High-flow harvesting

Part 2: guidance for devising water allocation rules with examples from Northland and Gisborne

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Executive summary

Rules in regional plans set water resource take limits to control how much water can be taken from the natural environment under what circumstances. The purpose of these rules is to clarify water allocation and protect in-stream values during low flow periods. However, in some regions these rules do not necessarily extend to higher flows, and the suitability of current rules for managing water takes during higher flows is uncertain.

This report provides improved guidance, methods, and analysis designed to inform the process of setting water take limits related to both run-of-river takes and high-flow harvesting. Run-of-river takes are defined as those where water is taken from a river, and then used immediately. High-flow harvesting takes are defined as those where water is taken from a river, generally during times of high river flows, and stored temporarily for use at a later date. In reality, flexibility within these descriptive definitions means that many takes could fit along a continuum between run-of-river takes and high-flow harvesting, depending on interpretation of the definitions. This report describes technical clarifications to unambiguously distinguish high-flow harvesting from run-of-river takes so that they can be treated differently within operational planning and consenting processes.

A four-step strategy was proposed to inform the process of defining water allocation rules and accompanying consent conditions with respect to high-flow harvesting:

1. **Principles** are proposed to aid water resource management with respect to high-flow harvesting that aligns with the National Policy Statement for Freshwater Management 2020 (NPS-FM) and its fundamental concept of Te Mana o te Wai.

2. **Heuristics** are proposed that describe actions required to apply each principle in relation to planning, management, and operation of water allocation when high-flow harvesting is combined with run-of-river takes. The heuristics call for water allocation rules to be:

   - practically implementable by ensuring that potential future water users can calculate water availability and existing users can operate within their consent conditions;

   - environmentally sustainable by delivering environmental flow regimes required to achieve desired environmental outcomes;

   - water efficient to ensure allocation does not exceed reasonable water demand; and

   - spatially consistent whilst recognising spatial inequalities in water use, water availability, and potential impacts on in-stream values.

3. **Analysis** to assess the degree to which hypothetical water allocation rules and consent conditions (in terms of placement of take, restrictions to taking, maximum rate of take, maximum storage capacity, etc.) conform with these heuristics.

4. **Recommendations** made in light of interpretation of results.

A water accounting system was developed to provide a framework for analysing water allocation rules. The system allows quantitative representation of water allocation rules and consent conditions to calculate daily river flows, water takes, water in storage, and soil water content of irrigated land under hypothetical situations. Analysis concentrated on water use for irrigation because this is the primary use of water in many locations across the country, although the system could also represent other water uses. River flow data from 42 sites obtained from Northland Regional Council and 14 sites obtained from Gisborne District Council were used to calculate water availability under a variety of water allocation rules. Climate data from NIWA's Virtual Climate Station Network (VCSN) were used to calculate water demand at each site. Constant soil conditions, crop type (grass), and irrigation procedures (i.e., maintain a specified proportion of plant available water) were applied in all locations in lieu of readily available site-specific information and to simplify interpretation of results. Results in this report therefore represent a set of idealised situations given realistic river flow and climate inputs, rather than an attempt to simulate real situations at each individual site.

It is proposed that high-flow harvesting rules could use a similar format as existing low flow rules by applying cease-to-take thresholds and maximum allowable rates of take. Under this proposal, rules could utilise a sequence of bands defined by paired cease-to-take thresholds and maximum rates of take. Rules that apply multiple bands would have the same information, practical, and operational requirements as current low flow water allocation rules. A multi-band configuration is proposed in which cease-to-take thresholds and maximum rates of take are defined as a function of 7-day mean annual low flow (7dMALF) and median flow. Use of generic hydrological metrics allows universal rules to be applied across different flow regimes. The lowest band (Band 1) corresponds to rules for run-of-river takes. Positioning of multiple bands relative to the flow regime at a monitored flow control site would facilitate higher total allowable rates of take at relatively high flow, relating hydrological alteration to river flow in a predictable way.

Analyses quantifying the consequences of water allocation rules for river flows and water supply were applied to demonstrate how variations on the proposed five-band system would conform with the pre-stated heuristics. Time-series and time-averaged results for take, storage, land, and river flow conditions were analysed. The experiments demonstrated a trade-off between water availability and hydrological alteration was mediated by interactions between bands defining water allocation rules, irrigated area, storage capacity, local climate, and local river flows. Results proved that universal rules will not result in universal consequences for either hydrological alteration or water supply, due in part to the interacting influences of flow regime variability on supply and climate variability on demand. Inconsistencies in consequences for river flow and water supply resulting from universal rules are further complicated when water storage is used because the size of storage will influence the degree of river flow alteration (bigger storages take more water compared to smaller storages).

Ultimately, a regional council must apply its own planning processes to define rules in plans that control flow-altering activities and thereby deliver environmental flows to support environmental outcomes developed in consultation with local communities and tangata whenua. This report recommends that a multi-band system can be used as a template for managing high-flow harvesting. The position and number of bands can be adjusted to meet local needs. The system would be operationalised via the process of declining consent applications or assigning consents (or parts of consents) to different bands depending on the level of current allocation for each band, estimated degree of hydrological alteration, estimated effects on in-stream values, specified environmental flow regimes, and other considerations (e.g., efficient irrigation) factored into water allocation decisions.

Various parts of the NPS-FM, and particularly the principles of Te Mana o te Wai, generally require that an environmentally conservative approach should be adopted. A more environmentally conservative set of rules would be represented by increasing cease-to-take flows, decreasing allowable rates of take, and choosing to not assign any consents to particular bands. For example, analysis in this report showed that removal of the second band from the five-band system produced a set of rules that better aligns with the outcomes sought under the NPS-FM.

1 Introduction

1.1 The need to consider water storage in regional plans

Aqua Intel Aotearoa (AIA) is a partnership between Kānoa-Regional Economic Development and Investment Unit, which is the delivery arm of the Provincial Growth Fund, and GNS Science. AIA is a national science platform on regional water availability and storage. One of AIA's workstreams is the assessment of high-flow harvesting from surface water sources and the potential impacts of this harvesting on instream values. AIA has an interest in bringing Māori land into production through greater knowledge about water availability and reliability. AIA wishes to explore whether there is scope to increase utilisation of high river flows for productive purposes, and whether water storage could contribute to environmentally sustainable utilisation of high river flows. For this work, AIA is particularly interested in issues relating to high-flow harvesting in the Northland and Gisborne regions, although their remit also covers Otago and Southland.

Northland-Te Tai Tokerau has a complex hydrological system, reflecting the region's variable geology, soils, topography, land uses and climate. Northland's river system consists of a very dense network resulting in relatively short river courses and many outlets flowing to the sea. Climatic and geological conditions in the region result in many streams with relatively low flow magnitudes during dry periods, but where higher, flashy flows can occur at any time of year after intense rainfall events.

Northland Regional Council (NRC) have recently set water resource use limits comprising minimum flows (the river flow below which consents must cease taking water) and total allocations (the sum of all maximum rates of consented water takes) as part of their regional planning process. These limits were set in response to the requirements laid out by the National Policy Statement for Freshwater Management 2020 (NPS-FM; Ministry for the Environment 2023) and the Resource Management Act (RMA) (Table 1-1 and Table 1-2). These water resource use limits were developed mainly with the intent of reducing risk to in-stream values (e.g., river ecosystem health) and clarifying availability of water for out-of-stream use in times of lower river flows or groundwater levels. NRC has also set a "high flow allocation policy" but this policy was based on work undertaken on flow harvesting impacts in regions with different climactic and hydrological characteristics, in-stream values, levels of water quantity over-allocation, water demands, and water infrastructure operations.

Table 1-1: Proposed minimum flows for rivers in Northland. Source: NRC Proposed Regional Plan: Appeal Version 8 December 2022. 7dMALF is 7-day mean annual low flow.

River water quantity management unit	Minimum flow
Outstanding rivers	100 percent of 7dMALF
Coastal rivers	90 percent of 7dMALF
Small rivers	80 percent of 7dMALF
Large rivers	80 percent of 7dMALF

Table 1-2: Proposed allocation limits for rivers in Northland. Source: NRC Proposed Regional Plan: Appeal Version 8 December 2022. 7dMALF is 7-day mean annual low flow.

River water quantity management unit	Allocation limit
Outstanding rivers	10 percent of 7dMALF
Coastal rivers	30 percent of 7dMALF
Small rivers	40 percent of 7dMALF
Large rivers	50 percent of 7dMALF

Gisborne-Tairāwhiti also has a complex hydroclimate system and is prone to hydrological extreme events: floods and droughts. Unlike Te Tai Tokerau, Tairāwhiti has several large freshwater catchments, including the Waipaoa (2,165 km^2), Waiapu (1,730 km^2) and Motu (700 km^2). Pressures on water resources has intensified in recent decades with increased demand for irrigation, industrial use and drinking purposes in some catchments, such as the Waipaoa. Over 37 Mm^3 of water is allocated a year for irrigation for the region. There has been a 51% increase in the area consented for irrigation since 2016, with 7,120 ha consented to be irrigated, predominantly on the Poverty Bay Flats. High sediment loads are also a key feature of the region, owing mostly to soft sediment geology (GDC 2018).

The Tairāwhiti Resource Management Plan (TRMP) covers all resource management plans, including the Regional Policy Statement and Freshwater Plan. The TRMP sets out the policies for management water quantity including water allocation. Gisborne District Council (GDC) has set minimum flow conditions in water permits for several key aquatic ecosystem waterbodies (e.g., Waipaoa, Motu and Te Arai rivers) at no less than the Mean Annual Low Flow (MALF; Table 1-3). It should be noted that MALF shall be determined using a methodology approved by the GDC, but it is not currently specified where MALF should be calculated from a 7-day or 1-day running average time-series. The minimum flow conditions for all other surface water takes shall be set at no less than 90% of MALF (Table 1-3). GDC set the allocation quantity on a catchment by catchment basis, and where no allocation quantity has been set the default allocation limit of 30% of the MALF is used. There is no current "high flow allocation policy" for the region.

Table 1-3: Proposed minimum flows for rivers in in Gisborne. Source: GDC Tairāwhiti Resource Management Plan 2018.

River water quantity management unit	Minimum flow
Aquatic ecosystem waterbodies	100 percent of MALF
Other waterbodies (non-aquatic ecosystem waterbodies)	90 percent of MALF

Both NRC and GDC anticipate increased demand for taking of water at higher river flows as a consequence of the combined effects of their current water allocation policies that define water resource use limits, increasing water demand, and anticipated climate change. Although many parts of the flow regime contribute to upholding river ecosystem health, ecosystem health is particularly vulnerable during prolonged dry periods due to factors such as decreases in wetted area, decreases in habitat quality, higher temperatures, dissolved oxygen depletion, reduced fish passage, and increased nutrient concentrations. Water availability and reliability is also reduced during prolonged dry periods. High-flow harvesting and water storage has been proposed as a viable option for providing access to water for out-of-stream uses such as irrigation thereby reducing the risk of producing detrimental effects on in-stream values such as those representing ecosystem health. In theory, if high-flow harvesting is operated within sustainable limits, it could represent an option for water use that is broadly consistent with the Te Mana o te Wai hierarchy of obligations and other clauses associated with safeguarding ecosystem health laid out in the NPS-FM. The Te Mana o te Wai hierarchy of obligations prioritises the health and well-being of water bodies and freshwater ecosystems, then the health needs of people, and lastly the ability of people and communities to provide for their social, economic, and cultural well-being. However, NRC and GDC have not developed, or do not have access to guidance/tools/methods/data that are fit for the purpose of managing current and anticipated "high-flow harvesting" that may come into operation in addition to current and anticipated "run-of-river" water takes.

1.2 The importance of river flow to in-stream values

River flow has been viewed as a "maestro" (Walker et al. 1995) or "master variable" (Power et al. 1995; Poff et al. 1997) with respect to riverine ecosystems because it influences all aspects of river condition (Poff and Zimmerman 2010; Sofi et al. 2020). Various components of flow regimes combine to control or influence channel structure, sediment delivery, hydraulic conditions, disturbance regimes, food resources and water quality, including nutrient and dissolved oxygen concentrations, and water temperature (Richter et al. 1997; Poff and Zimmerman 2010; Booker and Whitehead 2022). Ecological and evolutionary processes in river ecosystems are highly influenced by historical flow regimes (Lytle and Poff 2004). In New Zealand, key aspects of stream ecology, habitat and geomorphology that are directly influenced by river flows and river flow management include periphyton, benthic invertebrates and fish communities (Biggs et al. 2008; Greenwood and Booker 2015; Booker et al. 2016). Many flow-driven aspects of cultural, recreational, and aesthetic values are intertwined with stream ecology and ecosystem health (e.g., Harmsworth et al. 2011).

1.3 Sources of information on the importance of river flow regimes

There is a wide body of international literature on relationships between flow regimes and stream ecology, a discipline often referred to as ecohydrology. The literature is very broad because interest in ecohydrology for river flow management spans many topics including hydraulics, geomorphology, stream ecology, economics, social values, and the cultural importance of rivers. An overview of fundamental issues within ecohydrology associated with setting environmental flow regimes is provided in the book by Falkenmark and Rockström (2004). Many fundamental issues are covered in informative papers by Poff and Zimmerman (2010) on flow-ecology relationships, Arthington et al. (2018) on challenges for environmental flow science and management, Acreman et al. (2014) on managing highly altered river systems, and Bertassello et al. (2021) on linking ecohydrology to sociohydrology. Recent international reviews are provided by Sun et al. (2017) in relation to human altered river systems, and Lapides et al. (2022) in relation to streamflow depletion resulting from alteration of groundwater systems. Olden et al. (2012) also provides a useful discussion of many pertinent issues relating to flow regime characterisation for ecohydrological purposes. However, it should be noted that internationally accepted ecohydrological methods and nature-based solutions for river flow management or environmental flow setting do not exist. Lack of widely accepted solutions is partly because water-resource challenges require advances in the science of ecohydrology, and because current understanding is limited by a shortage of observational data and theories that synthesize complex processes across scales ranging from sub-millimetre to tens of kilometres (Guswa et al. 2020).

Booker et al. (2022a) provide an overview of links between river flow regimes and in-stream ecological conditions in the New Zealand context. Stoffels et al. (2022) provide details about the possible in-stream effects of reducing low flows, and propose methods that could be deployed under a nationally-coordinated strategy for monitoring and evaluating of these effects.

An accompanying literature review to this report provides details of the importance of river flow regimes for various aspect of stream ecology and cultural values in the New Zealand context (Hickford et al. 2023). Hickford et al. (2023) stated that in many cases it is possible to make conceptual links between high-flow harvesting and in-stream values but noted that it is very difficult to test hypotheses about flow-ecology relationships for any part of the flow regime in the absence of appropriate datasets, or the controlled experiments required to parameterise and test predictive models. Consequently, quantifying the impact of high-flow harvesting on in-stream values remains difficult and will depend on improved understanding of several interacting factors such as the size of the river, the characteristics of the flow regime, the size of the water storage, the level of water demand, and the nature of in-stream values.

1.4 Definition of high-flow harvesting and why it is different to run-of-river water takes

For the purposes of this work, run-of-river water takes are defined in general terms as those where the water is taken from the natural environment at relatively low flows in rivers or relatively low groundwater levels in unconfined shallow aquifers, transported to the location of use, and then used immediately. Under this definition, run-of-river takes include surface water taken from rivers, lakes, or wetlands. Run-of-river takes can also be thought of as including groundwater takes from shallow aquifers, although it should be noted that groundwater takes differ from surface water takes because they will have a delayed impact on river flows, and there can be uncertainty about the magnitude of their streamflow-depleting effects due to the complexities of groundwater-surface water interactions (Valerio et al. 2010). High-flow harvesting takes are defined in general terms as those where water is taken from the natural environment, generally during times of relatively high river flows or groundwater levels, stored temporarily, and then used later. Although flow harvesting generally applies to takes at higher flows, takes at lower flows could also fall under the same general definition if water is taken and stored for later use. Run-of-river water takes are likely to take water at a lower rate for more prolonged periods in comparison to high-flow water harvesting takes, given the same overall water demand. Because water taken under high-flow harvesting does not have to be used immediately it is possible to take water for shorter periods but at a higher instantaneous rate of take compared to run-of-river water takes. These definitions and the reasoning set out in Table 1-4 apply regardless of river size, position in the landscape, or precise operation of either run-of-river or high-flow harvesting takes. Given the above definitions and the same overall level of water demand, high-flow harvesting would be expected to differ with run-of-river water takes for several reasons (Table 1-4).

Table 1-4: Contrasts between high-flow harvesting and run-of-river water takes.

Issue	Run-of-river	High-flow harvesting
Operational controls	Timing of take is controlled by a cease-to-take condition that allows water to be taken at all times except during periods of relatively low flows or groundwater levels. Rate of take is controlled by a maximum rate of take which allows water to be taken at a relatively low rate.	Timing of take is controlled by a cease-to-take condition that allows water to be taken only during periods of relatively higher flows or groundwater levels. Rate of take is controlled by a maximum rate of take which allows water to be taken at a relatively high rate.
Possibly hydrological effects	Reduction of low to medium parts of the hydrograph for prolonged periods of time during period of high demand.	Reduction of medium to higher parts of the hydrograph at any time of year independent of immediate water demands and are therefore likely to have different environmental effects compared with run-of-river water takes.
Possible environmental considerations	Decreases in wetted area, decreases in habitat quality, higher temperatures, dissolved oxygen depletion, reduced fish passage, increased nutrient concentrations, etc.	Changes in river sediment transport and deposition, reduce removal of nuisance algae, alteration of fish migration cues, etc.
Physical infrastructure	Requires physical infrastructure for taking water from the environment and transporting water to location of use.	Requires additional physical infrastructure for water storage and sediment deposition, in comparison to run-of-river takes, because high-flow harvesting involves take and storage of water (possibly sediment-laden), followed by temporary storage of water, followed by later distribution and use.
Physical limitations for taking water	Water availability at location of take. Maximum rate at which the water can be used.	Maximum rate at which water can be taken from the natural environment, transported to and discharged to the storage. Maximum capacity of the storage. Consideration of suspended sediment load during high flows because high sediment loads may damage equipment and increase requirement for maintenance and clog ponds/canals etc.
Water losses and water use efficiency	Potential losses when transporting water from point of take to point of use mitigated by use of partially or fully piped networks which reduce water loss and pumping costs if actively maintained.	Potential losses when transporting water from point of take to storage and then point of use mitigated by use of partially or fully piped networks which reduce water loss and pumping costs if actively maintained. Additional losses due to leakage from storage and evaporation from storage

Issue	Run-of-river	High-flow harvesting
Possibility of enhancement of baseflows	In the case of irrigation, river flow augmentation would only occur if the water is being used inefficiently. Inefficiently irrigation practices are not a management option under the NPS-FM requirement for efficient water use.	Offers the possibility of return of some water to the river to enhance baseflows, but the environmental benefits or using stored water to enhance baseflow must consider the relative size of the storage compared to river flows, and the detrimental effects on the ability to meet water demand.

It should be noted that it is very difficult to test hypotheses about flow-ecology relationships for any part of the flow regime in the absence of appropriate datasets or controlled experiments (Stoffels et al. 2022). Furthermore, “high flow” and “low flow” are relative terms, with limited practical meaning for river flow management purposes unless they are quantified and translated into water allocation rules or consent conditions. However, one reason for utilising high-flow harvesting rather than run-of-river takes is to limit hydrological alteration to parts of flow regimes that are hypothesised as being functionally redundant from a physical, chemical, or ecological perspective, and thereby reduce demand for lower river flows that are hypothesised as being important for sustaining ecosystem health and other in-stream values. A second reason for harvesting high flows is because it represents a small proportional of water in the channel at the time, and therefore is likely to have a smaller adverse effect on ecosystem health. In theory, as flow decreases, the take required to meet water demand is likely to have increasingly disproportional negative effect on relative flow and ecosystem health. A further rationale for utilising high-flow harvesting is to allow for increased water take during periods of excess availability, in situations where the low flow part of the hydrograph is fully allocated according to water allocation rules in regional plans or best available information about impacts of run-of-river takes on in-stream values.

At the time of writing, various forms of allowable water take limits that relate to low/baseflow conditions are in place for nearly all Freshwater Management Units (FMUs) across the country (e.g., cease-to-take below a flow of 90% of MALF and total allocations of 30% of MALF). From an operational perspective, over-allocation can be defined as a situation where water use from consented and estimated permitted activities exceeds that which is allowable under the plan limits. It should therefore be possible to calculate over-allocation for each location where plan limits have been specified. It should be noted that overallocation can be defined from the perspective of environmental outcomes in addition to being defined from an operational perspective.

In situations where plan limits have been set with respect to low/baseflow conditions, but not according to high-flow conditions or flow variability, an operational definition of high-flow harvesting could be derived from the plan cease-to-take flow and total allocation with respect to low/baseflow. For example, “relatively high flows in rivers” within the definition of high-flow harvesting could be modified to equate to flows that are greater than the cease-to-take flow plus the total allocation rate plus a rate of flow that would allow for flow variability plus some margin for uncertainty.

Allowing some flexibility in the interpretation of definitions of “run-of-river takes” and “high-flow harvesting” would be beneficial because use of these terms with respect to a particular regional plan would have to fit with the context and development of that plan, including the wishes of tangata whenua and the community identified through consultation processes, target attributes states and desired environmental flow regimes. The definitions provided above therefore represent a starting point for planning and operation of water takes. However, flexibility within the definitions means that many takes could be described as fitting somewhere along a continuum between run-of-river takes and high-flow harvesting depending on interpretation of the definitions. More technical clarifications are therefore needed if takes are to be classified as being either run-of-river or high-flow harvesting, which are then treated differently within operational planning and consenting processes in terms of when water can be taken and how much water can be taken. Below we provide further commentary and some examples of technical clarifications of parts of the proposed definition of high-flow harvesting that would need to be established for operational use to provide the necessary precision. We emphasise that these technical clarifications should be adapted to fit within specific regional planning processes:

1. The phrase "relatively high flows in rivers" should be quantitatively defined as a flow threshold. For example, flows that are greater than the best available estimate of a specified flow statistic such as the naturalised long-term median flow, a multiple of the median flow, or a position on the flow duration curve (FDC). In this case, naturalised refers to flows estimated in the absence of abstractions, dams, or diversions, but with current landcover patterns (Booker et al. 2022a).
2. The phrase "relatively high groundwater levels in unconfined shallow aquifers" should be quantitatively defined as a groundwater level or related to a rate of aquifer recharge. For example, a level that is greater than the best available estimate of a specified groundwater level statistic, such as the long-term median groundwater level, or a mean annual recharge over the last five years, is greater than a threshold value that is deemed to ensure sustainable groundwater use.
3. The phrase "stored temporarily" refers to water held in an engineered structure that is designed for water storage, such as a storage pond, rather than infrastructure that is designed for transporting water such as pipes or raceways.
4. The word "used" in "used immediately" and "used later" relates to the final intended use of the water such as use for irrigation, or industrial or domestic purposes.
5. The phrase "used immediately" indicates there is no requirement to store water before it is used. Water that is "used immediately" is transported from the point of take to the point of use without the presence of an intermediate water storage device, and water is typically used within the same day it is taken from the natural environment
6. The phrase "used later" relates to the need to store water before it is used. Water that is "used later" is not used immediately after it has been taken from the point of take because it has been temporarily held in some form of intermediate water storage device. Water that is "used later" is typically used some time after the day that it is taken from the natural environment, although there may be exceptions in cases where water is transported very long distances.

The phrase "relatively high flows in rivers" is the most important part of the definition of high-flow harvesting because it directly relates to the river conditions when river flows would be impacted by high-flow harvesting, as well as water availability under those conditions.

1.5 Overarching requirements for a successful water allocation system

Several international studies have proposed overarching requirements for development and implementation of successful water allocation systems as outlined in Table 1-5 (Grafton et al. 2011; Speed et al. 2011; Maestu and Gómez 2012; Wheeler et al. 2017). Assessment of potential environmental and economic advantages should, in theory, provide the imperative for implementing a particular water management strategy. An allocation framework must then be devised and agreed by the appropriate stakeholders, institutions, and government. The framework must consider the complete hydrological management unit, including groundwater-surface water interactions (Hirji and Davis 2009). Institutional arrangements must be assessed, along with operational requirements, and the framework must be implemented into law. Consequently, effective implementation of a successful water allocation system would require six criteria to be considered. Booker et al. (2022b) provide a detailed description of these criteria and how they might relate to river flow management in the New Zealand context.

Table 1-5: Six criteria for effective implementation of a successful water allocation system. Outline by Booker et al. (2022b) and after Grafton et al. (2011); Speed et al. (2011), Maestu and Gómez (2013), Wheeler et al. (2017). See references within Booker et al. (2022b) for further details.

Criteria	Description
1. Hydrology	Hydrological conditions should be well understood and supportive of the implemented water system. Physical infrastructure may be required to move and store water in order to provide access to water resources.
2. Legislation	Well-defined property rights are needed to influence behaviour and to ensure efficient resource use. Water rights therefore need to have: a) legal clarity of definition; b) certainty of recognition (water regulators must be legitimate and trustworthy); and c) security of tenure (rights should be renewable and not be superseded by a new superior right and/or without consideration within a transparent process).
3. Regulation	Well-defined water rights should be complemented by clear and certain water use rules. Operational rules for water abstraction should clearly define when, where and how water is consumed.
4. Information	The regulatory authority should therefore provide access to consistent data on existing rights and allocations to the public. The regulatory authority should also report on the availability and potential scarcity of water resources, with on-going and effective monitoring of hydrological conditions, alteration, and the environmental effects of flow management on various elements of ecosystem health. Technical specifications for data collection, collation, quality assurance and frequency and modes of communication of information are required.
5. Management	A regulatory authority should be accountable for indirect effects such as water quality. Lack of monitoring and enforcement of water take rules could undermine water allocation systems – water users may overcome scarcity by exceeding their legal allocations.
6. Engagement	There should be community engagement and agreement when devising a new allocation framework in order to recognise the importance of cultural values or to respond to negative perceptions. When transitioning between water allocation systems, community support is key to overcoming issues of redistribution and equity.

1.6 The scope for this work

Regional Councils, through AIA, are seeking general guidance, technical advice on choice of methods, and access to tools that are fit for the purpose of planning for potential high-flow harvesting to supplement their current and anticipated run-of-river water takes. Ideally, guidance, methods, or tools relating to high-flow harvesting should be consistent with the general principles of the NPS-FM, particularly requirements that relate to the following.

- Setting environmental outcomes, including environmental outcomes as objectives in regional plans.
- Identifying attributes for each value, including setting baseline and target states for each attribute.
- Defining environmental flow regimes.

- Setting limits to water resource use as rules in regional plans that should deliver environmental flow regimes.
- Preparing actions plans to achieve environmental outcomes.

This work is intended to provide advice about the potential impacts of high-flow harvesting on in-stream values (see Hickford et al. 2023) and inform environmental planning and management processes (e.g., consenting and compliance) relating to anticipated demands for future high-flow harvesting. Guidance on the topic of setting limits as rules, calculating over/under-allocation and consenting in relation to high-flow harvesting activities are in scope. Recommendations about how to improve tools/methods/data that allow effective environmental planning and management processes relating to high-flow harvesting are in scope.

1.7 Out of scope for this work

The scope of this work was limited to consideration of general principles and advice. This work does not include any direct assistance to AIA, NRC, GDC or any other regional councils to undertake assessment of the effects of specific water take schemes, or direct engagement with water stakeholders or iwi partners.

This work provides information in the context of the Northland and Gisborne regions and the particular requirements of NRC, GDC, and AIA staff. The guidance, advice and methods developed here may be transferable to other regions in similar settings and needs. However, the requirement for transferability of the findings to regions other than Northland and Gisborne was not explicitly addressed as part of this project because it was out of scope.

Collection of new data was outside of the scope of this work. The work was therefore constrained to utilise existing data and information. Use of existing data, and use of models to estimate likely effects and to demonstrate principles with respect to the effects of high-flow harvesting is in line with NPS-FM requirement to use the best information available when setting water resource use limits in order to deliver environmental flow regimes as defined and described in further detail in the river flow management framework proposed by Booker et al. (2022a).

Issues relating to large in-river river impoundments (i.e., dams across rivers) are out of scope for this work. The work relates to planning for multiple off-river water storages rather than larger in-river dams, where consideration of residual flow releases for the purposes of river baseflow enhancement might apply.

Economic aspects and considerations are not in scope for this project. This work does not consider building costs, operation costs, or the economic benefits of water storages.

1.8 Overall aim

The overall aim of this work was to assist regional councils, exemplified by NRC and GDC, by providing improved guidance, methods and tools in areas that feed into the water resource use, limit setting process related to high-flow harvesting and water storage. This work is intended to improve NRC and GDC’s understanding of how to best manage anticipated high-flow harvesting to deliver economic and societal benefits within environmentally sustainable limits as required under the NPS-FM and RMA, whilst also recognising data availability limitations and uncertainties inherent in predicting the effects of high-flow harvesting on biophysical systems. One important question for this work is: does high-flow harvesting require different types of rules in regional plans and different types of consent conditions compared to run-of-river water takes in order to provide clarity about water availability for users whilst giving effect to the various requirements of the NPS-FM and RMA such as considering long-term visions and safeguarding ecosystem health?

2 Methods

2.1 Overall strategy

We applied an overall strategy that borrowed from cross-disciplinary work which often uses “principles” and “heuristics” to guide design and planning (Lidwell et al. 2010). In this context principles are a succinct way to translate experience and research into a piece of knowledge that is relatively stable to use and re-use. Heuristics relate to a principle and are also known as rules-of-thumb. Heuristics describe specific actions whereby principles are applied. Heuristics are not rules because they should be fit for a broad range of situations, and they are not guaranteed to apply to all circumstances. The decision-making process must identify what is a good heuristic for a particular situation, and which heuristics best align with a principle within a given context.

Our overall strategy was to devise and apply analyses to provide insight about how water allocation and consenting for both high-flow harvesting and run-of-river takes could operate to be consistent with the NPS-FM. Our strategy involved the following four steps designed to guide the process of devising water allocation rules in regional plans that include high-flow harvesting, and making consent conditions that fit with these rules.

1. First, we proposed some principles relating to water use that are intended to aid water resource management with respect to high-flow harvesting (see Section 2.2). We see these principles as giving effect to the NPS-FM in general, and being guided by the principles of Te Mana o te Wai described in Clause 1.3 (particularly Clause 1.3.4.d–f) of the NPS-FM.

2. Second, we proposed some heuristics (rules of thumb) that describe details about actions which would be required to apply the principles. We see these heuristics as being consistent with, and being guided by, various clauses of the NPS-FM that relate to the planning, management, and operation of water storages as described in Section 1 of this report.

3. Third, we proposed several numerical analyses designed to demonstrate how high-flow harvesting could operate and be assessed in light of our pre-defined heuristics. Each analysis proposed was designed to demonstrate the effects of changes in water use operations (e.g., placement of take, and application of cease-to-take restrictions, maximum rates of water take, maximum storage capacity, etc.) on river flows and water supply. We then applied some of our proposed analyses to demonstrate the utility of our heuristics by quantifying the consequences of idealised water take operations on river flows and on water supply.

4. Fourth, we summarised the findings of our analyses to explore options for planning and consenting with respect to water storages. We proposed a form of water allocation rules that could be used as a basis for setting rules in regional plans. More importantly, we demonstrate how principles, heuristics and analysis could be applied to assist the process of developing water allocation relevant to joint operation of run-of-river takes and flow harvesting.

We devised a method for representing idealised operation of various combinations of run-of-river and high-flow harvesting water takes across a catchment to help us demonstrate and assess our four-step process. A full technical description of the inputs, algorithms and outputs used to apply our analysis is provided in Sections 2.3–2.7 below. The method served two specific purposes for our work.

1. To assist us in translating hypothetical concepts about water allocation and consenting for high-flow harvesting and run-of-river takes into formalised operational algorithms.
2. To explore the potential effects of different water allocation and consenting scenarios on river flows and water availability within a simulated hypothetical setting.

2.2 Principles and heuristics for high-flow harvesting

We propose principles as generalised statements to inform water allocation and consenting in relation to water storages. Whilst these principles were intended to assist the regional planning processes, they are proposed from a physical sciences perspective (e.g., hydrology, ecohydrology, ecology, geomorphology) rather than a legal, economic, cultural, or purely planning perspective.

Regional councils are required by the NPS-FM to engage with communities and tangata whenua to determine how Te Mana o te Wai applies to water bodies and freshwater ecosystems in the region. We recognise that NPS-FM Clause 1.3.4.a–c specifically relates to involvement of tangata whenua (via Mana whakahaere, Kaitiakitanga, and Manaakitanga) in the management of freshwater. The processes used for engagement are not in scope of this work, but we recommend that regional councils engage with communities and tangata whenua to seek suggestions about further development of our proposed principles, as would be consistent with NPS-FM Clause 3.2.1.

We considered that the principles should follow on from NPS-FM Clause 1.3.4.d-f and be consistent with implementation of relevant clauses of the NPS-FM, recent MfE guidance on river flow management (Booker et al. 2022a), and the accompanying literature review on the possible effects of high-flow harvesting conducted as part of this work (Hickford et al. 2023). The following considerations were therefore particularly important when formulating our proposed principles.

<u>Parts of the NPS-FM particularly relevant to flow harvesting</u>

- Principles should follow on from the six principles of NPS-FM Te Mana o te Wai, particularly Clause 1.3.4.d–f about governance, stewardship, and care and respect.
- Principles should be consistent with the three-level hierarchy of obligations of the NPS-FM Te Mana o te Wai (Clause 1.3.5), which states that priority (for water use in relation to water quantity) should be given as follows:
  - first to the health and well-being of water bodies and freshwater ecosystems;
  - second to the health needs of people (such as drinking water); and
  - third to the ability of people and communities to provide for their social, economic, and cultural well-being, now and in the future.
- Principles should be consistent with NPS-FM Appendix 1A.1 which requires for a healthy freshwater ecosystem, that all five biophysical components (water quality, water quantity, habitat, aquatic life, ecological processes) are suitable to sustain the indigenous aquatic life expected in the absence of human disturbance or alteration (before providing for other values).

