water allocation, water abstractions, water discharges, and streamflow depletion, including: a) distinguishing missing data from genuine absence of abstraction; b) reproduceable treatment of raw data during quality assurance/checking; c) estimating the delayed streamflow depletion effects of groundwater abstractions; d) the possibility of double counting of abstraction; e) difficulty in specifying a natural baseline against which abstraction can be compared; and f) attribution of changes in river flows or groundwater levels to local anthropogenic activities versus broader-scale climate variability.

As outlined in Section 1.3, the objectives of this project were accomplished by completing seven tasks. The details of the work conducted, key findings, and recommendations for achieving nationally consistent water accounting related to each task are provided in Table 7-1.

Table 7-1: Description of how each task was completed, main findings, key results, and recommendations for nationally consistent water accounting.

Task	Advancements	Main findings	Key results from example analysis	Recommendations for national consistency
1. Collate and process water resource consent and plan limit data	Water resource consent data were accessed directly from councils and by querying the LAWA water take consent data for each of the studied councils. Plan limit data had to be obtained using a variety of approaches.	The availability of water quantity data varied between regions. Up-to-date LAWA water take consent data were not available for every council, but consent data were obtained for selected councils. Plan limit data are publicly available but were even more difficult compile into a database than consent information. Water resource use limits in plans and conditions for taking water in consents can currently be written in free text format, which has the benefit of flexibility but hinders subsequent collation and analysis across catchments and regions because the relevant data are not held in standardised formats.	We compared restriction trigger values written in consents from HBRC and ECan against observed median flow and estimated naturalised MALF. The level of low flow protection provided by different restriction trigger values was inconsistent between sites and between consents. We compared measured and naturalised flows against minimum flows in HBRC's regional plan for where gauging station data were available. We found considerable differences in the percentage of time that the observed flow and the naturalised flow were below minimum flow for 9 of the 12 sites that we analysed.	Standard procedures and technical infrastructure allowing transfer of standardised water quantity data (including plan limits, consent conditions, measured water abstraction, river flows, and groundwater levels) should be in place across regional councils. Standardised formats and calculation methods for water resource use limits in plans and conditions for taking water in consents should be applied across regions and catchments within regions. This stipulation would create less flexibility in writing of plans and issuing of consents but would ensure that water use can be more robustly assessed against limits from plans and consent conditions.
2. Analyse water resource consent and plan limit data	Water resource consent data were analysed by comparing instantaneous allowable rates with allowable annual volumes, by summing over sources and uses, by mapping abstraction locations, by accumulating upstream takes across a national digital river network, and by comparing maximum allowable rates with estimated median river flows.	Actual water use was generally much lower than the overall maximum allocated rate but exhibited similar spatial and temporal patterns. Restrictions to limit take did not play a large role in limiting take for some years at some sites in our analysis.	Plan limits controlling water resource use varied greatly in their format and composition. The proportion of consents controlled by either observation-based or predetermined restrictions varied greatly between HBRC, ECan, and ES.	Currently, the water resource consent module of LAWA uses a semi-standardised method for representing water abstraction consents. However, this LAWA pro-forma does not allow for the upload of all consent information required to calculate time-series of allowable abstraction. A more flexible pro-forma that allows information on consent restrictions should be applied.