Ecosystem health considerations following on from the NPS-FM

- Principles should be consistent with current MfE guidance on river flow management (Booker et al. 2022a) which recommends application of a framework that includes steps in which:
  - desired flow regime state (as known as environmental flow regimes) are devised to support in-stream attributes states aligned with stated long-term visions; and
  - desired in-stream states and flow regime states are described qualitatively or, ideally, quantitatively (e.g., in-stream attributes states are ideally represented by measurable objectives) where sufficient data and supporting models are available.
- Principles should be consistent with operation of water takes that are cognisant of potential risks to river ecosystem health as indicated by the literature review conducted as part of this work. For example, whilst all types of water takes should consider impacts on low flows, high-flow harvesting should also:
  - have a predictable effect on mid-range flows such that altered river flows can be compared to predefined environmental flow regimes and therefore assessed for their influence on in-stream values (e.g., nuisance periphyton growth, increased deposition of fine sediment); and
  - not reduce the magnitude or frequency of channel-forming flows that influence river habitat, physical structure, and natural character.

Six criteria for effective implementation of successful water allocation systems as suggested in the international literature (see Table 1-5 for further details)

- Hydrology; hydrological conditions should be well understood and this understanding should support the implemented water system.
- Legislation; principles should help create rules and consents that provide:
  - legal clarity of definition;
  - certainty of recognition (water regulators must be legitimate and trustworthy such that water users do not have their right to access water revoked without explanation or consideration in a transparent process); and
  - security of tenure (water users must know for how long they will have access to water).
- Regulation; principles should help create clear and certain water use rules with well-defined conditions that quantitatively describe access to water for current and potential future users.
- Information; principles should help create rules that allow potential future water users to assess future water availability, and consents conditions that allow current water users to assess their (day-to-day) access to water using reliable and timely information.
- Management; principles should help create rules in plans, and consents conditions that can be monitored and enforced.

- Engagement; community engagement and agreement when devising a new allocation framework should help recognise the importance of cultural values and mitigate potential negative social perceptions.

Table 2-1: Proposed principles, heuristics and quantitative analysis relating to planning and consenting of water use generally and high-flow harvesting in particular.

Issue: what issues prompt the principle?	Principle (piece of knowledge): what should happen?	Heuristic (ways to apply the principle): what needs to happen to apply what should happen?	Analysis (demonstrate quantitatively how the heuristic can be applied): assess whether what should happen can happen?	Rules in regional plans (demonstrate how heuristic could be used within rules of thumb): how could rules in plans and consent conditions be set to influence what might actually happen?
Water allocation systems need to be functional. Criteria for functional water allocation systems mentioned above relating to legislation, regulation, information, management, and engagement are all consistent with water allocation systems that are functional to implement. In order to be effectively operationalised, rules in plans and consent conditions that align to them must be clearly defined so that they can be interpreted, adhered to, monitored, and enforced. This is important because investment in water use infrastructure would be compromised if not enough water is available to be used.	Be clear about how much water is available for current and potential future water users. Rules in plans about water storage (and also run-of-river takes) should clearly describe "total allocatable water", to provide clarity for potential future water users. Consent conditions should be aligned with rules in plans. Consent conditions should be practical to communicate and enforce by the administering authority. Consent conditions should be practical to implement, adhere to, and monitor for the water user.	**Practically implementable** Use rules and consent conditions that are practical and implementable. Rules in plans about water storage (and also run-of-river takes) need to describe limits on water allocation quantitatively (rather than qualitatively) and be shown against current levels of water allocation so that potential future water users can calculate water availability. Allowable rate of take for each water user needs to be either: a) calculatable from the information available to the user at the time; or b) calculated and communicated to the user by the administering authority (council) in a timeframe in line with the consent conditions (e.g., daily).	Consent conditions that are practical and implementable (because they have been devised to align with a functional set of rules) should be defined numerically, and therefore should be able to be simulated within an idealised environment such as that represented in Figure 2-2. If water availability cannot be quantified for a given set of consent conditions, then this indicates that those conditions will be difficult to operationalise. If water allocation cannot be calculated from rules in plans, then this indicates that those rules will not be functional. This principle can be assessed by testing that rules and consent conditions can be applied within an idealised experiment.	See a proposed method laid out in Section 2.6.1.

Issue: what issues prompt the principle?	Principle (piece of knowledge): what should happen?	Heuristic (ways to apply the principle): what needs to happen to apply what should happen?	Analysis (demonstrate quantitatively how the heuristic can be applied): assess whether what should happen can happen?	Rules in regional plans (demonstrate how heuristic could be used within rules of thumb): how could rules in plans and consent conditions be set to influence what might actually happen?
Sustain ecosystem health by delivering environmental flows. NPS-FM and current river flow management guidance dictates that ecosystem health should be sustained by identifying environmental flow regimes that are delivered through limits on water use (take limits). However, defining environmental flow regimes is difficult and uncertain because various aspects of river flow regimes are likely to be important for maintaining river ecosystem health, but the relative importance of different parts of the flow regime and the trade-off between their degree of alteration and risk to ecosystem health is not known precisely and is likely to vary across the landscape. Furthermore, the degree to which a set of take limits can deliver predefined environmental flows is uncertain.	Hydrological impacts of allowable water use should be predictable and deliver environmental flow regimes. Environmental flow regimes required to sustain ecosystem health in a manner that is consistent with the NPS-FM should be defined before setting take limits. Rules in regional plans should not allow river flows to be altered by more than what is predefined by environmental flow regimes. Rules in regional plans should be associated with predictable levels of alteration to river flows (whilst accepting associated uncertainties) so that altered river flows can be compared with unaltered (naturalised) river flows and/or environmental flow regimes.	**Environmentally sustainable** Assess delivery of environmental flows by take limits. Streamflow depletion arising from water use allowed by rules in plans (and additional permitted water use activities where these can be estimated) needs to be calculated. Option 1: calculate daily time-series of streamflow depletion. Option 2: calculate changes to hydrological metrics representing ecologically-relevant and geomorphologically-relevant parts of the flow regime, for example drought conditions (low flow magnitude and duration), flushing flows (mid-range event magnitude and frequency), flow seasonality (magnitude of median summer flows), and channel forming flows (high flow magnitude and frequency).	Demonstrate how predictable changes to river flows can be calculated from different consent conditions by independently altering the cease-to-take flow and the allowable instantaneous rate of take for: a run-of-river take; and a high-flow harvesting take with infinite storage. Repeat using measured river flows from at least two different sites as control flows to demonstrate between-site differences in outcomes. This experiment is about temporal changes in flows rather than spatial impacts, therefore the take is assumed to be near to river flow measurement. See Analysis 2 for separate investigation of spatial issues.	State water resource use limits that align with a predefined level of allowable alteration to a river flow regime. For example, an allowable change in daily flow of less than 10% would be in-line with a "high level of protection" and a 11-20% change would be in-line with the "moderate level of protection" category of the presumptive standard proposed by Richter et al. (2012). Alternatively, predefined allowable changes to a subset of hydrological metrics (e.g., days below the flow that is exceeded 90% of the time, the frequency of events that exceed three times the median flow, median flow in February, days above the flow that is exceeded 10% of the time) could be proposed. Derive rules in regional plans that would limit flow alteration to be within the predefined allowable limit.

Issue: what issues prompt the principle?	Principle (piece of knowledge): what should happen?	Heuristic (ways to apply the principle): what needs to happen to apply what should happen?	Analysis (demonstrate quantitatively how the heuristic can be applied): assess whether what should happen can happen?	Rules in regional plans (demonstrate how heuristic could be used within rules of thumb): how could rules in plans and consent conditions be set to influence what might actually happen?
Use water efficiently. The NPS-FM acknowledges that water use is important for human health, societal, and economic purposes. The NPS-FM requires regional plans to include criteria for improving and maximising the efficient allocation of water (which includes economic, technical, and dynamic efficiency).	Don't give access to more water than is needed for efficient use. High-flow harvesting (water storage) should be encouraged over run-of-river takes where it can deliver environmental flow regimes and is also likely to increase reliability of supply and reduce environmental impact. Water storage should be encouraged if it can be used to maintain low flows at natural levels whilst altering other parts of the flow regime in a predictable way. Reduction of leakage from water storages should be encouraged to obtain efficient water use.	**Water efficient** Ensure water allocation does not exceed reasonable water demand. Water availability under allocation rules needs to be no greater than reasonable water demand, where reasonable water demand is the supply required to gain acceptable conditions (e.g., supply to maintain soil moisture within a range that is considered acceptable for crop production).	For a given irrigated area, calculate water supply needed to meet reasonable water demand by calculating efficient supply under unlimited water availability. Calculate what combination of storage capacity, cease-to-take, and allowable rate of take would match (or come within a given percentage e.g., 95% of the total irrigated area) water availability required to meet reasonable demand. Alternatively, calculate a summary statistic of the daily water demand time-series (e.g., its sum) to represent water availability required to meet demand.	Maximum allowable rate for a user should be linked to the demand (e.g., maximum allowable rate ($m^3\ s^{-1}$) harvested is equivalent to 1.5 times the maximum daily demand ($m^3\ s^{-1}$). Alternatively, maximum total volume allowed to be taken by a user should be linked to the total maximum demand. For example, this can be achieved through two approaches explained below*).

Issue: what issues prompt the principle?	Principle (piece of knowledge): what should happen?	Heuristic (ways to apply the principle): what needs to happen to apply what should happen?	Analysis (demonstrate quantitatively how the heuristic can be applied): assess whether what should happen can happen?	Rules in regional plans (demonstrate how heuristic could be used within rules of thumb): how could rules in plans and consent conditions be set to influence what might actually happen?
Consideration of spatial issues. River catchments are made up of a spatial hierarchy in which upstream activities cumulatively influence downstream conditions because many smaller tributaries flow into larger rivers. However, practical considerations mean that restrictions on taking water are often assessed and applied at a single point (e.g., a downstream gauging station).	Consider local and catchment-wide hydrological consequences of water use. Rules in regional plans should recognise that the largest hydrological impacts of a single take are proximal to that take, but the largest hydrological impacts of many takes can be distal from those takes because impacts can accumulate in space. The potential impact of additional upstream takes (e.g., water storages) on water supply to existing and potential downstream water takes should also be considered.	**Spatially consistent** Map the hydrological effects of water allocation. Hydrological and water supply impacts of takes needs to be assessed locally at the point of each take and across a broader spatial scale (catchment-wide or at critical points such as critical reaches for habitat) for the collective operation of multiple takes.	Repeat analysis described in the above row but move takes sequentially upstream away from a fixed control point and estimate the effect on flow regime and reliability of supply (Analysis 2a). Sequentially add more takes at random upstream locations and calculate the spatial patterns of hydrological impacts (Analysis 2b); where in the catchment does the largest hydrological impact occur?	Use transferable and scalable rules. Design rules to deliver a predefined level of allowable alteration to be scaled across a catchment by linking allowable water use to conditions that are known across catchments such as upstream catchment area, estimated mean flow, or estimated median flow.

* Further options for rules in plans that might fulfil the principle about efficient use of water are as follows:

1. Reasonable water use to meet the demand - generally, it is unrealistic, uneconomical, and poor use of the resource to fully meet demands 100% of the time. To recognise that water demand cannot be met 100% of the time for irrigation, we propose using the following criteria to determine reasonable irrigation water demand, which are used by Waikato RC (Rajanayaka et al. 2016):

   - 90% of time soil moisture should be above 50% of plant available water (PAW)
   - 99% of time soil moisture should be above 25% of PAW.

2. Reliability of supply from storage to meet demand – as above, developing a storage to supply water to meet demands 100% of time can be poor use of the catchment resources. To recognise that water demand cannot be met 100% of the time, we propose using the following storage capacity criteria to meet reasonable demands, which was used in the 'Scoping of Irrigation Scheme Options in Northland' (Frost et al. 2015):

- Mean annual and irrigation season average supply-demand ratio to be greater than 95%; and
- Periods of restrictions exceeding 10 consecutive days will occur in no more than 10% of the irrigation seasons modelled.

2.3 Representing water allocation and consent conditions

We devised a method to investigate how hypothetical water allocation rules and consent conditions might be configured to control run-of-river and high-flow harvesting operations to alter both water availability and streamflow conditions. We envisaged a flexible method for analysing various scenarios of water allocation rules and consent conditions. The method was therefore designed to represent water availability, water demands, water use, and hydrological impacts of water use as depicted in Figure 2-1. The method represented various entities (Table 2-2), relations between entities, and settings that could be altered to represent a range of water allocation rules and consent conditions. Entities, relations between entities, and settings were used to calculate resulting states representing water demand, water availability, soil water content, and river flows. River flows and climate conditions represented environmental inputs to the method. Inputs to the method that could be altered included details about water storage (maximum capacity, maximum fill rate, leakage, etc.), consent conditions (placement of take, maximum rates of water take, irrigated area), land conditions (soil characteristics that influence water demand, timing of irrigation season), and control conditions (cease-to-take restrictions on water take, position of control points). Calculated output states included the consequences of interactions between hypothetical operation of water takes, environmental constraints, river flows, and spatial aspects to influence water supply and impact hydrological impacts.

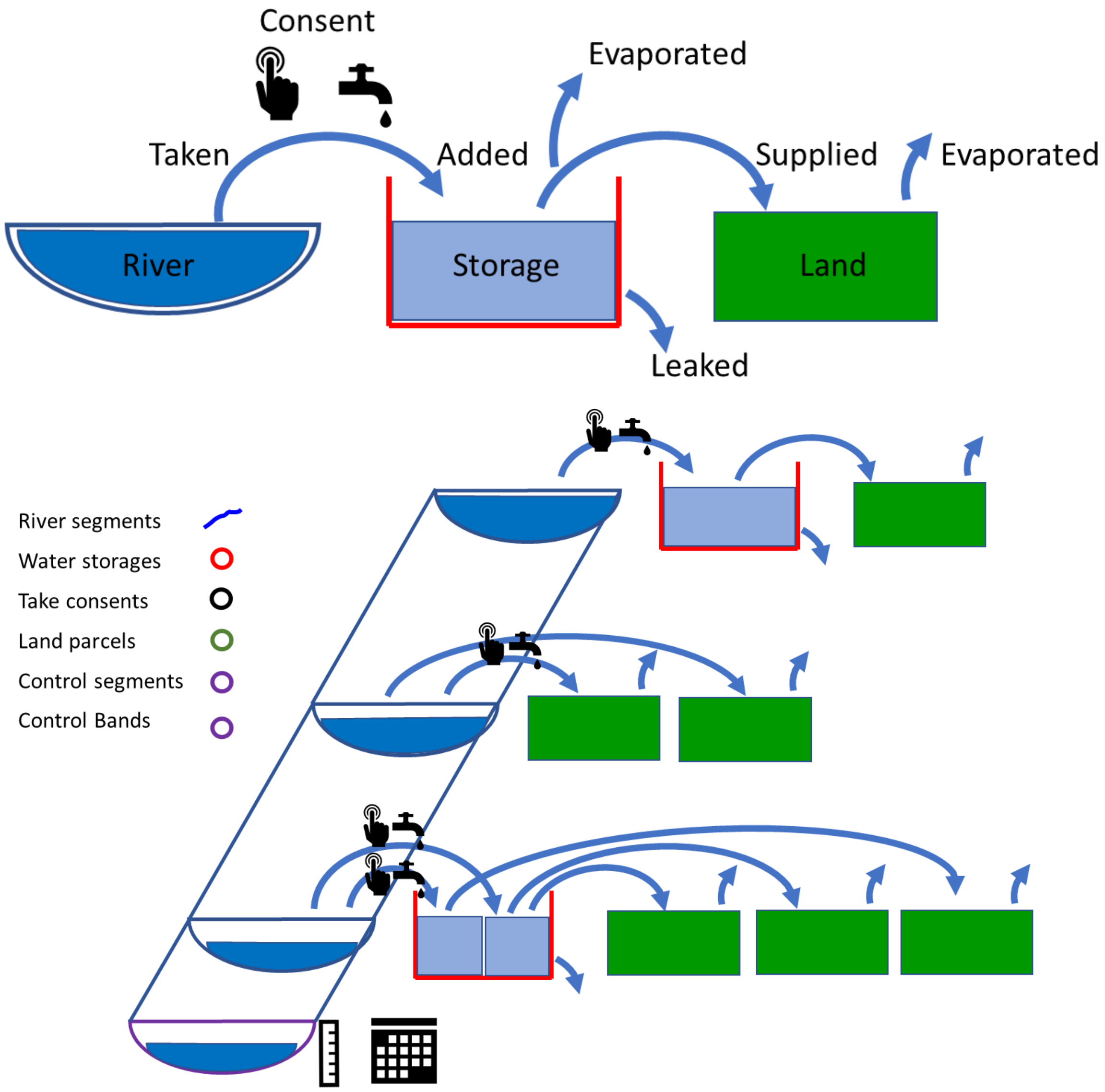

Figure 2-1: Diagrammatical representation of a method for representing water storages. Top: water fluxes between entities (river, storage, and land). Bottom: a possible configuration of run-of-river or high-flow harvesting takes, supply of water from one consent to multiple land parcels, and sharing of storage between water users. Colours shown in legend refer to colours of different depicted entities.

Table 2-2: Entities used to represent water allocation rules and consent conditions.

Entity	Description
Segments	Parts of a river which inter-connect to collectively represent a river network including upstream-downstream connectivity. River flows at segments where consents are located determine local water availability.
Consents	Instruments that define where, when and at what rate taking of water is allowed.
Storages	Facilities to store water that can be filled by consented water takes and subsequently emptied to meet water demands. These are off-river water storages rather than in-river dams.
Land parcels	Areas of land to be irrigated for which water demands can be calculated. Non-irrigation water uses that take water at a constant rate can also be represented (as might represent takes for industrial or domestic purposes).
Control points	Locations on the river network where local river flow conditions determine temporal restrictions applied to takes. In reality, control points are often streamflow gauging stations.
Bands	Flow thresholds that determine whether consented takes must cease to take, are partially restricted, or can take at the maximum allowable rate of take.

The remainder of this section describes a set statements and descriptions used within our method to emulate hypothetical water allocation rules and consent conditions.

Relationships between entities described in Table 2-2 and depicted in Figure 2-1:

- Each consent is associated with a river segment from which water is taken.
- Each consent is associated with at least one set of consent conditions.
- Each set of consent conditions is associated with a band.
- Each band is associated with a control point.
- Each control point is located on a river segment.
- Following the previous three statements, each consent is associated with one or more bands, and each set of consent conditions is controlled by conditions at a control point.
- Each consent is associated with either no storage (for run-of-river takes) or one storage. A consent cannot be associated with more than one storage.
- Each storage is associated with one or more consents.
- Each consent is associated with either no land (for a non-irrigation take with constant water demand), one land parcel, or more than one land parcel.

Input driving time-series:

- Each river segment at or downstream of all take and control points has a streamflow time-series.
- Each land parcel has a potential evapotranspiration time-series and a rainfall time-series.

Operation of consents:

- Each consent can take water from one river segment.
- For each consent, water cannot be taken at a rate greater than the local river flow rate.
- Each consent cannot take any water when local flow is above a specified rate (as might be the case when a flood flow is occurring) unless this specified rate is set to be infinity.
- All consents are active across the analysed time-series because consents do not commence or expire within each analysis.
- Streamflow depletion resulting from takes is calculated in the order in which consents are entered into the calculations.
- Streamflow depletion resulting from takes alters river flow rate by the same amount for all reaches downstream of each take within the calculation time step.
- Each consent is either for irrigation purposes or non-irrigation purposes.
  - Each consent for irrigation purposes has an irrigated area which is used together with soil characteristics at land parcels associated with the consent to calculate overall water demand for the consent.
  - Each consent for non-irrigation purposes takes water at a constant rate and does not have an irrigated area (as indicated by an irrigated area of NA denoting “not applicable”).
- Each consent has at least one set of conditions that determines when and at what maximum rate water can be taken.
  - Each set of consent conditions is associated with a start date and an end date which determines a period during the year when water can be taken. Each set of consent conditions therefore relates to a specified part of the year (1 Jan to 31 Dec indicates a consent that operates all-year-around).
  - Consent conditions can be constant throughout the year or can vary through the year. For example, specific consent conditions can be applied in different months. No takes are allowable on days of the year for which no consent conditions are entered into the calculations.
  - Each set of consent conditions describes a maximum rate at which water can be taken.

- Each set of consent conditions is associated with a band that determines restrictions on rate of take based on river flow rate at a control point associated with that band.
- Restrictions are calculated after having considered the impact of other takes on river flow that have already been calculated.
- Each consent condition has a Boolean setting (on or off) that determines whether the rate of take must be reduced in order to maintain flow at the control point at or above the cease-to-take flow. If this setting is enabled, then the rate of take cannot be greater than the flow at the control point minus the cease-to-take flow. If this setting is not enabled, then the rate of take can exceed the flow at the control point minus the cease-to-take threshold at the control point. If the setting is not enabled, then taking water can cause flow at the control point to fall below the cease-to-take threshold. This setting is colloquially referred to as the "anti-yoyo".

Conditions on land:

- Each land parcel (defined by a consent-land parcel combination) has a latitude and longitude used to obtain rainfall and potential evapotranspiration time-series for that land parcel.
- A proportion of the total irrigated area of each consent is assigned to each land parcel associated with that consent. The proportion of the total irrigated area assigned to all land parcels associated with each consent must sum to one.
- Each land parcel has an irrigation season defined by a start date and an end date. Water is not supplied to the land parcel outside of this irrigation season. It is possible that the irrigation season can be defined as year-round (1 Jan to 31 Dec).
- Each land parcel has a set of parameters that defines its inherent soil characteristics (plant water availability, stress factor, fast drainage threshold, slow drainage rate). These soil characteristics do not change with time, but they do interact with water supply, target water content, Potential Evapotranspiration (PET), and rainfall to allow calculation of soil water content and irrigation demand.
- Each land parcel has a number that determines the frequency at which water can be applied. This number is colloquially referred to as "wait days". If "wait days" is one, then water can be supplied to land on a daily basis.
- Each land parcel is assigned a trigger soil water content for each calendar month. Trigger soil water content can vary between months but cannot vary within months.
- No water is supplied to a land parcel when soil water content for that land parcel is greater than the relevant trigger soil water content.
- If soil water content is below the trigger soil water content, then water supplied to each land parcel is calculated using one of two methods as indicated by a Boolean condition. This condition is colloquially referred to as "is amount efficient". If the setting is not enabled, then a predefined amount of water is supplied (e.g., 10 mm per

day) regardless of demand. If the setting is enabled, then water is supplied to meet demand (i.e., efficient irrigation practice is followed). The amount of water needed to meet irrigation demand is the amount needed to bring soil water content within that land parcel up to the predefined trigger soil water content after having account for rainfall and evaporation on that day (as described in the next statement). If the amount of available water is less than that needed to meet irrigation demand, then all available water is supplied to land.

- Irrigation demand is calculated on each day for each land parcel regardless of consent conditions or trigger soil water content. Irrigation demand is calculated for each day, accounting for rainfall and evaporation on that day and assuming no irrigation was supplied on that day. Irrigation demand for land is therefore the water supply required to bring soil water content up to the trigger soil water content at the end of each day. This method for calculating irrigation demand assumes that water users have accurate weather forecast information and good knowledge about both current soil water content and the effects of irrigation supply on soil water content.

- Water availability for a consent and irrigation demand for all land parcels associated with that consent are calculated prior to calculation of supply of water to any land parcels associated with that consent. Water is supplied to each land parcel associated with a consent in a specified order of priority until irrigation demand exceeds water availability. If irrigation demand (or predefined amount of water to be supplied) exceeds availability, then all available water is supplied to the land. The consequence of this statement is that water users always attempt to meet irrigation demand, always attempt to meet demand for the highest priority land parcels first, and do not reduce supply in anticipation of upcoming limitations to water availability.

Operation of storages:

- Each storage has a latitude-longitude position, which is only used for mapping purposes within our calculations.

- Consents associated with storages supply water taken from the river directly to meet their demand (for either irrigation or non-irrigation purposes) prior to filling their storage. Storages are only filled when available water supply exceeds demand, including times when there is no demand.

- Each storage has a capacity that determines the maximum volume of water it can hold. If more than one consent is associated with a storage, then each consent is associated with a fixed proportion of the capacity of the associated storage. In this case each consent acts as if it's part of the storage operates independently of the parts of the storage associated with other consents as represented in Figure 2-2.

- Each storage has a maximum rate at which it can be filled. This maximum rate is ignored if set to infinity. If a consent is associated with a storage, then water cannot be taken in association with that consent at a rate higher than the maximum rate at which the storage can be filled. If multiple consents are associated with a storage and their summed consented rate is greater than the maximum rate at which the storage can be filled, then the consented rates are reduced in reverse order in which they were entered until the summed consented rate equals the maximum rate at which the storage can be filled.

- Each storage has an initial volume that indicates how much water is in the storage on the first day of calculations.
- A proportion of stored water is lost from the storage each day. Leakage from storages is ignored if the proportion is set to zero.

Operation of bands and control points:

- Each band is associated with a control point whose river flow conditions determine the degree to which consented water takes associated with that band are restricted to take at a rate below their maximum allowable rate of take.
- Each band has a cease-to-take threshold indicating the flow at the control point below which no water can be taken. Each band has a full-take threshold indicating the flow at the control point above which the full consented rate of take can be taken. If the cease-to-take threshold equals the full-take threshold, then the consent is either fully allowed (unless the "anti-yoyo" is enabled) or not allowed depending on flow at the control point for that band. If the cease-to-take threshold is less than the full-take threshold and the flow at the control point is between these two values, then the allowable rate of take is calculated by interpolating the flow at the control point between the cease-to-take threshold and the full-take threshold; a situation is known as flow sharing. See Figure 2-3 for graphical representation of this calculation.
- Each band has a start date and end date indicating the part of the year that the cease-to-take and full-take thresholds apply to. No takes are allowable on days of the year for which no information describing restrictions is supplied to our calculations.

Some special notes to be aware of:

- Sets of consent conditions, irrigation season for land, and bands are each associated with times of the year during which they are active (including being active year-round). Failure to synchronise these three sets of dates may lead to no water being allowed for the consent. For example, times of the year associated with consent conditions will need to be synchronised with times of the year when the band with which the consent conditions is associated is active.
- A band which operates a cease-to-take threshold of zero all year around will result in the only limitations no taking water is the maximum allowable rate of take and local water availability. This situation can be used to calculate maximum water availability when no environmental constraints are in place.
- A cease-to-take threshold can be set to be greater than the highest river flow at the control point to calculate soil water content under no water supply because taking of water is never allowable.

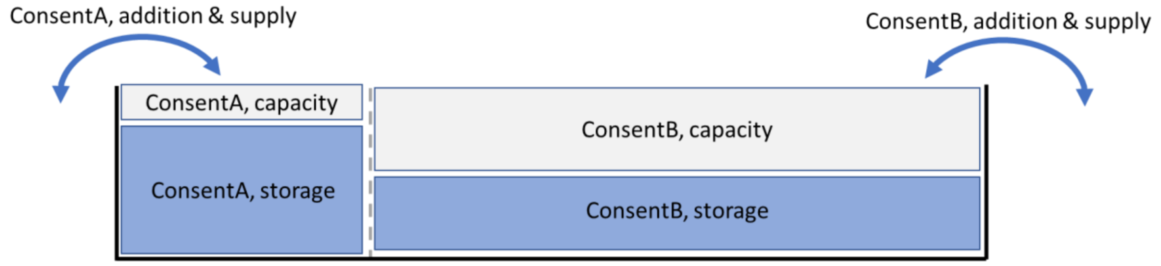

Figure 2-2: Idealised representation of available storage and capacity when two consents are associated with one storage.

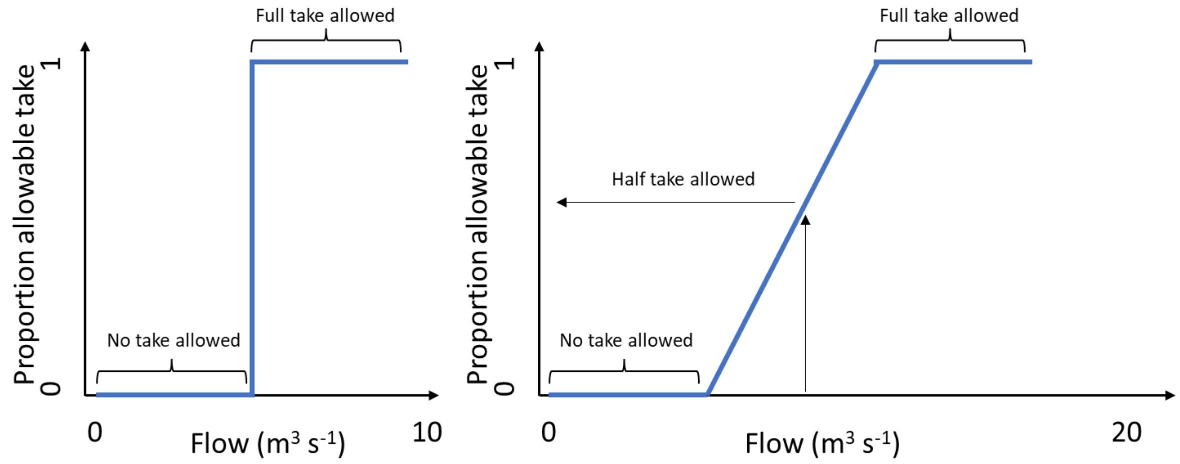

Figure 2-3: Hypothetical examples of the relationship between river flow and the proportion of consented take that is allowable. Left: take is either fully allowable or fully restricted. Right: take can be partially restricted.

2.4 Data

Various sources of data were used as input to our method as described in Table 2-3 and in more detail below.

Table 2-3: Input data and algorithms used to represent water use and demand.

Description	Utility	Source and additional comments
River network for any catchment of interest.	Allows calculation of streamflow depletion through representation of upstream-downstream connectivity.	National Digital River Network (version 2.3). See Snelder and Biggs (2002) for details.

Description	Utility	Source and additional comments
Hourly river flow time-series for each segment downstream of takes within the catchment of interest.	Provides information on surface water availability and a basis for calculation of hydrological impacts.	Observed hourly river flow time-series extracted from NRC and GDC data servers were used to produce the results provided in this report. For completeness within this project, we confirmed that river flow time-series produced from an uncalibrated TopNet model (see McMillan et al. (2016) for details) produced via HydroDesk could also be used as input to our calculations. Simulated flow data extracted from any hydrological model could be used as an alternative input, if the data are formatted appropriately.
Daily rainfall and Potential Evapotranspiration (PET) across the catchment of interest.	Input to soil moisture and water demand calculations.	Virtual Climate Station Network (VCSN). Clidb data version of rainfall estimates. See Tait and Woods (2007) for details about PET. See Tait et al. (2012) for details about rainfall.
A set of equations and default values for soil parameters used to simulate soil moisture.	Allows calculation of soil moisture and water demand for irrigation.	Soil moisture equations from IrriSet developed under NIWA's MBIE Justified Irrigation Programme. See Srinivasan et al. (2021) for details.
Algorithms used to simulate water availability resulting from consent conditions.	Allows representation of consent restrictions such as "cease-to-take" restrictions.	Bespoke code developed under NIWA project FWWA2308 and applied in work for MfE/StatsNZ. See Booker (2018) for details.
Algorithms used to simulate streamflow depletion.	Allows representation of impacts of upstream water takes on downstream flows.	Bespoke code developed under NIWA project FWWA2308. See Booker et al. (2018) for details.
Algorithms used to simulate filling and emptying of water storages.	Allows representation of storage operations	Bespoke code developed under NIWA project FWWA2308 for water accounting purposes.
R shiny interactive app.	Allows inspection and changing of user inputs, viewing of results, and re-running of calculations.	Bespoke code developed for this project.

All available river flow data were extracted from Hilltop servers hosted by NRC and GDC. We obtained a list of all available sites from each server. We then obtained a list of all measured parameters for each site. For each site where "Flow" was listed as an available parameter, we obtained mean-hourly values for all full calendar years following the first available observation and prior to the last available observation. The ideal data format for our purposes was a sequence of flow values positioned through time at precisely hour intervals (after having adjusted for leap seconds). However, our request for mean-hourly data did not return a flow value on-the-hour of each hour; some of the date-times did not correspond to exact hours and some gaps were present. We therefore interpolated the downloaded flows and date-times onto a sequence of hourly intervals. A linear interpolation was applied in $\log_{10}$ flow space in order to minimise interpolation errors. We calculated the time gap between each interpolated point and the nearest available downloaded date-time. Many of the calculated time gaps between measured data and interpolation points were zero or a few seconds, but longer gaps in the observed records were also present.

For each region, we produced a pdf document containing plots of hourly hydrographs for all years at all sites. We supplied the pdf documents to staff from NRC and GDC for their inspection and feedback. We inspected all hydrograph plots visually to identify suspicious data. Several features of the flow data from some sites were noteworthy. Some hydrographs contained known gaps as indicated by the pink line in Figure 2-4. Some hydrographs contained suspicious data such as spikes or periods of flow that were more variable than all other periods (e.g., Figure 2-5 and Figure 2-6). Some hydrographs contained straight lines or gently curved lines in logged-flow space, indicating that the downloaded data had been interpolated to fill gaps prior to being obtained by our query (Figure 2-6 and Figure 2-7). After completing visual inspection, we identified a list of 42 sites from NRC that contained at least five years of data since 1990 that we judged to be viable for further analysis (Figure 2-8). Identification of sites that were viable for further analysis was more difficult for the GDC region due to the increased prevalence of gaps and suspicious data. We selected 14 sites from GDC that contained at least five years of data since 1990 that we judged to be viable for further analysis (Figure 2-9).

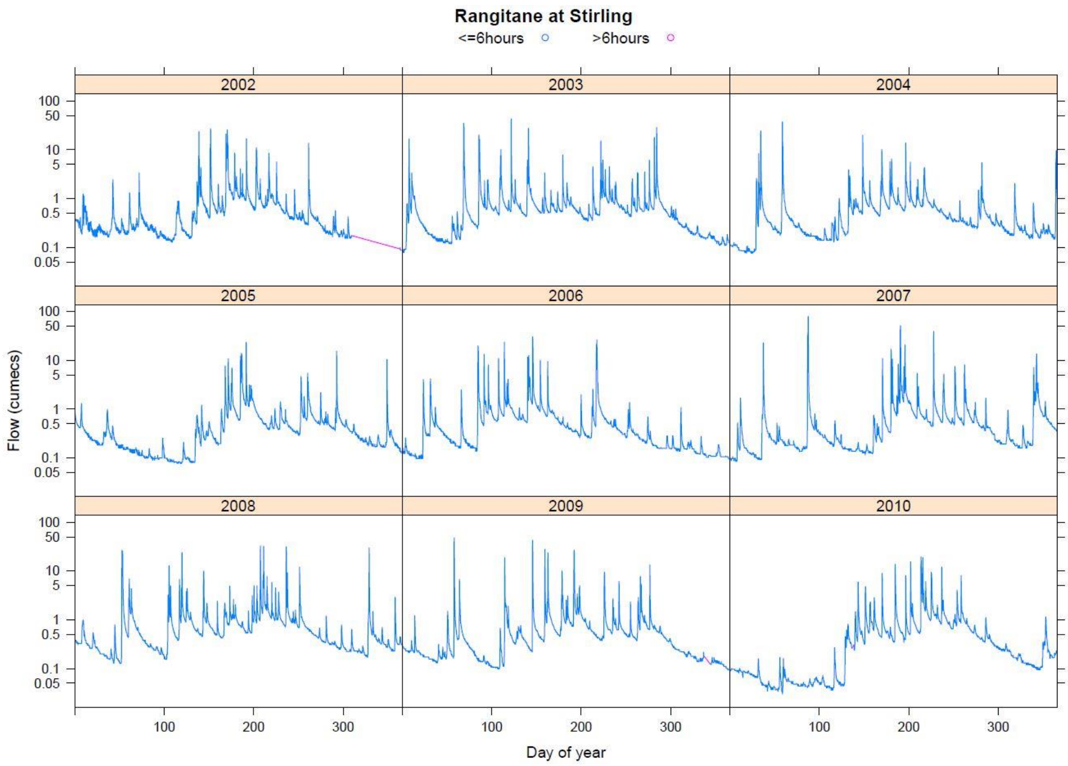

Figure 2-4: Hourly flows for Rangitane at Stirling (NRC). Note known gap represented by pink line indicating that the nearest available data were more than six hours from the points being interpolated to.

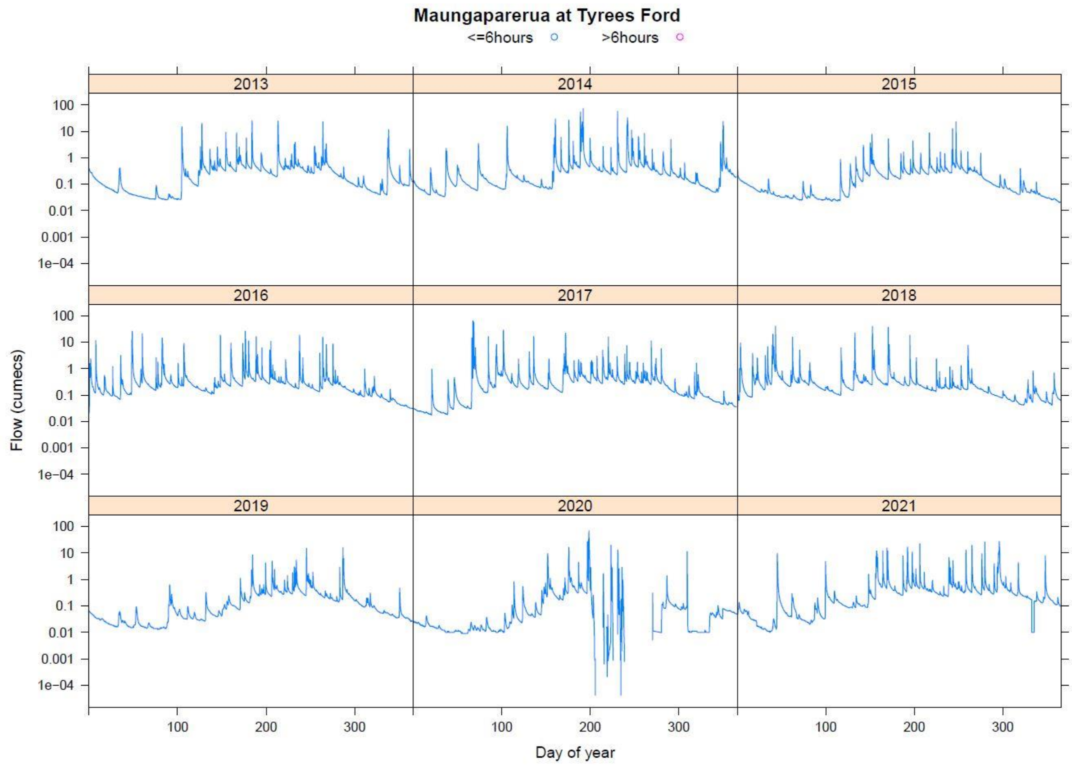

Figure 2-5: Hourly flows for Maungaparerua at Tyrees Ford (NRC). Note some suspiciously low and variable values in 2020 and 2021 which were removed before subsequent analysis.

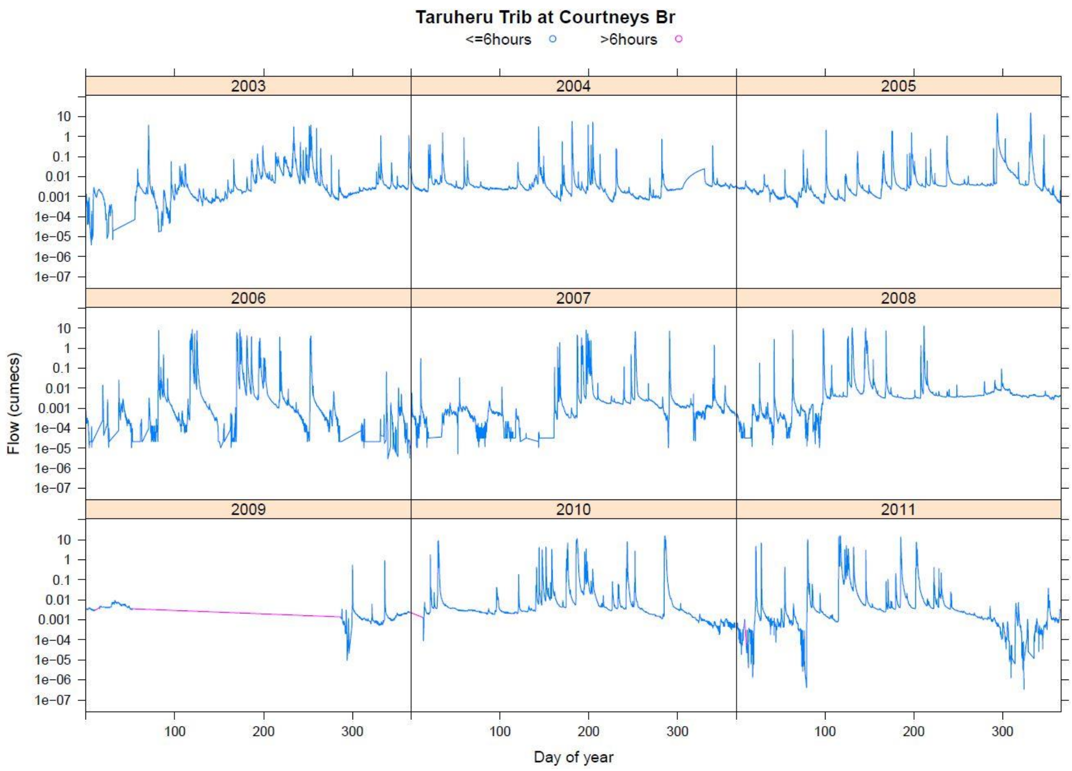

Figure 2-6: Hourly flows for Taruheru Trib at Courtneys Bridge (GDC). Note long known gap (pink line, 2009), suspicion of unknown gaps (e.g., straight lines in 2006), and suspiciously low and variable flows (2011).

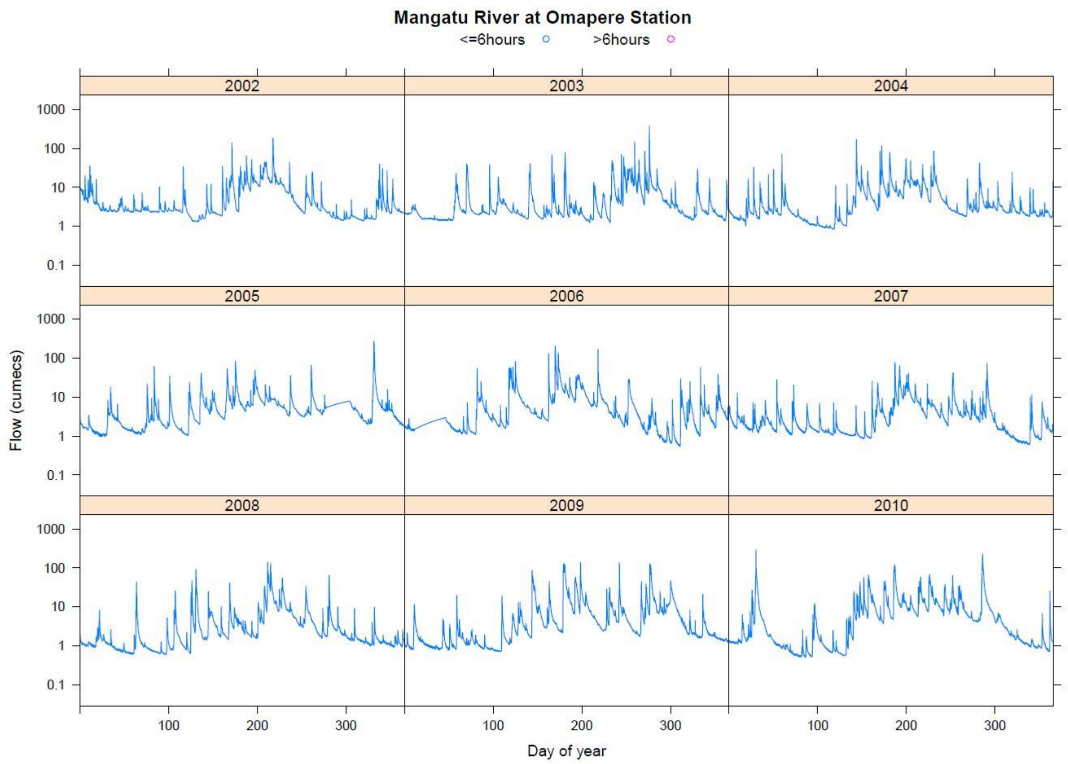

Figure 2-7: Hourly flows for Mangatu River at Omapere Station (GDC). Note some suspicion of unknown gaps (e.g., straight lines in 2005 and 2006).

Figure 2-8: Periods of river flow data used for analysis for sites in Northland. Grey indicates flow data used in analysis.

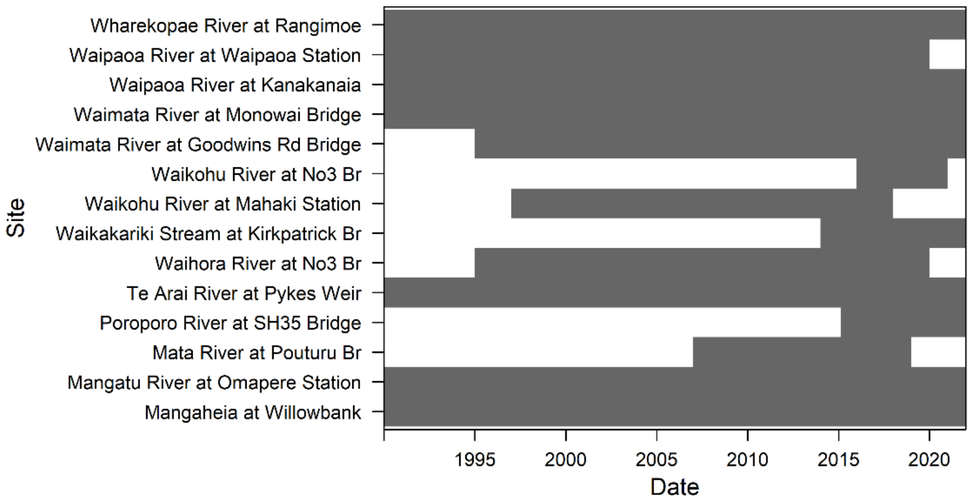

Figure 2-9: Periods of river flow data used for analysis for sites in Gisborne. Grey indicates flow data used in analysis.

We applied a method such that mean-hourly flows could be subsequently converted to represent means per various time-steps (e.g., quarter day, half day, or daily) depending on how our calculations were set up. Since we required continuous records for our calculations of water availability and our aim was to inform high-flow harvesting in general (rather than site-specific analysis), we included hydrographs where interpolation was used to fill gaps (e.g., Figure 2-4).

Daily time-series of rainfall (mm d^{-1}) and potential evapotranspiration (PET; mm d^{-1}) were obtained from NIWA's Virtual Climate Station Network (VCSN), which is a representation of measured conditions on a 0.05° (approximately 5 km) grid covering all New Zealand. VCSN values at each grid location were derived from a spline interpolation of values recorded at weather stations with available quality-controlled data (Tait and Woods 2007). VCSN PET is calculated as the 24-hour Penman Potential Evapotranspiration total which is calculated from daily mean temperature, wind speed, air pressure, and solar radiation. The mean absolute error of the VCSN data is 0.9°C for maximum daily temperature and 1.2°C for minimum daily temperature (Tait and Macara 2014). The mean absolute error in VCSN daily rainfall for locations below 500 m elevation is approximately 2-4 mm (95% of the range) for rain days (rainfall ≥ 1 mm), whereas the error in areas above 500 m elevation is approximately 5-15 mm (Tait et al. 2012).

We used the IrriSET soil water balance model as described in Srinivasan et al. (2021). Storage within top 600 mm of soil was considered as PAW as that represents pasture rooting depth. Soil water between 50% and 100% PAW is assumed optimal or readily available for pasture growth. Drainage occurs only when available soil water exceeds PAW. When soil water exceeds 105% PAW, then all water in excess of 105% PAW is drained at the end of the same day. Excess water between 100% and 105% PAW drains according to soil texture. We assumed that 50% of excess water is drained in a day until it reaches 100% PAW.

2.5 Inputs

Our method for simulating the operation and influences of combinations of run-of-river and high-flow harvesting water takes took five tables as inputs (Table 2-4, Table 2-5, Table 2-6, Table 2-7, and Table 2-8).

Table 2-4: Inputs describing storages.

Label	Format	Description
StorageID	Unique text or numbers	Identifier of storage. Unique per row within this file.
Longitude	Numeric coordinate	Position of storage for mapping.
Latitude	Numeric coordinate	Position of storage for mapping.
CapacityVolume	Cubic metres	Maximum volume of water storage can hold.
MaxFillRate	Cubic metres per second	Maximum rate at which storage can be filled (Inf = no maximum).
InitialVolume	Cubic metres	Volume of water in storage at start of simulation.
LeakageProportion	Numeric Proportion of per day	Proportion of water volume lost through leakage.
Include	Logic	Whether to include this storage in the calculations.

Table 2-5: Inputs describing consents.

Label	Format	Description
ConsentID	Any text or numbers	Identifier of consent. Not necessarily unique per row within this file.
Start date	dd/mmm	Day of the year on which condition starts.
End date	dd/mmm	Day of the year on which condition ends.
MaxTakeRate	Cubic metres per second	Maximum allowable rate at which water can be taken in association with this consent.
BandID	Any text or numbers	Identifier of band.
AntiYoYo	Boolean (TRUE or FALSE)	If true, then the take is reduced in an attempt to maintain the cease-to-take flow at the control site.
Include	Logic	Whether to include this storage in the calculations.

Table 2-6: Inputs describing bands.

Label	Format	Description
BandID	Any text or numbers	Identifier of band. Not necessarily unique per row within this file.
StartDate	dd/mmm	Day of the year on which condition starts.
EndDate	dd/mmm	Day of the year on which condition ends.

Label	Format	Description
ManagementNzsegment	Integer, nzsegment of RECv2.3	Identifier of segment within digital river network to be used as the control point. Not necessarily unique per row within this file.
QminCeaseTake	Numeric, cubic metres per second	River flow below which no take is allowable.
QfullTake	Numeric, cubic metres per second	River flow above which water can be taken at the maximum allowable rate.

Table 2-7: Inputs describing matching between consents and storages.

Label	Format	Description
ConsentID	Any unique text or numbers	Identifier of consent. Unique per row within this file.
StorageID	Any text or numbers	Identifier of storage associated with this consent. Not necessarily unique per row within this file. NA or blank indicates no storage associated with this consent.
nzsegment	Nzsegment of RECv2.3	Identifier of nzsegment. Not necessarily unique per row within this file.
QmaxCeaseTake	Numeric, cubic metres per second	Local flow rate above which no water can be taken in association with this consent (e.g., because of high sediment loads).
IrrigatedArea	Numeric, square metres	Maximum irrigated area associated with this consent summed over all land parcels.
ProportionStorage	Proportion, numeric value 0-1	The proportion of the storage associated with the consent.
Include	Boolean, TRUE or FALSE	Whether to include this storage in the calculations.

Table 2-8: Inputs describing matching between consents and land parcels.

Label	Format	Description
LandID	Text or numbers	Identifier of land parcel. LandID does not have to be unique per row within this file. Each combination of LandID and ConsentID must be unique per row within this file.
ConsentID	Text or numbers	Identifier of consent. Not necessarily unique per row within this file.
ProportionOfArea	Proportion, numeric value 0-1	Proportion of the maximum irrigated area of consent associated with land parcel.

Label	Format	Description
Priority	Sequence integers 1 to n	The priority order in which water is applied to land parcels within each consent. Must be unique to LandID within ConsentID.
StartDate	dd/mmm	Day of the year on which irrigation season starts.
EndDate	dd/mmm	Day of the year on which irrigation season ends.
PAW	Numeric, millimetres	Volume of water stored within the soil available to plants.
StressFactor	numeric unitless	Water stress reduction factor which is a function of the soil water status. StressFactor equals 1.0 when the soil water content is equal to the readily available water content, and then reduces linearly down to a value of zero at wilting point.
FastThreshold	numeric unitless	Coefficient applied to calculate fast drainage (overland flow).
SlowRate	numeric unitless	Coefficient applied to calculate slow drainage.
TriggerFactor_month (TriggerFactor_Jan, TriggerFactor_Feb, etc.)	Numeric value multiplied with PAW	Coefficient applied to calculate target soil moisture conditions in each calendar month of the year.
WaitDays	Numeric, days	Number of days to wait before reassessing soil moisture demand.
IsAmountEfficient	Boolean, TRUE or FALSE	If true, supply enough to meet demand. If false, apply a set amount.
Amount	numeric mm	Set amount of water to supply if IsAmountEfficient is false. Not used when IsAmountEfficient is true.
Longitude	numeric coordinate	Position of storage for mapping.
Latitude	numeric coordinate	Position of storage for mapping.
Include	Boolean, TRUE or FALSE	Whether to include this land parcel in the calculations.

2.6 Experiments

2.6.1 Experiment 0: spatial variability in water demand

Before considering water allocation rules, we applied an initial experiment to demonstrate the effect of spatial variations in PET and rainfall (but not soil conditions or vegetation characteristics) on water demand. For each location with a gauging location (Figure 2-8 and Figure 2-9), we calculated the water supply needed to meet water demand for a given irrigated area under a hypothetical scenario of infinite water supply for the period 1990 to 2021 inclusive.

We used the following parameters for this experiment:

- Period of flow harvest from all bands: 1 January to 31 December.
- Irrigated crop type: pasture.
- Soil PAW: 100 mm for 600 mm depth (pasture soil-water reservoir).
- Trigger to stop irrigation/Irrigation application depth: soil-moisture deficit minus 10 mm or irrigate up to 90% of 100 mm PAW (leaving 10 mm capacity will enable taking advantage of high rainfall events and reducing deep drainage and nutrient losses, and further aligns with our heuristic about water efficiency and our assumption 5 in Section 2.6.2 to support water use efficiency).
- Irrigation season: from 1 October through to 30 April.
- Irrigated area: 1,000,000 m^2 (1 km^2).

Experiment 0 was independent of any water allocation rules.

2.6.2 Devising rules and consent conditions to be consistent with heuristics

We devised sets of water allocation rules and accompanying consent conditions that were relevant to both run-of-river takes and high-flow harvest whilst considering the four principles and their accompanying heuristics set out in Section 2.2 relating to: 1) practical implementation; 2) environmental sustainability; 3) water efficiency; and 4) spatial consistency.

Water use limits and consent conditions must be definitive and easily communicated to water users to be consistent with our first heuristic about practicality of implementation. We therefore devised rules defined by multiple bands where each band is characterised by a cease-to-take threshold and a maximum allowable rate of take describing the maximum rate at which water can be taken when flow at a control point exceeds the relevant cease-to-take threshold. We surmised that continuous monitoring of flow at a control point together with paired cease-to-take thresholds and maximum allowable rates of take would be the main inputs to a water allocation system that could be practical to implement by providing clarity about water availability to water users. Thus, proposed rules that apply multiple bands would have the same information, practicability, and operational requirements as current low flow water allocation rules.

Water use limits and consent conditions must deliver a specified level of protection to local river flow regimes to be consistent with our second heuristic about environmental sustainability. This is done by limiting environmental impact through delivery of environmental flow regimes that include low flows, high flows, and flow seasonality. Cease-to-take thresholds and maximum rates of take relevant to low flows are currently used in the Northland and Gisborne to limit hydrological impacts of run-of-river takes on low flows (e.g., Table 1-1 and Table 1-2 for Northland and Table 1-3 for Gisborne). We proposed rules that could be implemented in regional plans to limit water use during high flows. Since high-flow harvesting is often used in situations where run-of-river takes are in operation, rules for high-flow harvesting should be developed together with rules for run-of-river takes.

Although our rules for run-of-river takes were designed to closely represent those in use in Northland and Gisborne regions, it was necessary to make them generic to accommodate variations of rules within and between these regions (see Table 1-1, Table 1-2 and Table 1-3). Our run-of-river rules therefore represent the current rules in all regions. We assumed that cease-to-take thresholds and maximum rates of take could be used to limit the hydrological impacts of high-flow harvesting on high flows and flow seasonality., We surmised that cease-to-take thresholds and maximum rates of take relevant to high-flow harvesting could be applied to limit hydrological impacts of high-flow harvesting takes on high flows and flow seasonality. Our high-flow harvesting rules used a similar format as current low flow rules by applying cease-to-take thresholds and maximum rates of take. When a sequence of paired cease-to-take thresholds and maximum rates of take are applied across a range of flows, these rules describe a set of bands as described by the logic set out in Section 2.3. Band1 corresponds to rules for run-of-river takes. We surmised that multiple bands can be quantitatively defined by a sequence of flow thresholds that are relevant to local river flows in order to manage all takes along a continuum between run-of-river and high-flow harvesting water takes. We surmised that relating the thresholds of multiple bands to the flow regime at the control point would allow rates of take to be related to river flows in a predictable way and limit hydrological impacts to lie within a predictable range.

Water use limits and consents conditions must only allow reasonable and efficient water use in order to be consistent with our third heuristic about water efficiency. We surmised that consent conditions could include an accompanying maximum irrigated area and the requirement to use water efficiently, but we recognise that this type of clause may be difficult to enforce and would have to be accompanied by education of water users.

Water use limits and consents conditions must take account of spatial considerations in order to meet our fourth heuristic about spatial consistency. We surmised that cease-to-take thresholds and allowable rates of take must be specified relative to naturalised river flows in order to operate water allocation rules that deliver similar levels of hydrological alteration across different river flow regimes regardless of river size, climate, and flow regime characteristics. In the analysis presented here, we concentrated on differences in the flow regime and climate conditions at control sites arising from spatial differences in these factors. We applied experiments to demonstrate how the same rules would produce different impacts depending on the flow regime at control sites. Our numerical experiments positioned takes and land parcels adjacent to control points. We did not conduct further experiments to investigate the influence of positioning of consents in various positions across river catchments because: a) spatial configurations of water takes can be complex due to complicating interactions between surface water and groundwater; b) there can be a very high number of spatial configurations of takes; and c) we wished to analyse relationships between rules, supply and river flows at a single location before introducing uncertainties related to estimation of hydrological patterns across a catchment.

Having surmised that rules and consent conditions formulated using bands could be consistent with the four heuristics (relating to practicality, sustainability, efficiency, and spatial consistency), we devised water allocation rules comprising five-bands that could represent a practically implementable flow harvesting regime. These rules were designed to achieve a defined level of protection of instream values across a flow regime, whilst providing adequate water supply reliability to water users (Table 2-9). We then applied experiments to demonstrate how specification of bands (which determine water allocation rules and consent conditions) could interact with storage capacity and irrigated area to produce positive outcomes in terms of river flows and water availability.

We first conducted several numerical experiments to analyse whether rules and consent conditions would be consistent with heuristics using flow data from the Awanui Stream at School Cut site in Northland, using rainfall and potential evaporation data collected at a site near to this location. In these examples, we used five allocation bands (Table 2-9). Figure 2-10 depicts a hydrograph for the period July 1990 to June 1995. As is true for many areas in Northland, mean daily flows in summer (January to February) can be significantly lower than that in winter (July to August). The 7dMALF (mean annual low flow) and median flow what we estimated for the Awanui Stream at School Cut were 0.58 and 2.71 m^3 s^{-1}, respectively.

Table 2-9: Flow harvesting rules used to define five-band harvesting with example values for the Awanui Stream at School Cut.

Band	Cease-to-take		Maximum allocation rate	
	Description	Value (m^3 s^{-1})	Description	Value (m^3 s^{-1})
1	0.8 * 7dMALF	0.465	0.3 * 7dMALF	0.175
2	1.1 * 7dMALF	0.640	1.0 * 7dMALF	0.553
3	3 * 7dMALF	1.745	0.2 * Median	0.542
4	1.3 * Median	3.522	0.2 * Median	0.542
5	2 * Median	5.418	0.2 * Median	0.542

Based on the numerical experiments conducted using data for the Awanui Stream at School Cut site, we applied the allocation rules to 42 river catchments in Northland, and 14 in Gisborne regions. We hypothesised that application of the same rules developed for the Awanui Stream to the 56 river catchments with diverse hydroclimatic conditions and flow patterns would assist us and regional councils to determine the suitability of rules for those catchments, and allow us to alter the rules to meet the principles and heuristics for high-flow harvesting where necessary. To gain this understanding, we also applied our initial experiment (Experiment 0) across all sites to assess the effect of spatial variations in climate on water demand (described in Section 2.6.3).

We applied the following rules and assumptions for all experiments involving water allocation rules:

1. Water allocation rules and consent conditions can be applied at a daily temporal resolution based on mean-daily river flows. We therefore applied all calculations to mean-daily flow data. Use of mean-daily flow data matched well with daily rainfall data, PET data, and water demand algorithms that were available for this work.

2. No takes will operate when flows are above five times the median to prevent high sedimentation of storages and fouling of water take infrastructure due to “dirty water’.

3. We applied the “AntiYoYo” assumption described in Section 2.5 that assumes that water users can operate their take so as not to drop the flow below the cease-to-take threshold.

4. Water users would take water to i) meet reasonable water demands for irrigation purposes (by applying enough water to reach a specified target soil moisture condition), and ii) fill storages if soil water demands were satisfied and storages were not at full capacity. Water users would not take water if target soil water content was met and storages were full.

5. Water users have access to accurate weather forecast information, irrigate to achieve a water efficient target soil water content, and have perfect knowledge about the effects of irrigation supply on soil water content.

6. Water users irrigated their land uniformly, rather than applying available water to a limited area at higher rate in times of water scarcity.

7. In order to simplify our analysis (and in the absence of ideal information about soil conditions and crop types), we assumed that all water was used to irrigate grass growing on soils with uniform soil conditions.

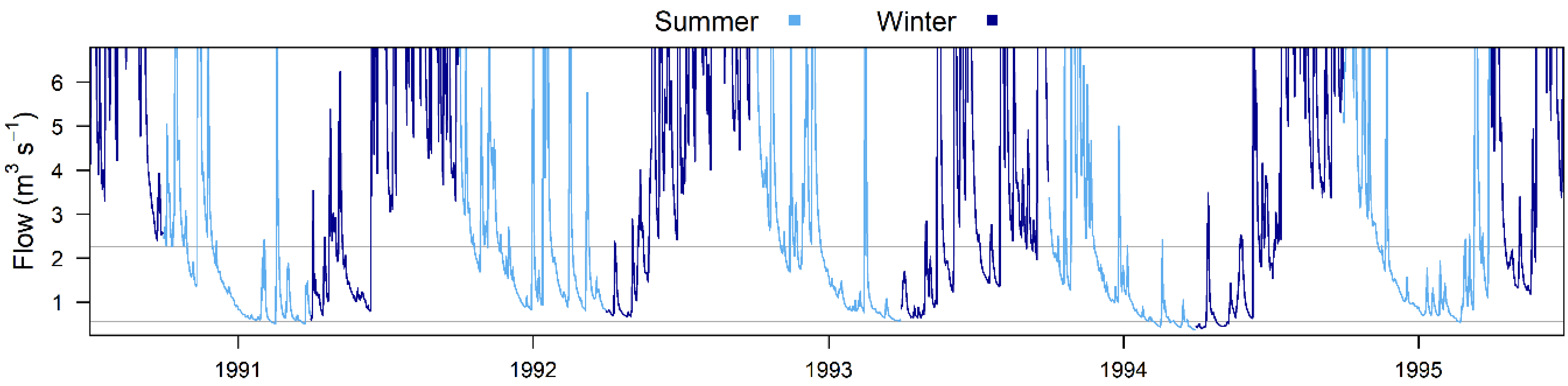

Figure 2-10: Hydrograph of the Awanui Stream at School Cut for July 1990 to June 1995. Flows are shown up to 7 m^3 s^{-1} only, and displayed using different colours for summer (light blue) and winter (dark blue) to demonstrate the typical variation in flow between seasons.

2.6.3 Experiment 1: Five-band harvesting

In this experiment we used all five bands for flow harvesting, termed "five-band harvesting". This allocation experiment forms a basis for us to test the principles and heuristics set out in Section 2.2, and to compare other allocation scenarios against this baseline scenario.

This example of flow harvesting is based on the following assumptions:

1. Flow harvesting occurs from all five allocation bands. This assumes available water within the primary allocation band (which would typically be utilised by run-of-river takes) is also harvested and stored in the storage. It should be noted that procedure deliberately produced harvesting of relatively low flows as well as harvesting of relatively high flows.

2. There is one consent for a single water take. Thus, water is taken from all five bands to supply a single consent. However, rules to take water vary within each band.

3. All water is taken from a single river reach located near to the control site. Thus, we ran the numerical experiments to examine our pre-defined heuristics using observation flow sites, taking water near to the site where flow data were available (i.e., at the river reach of the observation flow site).

Table 2-9 lists the "cease-to-take" flow and 'maximum allocation rate' for the five allocation bands for the Awanui Stream at School Cut. We devised the cease-to-take and maximum allocation rate using 7dMALF and median flow. We used the 7dMALF to set the values for lower two bands. The rationale for using the 7dMALF is that most regional councils currently use 7dMALF to set cease-to-take flows and maximum allocation rates for the primary allocation (Band 1 in our experiment), for example, Table 1-1, Table 1-2 and Table 1-3 for Northland and Gisborne. Thus, we surmised that use of 7dMALF for setting flow allocation rules for lower bands closely aligned with those in current use. We used the median flow to define thresholds for the three higher bands. We consider that use of 7dMALF, which is calculated using lowest annual flows, may not be appropriate for devising rules for higher flows.

Figure 2-11 shows the cease to flow and allocable resources within each band for the Awanui Stream at School Cut.

We used the following parameters for this experiment:

- Period of flow harvest from all bands: 1 January to 31 December.
- Irrigated crop type: pasture.
- Soil PAW: 100 mm for 600 mm depth (pasture soil-water reservoir).
- Irrigation season: from 1 October through to 30 April.
- Irrigated area: 11,000,000 m^2 (1,100 ha).
- Storage capacity: 1,500,000 m^3 (1.5 Mm^3).
- Water takes cease when flow falls below the cease-to-take threshold ("AntiYoYo" assumption described in Section 2.5).

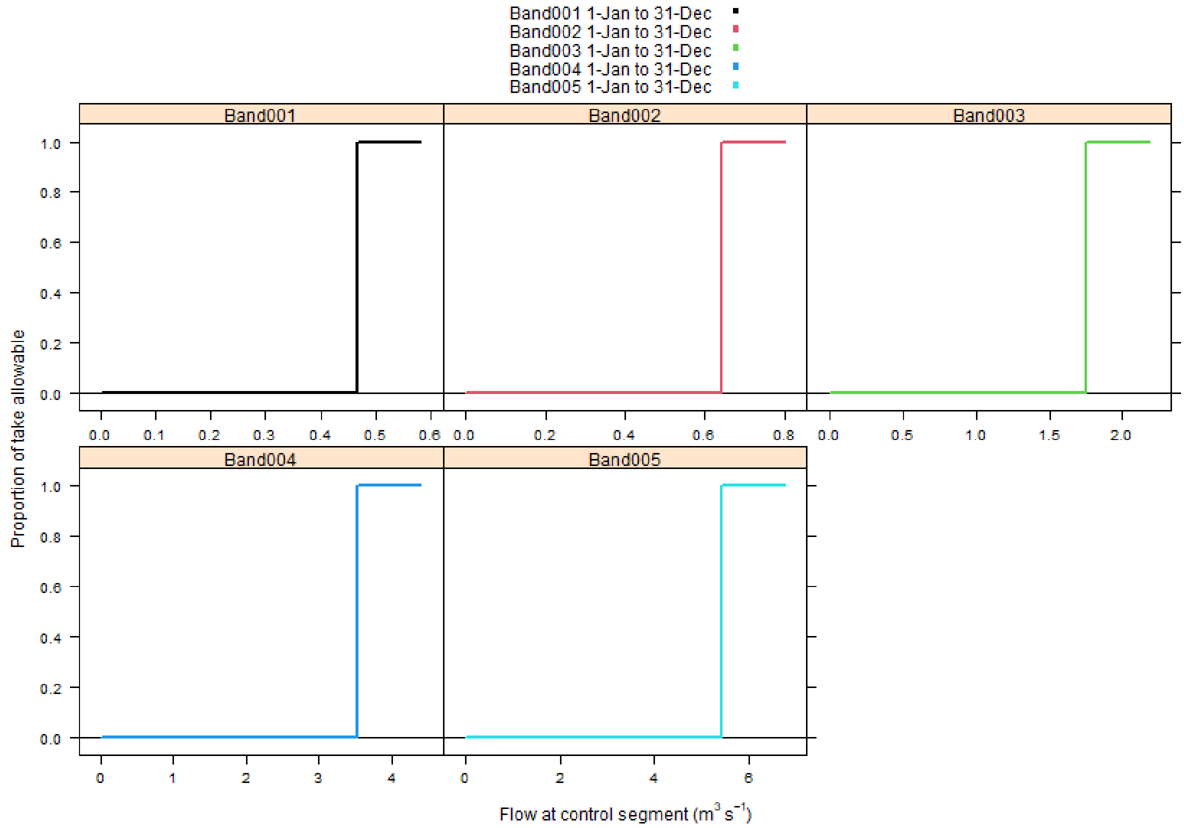

Figure 2-11: Details of allocation bands: cease to flow and allocable resources within each band for the Awanui Stream at School Cut.