Task	Advancements	Main findings	Key results from example analysis	Recommendations for national consistency
3. Assess methods for analysing water allocation and use with respect to environmental needs, human health needs, and economic uses	Definitions and contextual information about environmental needs, human health needs, and economic uses with respect to water allocation and use was set out. Methods for analysing water allocation and use with respect to human health needs and economic uses includes splitting water quantity data by primary use, but this approach assumes that water used for human health are solely represented by consents labelled as drinking. This approach may be technically misleading because the drinking label was not intended for this purpose, and methodologically flawed if a broad definition of human health is applied.	Environmental needs for fresh water cannot be assessed through an analysis of water allocation and use alone because environmental conditions are defined by flows and levels experienced in the natural environment rather than water that is allocated or used. Streamflow depletion modelling was applied to allow estimation of naturalised flows and influences on ecologically-relevant aspects of flow regimes. However, these methods are highly uncertain because they rely on complete and accurate observed meter data, aquifer parameters, and gauging station data. More importantly these methods can only be applied at gauging station sites. Thus, it was very difficult to assess environmental impacts of water use across entire catchments including smaller tributaries.	The World Health Organization (WHO) definition of human health is "the state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity". Under the WHO definition uses of water supporting human health would extend beyond just drinking water to arguably include water used to support local food production, recreation, cultural values, and possibly power production.	Conceptual and technical definitions should be carefully considered and agreed across institutions for assessing water allocation and actual use for competing needs. It is possible that definitions of environmental, human health, and economic needs for water indicate that they are inseparable. In this case it would not be possible to isolate and then prioritise water allocation between these three entities because they are interpreted as being part of an interlinked system.

Task	Advancements	Main findings	Key results from example analysis	Recommendations for national consistency
4. Conduct a stocktake of actual water use data	An interactive questionnaire was applied to ascertain the degree to which water allocation use data were available across all regional councils.	There was considerable variety between regions relating to availability of actual use data. In some situations, water is abstracted from the natural environment and used relatively locally and relatively immediately. However, in other situations, water is transported to be used at a distal location after having been abstracted from the natural environment. Water can also be temporarily stored for later use. Thus situations can arise where some observed time-series represent water being measured at the point of take, other observed time-series represent water being measured at the point of use, and some observed time-series represent simultaneous take and use.	All councils are receiving or collected actual metered take data. All councils acknowledge the importance of data quality of metered take data. Of 12 councils, 25% indicated “no”, 33% “yes”, and 41% indicated “other” when asked whether they apply prescribed procedures for quality checking meter data. Only raw metered data are available from some councils, whereas both raw and processed data are available from some councils, and no data are available for other councils.	Standardised formats should be developed, accepted, and adopted for storing actual water use data, including quality-control and quality assurance procedures. Standardised formats must include some flexibility as actual take data can take a variety of formats (e.g., observations over different time periods, regular versus irregular observations, observations of rates versus cumulative totals, etc.). Any system for storing and analysis of actual water use data should recognise that there are complex relationships between observed time-series of take, water users, abstraction points, consents, and plans. Any system for storing and analysis of actual water use data should recognise differences between take and use of water.

Task	Advancements	Main findings	Key results from example analysis	Recommendations for national consistency
5. Make recommendations for future management of water quantity data	Several recommendations for future management of water quantity data were set out. Part of the brief for this work was to provide recommendations that can be relayed back to councils through council representatives and the LAWA team who were active participants during this project.	Currently, for nationally available data (LAWA), sources are listed as a single primary source, which is not suitable for accounting in situations where a take affects multiple sources / water management zones. Currently, for nationally available data (LAWA), uses are listed as a single primary use, which is not suitable for accounting in situations where a take is for multiple uses, as is the case for many consents. Currently, for nationally available data (LAWA), consents restrictions on abstraction quantity are provided as a maximum instantaneous rate and maximum annual volume. For ECan, inspection of real free-text consents revealed annual volumes are rarely present. For several consents, a type of secondary restriction was seen, which was usually defined by a maximum allowable volume over a given period. The period was not the same across consents (e.g., 3 days, 7 days, 21 days). The secondary restriction is important for calculating availability of water.	Water accounting must be comprehensive. Water accounting must be fit for specified purposes. Water accounting must explicitly quantify variability in time and space. Water accounting must be standardised.	Source should be recorded as a percentage of fixed labelled columns (e.g., groundwater, surface water). Percentages of the take from different sources could be based on location of consented takes, or potentially model-derived. Source columns must add up to 100%. However, this recommendation would require more detailed information than is currently used, and which may not explicitly be stated in the consent. Alternatively, a separate approach should be used to allow assessment of the degree to which groundwater takes are likely to be directly depleting nearby surface water flows. Use should be recorded as a percentage of fixed labelled columns (e.g., irrigation, drinking, Hydropower, etc.). Percentages could be based on consented details, or potentially equal splits. Use columns must add up to 100%. However, this recommendation would require more detailed information than is currently used, and which may not explicitly be stated in the consent. Uses may arise that are not included in the fixed labelled columns. Information representing secondary restrictions should be stored in a flexible database structure. These restrictions could be represented as a paired rate and period in a larger table of consent rules where each restriction is represented as a row. It may be useful to additionally define whether each period is a rolling period or fixed duration (e.g., a limit for each season). Additional columns could be used to define a season for each restriction.