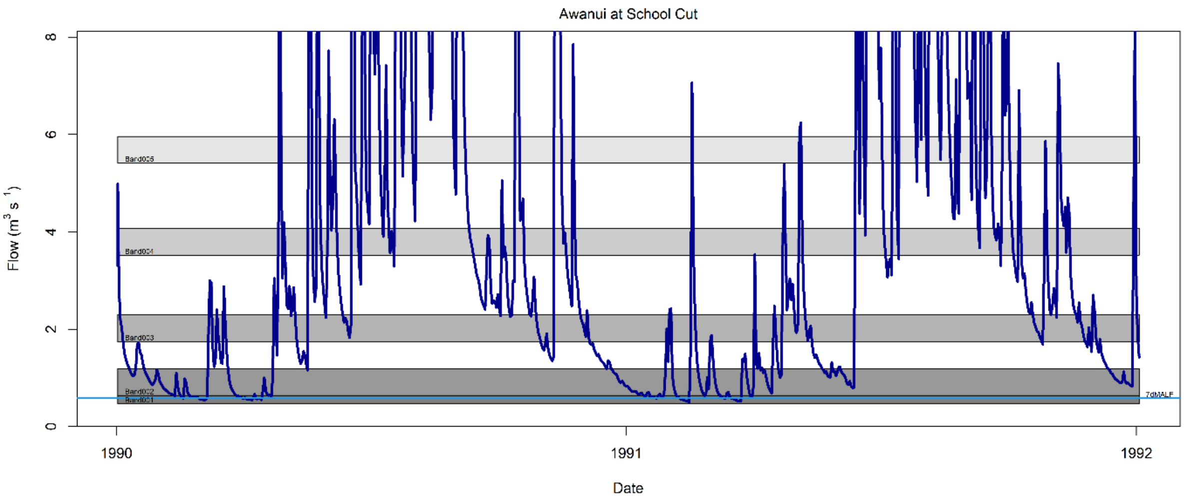

Figure 2-12: Graphical depiction of multiple bands that could control takes. Water can be taken from a band when the grey area is below the blue line. Example hydrograph for the Awanui Stream flows at School Cut.

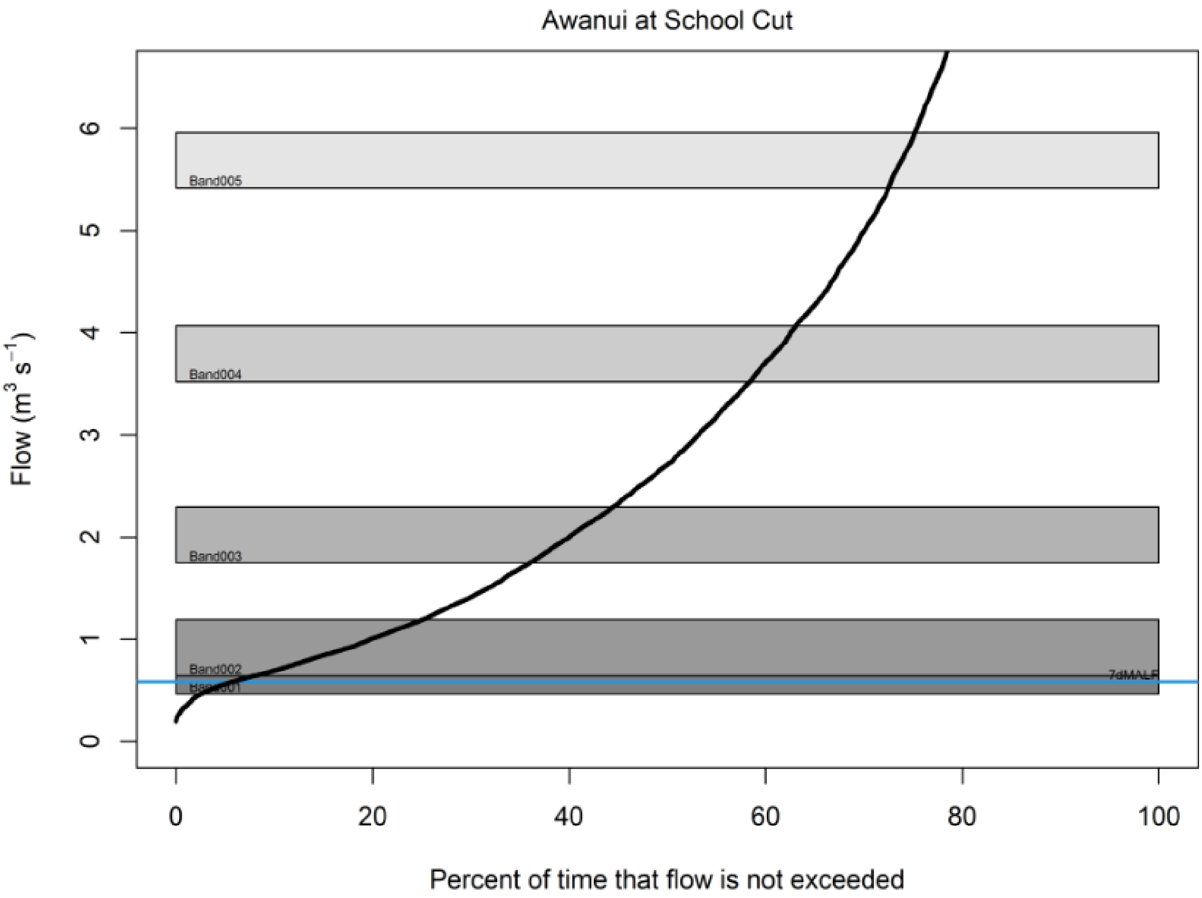

Figure 2-13: Graphical depiction of multiple bands on the flow duration curve. Water can be taken from a band when the grey area is below the black line. Example hydrograph for the Awanui Stream flows at School Cut.

2.6.4 Experiment 2: four band harvesting with Band 1 for run-of-river

The experiment presented in Section 2.6.3 assumes that flow can be harvested from all five bands and delivered to a storage(s). However, Band 1 water flows (generally termed 'primary allocation') have been fully- or over-allocated in many regions (Tait 2010), primarily as direct run-of-river takes. This is because there is a significant variation between water sources in terms of cost to irrigators — generally direct run-of-river sources tend to be the cheapest. Thus, Band 1 may not be available for flow harvesting in many catchments.

To simulate the unavailability of water resources with Band 1 for harvesting, we repeated the *five-band harvesting* experiment described in Section 2.6.3 but flow harvesting only from Band 2 to 5 water resources. However, it is important to mimic the run-of-river abstraction under Band 1 within this experiment to understand the total flow alterations. Thus, we modelled water take(s) from Band 1 and used for irrigation through simulating a separate consented water take/use. In other words, we simulate two types of water take consents within this experiment: (1) Consent 1: high-flow harvesting from Band 2 to 5, and (2) Consent 2: run-of-river takes from Band 1. To simulate the general high demand for Band 1 run-of-river water resources, we model irrigation of a large land parcel; accordingly Band 1 water is heavily abstracted within our numerical experiment.

We name this experiment as '*four-band harvesting*'.

2.6.5 Experiment 3: harvesting from three bands with Band 1 for run-of-river

Experiment 3 replicated Experiment 2 with two differences: i) only the top three bands were used to supply storage; ii) no abstractions occurred under Band 2 conditions. We used this experiment to assess flow harvesting from a higher spectrum of flow ranges than in Experiment 1 and 2.

2.7 Outputs

Our method output several time-series (Table 2-10). Each set of outputs relates to an entity within the method. Each output is calculated for each time step of a time-series, except for outputs that relate to land – these were calculated as daily time-series only.

Table 2-10: Time-series calculated outputs. All rates represent averages over the calculation timestep. * = outputs gained directly from input.

Entity	Variables	Units	Description
Storages	Added	$m^3 s^{-1}$	Rate at which water is added to the storage. Net of take and supply. Negative values indicate net loss from storage.
	Leaked	$m^3 s^{-1}$	Volume of water lost from the storage
	Supplied	$m^3 s^{-1}$	Rate at which water is supplied from the storage
	Stored	m^3	Volume of water within the storage
Consents (takes)	MaxTakeRate	$m^3 s^{-1}$	Maximum rate at which water could be taken regardless of restrictions
	AllowableTake	$m^3 s^{-1}$	Maximum rate at which water could be taken after having considered restrictions
	Taken	$m^3 s^{-1}$	Rate at which water was taken (to meet demand and/or fill storage)
	Added	$m^3 s^{-1}$	Rate at which water was added to storage
	Leaked	$m^3 s^{-1}$	Rate at which water is lost from the associated storage
	Supplied	$m^3 s^{-1}$	Rate at which water is supplied to land
	Demand	$m^3 s^{-1}$	Rate at which water would be supplied to meet demand
	Stored	m^3	Volume of water within the associated storage and assigned to the consent
Land	Rainfall*	$mm\ d^{-1}$	Rate at which water fell from the sky
	Potential evapotranspiration*	$mm\ d^{-1}$	Rate at which water would evaporate if sufficient water were available (i.e., high soil water content)
	Actual evaporation	$mm\ d^{-1}$	Rate at which water would evaporate given actual soil water content

Entity	Variables	Units	Description
	Demand	mm d^{-1}	Rate at which water would need to be applied to meet demand as defined by a trigger water content
	Supplied	mm d^{-1}	Rate at which water was supplied to the land
	Trigger*	mm	Threshold for amount of water held within the soil that will trigger supply to land.
	Drainage fast	mm d^{-1}	Rate at which water was lost from the land via fast drainage
	Drainage slow	mm d^{-1}	Rate at which water was lost from the land via slow drainage
	Soil water content	Mm	Amount of water held within the soil
River	Unaltered*	$m^3 s^{-1}$	River flow rate
	Altered	$m^3 s^{-1}$	River flow rate
	Percent change	%	100*(Altered/Unaltered)
Band	Proportion allowable	Proportion (unitless)	Allowable proportion of maximum rate of take

Time-series outputs provide many interesting details about temporal patterns in calculated water demands, soil moisture conditions, water use, and streamflow depletion. Examples of output time-series relating to storages, consents, land parcels, river flows, and bands are provided in Section 3.1. However, our experiments (see details in Section 2.6.1) required comparisons of calculated outputs across combinations of storage capacity, irrigated area, river flow regime, and water management scenario. We were particularly interested in two types of outcomes resulting from our experiments. The first type of outcome related to ability to limit hydrological alteration and therefore either deliver or fail to deliver predefined environmental flow regimes. The second type of outcome related to the ability to meet reasonable water demands and therefore deliver sufficient or insufficient water to meet reasonable water demands. We therefore summarised some calculated time-series to aid comparisons between sets of outputs using the methods described in Table 2-11. It should be noted that various summary statistics could be applied to various variables. The rationale for selection of summary statistics and variables is also provided in Table 2-11.

Table 2-11: Summary statistics calculated over time-series.

Entity	Variables	Units	Description	Why chosen
Consent	Mean Taken	$m^3 s^{-1}$	Average rate at which water is taken from the river	Represent overall amount of water taken from river
Storage	Mean Stored	m^3	Average volume of water in storage	Represents overall degree to which storage is being utilised
Land	Time Soil water > 0.5*PAW	%	Percent of time that soil water content is greater than half of plant available water	Represents effectiveness of irrigation to keep soil water content within readily available water level for unrestricted plant growth
River	7dMALF	$m^3 s^{-1}$	Mean of series of annual minima after having fitted a 7-day running window	Indicates magnitude of low flow conditions, also used to describing water allocation rules
River	Median	$m^3 s^{-1}$	Median of all mean-daily flows	Indicates magnitude of general flow conditions, also used to describing water allocation rules
River	Time Change FebQ < 80%	%	Percent of time in February that altered mean daily flow is within 80% of unaltered mean daily flow	Represents impacts on very low flows
River	Change in 90-day Qmin	%	Percent change in 90-day mean annual low flow (90-dMALF) between unaltered and altered flows	Represents impact impacts on summer low flows

An 80% change in flow was selected for "Time Change FebQ < 80%" to align with the "presumptive standard" method of Richter et al. (2012), which is an example of an approach that proposed rules of thumb for limits to hydrological alteration. See "river flow management guidelines" of Booker et al. (2022a) for further discussion of approaches to environmental flow regime setting that range from "limit to hydrological alteration" approaches to more "designer flow regime" approaches. In brief, "limit to hydrological alteration" approaches are more applicable to natural and semi-natural rivers where the primary objective and opportunity is ecological conservation (see Richter et al. 2012 for details). "Designer flow regime" approaches are better suited to modified and managed rivers where return to natural conditions is no longer feasible and the objective is to maximize natural capital, as well as support economic growth, recreation, or cultural values (see Acreman et al. 2014 for details). In both approaches, environmental flow regimes often aim to mimic naturalised flow patterns and ecological outcomes of the natural flow regime.

2.8 Analysis

We used the results from our numerical experiments to assess three aspects of the hydrological system resulting from run-of-river takes and high-flow harvesting:

1. River – assessment of alteration of river flows compared to the unaltered/natural state. This assessment supports the evaluation of environmental sustainability of high-flow harvest relevant to our second principle and heuristic set out in Section 2.2 relating to environmentally sustainability.

2. Storage – dynamics of the storage in terms of its adequacy to store available harvested water and to support irrigation demand. This assessment assists with designing adequate storage capacity to meet the reasonable irrigation demand associated with water use efficiency (third principle and heuristic).

3. Land – assessment of irrigation demand and available water to meet reasonable water use. As outlined in Section 2.2, we consider it is poor use of the resource and uneconomical to fully meet irrigation demands. This is because irrigation demand varies between years for the same crop due to variation in climate (e.g., rainfall and potential evaporation), and it is not efficient use of resource to allocate water to meet the maximum possible demand over a long period. Maximum demand may occur rarely (e.g., every 1-in-20 years on average) and leads to under-utilisation of the resource in other years within the current consenting regime of fixed allocation limits. Thus, this assessment supports examination of water use efficiency (out third principle and heuristic).

Results are presented for the experiments described in Section 2.6. River alterations due to water abstractions along with dynamics of the storage (change in water volume in the storage) and land (soil-water stress due to change in water availability to meet irrigation demand) are compared between experiments. We present results for our example site, Awanui at School Cut, for the period 1990–1995 in Section 3.1 in order to explain the format of results produced by our methods. Results for this example site are also used to describe interactions between river, storage and land that are relevant to management of flow harvesting. In Section 3.2, we present a systematic analysis of results for all sites for all periods when flow data were available.

After having completed our modelling, we then presented results for flow alteration, storage, and land conditions against median flow in Section 3.2.6. This final step in our analysis was designed to assess if results were generalisable across sites, and therefore could be transferred to new sites. We used median flow as it represents river size in terms of river flow magnitude. Use of median flow is also advantageous because estimates of median flow are available for all locations across the national river network, although they are subject to uncertainties (see Booker and Woods 2014), (see nzrivermaps tool described by Whitehead and Booker 2019).

3 Results

3.1 An example site; Awanui at School Cut

3.1.1 Experiment 1: five-band harvesting

Figure 3-1 shows an example of river flows for unaltered and altered settings for the Awanui at School Cut site for the period from July 1990 through to June 1991. Flow alteration is greater during the irrigation season, especially in the months of high plant-water demand (December to February) to replenish the storage when supply from storage is high due to high demand for irrigation. Flow alteration (very minor) only occurs in the non-irrigation season (winter) in order to replenish leakage from the storage.

Figure 3-1 can be used to assess the level of flow alteration to a river flow regime and to support water allocation regimes to sustain ecosystem health by delivering environmental flows.

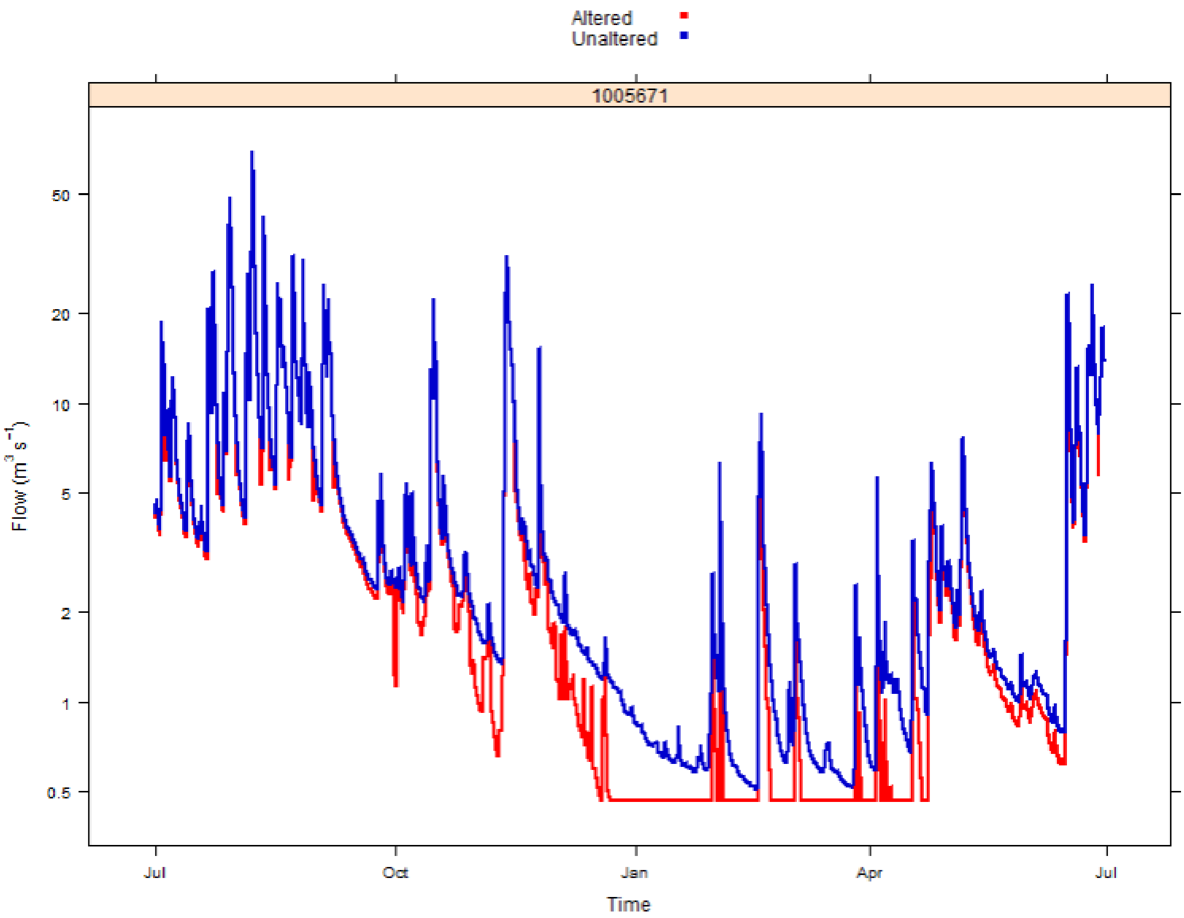

Figure 3-1: Calculated time-series for river flows for the *five-band harvesting* experiment. Results are for water year (1990–1991) for the Awanui at School Cut.

Figure 3-2 depicts the calculated time-series of proportion allowable to take for the five bands used in our experiments for the Awanui at School Cut for water year 1990–1991. This shows that except for some periods during the summer, all allocated water associated with Band 1 is available for abstraction throughout the year. Water is less available for harvesting in higher bands, indicating decreased supply reliability. Figure 3-2 also exhibits changes in availability of water between bands with gradual changes in availability over many days in lower bands and abrupt changes in availability within a short period for higher bands (i.e., daily availability associated with higher bands is either on or off).

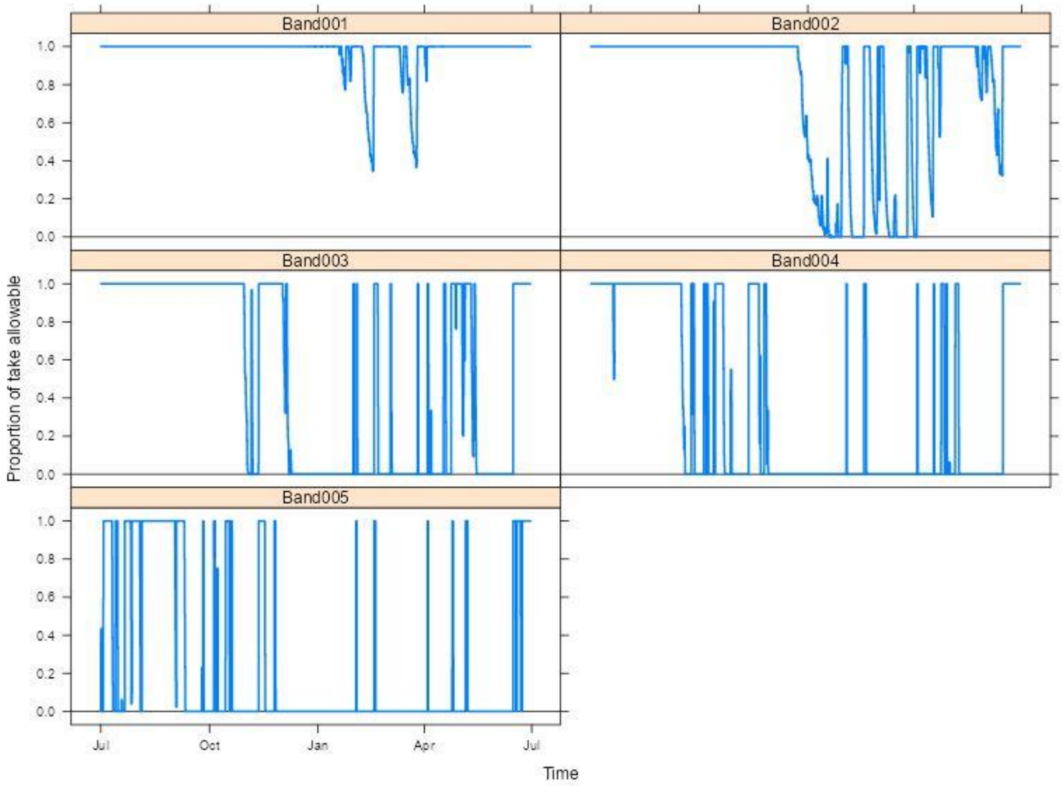

Figure 3-2: Example calculated time-series of proportion allowable to take for five bands. Results are for the Awanui at School Cut for one example water year (1990–1991).

Figure 3-3 shows the maximum water harvesting potential ("Allowable Take") and calculated water taken from the stream ("Taken"). This shows that there is a surplus of water available for harvest in many years bar in February to May 1994. Surplus availability results when the storage is full and the soil water content is at or near its target level.

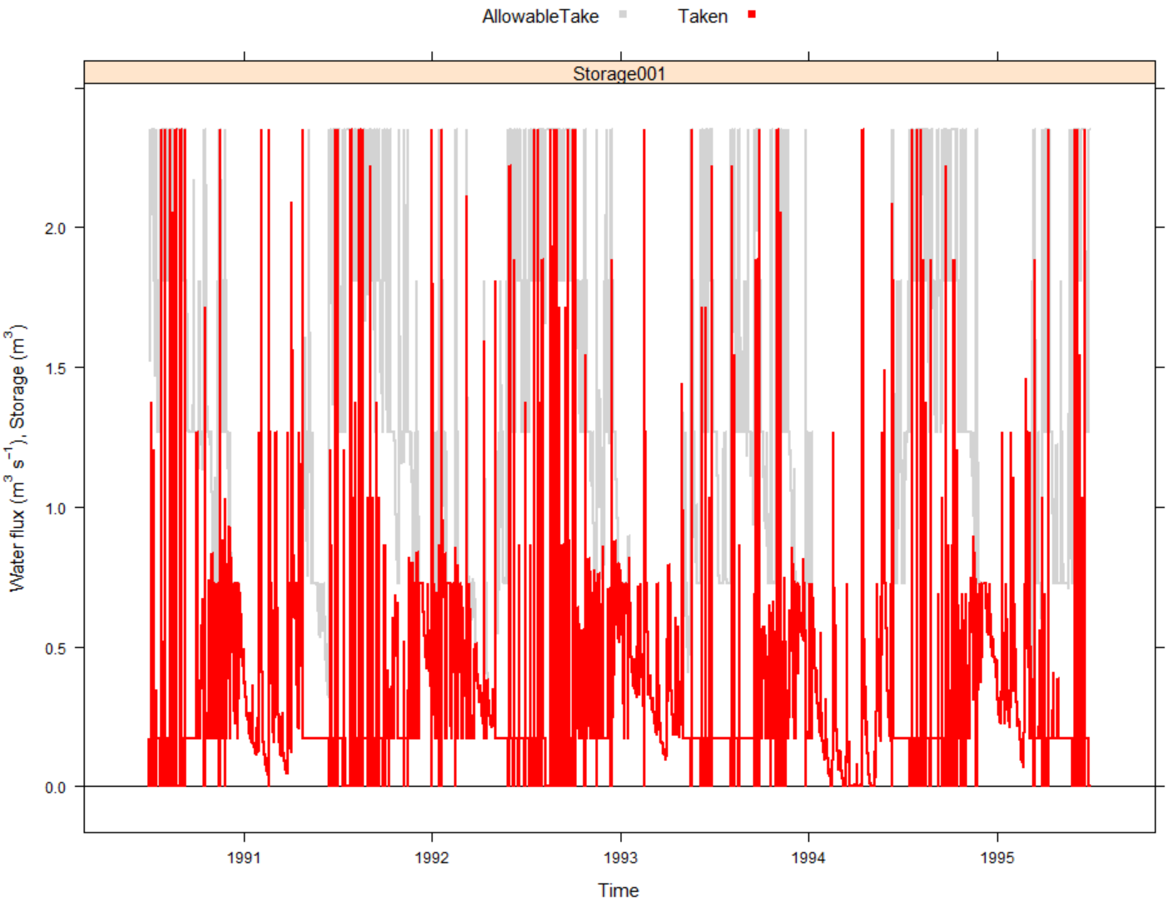

Figure 3-3: Calculated time-series of water harvesting potential and likely volume of harvest under the *five-band harvesting* experiment for the Awanui at School Cut for July 1990 to June 1995. "Allowable" refers to the maximum allowable rate at which water can be taken. "Taken" refers to water taken from the environment to meet demand or fill storage.

Figure 3-4 shows percent of time that flow is not exceeded for unaltered and altered scenarios. Over 25% flow alteration occurs just above the cease-to-take flow of Band 1 and gradually decreases as flows increase. However, minor step changes are also visible at cease-to-take thresholds associated with the other bands (see Table 2-9). Figure 3-5 illustrates monthly flow alterations (expressed as median flow) – greater monthly flow alteration occurs in lowest (e.g., December and January) and highest flow (e.g., July and August) periods. The flow alterations during the summer low flows are primarily due to higher percent alteration of a low flow value. Larger change to flow in winter result from harvesting of available water resources for storage. Under our assumptions, irrigation was supplied in summer months but water was still taken from the river in winter months to fill storages. Furthermore, some supply to storage was required throughout the year to replenish losses through leakage, even when a storage is full.

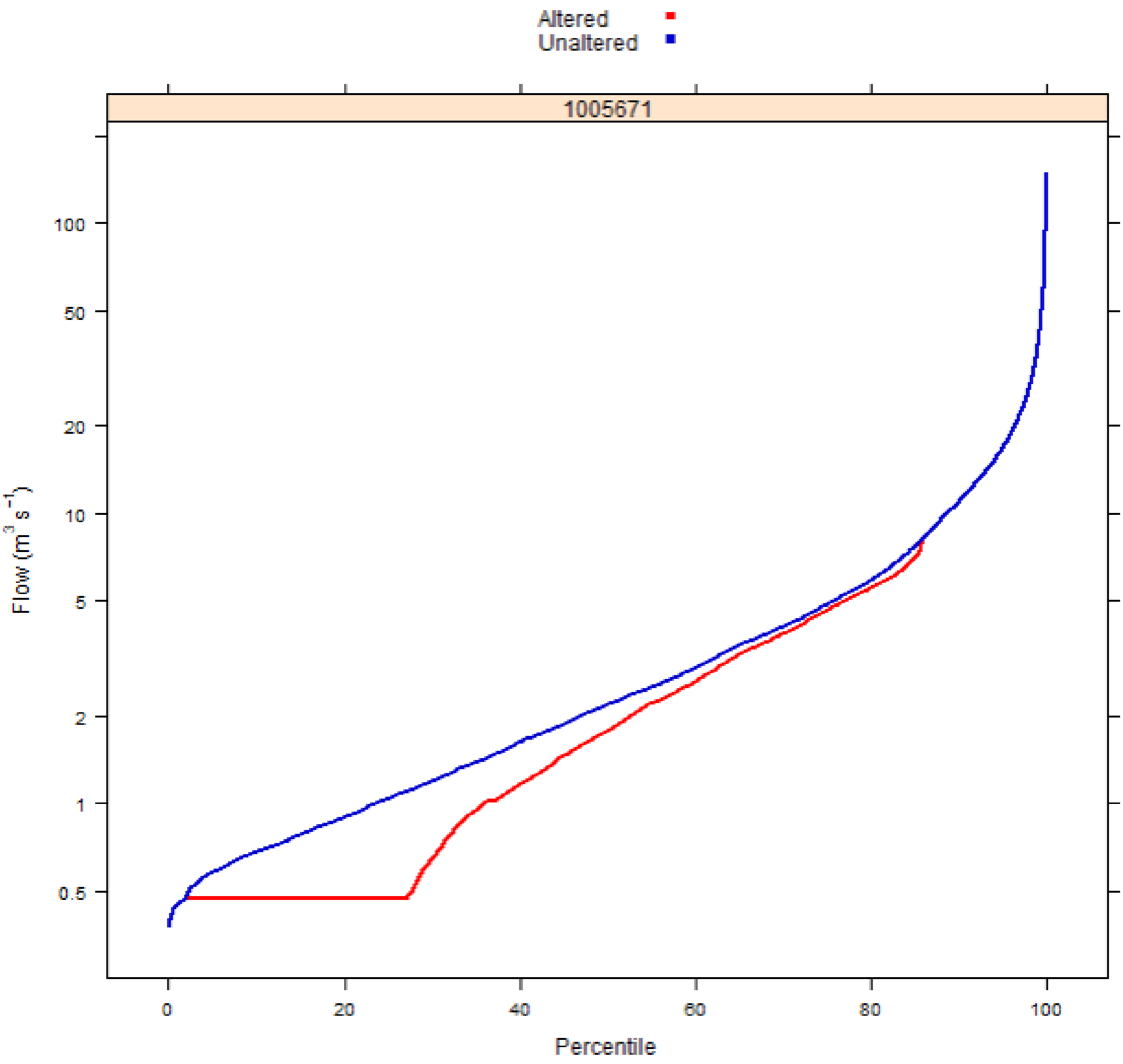

Figure 3-4: FDCs for unaltered and altered flows under the *five-band harvesting* experiment for the Awanui at School Cut for the period of July 1990 to June 1995. Y-axis is in log scale.

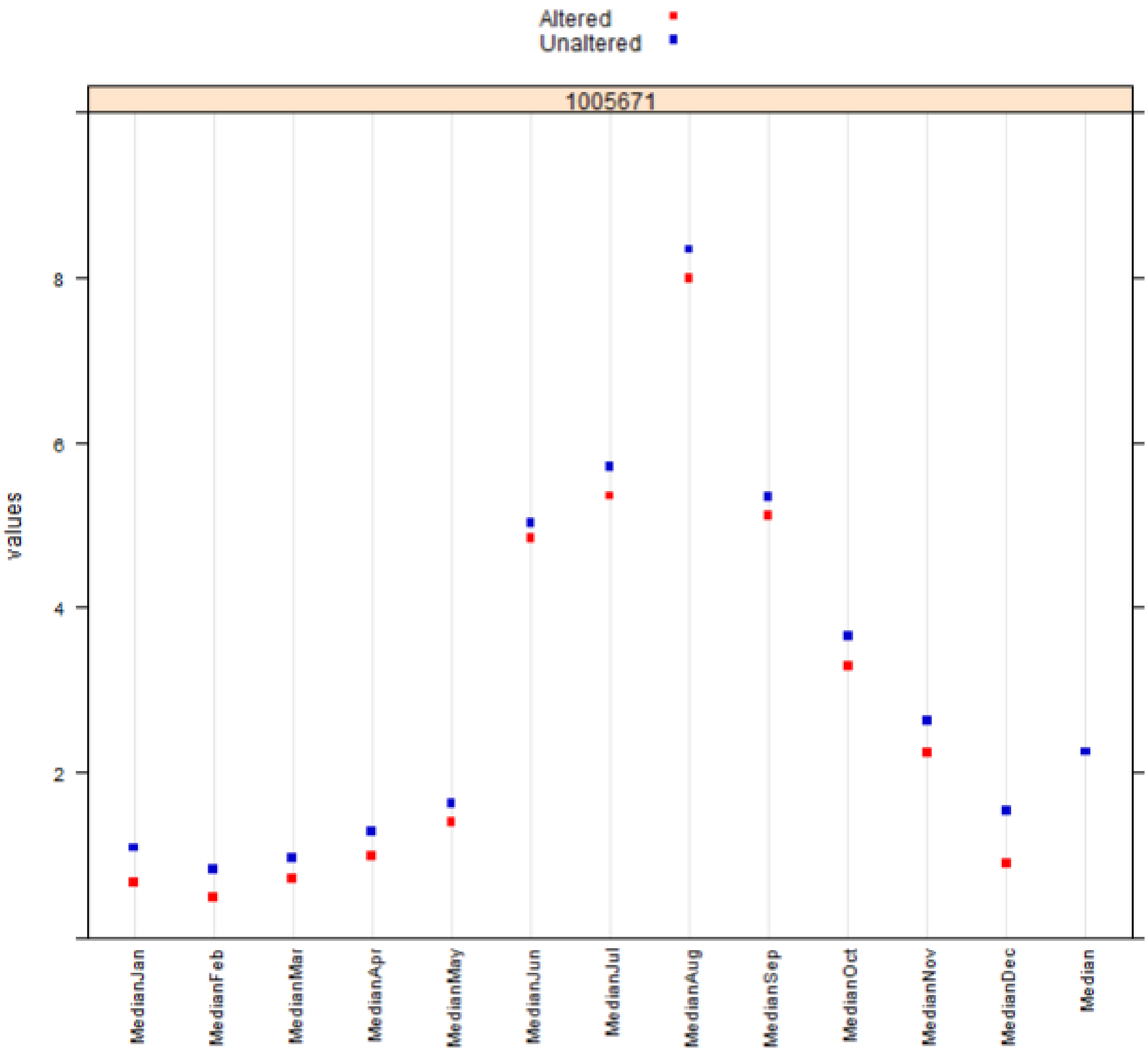

Figure 3-5: Mean monthly unaltered and altered flows along with the overall mean for the Awanui at School Cut under the *five-band harvesting* experiment for July 1990 to June 1995. Y-axis values give median flow in $m^3 s^{-1}$.

Time-series of water fluxes for the storage associated with the Awanui at School Cut is shown Figure 3-6. Inflows into the storage ("Taken") occurs throughout the year but is most prominent in the winter (non-irrigation season) when the allocable resources are greater (as shown in Figure 2-10).

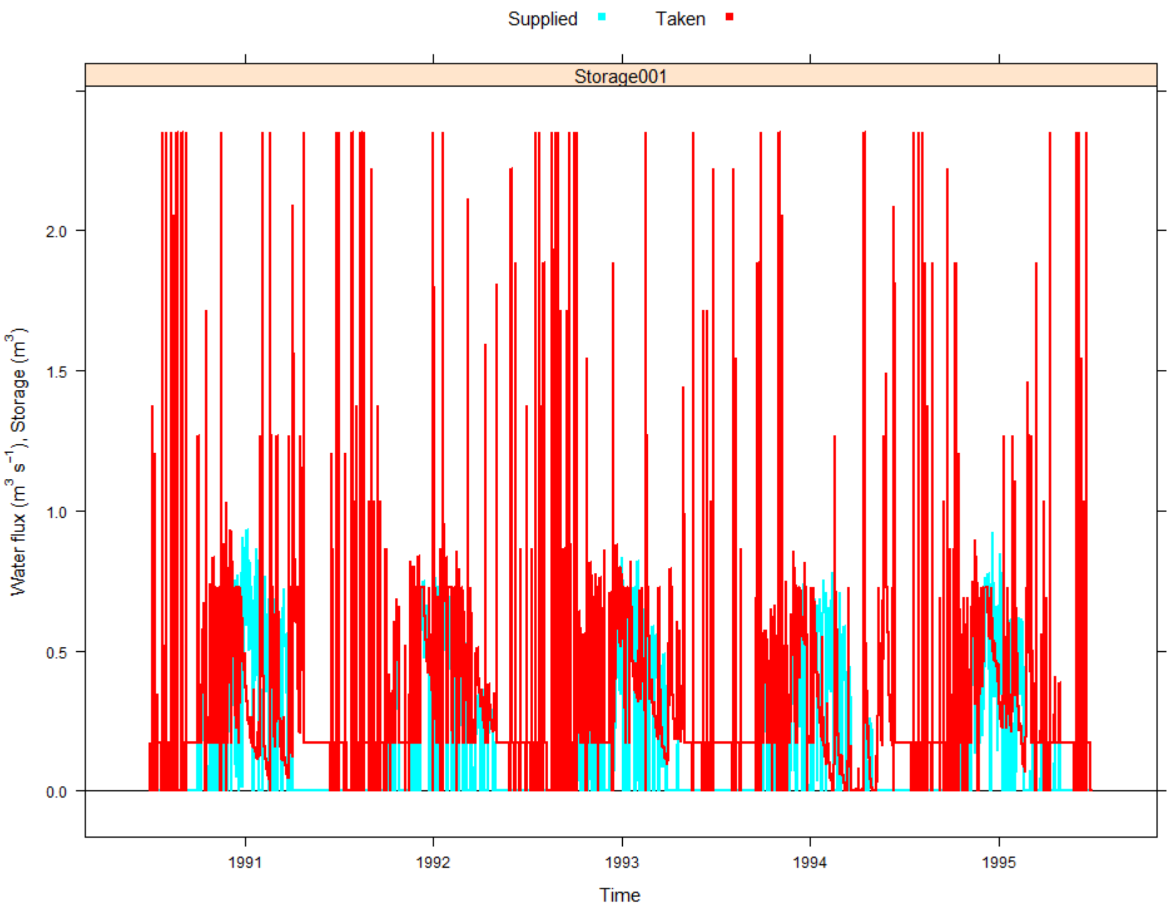

Figure 3-6: Calculated time-series for water fluxes for the storage associated with the Awanui at School Cut under the *five-band harvesting* experiment for July 1990 to June 1995. "Supplied" refers to water supplied to land. "Taken" refers to water taken from the environment.

A storage volume hydrograph is shown in Figure 3-7. It shows that volume of water stored generally decreases during the irrigation season (mainly around January and February) due to greater water supply to land to meet irrigation demand. The storage capacity modelled in our numerical experiment was sufficient to meet demand (storage volume > 0 m^3) except during summer 1994 that resulted from lack of available water resources for harvest from the stream as shown in Figure 3-6 ("Supplied" is zero or low).

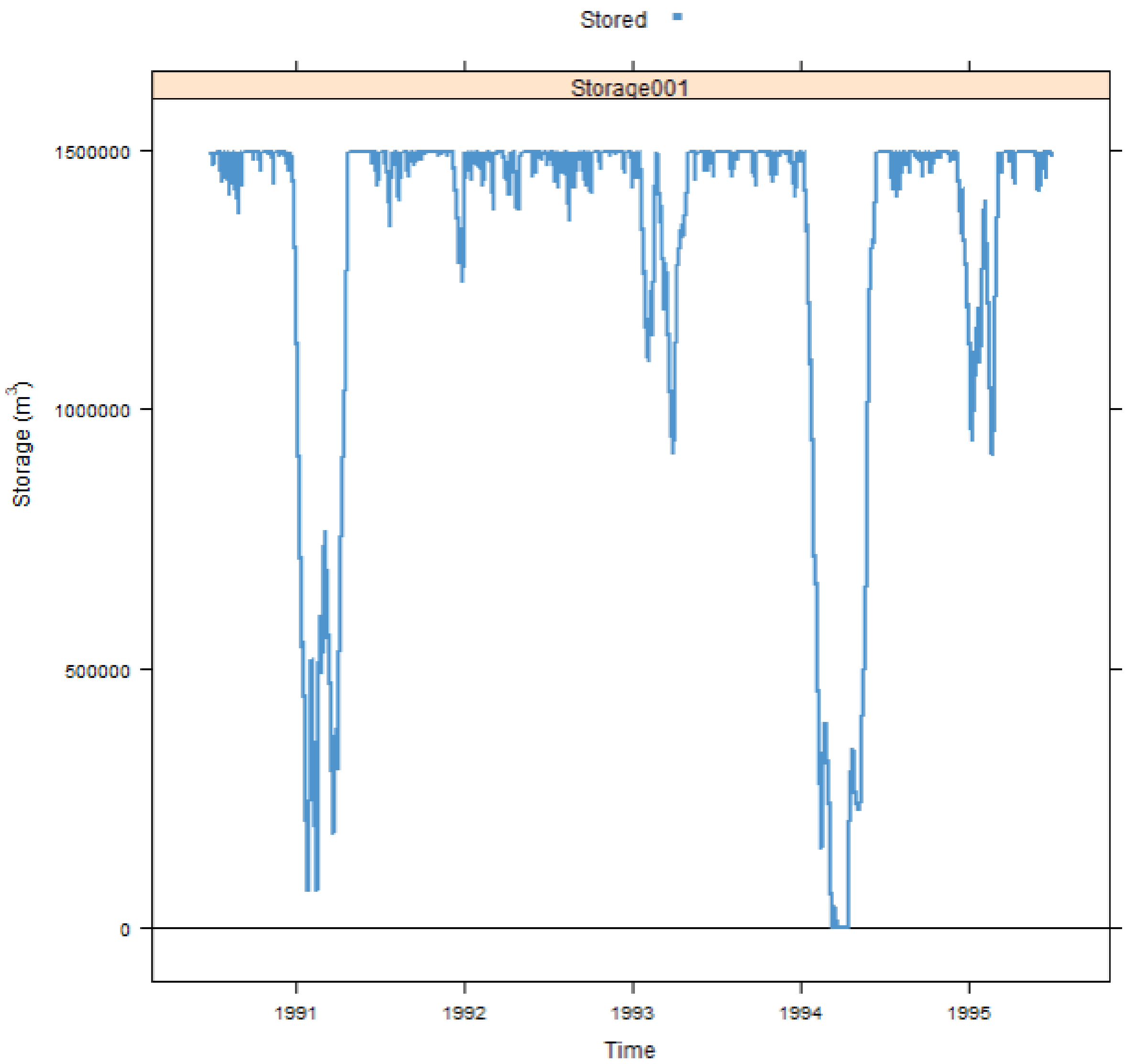

Figure 3-7: Storage volume hydrograph associated with flow harvesting from the Awanui at School Cut under the *five-band harvesting* experiment for July 1990 to June 1995.

Figure 3-8 shows a time-series of irrigation water demand for pasture and soil water content of the land parcel (we assumed homogeneous PAW of 100 mm over the land parcel). This figure indicates that water supply reliability from the storage is generally high to maintain a reasonably high soil water content and soil water consent only drops below the preferable 50% PAW (that we modelled as the readily available water content) for only a few days in 1994 when the storage was empty (Figure 3-7).

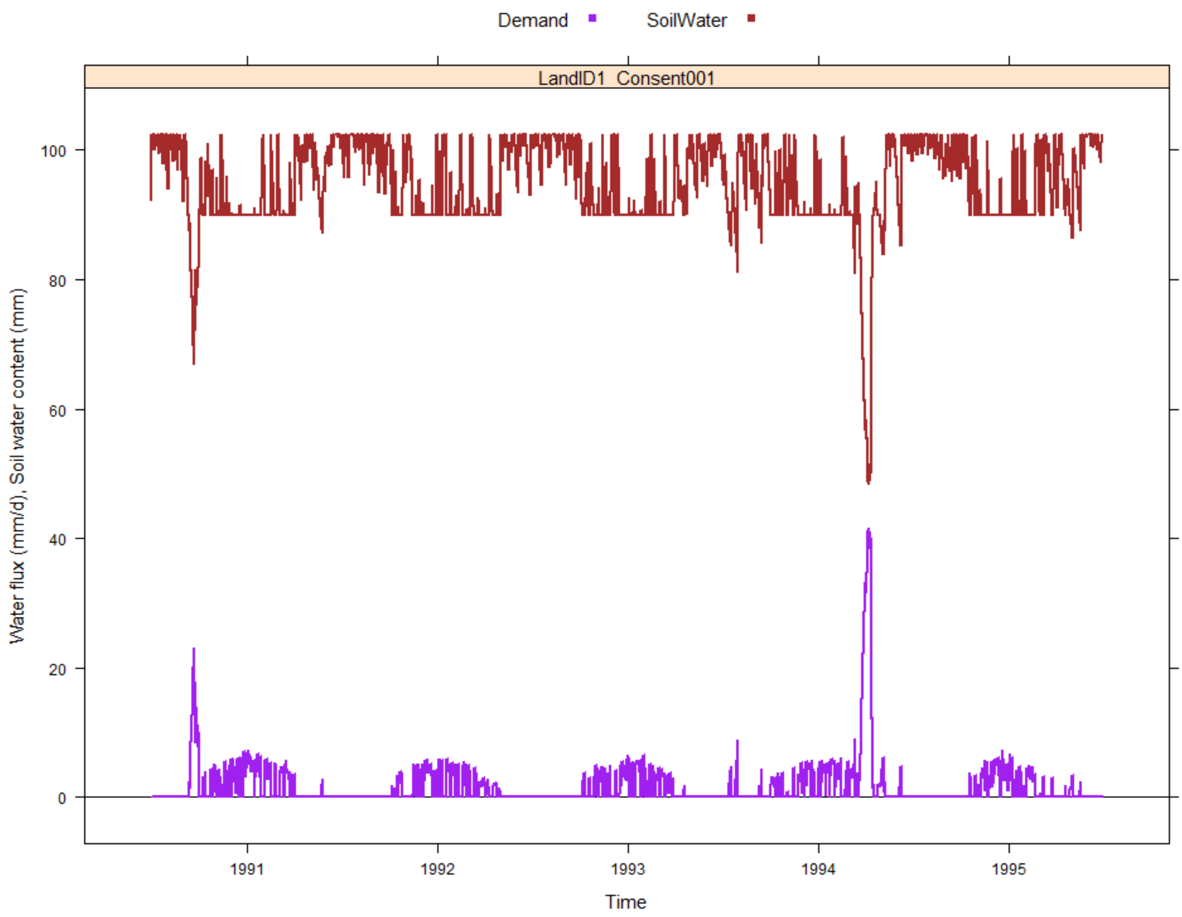

Figure 3-8: Calculated time-series of irrigation water demand and soil water content under the *five-band harvesting* experiment for July 1990 to June 1995.

3.1.2 Experiment 2: four-band harvesting

Flow alteration due to abstractions for the *four-band harvesting* experiment for the Awanui at School Cut site for the period July 1990 through to June 1991 is shown in Figure 3-9. The flow alteration occurs due to both run-of-river abstractions from Band 1 and flow harvesting from Band 2–4, as described in Section 2.6.4.

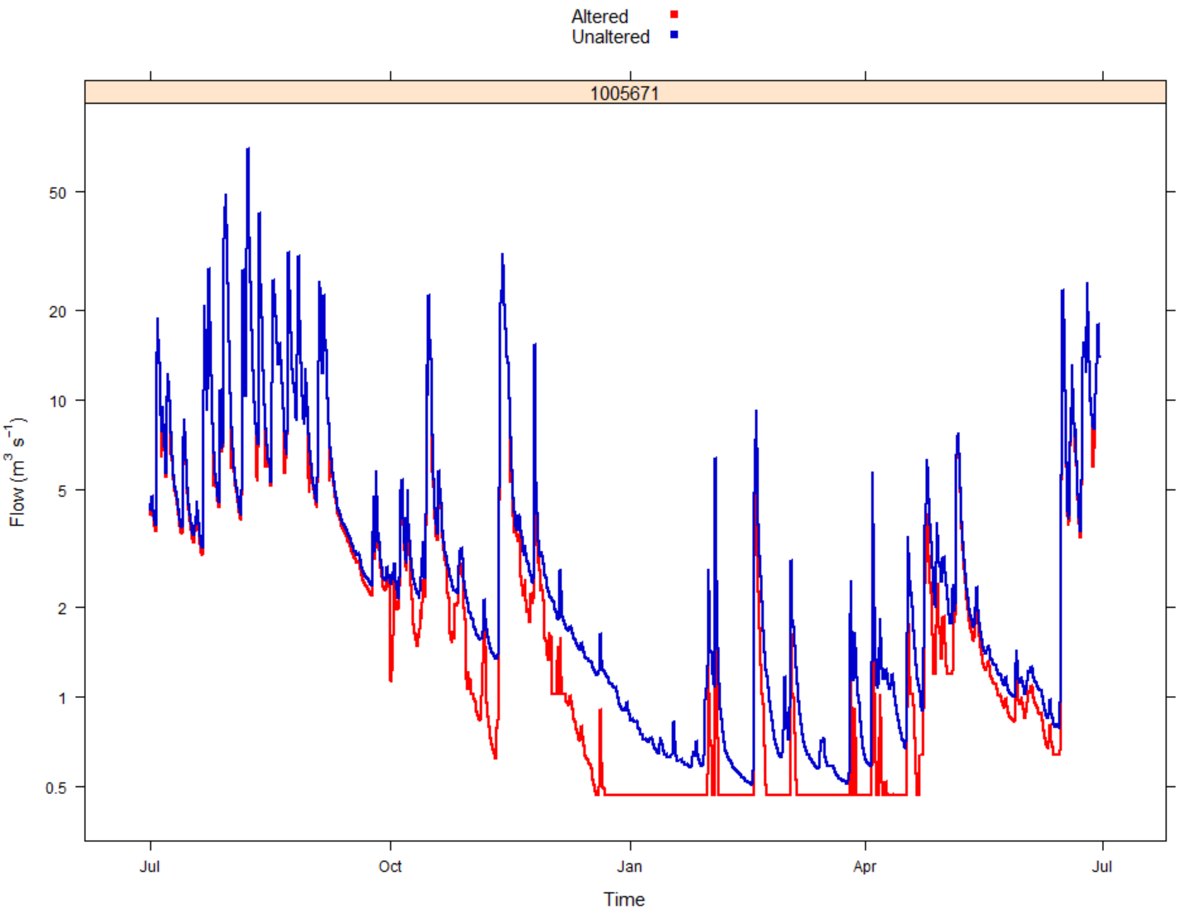

Figure 3-9: Calculated time-series for river flows for the *four-band harvesting* experiment. Results are for water year (1990-1991) for the Awanui at School Cut.

Figure 3-10 illustrates the unaltered and altered FDCs for the *four-band harvesting* experiment. Compared to Figure 3-8 (*five-band harvesting* experiment), Figure 3-10 shows more noticeable step changes along the altered curve, particularly around flows at 0.64 and 1.2 m^3 s^{-1}; these flows coincide with the cease-to-take (0.64 m^3 s^{-1}), and maximum allocation rate above the cease-to-take (1.19 m^3 s^{-1} = cease-to-take (0.64 m^3 s^{-1}) + maximum allocation rate (0.55 m^3 s^{-1})) for Band 2. This figure indicates that major flow alterations occur within Band 1 and 2 that are the most reliable water for flow harvesting under this configuration of rules.

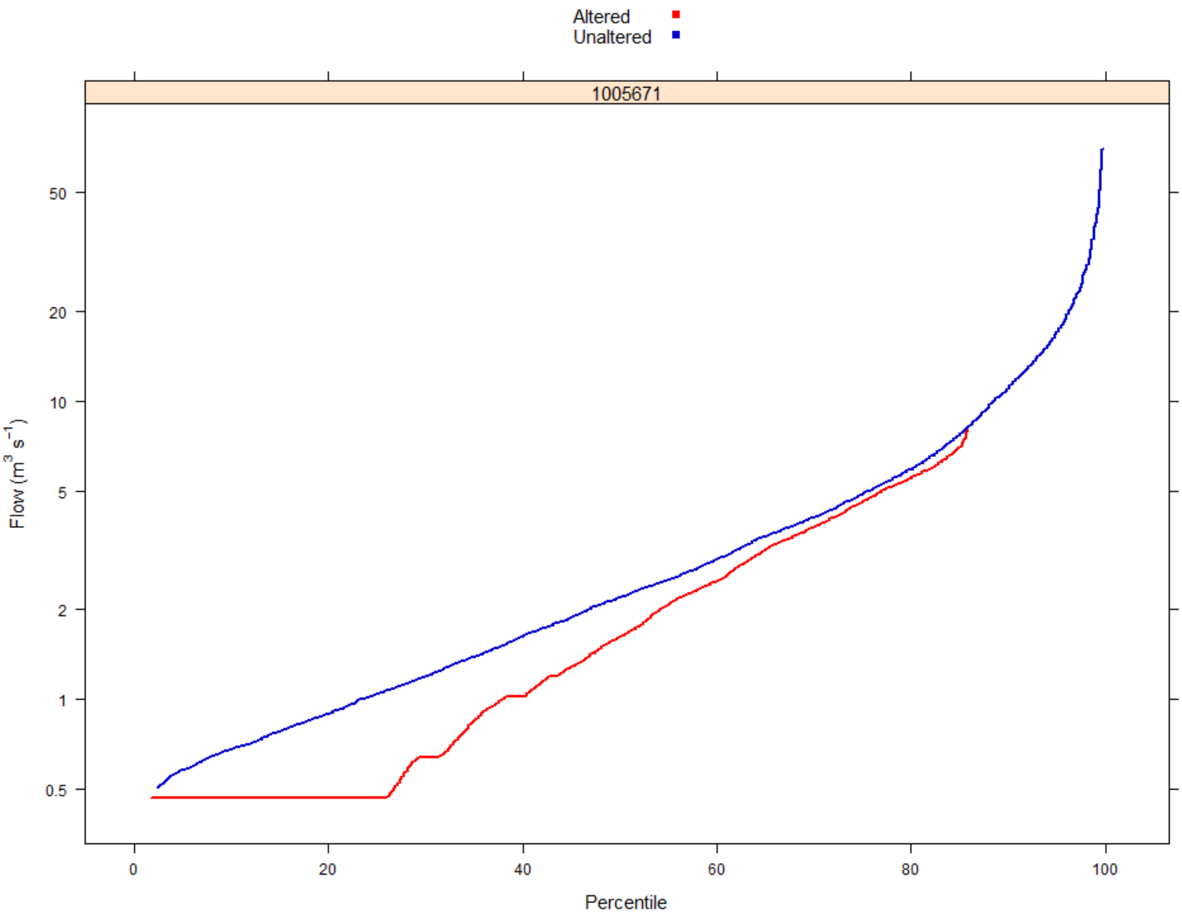

Figure 3-10: FDCs for unaltered and altered flows for the *four-band harvesting* experiment for the Awanui at School Cut for the period of July 1990 to June 1995. Y-axis is in log scale.

Figure 3-11 shows the in- and out-flows (excluding evaporation and leakage) to and from the storage for the *four-band harvesting* experiment. It illustrates that available water resources from the storage were not sufficient to supply to the land ("Supplied") in at latter part of the irrigation season especially in 1990–91 and 1993–94 seasons. Figure 3-11 also shows that limited water is available to harvest from the river ("Taken") in summer months. Thus, it indicates that the storage capacity is too small to provide adequate supply reliability for irrigation under the modelled water harvesting allocation rules.

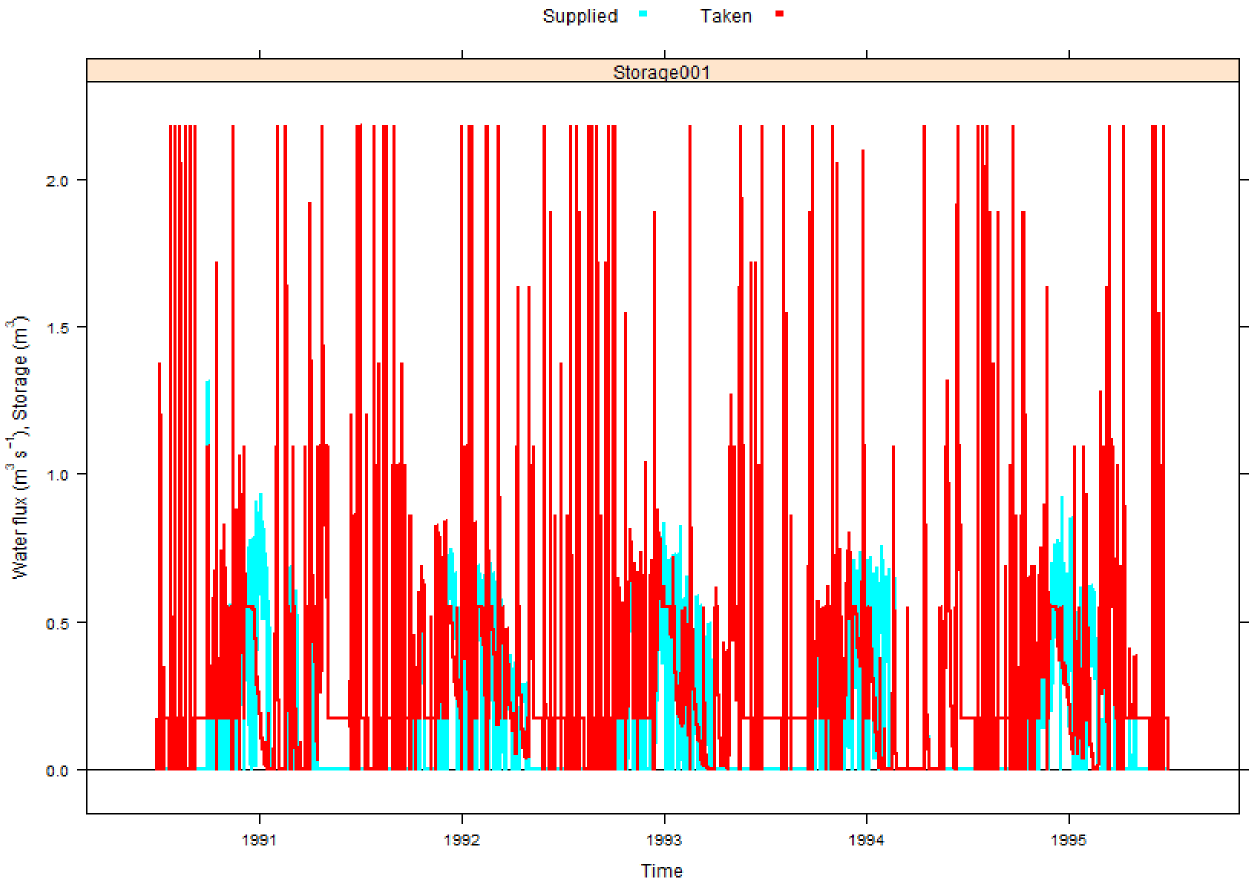

Figure 3-11: Calculated time-series for water fluxes for the storage associated with the Awanui at School Cut under the *four-band harvesting* experiment for July 1990 to June 1995. "Supplied" refers to water supplied to land. "Taken" refers to water taken from the environment.

Figure 3-12 illustrates the storage volume hydrograph for the *four-band harvesting* experiment. The storage is empty in the latter part of the irrigation season in 1990–91 and 1993–94 (low supply reliability in two out of five seasons modelled), and reached very low levels in another two years. This result shows the storage capacity is inadequate to store more water during high flow periods (e.g., winter and spring) to supply water to meet the irrigation demand during high crop water demand in the summer.

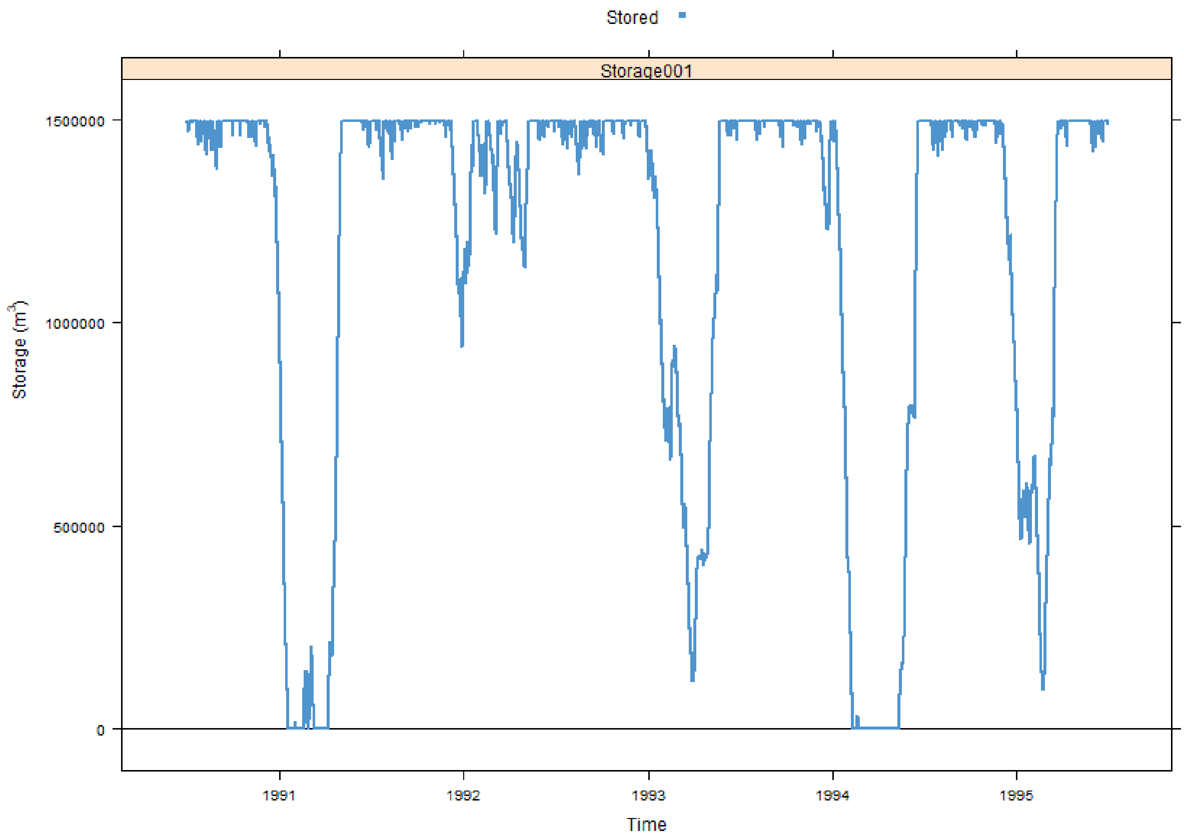

Figure 3-12: Storage volume hydrographs associated with flow harvesting from the Awanui at School Cut under the *four-band harvesting* experiment for July 1990 to June 1995.

Time-series of irrigation water demand and soil water content of the land parcel (Consent 1), which is irrigated from the water supply from the storage, are shown in Figure 3-13 (Land 2 that is irrigated using run-of-river takes under the Consent 2 is not shown as our primary interest in this study is water harvesting and storage). This shows irrigation water deficit ("Demand") reached more than 70 mm d^{-1} in all years. Soil water content also fall below 20 mm (or 20% PAW) – reduction of soil water content. We consider that high irrigation water deficit and low water content in all modelled irrigation seasons represents "very poor reliability" (Frost et al. 2015). As described above, the poor reliability indicates inadequate storage capacity for the modelled irrigation scenario.

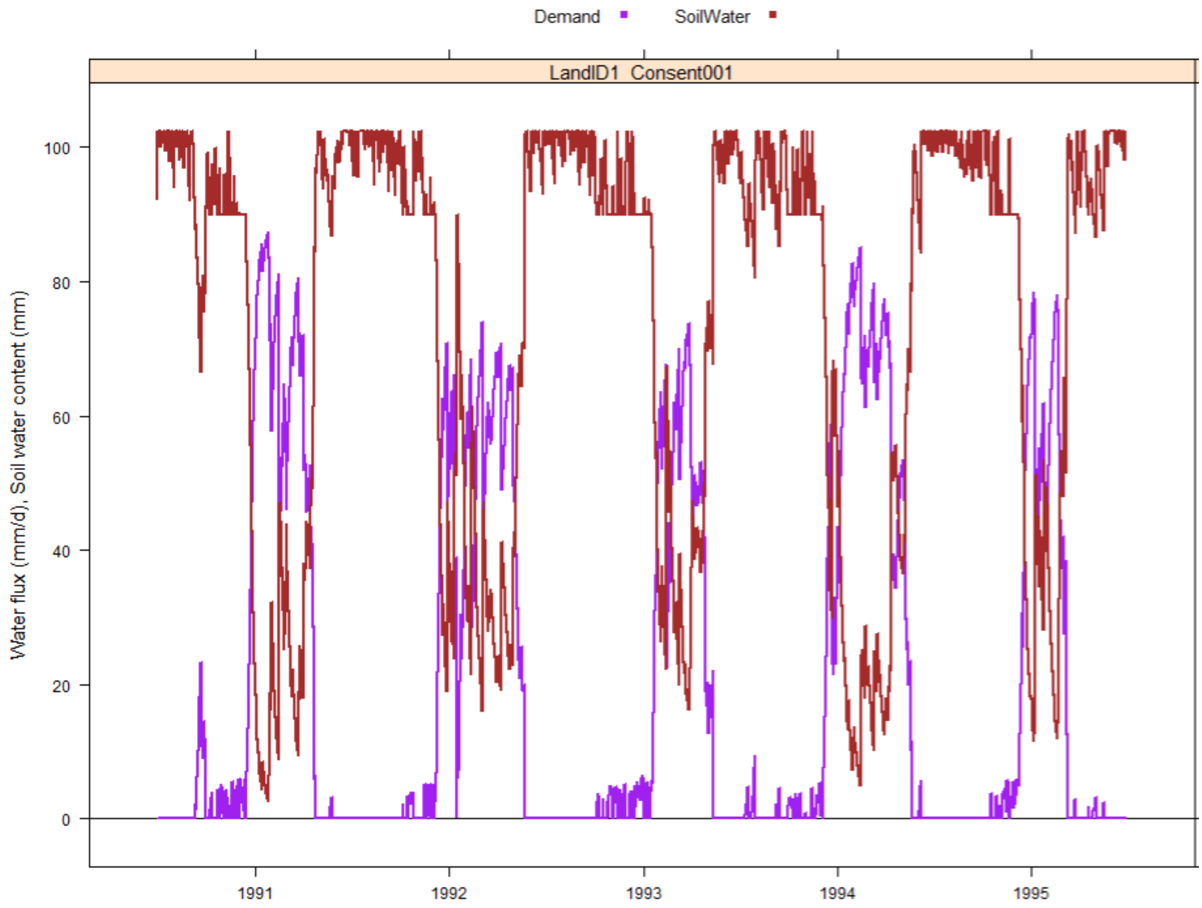

Figure 3-13: Calculated time-series of irrigation water demand and soil water content under the *four-band harvesting* experiment for July 1990 to June 1995.