Task	Advancements	Main findings	Key results from example analysis	Recommendations for national consistency
6. Demonstrate methods for estimating ecologically-relevant hydrologic effects of streamflow depletion	Ecologically-relevant hydrologic metrics were calculated for example gauging stations. A suite of hydrological metrics was used to demonstrate the influence of measured abstraction on river flows by comparing naturalised and altered hydrological conditions.	A range of hydrological metrics are available to demonstrate influences on low flow magnitude, higher flow magnitude, seasonality, and mid-range flow variability. However, there is no “best set” of hydrological metrics that can be uniformly applied across sites because different environmental, ecological, and cultural values will be linked to different hydrological metrics.	We estimated naturalised river flows at 24 gauging stations in the Hawke’s Bay region by summing measured flows with estimated streamflow depletion for demonstration purposes. We summarised differences between measured and naturalised flows to assess the effects of water abstraction on various aspects of flow regimes using a suite of ecologically-relevant hydrological metrics. We found that low flows were altered considerably at some sites but not altered at other sites as was expected because they had very few upstream abstractions.	A standard set of ecologically-relevant and environmentally-relevant hydrological metrics can be devised. Methods for calculating hydrological metrics, and then comparing naturalised and altered conditions must be both transparent and standardised if nationally consistent results are to be obtained. A flexible approach is required for selecting which hydrological metrics are most appropriate in which circumstances because different ecological, environmental, and cultural values will be most closely associated with different hydrological metrics.

Task	Advancements	Main findings	Key results from example analysis	Recommendations for national consistency
7. Explore patterns in actual versus consented water use; including infilling of missing data and streamflow depletion modelling.	Methods for infilling of incomplete records were devised, applied, and assessed. Methods for calculating streamflow depletion from both surface water and groundwater abstraction were applied across an entire region. Patterns in actual versus consented water use were calculated.	Abstraction can be predicted from time of year and weather within many sites with sufficient training data, however, abstraction at sites with no data were difficult to predict. The downstream streamflow depleting effects or abstraction can be broadly assessed using streamflow depletion modelling to quantify time-series of accumulated streamflow depletion. Assumptions about the extent and timing of the streamflow depleting effect of groundwater takes must be applied. Analysis of metered take data from HBRC and ECan indicated that completion rates for consents with rates greater than 5 L s^{-1} were relatively high.	There was theoretical headroom in water availability as around a quarter of consented water for ECan metered takes was actually taken during the summer for the period assessed. Theoretical headroom was greater for HBRC than for ECan. Metered take was predictable from time of year and weather within many sites with sufficient training data. Predictive performance was stronger at monthly resolution compared to daily resolution. When assessed at monthly resolution, cross-validated variance explained was greater than 0.5 for 97% of meters. Regionwide streamflow depletion modelling was applied but required some aquifer parameters inputs to model the delayed effects of groundwater abstraction.	Methods for identifying and infilling missing abstraction data must be devised, agreed, and applied in order to avoid systematic underestimation of overall abstraction. Two main types of missing data must be dealt with: a) missing data from within time-series of observed metered abstraction for a site; and b) lack of any observed abstraction data from a site. Consistent parameterisation and application of streamflow depletion models is required if national consistent results are to be obtained.

8 Acknowledgements

Many thanks to numerous regional council staff who supplied information relating to this work. Thanks to Abi Loughnan for her contributions to discussions about water quantity data on behalf of LAWA. Thanks to Ton Snelder of LWP and Tim Chambers of University of Canterbury for providing data for this work.

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