3.1.3 Experiment 3: three-band harvesting

Figure 3-14 shows the flow alteration due to run-of-river take from Band 1 and harvesting under the top three bands only (Bands 3 to 5), with no takes associated with Band 2, and a run-of-river take from Band 1 for the 1990–91 water year. Results show lower levels of flow alteration in general compared to other experiments, particularly due to no harvesting from Band 2 flows; thus, flow alteration only arises owing to Band 1 takes when the unaltered flow is less than 1.75 $m^3 s^{-1}$ (cease-to-take flow for Band 3). Summer flows are typically low at this example site (Awanui at School Cut) and therefore flow alterations generally mimic those of Experiment 2 due to run-of-river takes during the irrigation season that are common to both experiments.

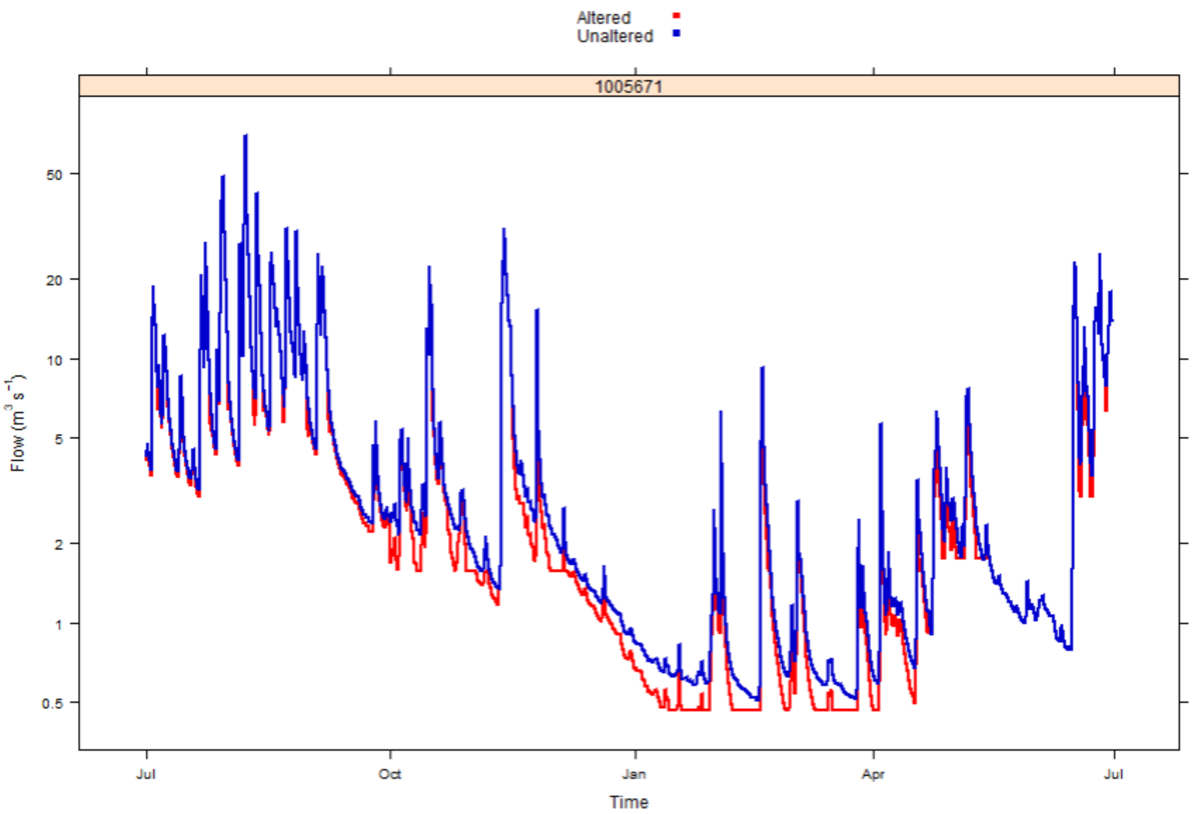

Figure 3-14: Calculated time-series for river flows for the *three-band harvesting* experiment. Results are for water year (1990–1991) for the Awanui at School Cut.

FDCs in Figure 3-15 show that differences between the unaltered and altered flow were primarily influenced by the cease-to-take flows within each band. With no harvesting from Band 2, the alteration in the lower flow bands is approximately 5% up to start of Band 3 at 1.75 $m^3 s^{-1}$.

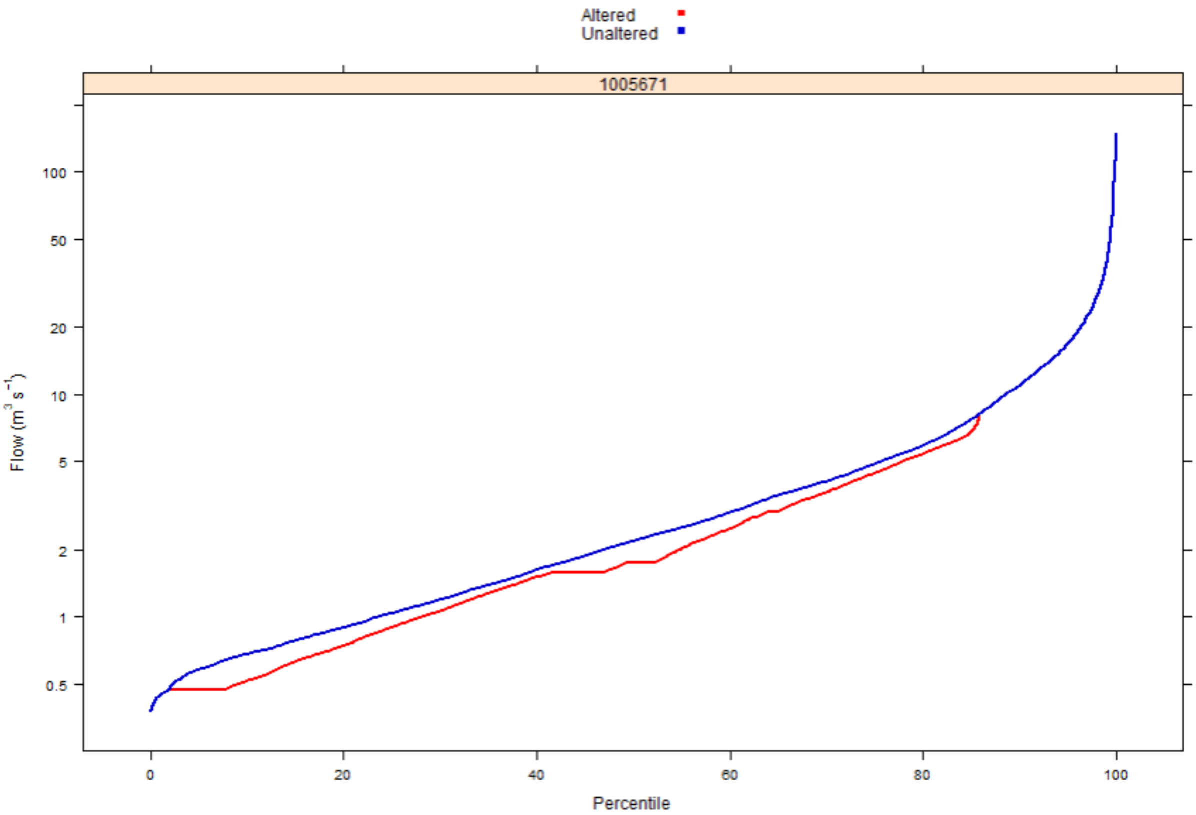

Figure 3-15: FDCs for unaltered and altered flows for the *three-band harvesting* experiment for the Awanui at School Cut for the period of July 1990 to June 1995. Y-axis is in log scale.

Water fluxes in response to storage for the Awanui at School Cut example under the *three-band harvesting* experiment (shown in Figure 3-16) demonstrate that water taken from the environment is insufficient to meet irrigation demand. Available water resources for harvesting into the storage is small in the summer months. When flows are available for harvesting, while it is not clear from Figure 3-16 (as the red line overplots the light blue line), storage does not play a role in most periods in the summer as water is being simulated to be directly delivered to the land as would be the case in a run-of-river supply.

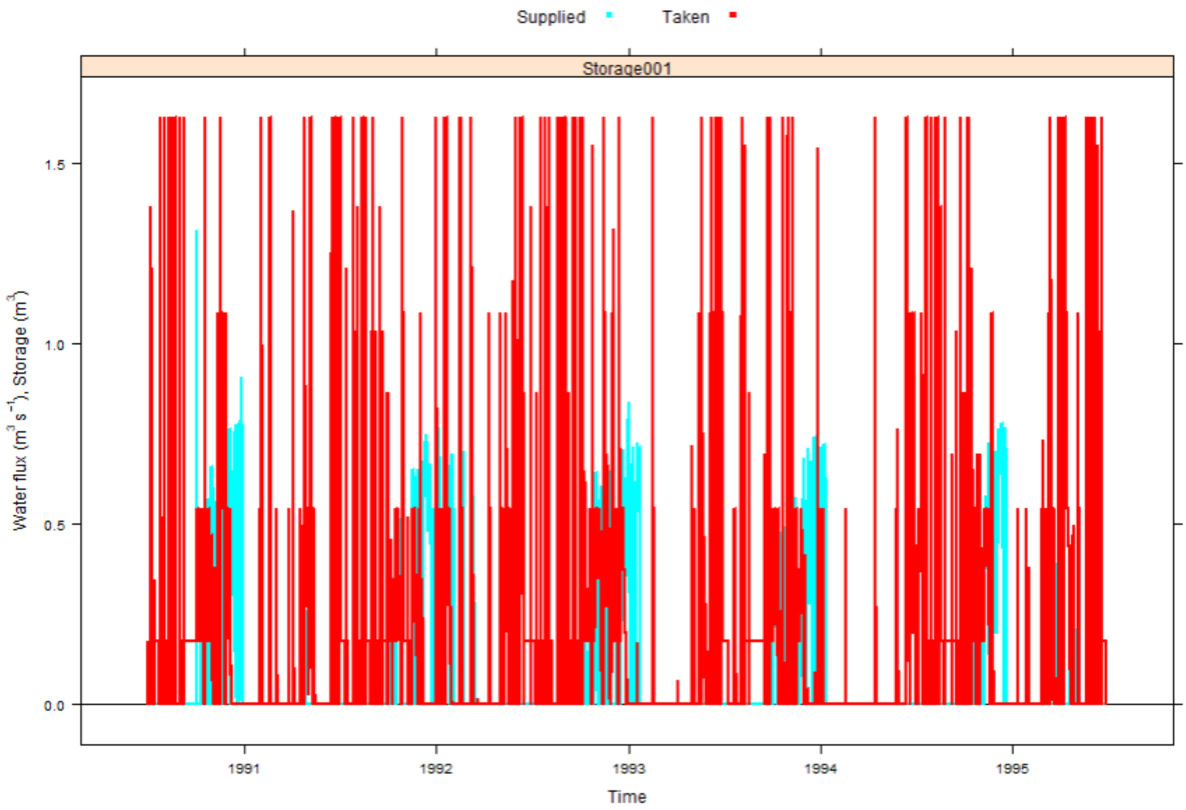

Figure 3-16: Calculated time-series for water fluxes for the storage associated with the Awanui at School Cut under the *three-band harvesting* experiment for July 1990 to June 1995. "Supplied" refers to water supplied to land. "Taken" refers to water taken from the environment.

Figure 3-17 shows the storage volume hydrograph for the *three-band harvesting* experiment for the Awanui at School Cut example. Results shows that depletion of the storage volume starts early in the irrigation season at a slow pace and worsens in the high evapotranspiration period as demand from the land increases. These results indicate that storage capacity is not large enough to store a sufficient quantity of water harvested from the stream needed to meet the demand, even if resources are available for harvesting.

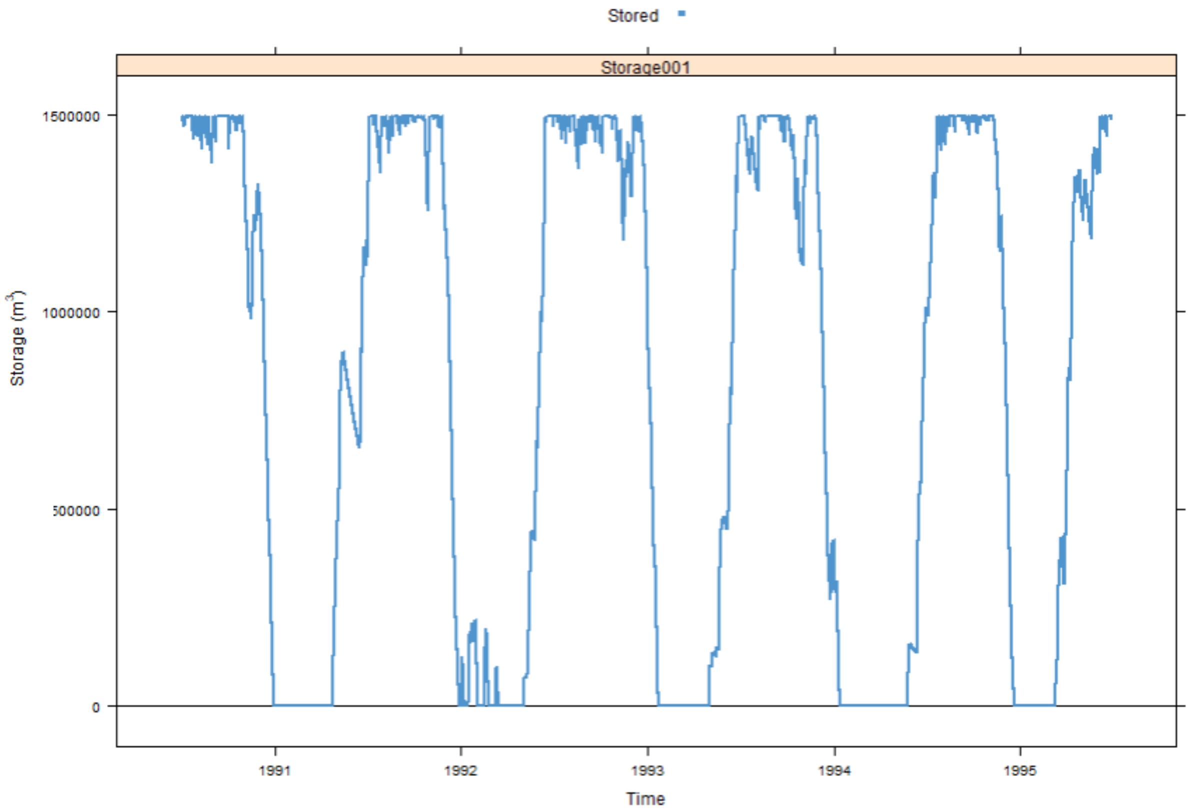

Figure 3-17: Storage volume hydrographs associated with flow harvesting from the Awanui at School Cut under the *three-band harvesting* experiment for July 1990 to June 1995.

As described in Section 3.1.2, predicted soil water content is considerably below the satisfactory level, and results in unacceptable irrigation water deficit in summer months. This again indicates that the storge capacity is inadequate to meet the irrigation demand.

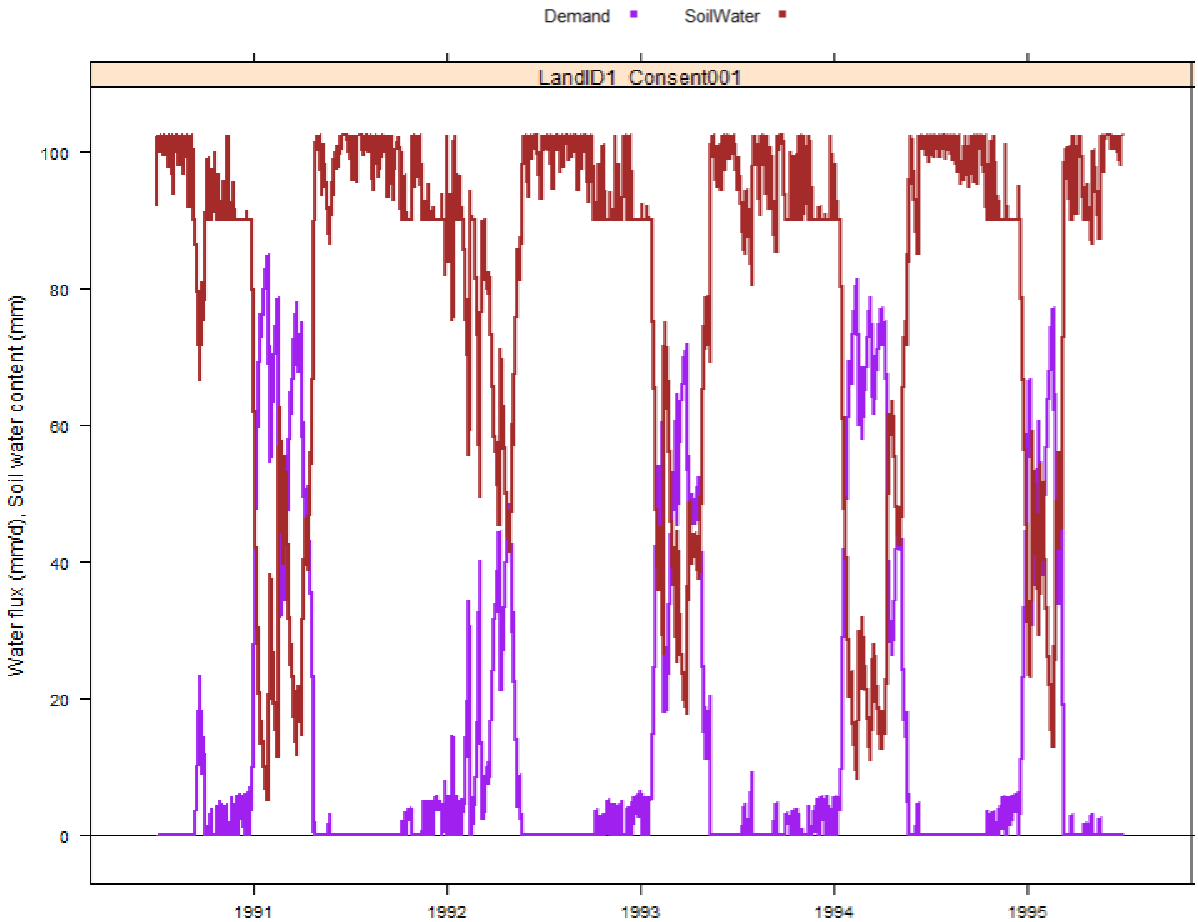

Figure 3-18: Calculated time-series of irrigation water demand and soil water content under the *three-band harvesting* experiment for July 1990 to June 1995.

3.1.4 Comparing across Experiments 1-3

Modelling has revealed details about different components of the system (e.g., river flows, storage and land/irrigation) and interactions between these components for the three experiments in Sections 3.1.1 to 3.1.3. However, as described in Section 2.7, it is important to compare results across water management scenarios and across river flow regimes to understand the inter-connections and impact of one part of the system (e.g., flow, consent conditions, storage or land) on other parts. In this section we present the calculated change in river flow, storage and soil water content (see Table 2-11 for details) in response to differences in areas irrigated and storage capacity.

Figure 3-19 compares results between experiments 1, 2, and 3 (see Sections 3.1.1 to 3.1.3) using time-averaged water harvest, stored water, soil water above the readily available water threshold (0.5 * PAW) and modelled low flow conditions in relation to irrigated area, storage capacity, and river size for Awauni at School Cut. We assess the low flow conditions using two different metrics: (1) percentage of time during February (considered as the lowest flowing month) that altered flow is kept within 80% of the unaltered flow, and (2) the altered 90-day MALF (90dMALF) as a percentage of the unaltered 90dMALF. We assessed the results for combinations of four different irrigated areas (10,000, 100,000, 1,000,000 and 10,000,000 m^2) and four different storage capacities (10,000, 100,000, 1,000,000 and 10,000,000 m^3). Figure 3-20 illustrates the FDCs for three experiments along with the unaltered flows for the period 1990 to 2021.

We make the following observations when results derived from the three experiments described in Sections 3.1.1 to 3.1.3, are compared in Figure 3-19 and Figure 3-20 for Awanui at School Cut site:

- Hydrograph - Figure 3-1, Figure 3-9 and Figure 3-14 revealed that although the level of alteration is different between the *five*- and *four-band harvesting* experiments, similar flow alteration patterns resulted from these experiments and total alteration was less in the *three-band harvesting* experiment. This was because abstractions were similar under *five*- and *four-band harvesting* experiments compared to *three-band harvesting* in which there was no abstraction from Band 2. Although Band 1 water was not used for flow harvesting in *four*- and *three-band harvesting* experiments, run-of-river resources were used for irrigation of a large land parcel (Land 2) under a consent that was not associated with storage (labelled Consent 2). As the purpose of both water takes was irrigation, including the ultimate use of harvested water under Consent 1, we found that the major flow alterations happen during the irrigation season in all experiments. The magnitude of flow alteration was greater under the *four*- and *three-band harvesting* experiments during the non-irrigation season; this was because water from Band 1, which is the most reliable water, and from Band 2 for *three-band harvesting* was not available for harvesting – therefore flow harvesting needs to be carried out virtually throughout the year to replenish the storage.

- FDC - comparison of Figure 3-4, Figure 3-10, Figure 3-15 and Figure 3-20 show that the highest flow alteration occurred in the *five-band harvesting* experiment and the least flow alteration occurred under the *three-band harvesting* experiment.

- Row 1 of Figure 3-19 shows that when storage capacity and irrigated area are both small, average flow taken from the river to storage is similar for all three experiments. With increasing storage capacity and irrigated area, variation in flow taken can be seen between the experiments with most and least for *five-band harvesting* and *three-band harvesting*, respectively.

- Row 2 of Figure 3-19 demonstrates that sufficient water can be taken from the river to keep the storage full for most combinations of storage capacity and irrigated area, however, stored volume for *three-band harvesting* reduces with increasing storage capacity and area.

- Row 3 of Figure 3-19 indicates that modelled soil water status was maintained at an acceptable level (over 50% of PAW for over 90% of the time) for most of the time for all irrigated areas modelled by boosting the storage capacity. However, maintaining soil water above the acceptable level is more difficult under *three-band harvesting* due to limited resource available for harvesting.

- Row 4 and 5 of Figure 3-19 show similar trends for both low flow metrics. When storage capacity and irrigated area for Consent 1 are both small, modelled low flow alteration for *four*- and *three-band harvesting* is significantly higher than for the *five-band harvesting* experiment; this is primarily due to run-of-river supply to Consent 2 (for a large irrigated area) under the former experiments. However, for larger storage capacities and irrigated areas, low flow alteration is greater for five- and *four-band harvesting* relative to *three-band harvesting*, for which modelled low flow alteration is consistent (e.g., altered 90dMALF lies between 85% and 90% of unaltered 90dMALF) for all combinations of storage capacities and irrigated areas. This behaviour is mainly due to no abstractions from Band 2 for *three-band harvesting*.

- It should be noted that Row 4 and 5 of Figure 3-19 show metrics that represent alteration of lower flows only. Figure 3-18 represents alteration across the entire flow range. In general, Figure 3-19 indicates great potential for storage capacity, and also irrigated area, to determine river flow alteration given the combination of conditions we modelled. This is an important finding because it indicates that it cannot be assumed that there is a limit to river flow alteration just because a storage is being used. There is a point when storage size (and therefore storage capacity to be filled and leakage to be replaced), and irrigated area (and therefore demand for supply to land) are large enough for all available water to be taken even when efficient water use is assumed.

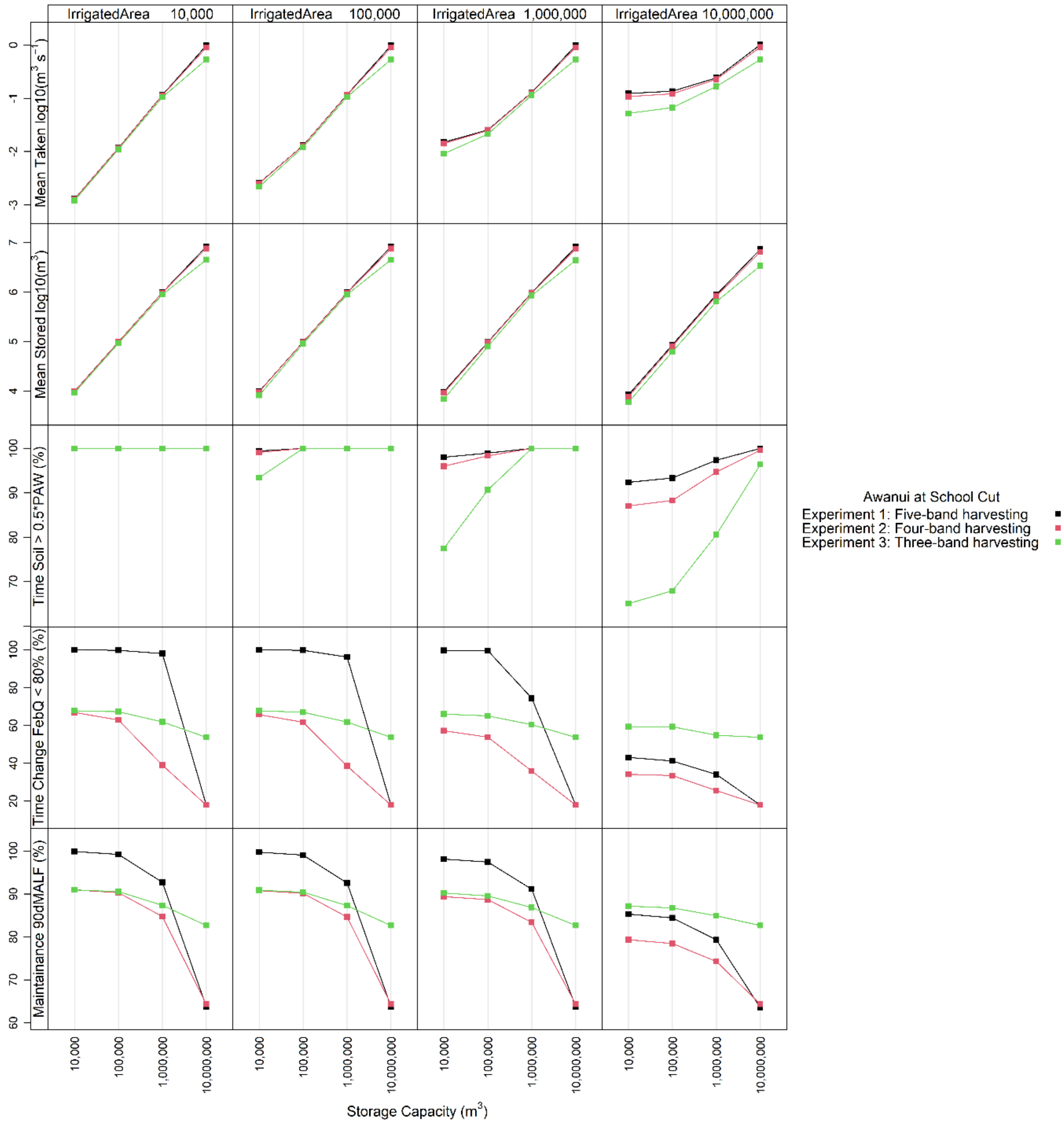

Figure 3-19: Time-averaged take, storage, soil water of the irrigated area above the readily available water (0.5 * PAW), and low flow conditions in relation to irrigated area, storage capacity, and river size, under different water allocation experiments for Awanui at School Cut. Note: y-axes of first and second rows are in log scale (first row: $\log_{10} 1 = 0$, $\log_{10} 0.1 = -1$, $\log_{10} 0.01 = -2$, $\log_{10} 0.001 = -3$; second row: $\log_{10} 10000 = 4$, $\log_{10} 100000 = 5$, $\log_{10} 1000000 = 6$, $\log_{10} 10000000 = 7$).

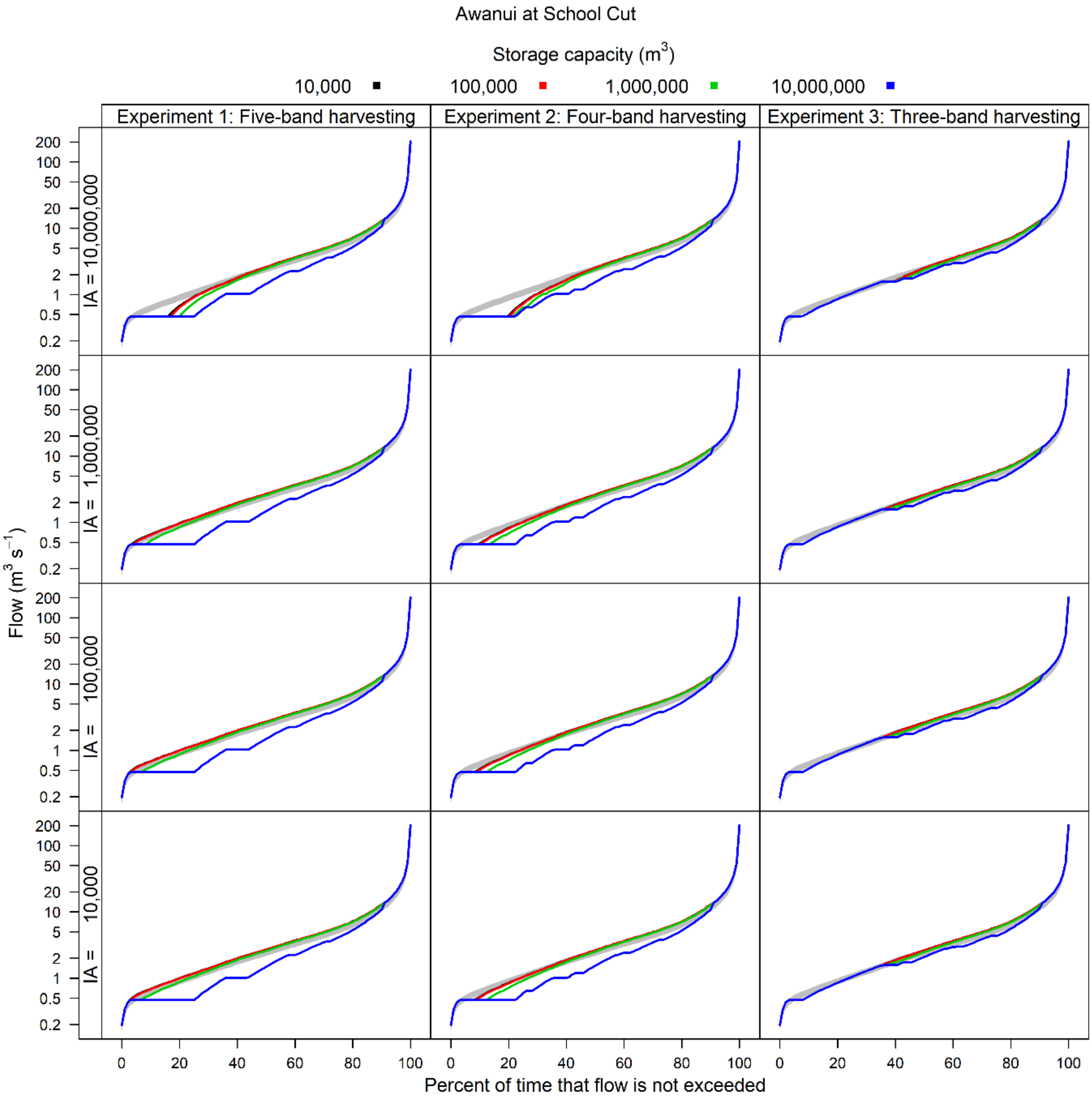

Figure 3-20: FDCs for unaltered and altered flows under the three experiments for the Awanui at School Cut for the period of July 1990 to June 2021. Note: grey polygon shows ranges of flows between unaltered and an 80% reduction. IA = irrigated area (m^2).

Figure 3-21 and Figure 3-22 compare flow hydrographs and soil water content time-series for two combinations of irrigated area and storge capacity against the unaltered regime (no abstractions and no irrigation) for the three experiments for Awanui at School Cut. We maintained the storge capacity constant at 10,000 m^3 and varied the irrigated area from 10,000 to 10,000,000 m^2 for the altered scenarios to obtain further insights on interactions between flow, storage and land.

Key observations from Figure 3-21 are:

- The *five-band harvesting* experiment shows that when storage capacity and irrigated area are both small, flow alteration is minor. This is expected as the water demand for irrigation is low for the small area, and no capacity exists to store large quantity of water. When irrigated area is large, flow alteration is greater, particularly in the irrigation season; this occurs because storage of large volumes of water prior to the irrigation season is not possible.

- Flow alteration for small storage capacity and small irrigated area scenarios is significantly greater for the *four-band harvesting* experiment relative to the *five-band harvesting* experiment. This is mainly due to run-of-river takes for irrigation of a large land under Consent 2 in the four band harvesting scenario. Flow alteration is even greater with the increased irrigated area because water demand increases. The alterations are pronounced in the irrigation season.
- The *three-band harvesting* experiment illustrates that flow alterations are lower than those for the *four-band harvesting* experiment for both small and large irrigated area scenarios – limited water is available (from top three bands) to supply storage.

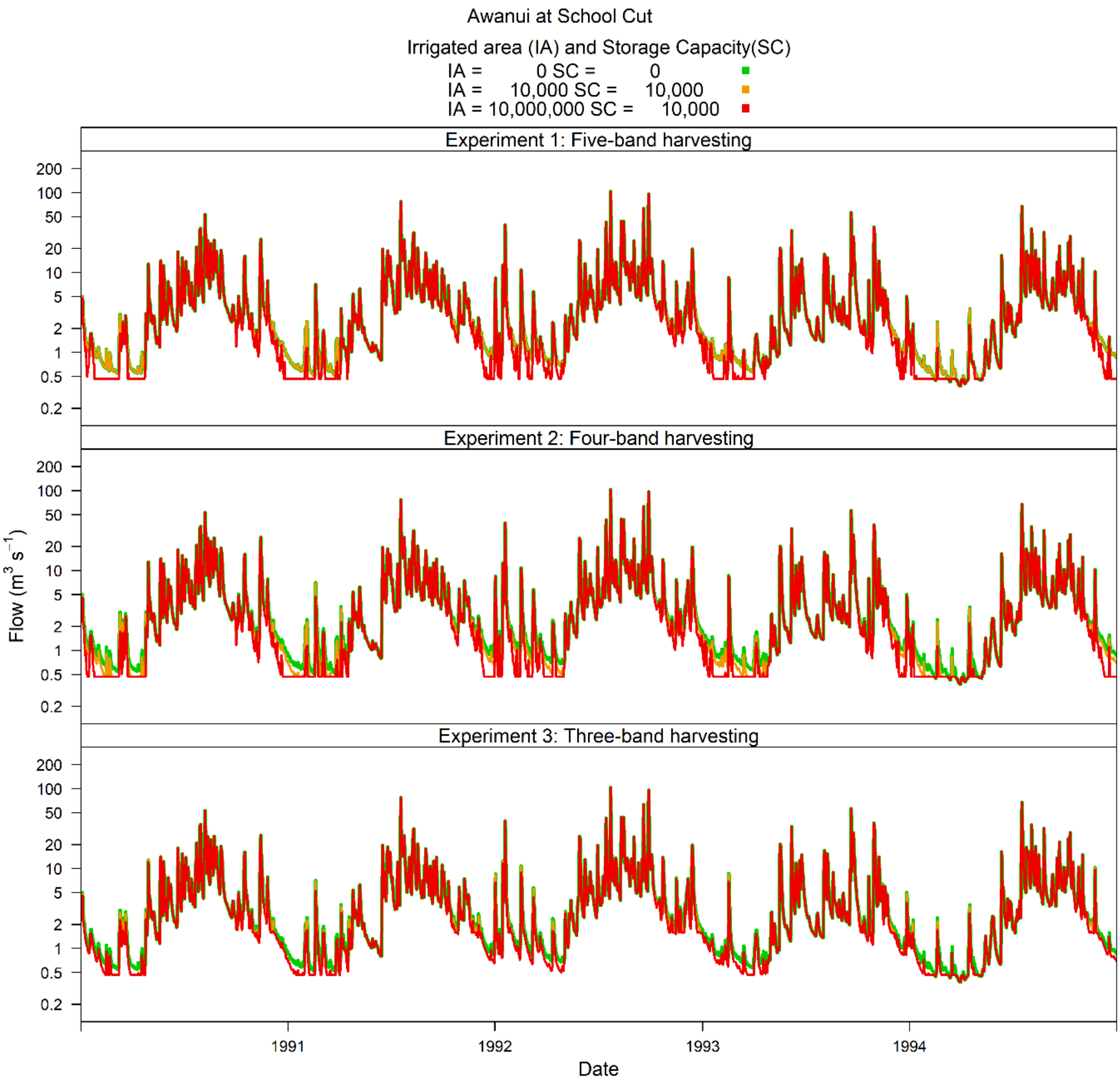

Figure 3-21: Hydrographs for unaltered, and altered flows at the Awanui at School Cut site for two irrigated area and storage capacity scenarios for three experiments.

Key observations from Figure 3-22 are:

- Soil water content can be maintained at a very high level when irrigated area is small for the *five-band harvesting* experiment, but decreases to unfavourable levels (below 50% of PAW) during some summer periods when the irrigated area is large.
- Under the *four-band harvesting* experiment, soil water content further reduces compared to *five-band harvesting* experiment because water supply to storage is reduced (is only available from four upper bands).
- *Three-band harvesting* experiment shows comparable high level soil water content to other experiments when storage capacity and irrigated area are both small, despite water being available from the three upper bands only. Soils water content reduces considerably when the irrigated area is increased – the resulting soil water deficit is reminiscent of the dryland scenario for most periods.

The observations presented in Figure 3-21, Figure 3-22, and previous sections, indicate that all components of the system, including storage capacity, need to be considered and optimised to achieve environmental outcomes through delivery of environmental flow regimes (in terms of allowable level of flow alteration), as well as adequate level of production by maintaining high soil water levels (achieved by increasing water supply reliability).

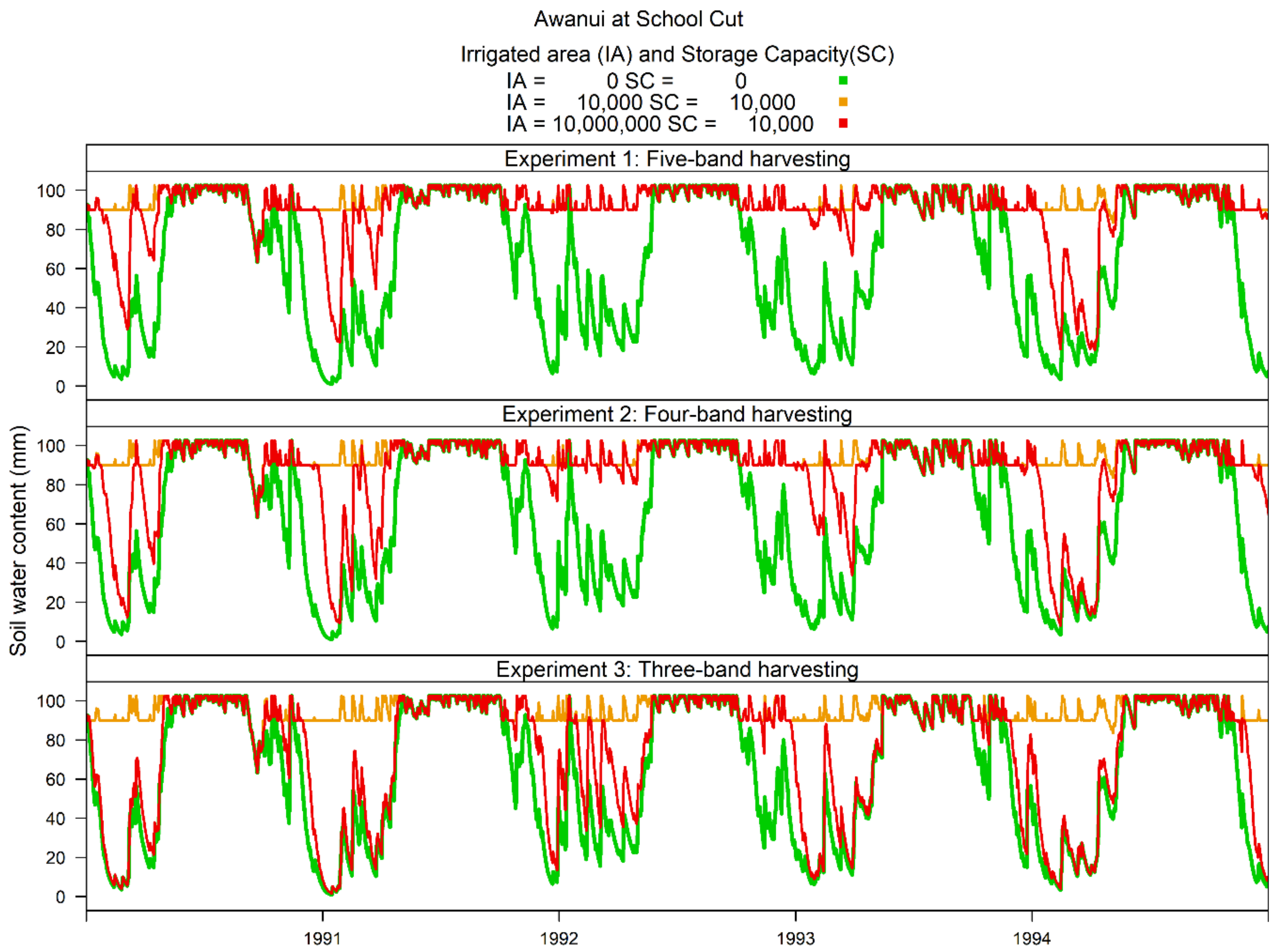

Figure 3-22: Time-series of soil water content for unaltered, and altered flows for two irrigated area and storage capacity scenarios for three experiments for the Awanui at School Cut. Note: unaltered represents a dryland (unirrigated area) scenario for Consent 1/Land 1.

3.2 All sites

3.2.1 Flow regimes across sites

We applied the allocation rules used for the Awanui Stream at School Cut numerical experiments to 42 river catchments in Northland and 14 catchments in Gisborne regions to assess the suitability of these rules across varied hydroclimatic conditions and flow patterns. The magnitude of river flows varied greatly between the 56 sites. For example, there was a broad range of median flows across sites when this flow statistic was calculated over the entire length of each river flow time-series included in our analysis (Figure 3-23). Variability in the relationship between 7dMALF and median flow indicated that flow regimes also varied between sites. Values of 7dMALF and median flow were relevant to our analysis because they determined the position of cease-to-take thresholds and maximum allowable rates of take that defined flow bands. Sites in Gisborne had lower 7dMALF relative to their median flow when compared to sites in Northland. However, this pattern was not consistent across every site within the Gisborne region as indicated by higher values of 7dMALF compared to median flow for the Mata River at Pouturu Br. In general, sites with larger flows tended to have less between-site variability in their ratio of 7dMALF to median flow.

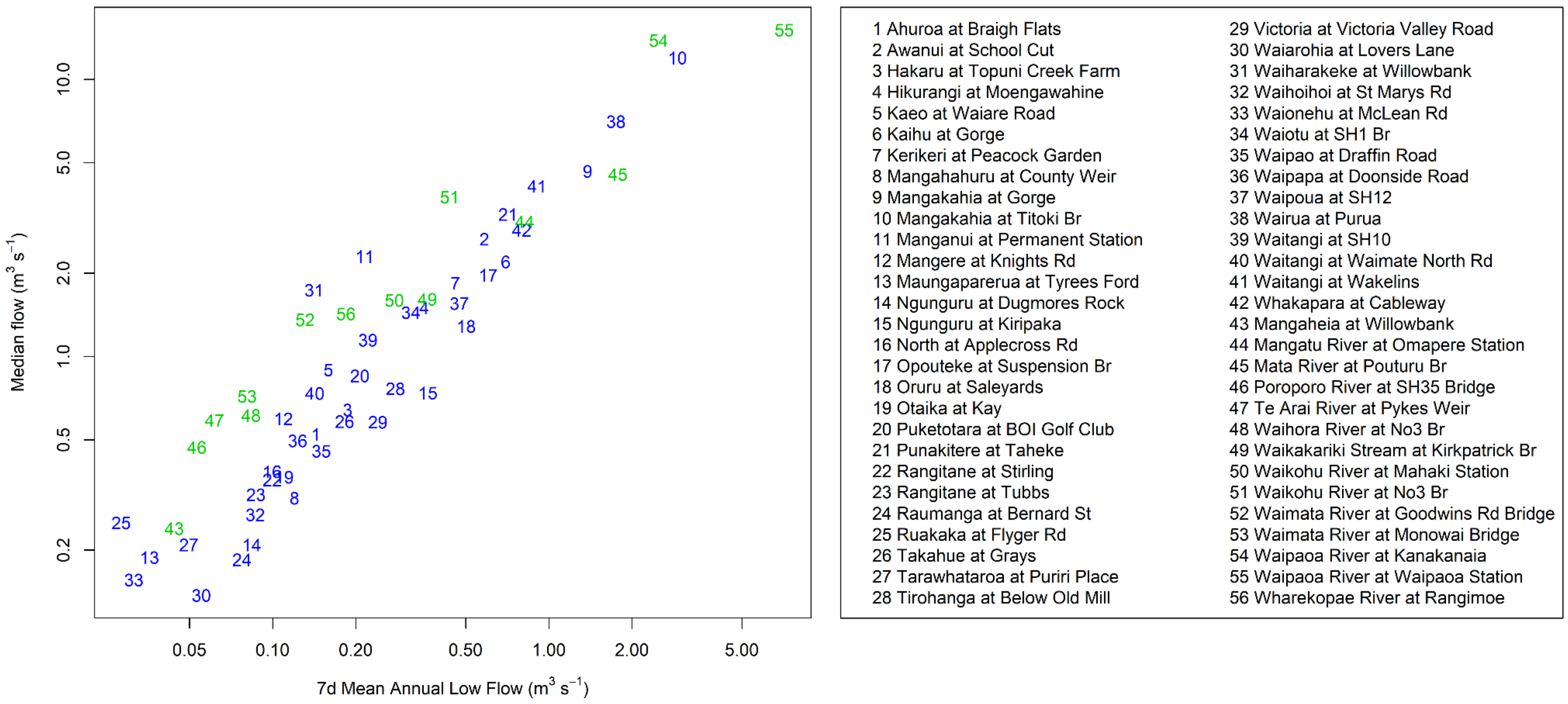

Figure 3-23: Median flow compared to 7dMALF for Northland and Gisborne sites. Northland sites (1 to 42) shown in blue. Gisborne sites (43 to 56) shown in green.

Strength of flow seasonality varied between the sites included in our analysis (Figure 3-24 and Figure 3-25). Some sites exhibited very strong seasonality. For example, Manganui at Permanent Station had much higher median July flows than median flows in other months. Other sites exhibited less strong seasonality, for example, Waipaoa River at Waipaoa Station had very similar median monthly flows across the year. However, it should be noted that Figure 3-24 and Figure 3-25 show results only for the period of river flow time-series included in our analysis (rather than a standardised analysis period), therefore some between-site variability in flow seasonality may be associated with inter-annual climate variability rather than inter-site climate and hydrological variability. It should be noted that different lengths of data were available at different sites (Figure 2-8; Figure 2-9).

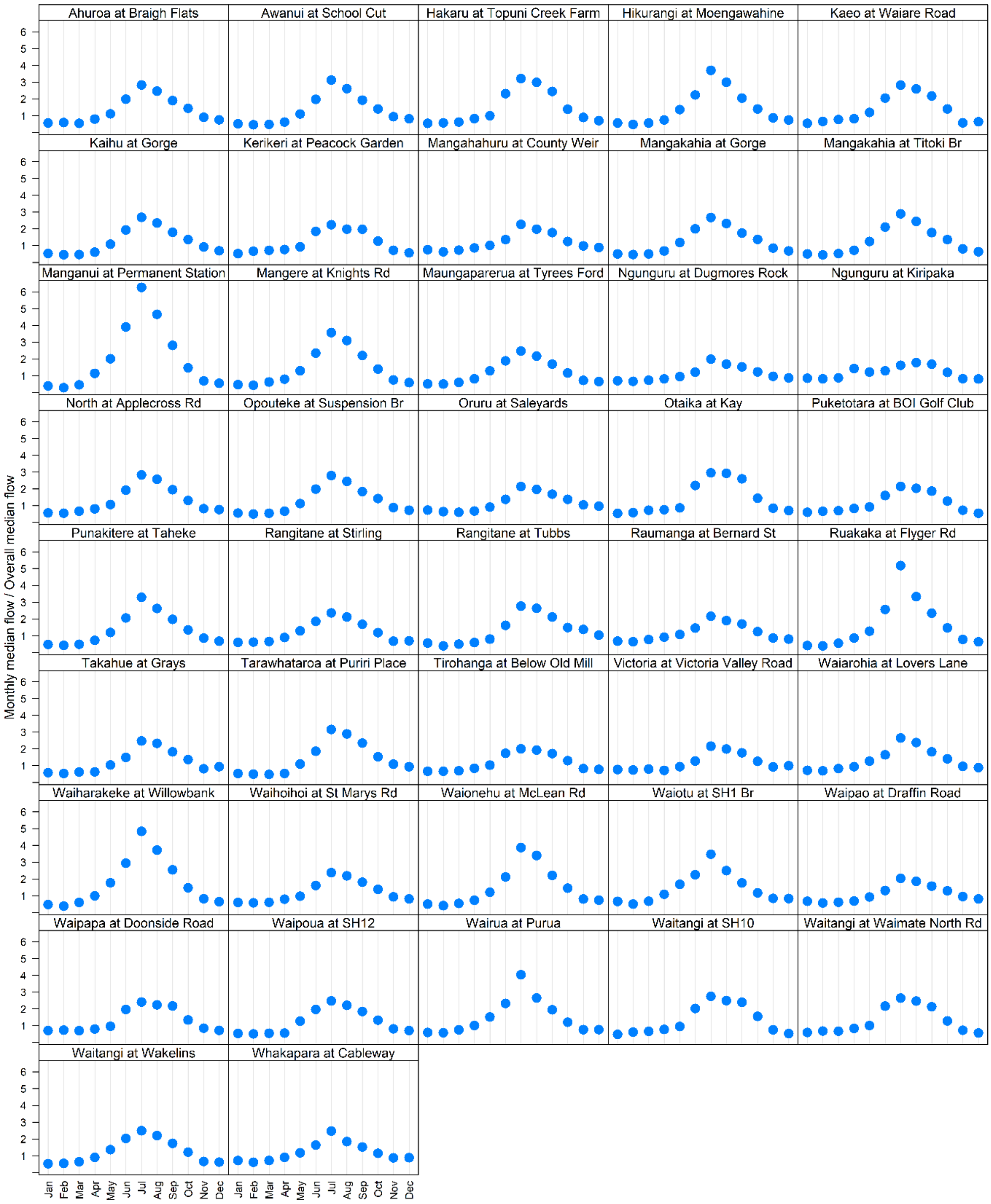

Figure 3-24: Seasonality of flow regimes for Northland sites. Seasonality is represented here by the mean of an annual series of monthly median flows divided by the overall median flow.

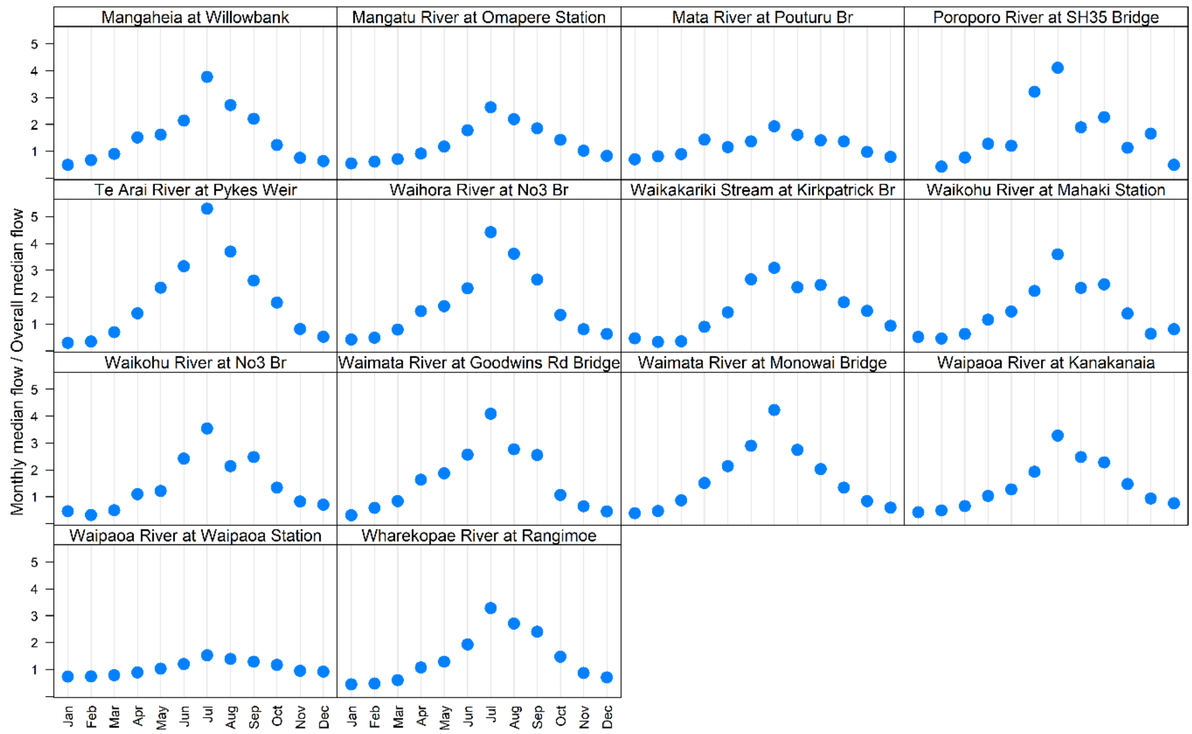

Figure 3-25: Seasonality of flow regimes for Gisborne sites. Seasonality is represented here by the mean of an annual series of monthly median flows divided by the overall median flow.

3.2.2 Experiment 0: spatial variability in water demand

We applied Experiment 0 to calculate the effect of spatial variations in PET and rainfall on water demand under hypothetical infinite water supply whilst holding soil conditions, vegetation characteristics, irrigation practices constant. Results from this initial experiment demonstrated the degree to which water demand varies both between regions and within regions due to spatial variations in PET and rain (Figure 3-26; Figure 3-27). Both PET and rain were generally less for sites in the Gisborne region compared to the Northland region. Results from our simplified experiment demonstrated that patterns in PET and rain combine to produce generally lower water demand in Northland than Gisborne. However, considerable variability exists between sites within each region. It should be noted that this experiment did not include the influence of spatial variation in soils, irrigation practices, or crop type, therefore true spatial variability in water demand may be higher than shown in Figure 3-26 and Figure 3-27.

It should be noted that demand represents the time-averaged demand across all days of the year. Thus, demand for the irrigation season will be higher than the values presented here.

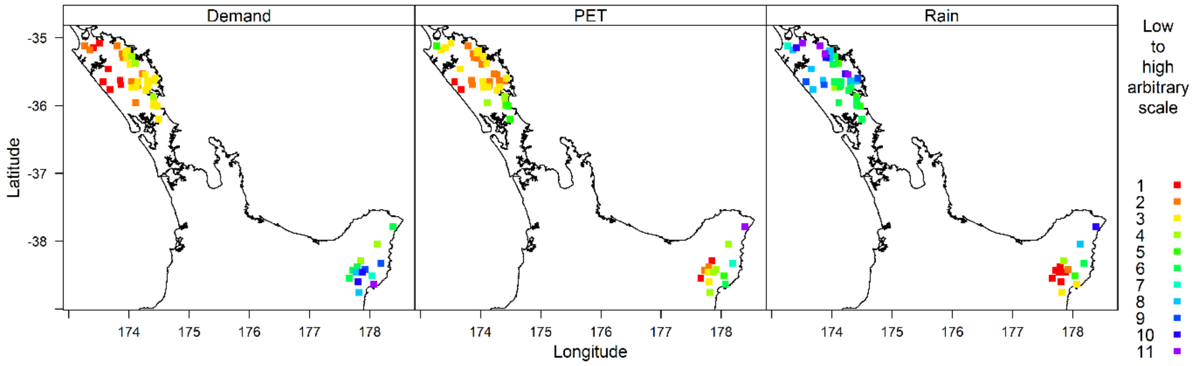

Figure 3-26: Spatial patterns of water demand, PET and rain at each site averaged over the period 1990 to 2021 inclusive. Experiment 0: one consent, infinite water supply, and irrigated area of 1,000,000 m^2. Lowest = 1 and Highest = 11.

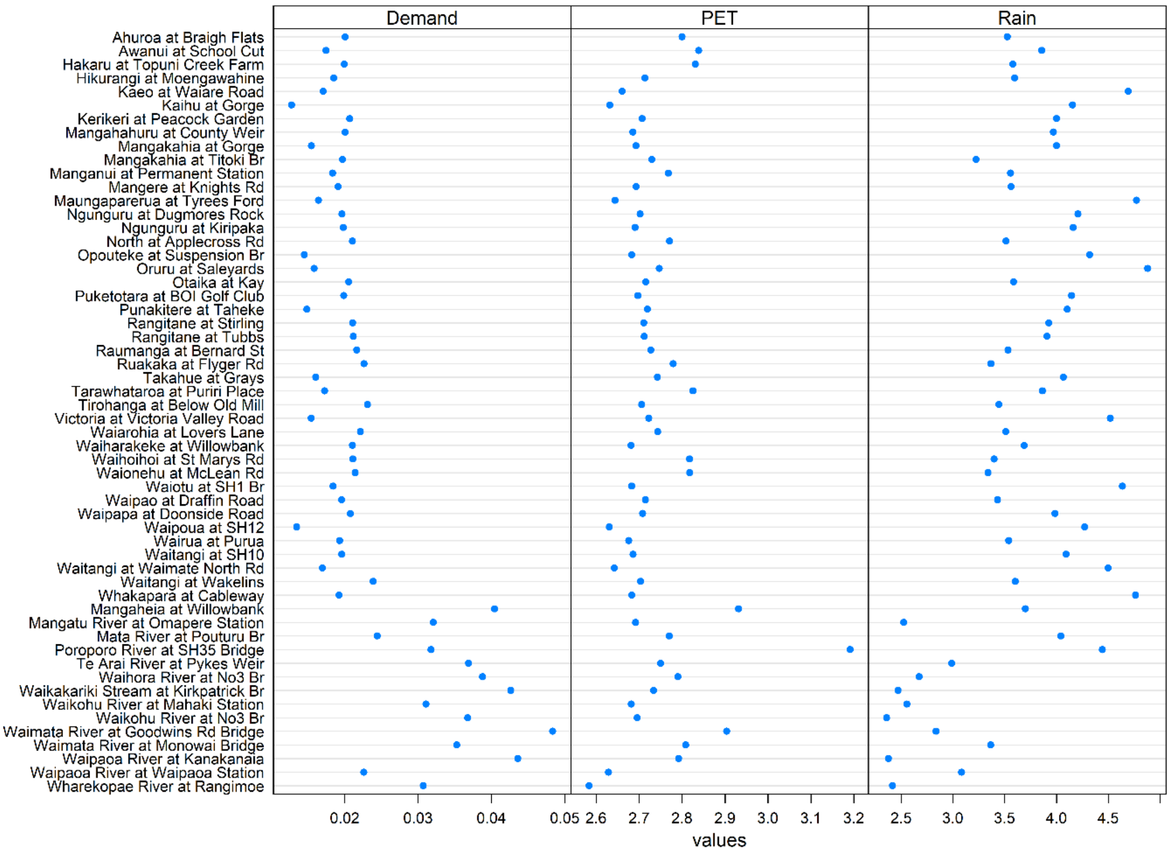

Figure 3-27: Water demand, PET and rain at each site averaged over the period 1990 to 2021 inclusive. Experiment 0: one consent, infinite water supply, and irrigated area of 1,000,000 m^2. Results are time-averaged across all days of the year. Units are $m^3\ s^{-1}$ for demand, and mm d^{-1} for PET and rain. Bottom 14 sites are in Gisborne whilst all other sites are in Northland.

When conducting Experiment 0 (which did not require flow data as input), we initially calculated demand for only the period for which flow data were available for each site as indicated in Figure 2-8 and Figure 2-9). Our initial results (not shown here) indicated that PET and rainfall, and therefore water demand, varied between sites that were relatively close together because their analysis periods were different. This initial result was noteworthy because it indicated that calculation of water demands is sensitive to analysis period as well as spatial position.

3.2.3 Experiment 1: five-band harvesting

Experiment 1 applied the same rules (specified relative to flow regimes using 7dMALF and median flow) to different irrigated areas, different storage capacities, and different river flow time-series as described in Section 2.6.3. Figure 3-28 shows the average amount of water taken, the average amount of water stored, the average soil water content, and two summaries of river flow conditions under combinations of irrigated area and storage capacity when all five bands were used to supply a storage.

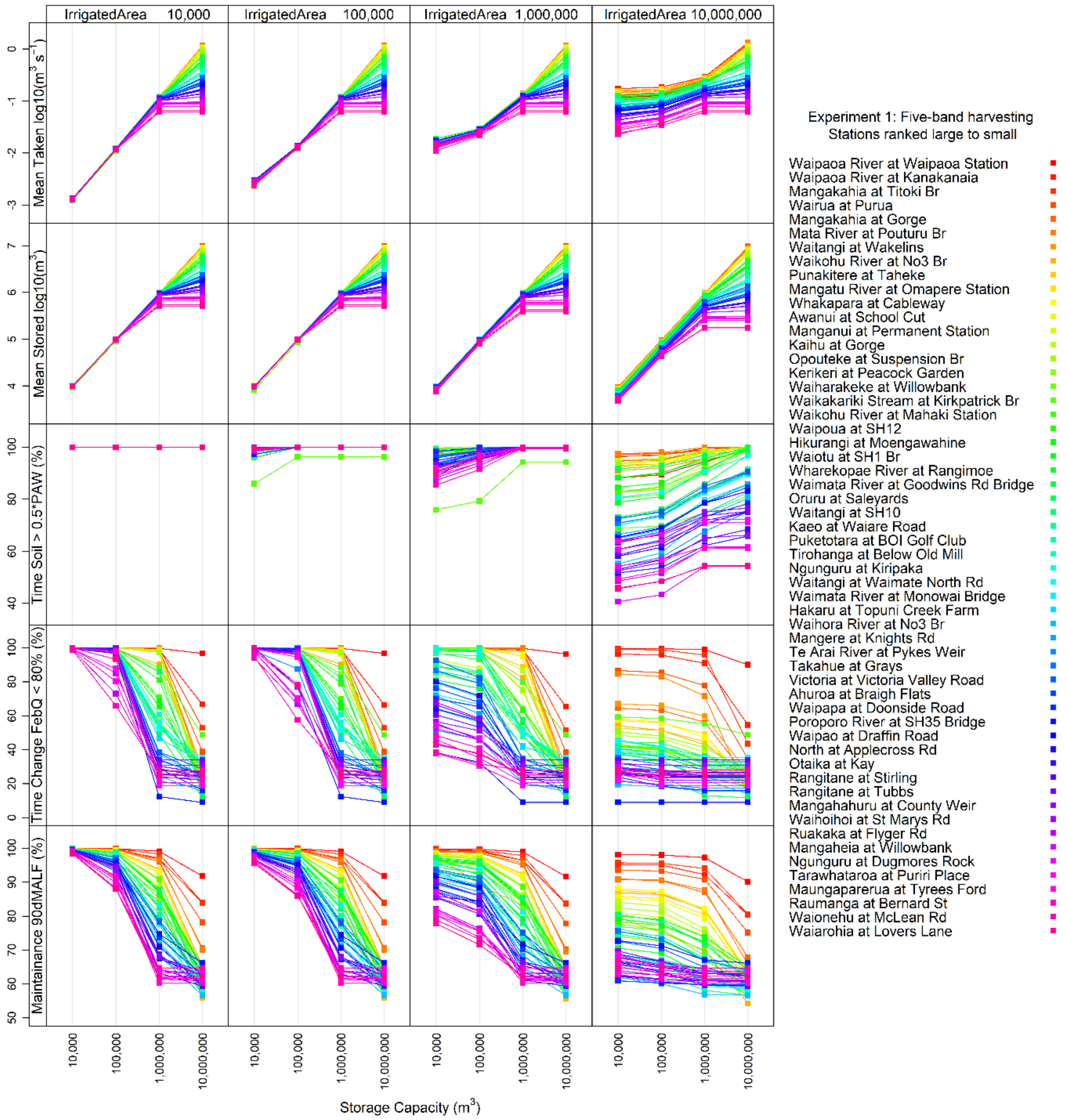

Figure 3-28: Time-averaged take, storage, land, and river flow conditions in relation to irrigated area, storage capacity, and river size, when five band harvesting occurs. Experiment 1: one consent using five bands to supply one storage and one land parcel. Note: sites ranked by median flow. Refer to Figure 3 19 for details of the y-axes.

We found the following under the water allocation rules (five bands supplying storage), assumptions and model inputs that we applied for *five-band harvesting* experiment:

- When storage capacity and irrigated area are both small, sufficient water can be taken from the river to keep the storage full for most of the time, regardless of river size or flow regime; this is indicated by points plotting near to 1:1 toward the bottom left of row 2 column 1 of Figure 3-28.
- When irrigated area is small soil moisture remains relatively high for longer periods of time as indicated by points plotting high on the y-axis of row 3 of Figure 3-28.
- Only when irrigated area is very large and river size is relatively small, was soil moisture simulated to decline below half of PAW in these experiments as indicated by points plotting lower on the y-axis of row 3 of Figure 3-28. This indicated that the size of a viable irrigated area could be calculated for a given river flow regime, set of band rules, and storage capacity.
- Larger storages were associated with higher soil water content when irrigated area was very large, as indicated by the pattern of points in row 3 column 4 of Figure 3-28. This is particularly true for larger rivers as abstractable resources to supply storage also increases.
- Water take generally increases as storage capacity increases regardless of river size and irrigated area as indicated by diagonal lines in the row 1 and 2 of Figure 3-28. However, as storage capacity increases, water taken from small rivers is unable to meet demands to fill very large storages even when irrigated area is small. This result is partly influenced by increases in demand needed to fill storages associated with leakage and evaporation (losses) from very large storages. This result was produced because we calculated losses to be proportional to storage volume, thus very large storages had very high losses and therefore relatively high amounts of water were needed to keep them full.
- As irrigated area increases, the size of river flow needed to meet demand increases, indicated by smaller rivers plotting lower than larger rivers as irrigated area increases (row 1 of Figure 3-28).
- As irrigated area increases, a point is reached for smaller rivers where water stored does not increase as storage capacity increases – indicated by horizontal pink lines in row 2 column 4 of Figure 3-28. This result represents a situation where nearly all water available from the storage or the river is used to satisfy immediate irrigation demand, therefore no surplus water is available to fill the storage. In this situation the storage is excessively large, and its full capacity is not utilised.
- For smaller irrigated areas, the amount of water stored mirrored the amount of water taken as indicated by very similar patterns in rows 1 and 2 of column 1 of Figure 3-28. These results represent situations where demand can be satisfied for the majority of the time, and therefore enough water is available and can be taken to maintain storage at capacity for most rivers except very small rivers.

- For larger irrigated areas and smaller storage capacities, correspondence between the amount of water stored and the amount of water taken was weaker, indicated by row 1 column 4 showing a different pattern to row 2 column 4 in Figure 3-28. This result represents a situation where most water is being used to directly meet demand, and relatively little water is being stored in the storage.
- Relatively lower summer river flows (as indicated by 90day-MALF and alteration of flows in February) were associated with both larger irrigated areas and higher storage capacities. This was indicated by lines sloping down to the right in row 4 and 5 of Figure 3-28. This effect was partly the result of high demand to replace losses in large storages because we modelled losses to be proportional to the amount of water stored.
- February flows were altered by more than 80% for some of the time under nearly all scenarios except when storage capacity was very low (causing limited demand on Band 2–5 water), or river size was very large as indicated by row 5 of Figure 3-28. This indicates that the positioning of our Band 1 would allow substantial alteration of February flows such that they were unlikely to be maintained within 80% of natural flows for significant proportions of the time for many sites.
- Although smaller sites tended to exhibit a susceptibility for more alteration of lower flows, this pattern was not systematic across all sites. This was indicated by the lowest points plotting in row 5 of Figure 3-28 not always being purple (smallest rivers). This indicates that flow regime characteristics, rather than river size, is a dominant factor in determining low flow alteration.

3.2.4 Experiment 2: four-band harvesting

Experiment 2 replicated Experiment 1 with the exception that only the top four bands were used to supply storage, with the bottom band used to supply a very large irrigated area. Results from the *four-band harvesting* experiment are shown in Figure 3-29.

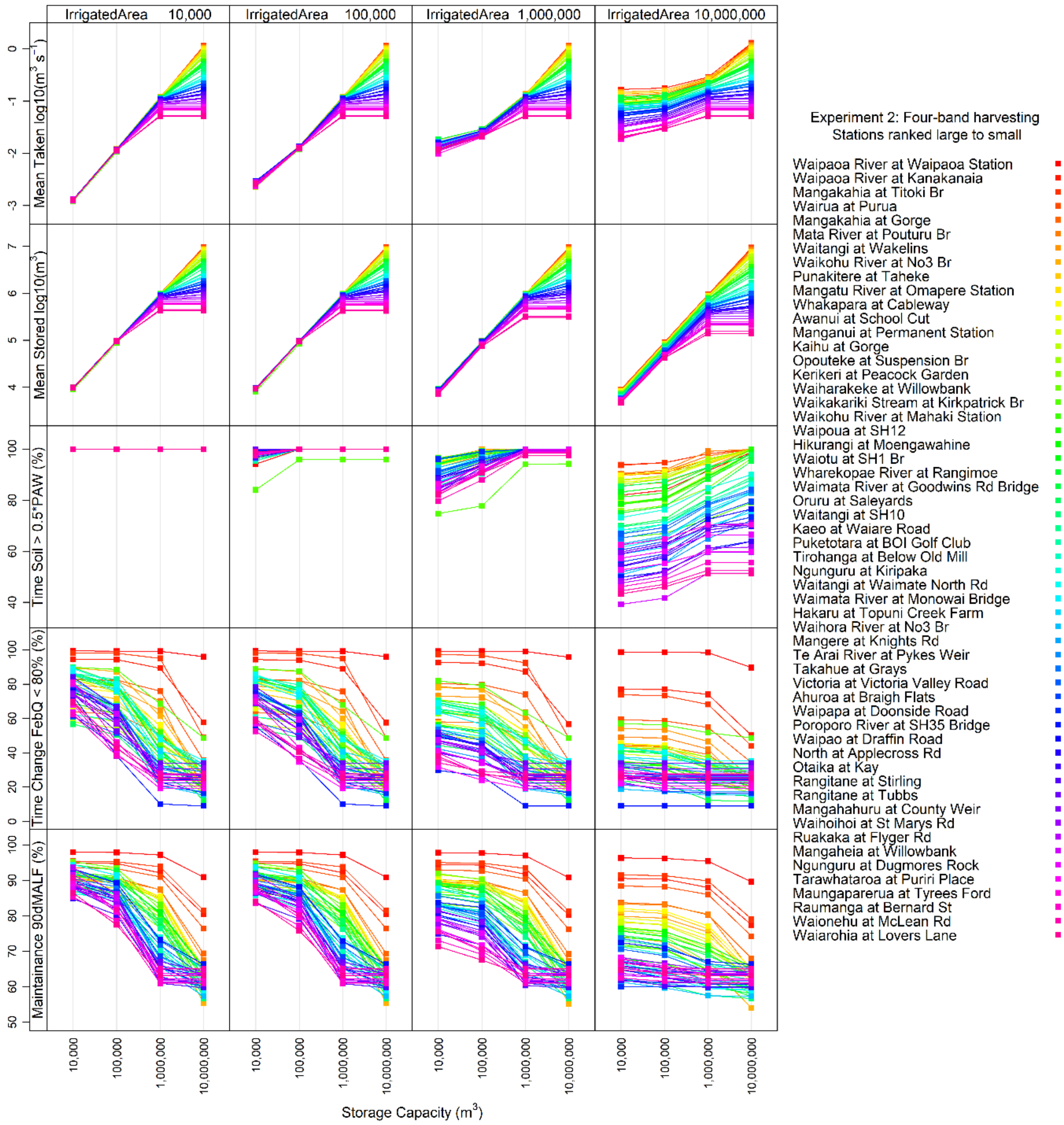

Figure 3-29: Time-averaged take, storage, land, and river flow conditions in relation to irrigated area, storage capacity, and river size, when four-band harvesting occurs. Experiment 2: two consents exist: one consent supplies a large irrigated area with no storage, and one consent using four bands to supply one storage and one land parcel. Note: sites ranked by median flow.

There were many similarities, but some differences, in results produced for the *five-band harvesting* experiment (Figure 3-28) compared to results produced for *four-band harvesting* experiment (Figure 3-29):

- For the consent that was associated with storage (associated with Bands 2 to 5), less water was taken because water from the lowest band was not available to supply the storage, but this was only the case for larger storage capacities and larger irrigated areas as indicated by lower lines for row 1 and 2 column 4 of Figure 3-29 compared to Figure 3-28.

- For land that was supplied by storage, soil moisture was slightly more likely to be below half of PAW for the *four-band harvesting* experiment compared to *five-band harvesting* experiment as indicated by lines at lower values in row 3 of Figure 3-29 compared to Figure 3-28; this was only the case for very smaller storages and/or very larger irrigated areas.
- Alteration of low flow characteristics (as indicated by time for which flow in February was reduced by more than 80%, and change in 90dMALF) was more pronounced for the *four-band harvesting* experiment compared to *five-band harvesting* experiment, indicated by lines at higher values in rows 4 and 5 of Figure 3-29 compared to Figure 3-28. This indicates that impact on low flows can be reduced by switching the lowest band from run-of-river take to flow harvesting. However, it should be noted that the overall irrigated area for *four-band harvesting* experiment (irrigation of Land 1 and 2 under two different consents) was larger than that for *five-band harvesting* experiment (Land 1 only).

3.2.5 Experiment 3: three-band harvesting

The *three-band harvesting* experiment replicated the *four-band harvesting* experiment with the exceptions that only the top three bands were used to supply storage, and the bottom band was used to supply a very large irrigated area as a run-of-river take. Effectively, abstraction from Band 2 was removed from the *four-band harvesting* experiment. Results from the *three-band harvesting* experiment are shown in Figure 3-30.

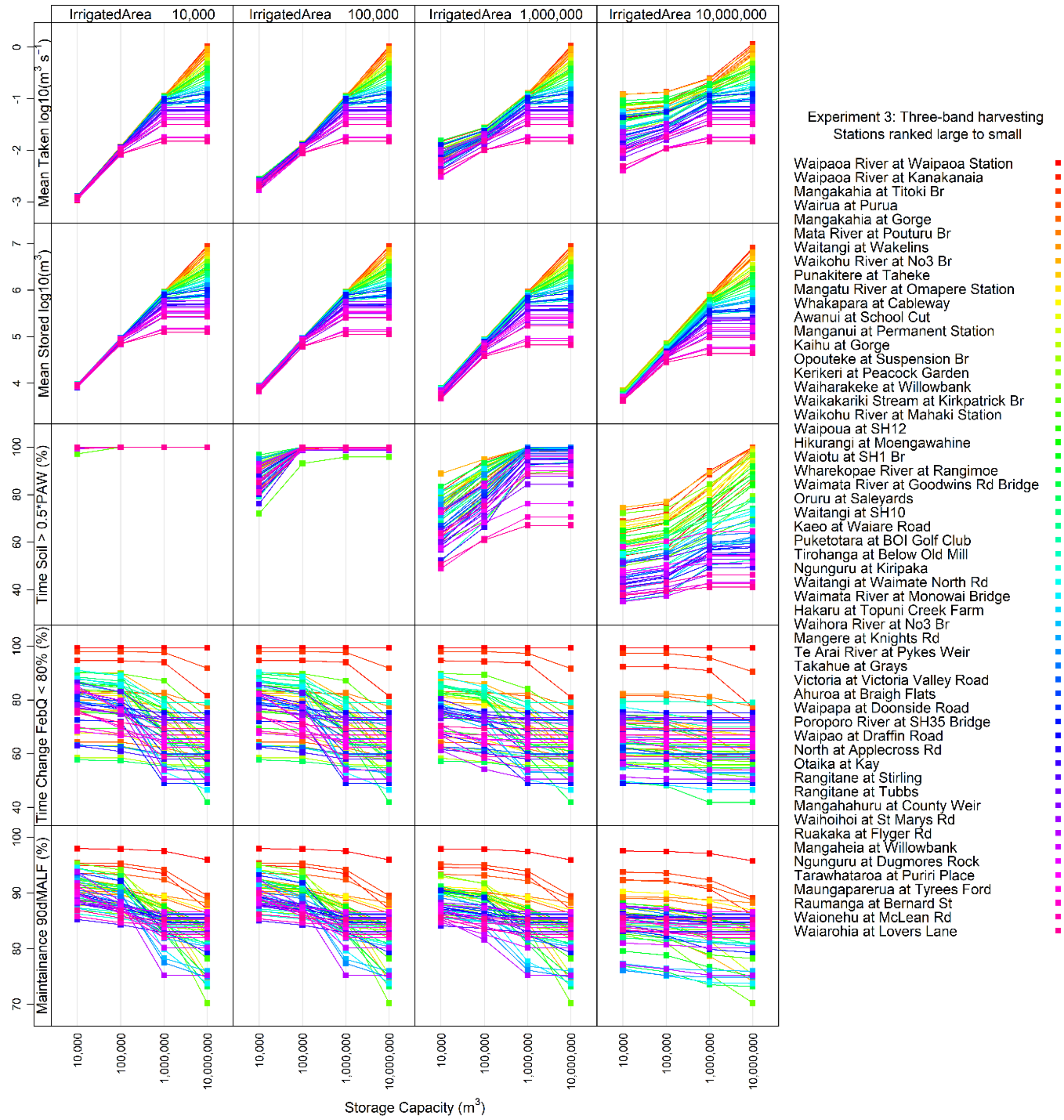

Figure 3-30: Time-averaged take, storage, land, and river flow conditions in relation to irrigated area, storage capacity, and river size, when three-band harvesting occurs. Experiment 3: two consents – one consent supplies a large irrigated area with no storage, and one consent uses three bands to supply one storage and one land parcel. Note: sites ranked by median flow. Note difference in y-axis scales compared to Figure 3-29 and Figure 3-28.

Despite some similarities, the results produced for *three-band harvesting* experiment (Figure 3-30) differed in many ways from results produced in the *four-band harvesting* experiment (Figure 3-29):

- Average water take and average water stored had broadly similar patterns for the two experiments for some sites. However, several sites were able to take and store less water under the *three-band harvesting* experiment as indicated by lines at lower values in row 1 of Figure 3-30 compared to Figure 3-29. This was particularly the case for smaller rivers and for larger irrigated areas.

- There was also more between-site variability in average take for the *three-band harvesting* experiment compared to the *four-band harvesting* experiment, indicated by the greater vertical spread of lines in row 1 of Figure 3-30 compared to Figure 3-29. This result indicates that reduced access to water following removal of a band through rules is not consistent across sites due to differences in flow regimes.
- Patterns observed for average stored water were similar to average water take, described in the two points above.
- The tendency for soil moisture decline below half of PAW to be more prevalent when the irrigated area was larger (seen in the *four-band harvesting* experiment) was also the case for *three-band harvesting* experiment. However, soil moisture was reduced for nearly all sites for *three-band harvesting* experiment compared to *four-band harvesting* experiment in scenarios where the irrigated area was large, indicated by lines plotting at lower values in row 3 and columns 3 and 4 of Figure 3-30 compared to Figure 3-29. This indicates that removing a band from the rules reduced irrigation effectiveness for larger irrigated areas and smaller storage capacities.
- We note the difference in y-axis scales for rows 4 and 5 of Figure 3-30 compared to Figure 3-29. Alteration of low flow characteristics (indicated by time for which flow in February was reduced by more than 80%, and change in 90dMALF) was greater for the *four-band harvesting* experiment compared to *three-band harvesting* experiment as indicated by the much higher value lines in rows 4 and 5 of Figure 3-30 compared to Figure 3-29. This indicates that use of Band 2 in the *four-band harvesting* experiment contributed significantly to low flow alteration, whereas removal of Band 2 in the *three-band harvesting* reduced impacts on low flow characteristics.
- Decreases in irrigation effectiveness coupled with decreases in alteration of river flows when Band 2 was removed from the rules is an important finding because it demonstrates the trade-off between in-stream and out-of-stream water uses that will occur when bands are removed or repositioned. These experiments also indicated that this trade-off could be quantified within these idealised numerical experiments and assumptions that we applied.

3.2.6 Comparing across Experiments 1-3

In Sections 3.2.3-3.2.5 we presented the results for all sites using five different assessment metrics (mean flow taken to storage, mean stored, percentage of time soil water above 50% of PAW, time that flow in February is within 80% of unaltered flow and change in 90dMALF), for three different configurations or rules using bands (described by our experiments). In this section we combine the results of each metric over all three experiments and all sites using a graphical form that allows easier comparison between the experiments, as well as identification of the effect of different allocation rules for different rivers. We used median flow as a general representation of flow magnitude with a view to generalising results to ungauged sites.

Figure 3-31 shows results for one summary indicator – mean flow taken to storage from the river – for all sites, over storage capacities, irrigated areas, and experiments against median flow. Figure 3-31 indicates the following points:

- When irrigated area is small (row 1 of Figure 3-31), mean take increases with storage capacity. Mean take is not sensitive to median flow across sites for smaller storage capacities. There is a consistent relationship between mean take and median flow for the largest irrigated area, regardless of irrigated area. For the largest storage capacity, mean take increases as median flow increases up to around 3 $m^3 s^{-1}$. Mean take remains constant above around 3 $m^3 s^{-1}$. This indicates that the magnitude of river flow regimes needed to attain a given level of mean take to meet demand for a given size of storage capacity and irrigated area is predictable. For all experiments, the same pattern is present across irrigated areas but with a shift towards higher mean take as irrigated area increases. The same pattern is present for Experiment 3 (*three-band harvesting*) but with more between-site variability and a shift towards lower mean take. Water take increases as storage capacity increases, partly due to high losses from large storages.
- Rows 2 to 4 of Figure 3-31 show that water take increases as irrigated area increases, initially for smaller storage capacities, subsequently for larger capacities, indicating that water take is influenced by both storage capacity and irrigated area (see next bullet).
- When both irrigated area and storage capacity are large, mean flow taken tends to converge for all storage capacities, indicating that water take is predominantly influenced by irrigated area.
- More variability in mean flow taken (visible in rows 3 and 4, but particularly in column 4 of Figure 3-31) indicates that different flow regime magnitudes will not yield the same mean flow takes across sites due to differences in flow regimes, and flow taken is also a function of allocation rules. In particular, flow taken is reduced for some sites when Band 2 was removed from allocation bands in the *three-band harvesting* experiment.

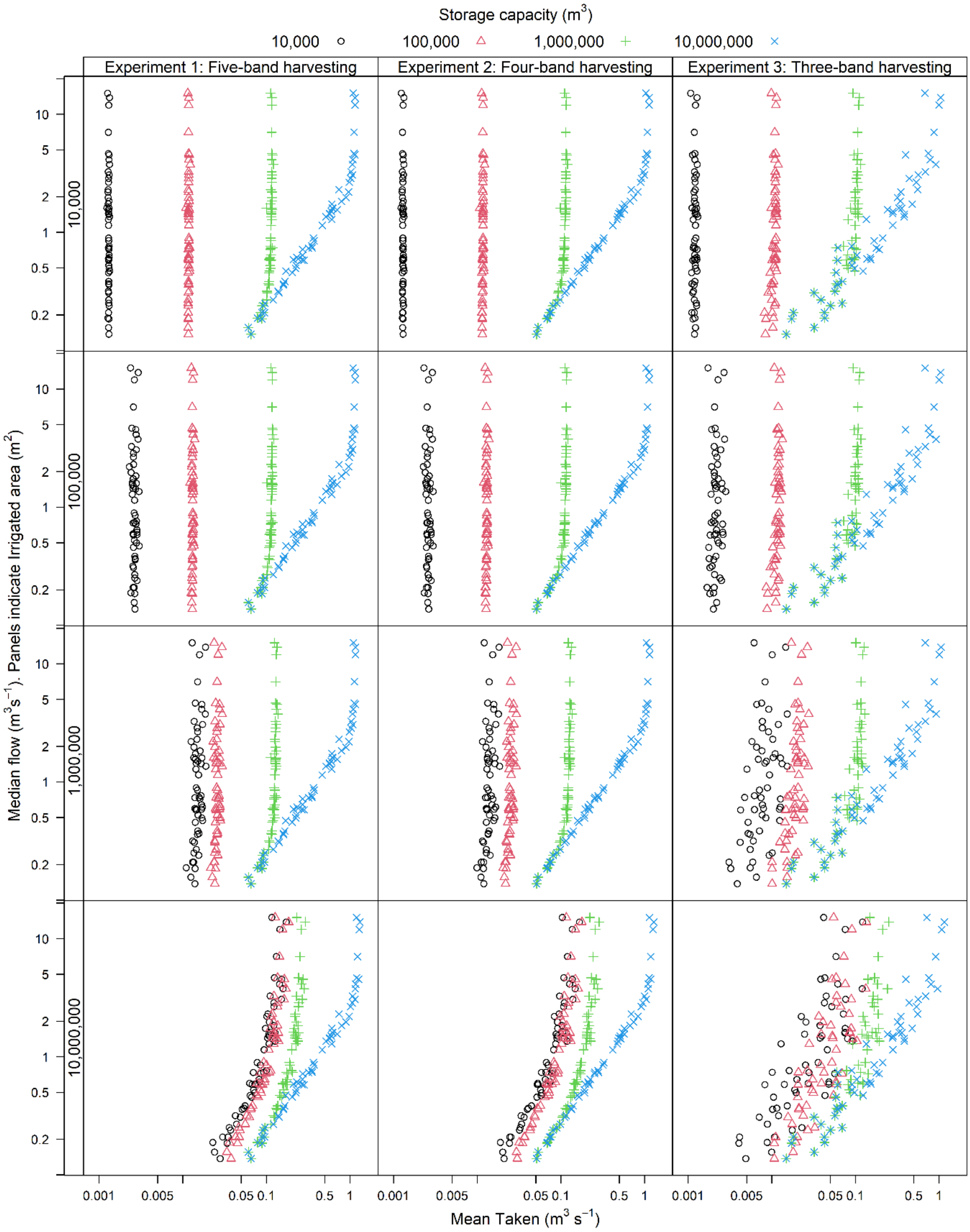

Figure 3-31: Relationship between mean flow taken to storage from the river against unaltered median flow when different band configurations, irrigated areas, and storage capacities are applied across sites.

The summary indicator of mean stored for all sites over storage capacities, irrigated areas, and experiments against median flow is shown in Figure 3-32, which reveals the following points:

- When irrigated area is small (row 1 of Figure 3-32), mean stored volume varies with storage capacity. Mean stored volume is not sensitive to median flow across sites for smaller storage capacities. There is a consistent relationship between mean stored volume and median flow for the largest irrigated area. For the largest irrigated area, mean stored volume increases as median flow increases up to around 3 $m^3 s^{-1}$. Mean stored volume remains constant above around 3 $m^3 s^{-1}$. This indicates that predictability in the amount of river flow that is needed to attain a given level of mean stored volume for a given size of storage capacity. For experiments 1 and 2, the same pattern is present across irrigated areas, but with a shift towards lower mean stored volume for the largest irrigated area. The same pattern is also present for Experiment 3 (*three-band harvesting*), but with more between-site variability and a further shift towards lower mean storage volume.
- Patterns in mean stored volume against median flow for a given storage capacity are similar across different irrigated areas.
- When storage capacity is large, mean stored volume is lower for smaller rivers than large rivers, indicating that storage capacity is excessively large and difficult to fill using resources from smaller rivers.
- When irrigated area is large (row 3 and 4 of Figure 3-32) and storage capacity is small, mean stored volume is less than that for smaller irrigated areas (row 1 and 2 of Figure 3-32) for smaller rivers. This is mainly due to available water from smaller rivers being used for irrigation directly, with no surplus water available to fill the storage.

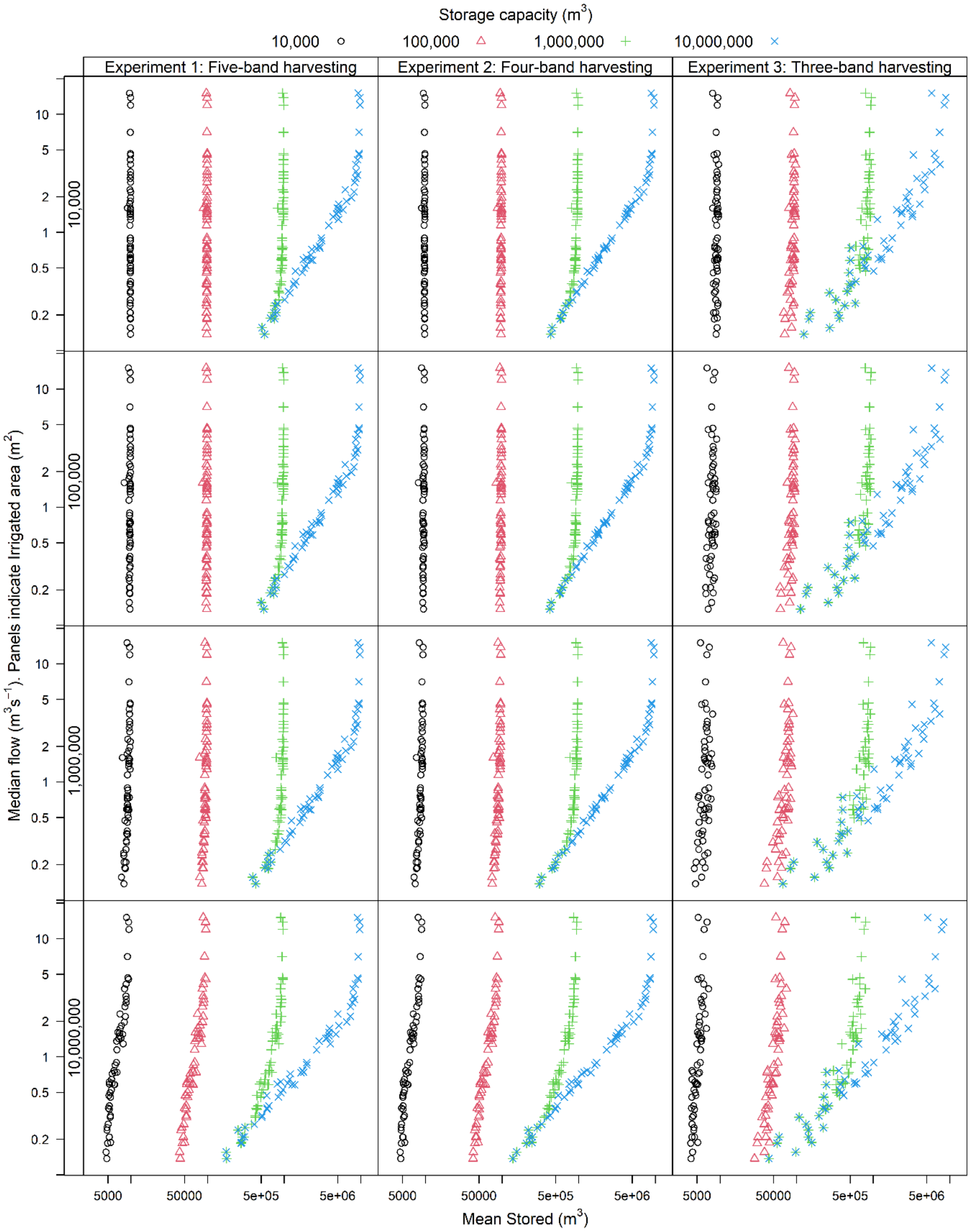

Figure 3-32: Mean stored volume against unaltered median flow when different band configurations, irrigated areas, and storage capacities are applied across sites.

Figure 3-33 shows results for the metric showing percentage of time soils water level is over 50% of PAW for all sites according to storage capacity, extent of irrigated area, and experiment, against median flow. Figure 3-33 indicates the following points:

- Row 1 of Figure 3-33 shows that when irrigated area is small, modelled soil water status is above 50% of PAW nearly 100% of the time, irrespective of the storage capacity size of the river or experiment. This represents situations where adequate water resources are available to meet irrigation demand at high level of reliability.
- As irrigated area increases, the percentage of the time soils water exceeds 50% of PAW decreases. Lower soil water content was particularly evident for larger irrigated area when median flow was lower. For a given median flow, soil water content decreased under the *four-flow harvesting* experiment (Experiment 2) and then the *three-flow harvesting* experiment (Experiment 3) when irrigated area was larger.
- Results generally indicated that reduced available water resources had a predictable impact on soil water content across sites under different allocation rules.

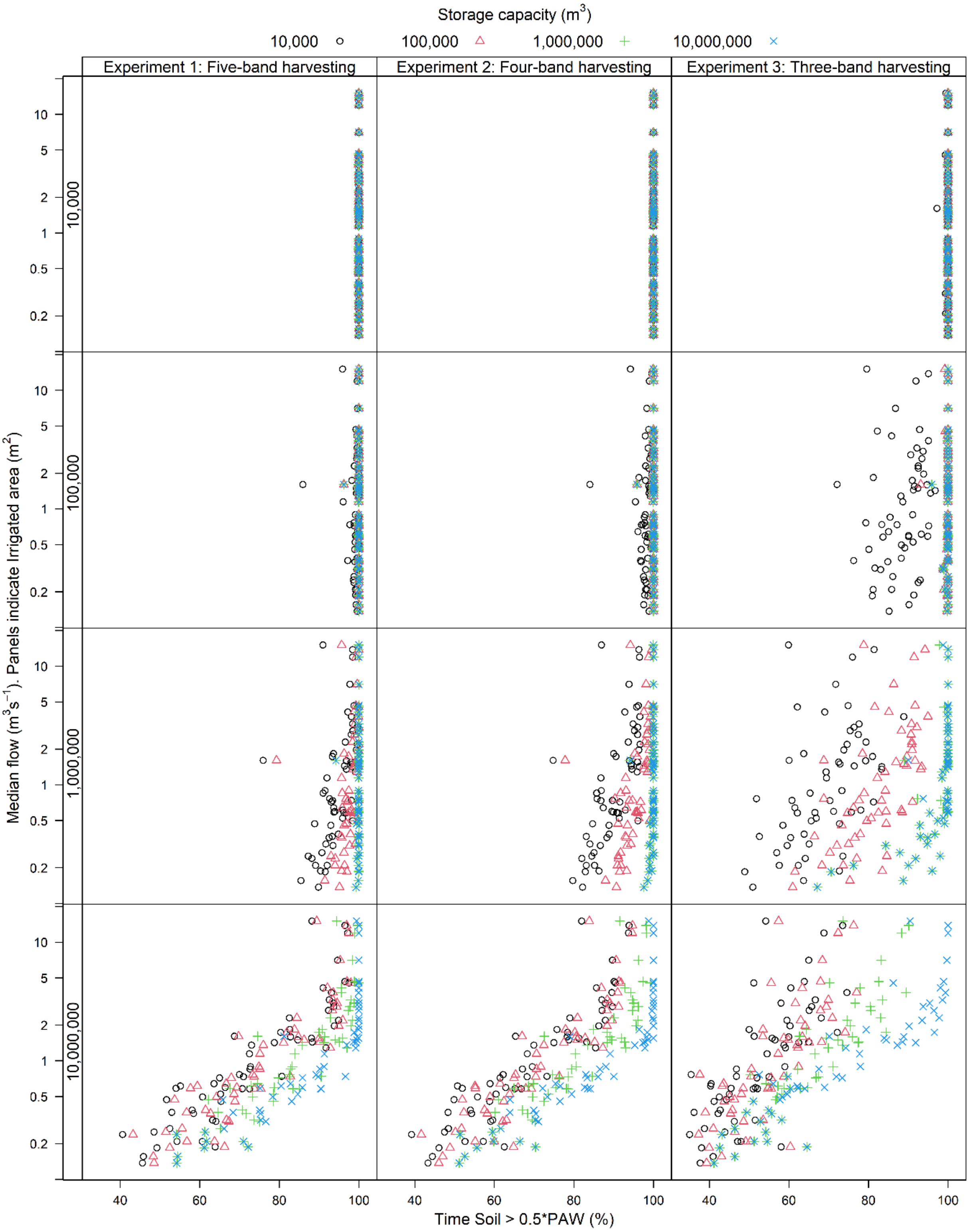

Figure 3-33: Time that soil water exceeds 50% of PAW of land that is irrigated using water from the storage according to band configuration, irrigated area, and storage capacity, by site.

Figure 3-34 and Figure 3-35 shows results for two summary indicators of low flow alteration (time for which flows deviate significantly from altered in February, and change in 90dMALF) over all sites, storage capacities, irrigated areas, and experiments, against median flow. Although some differences are evident, similar patterns in results are shown for Figure 3-34 and Figure 3-35, with slightly more coherent patterns evident in Figure 3-35 compared to Figure 3-34. We therefore describe the main results for change in 90dMALF (Figure 3-35) as follows:

- When storage capacity and irrigated area are both small (row 1 column 1 of Figure 3-35), flow alteration is very low for all sites for the *five-band harvesting* experiment. For the same irrigated area, flow alteration increases predictably as storage capacity increases, except for the combination of largest irrigated area and sites with median flows below around 3 $m^3 s^{-1}$, which produce the same level of low flow alteration. This finding indicates that for a given storage capacity and irrigated area, all available water is taken and water allocation rules alone control flow alteration.
- The flow alteration is greater for smaller rivers given the same storage capacity and irrigated area, until a point is reached where water allocation rules alone control flow alteration.
- Low flow alteration was significantly reduced under the three-band harvesting experiment regardless of storage capacity or irrigated area.

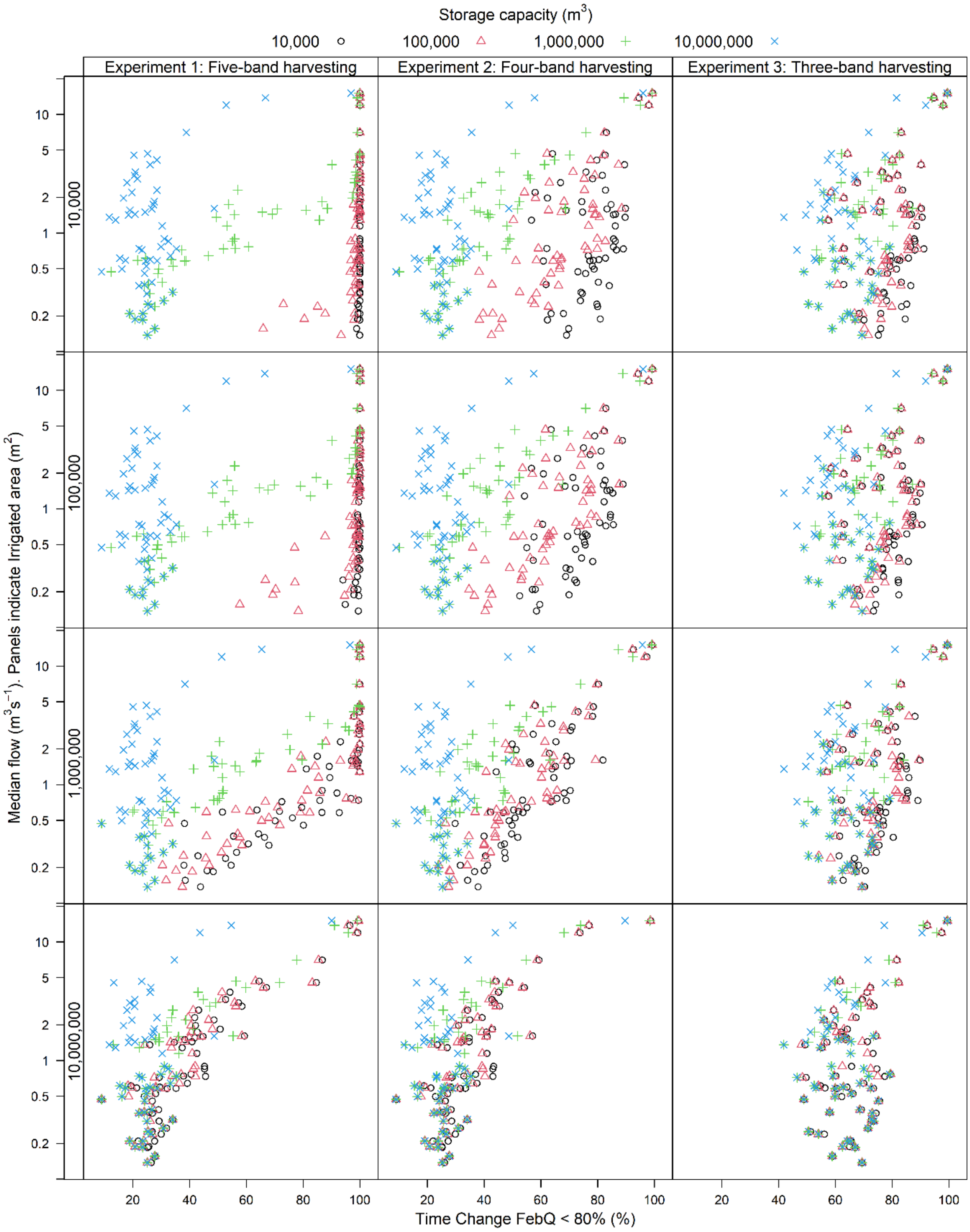

Figure 3-34: Time that flow in February is within 80% of unaltered flow against unaltered median flow when different band configurations, irrigated areas, and storage capacities are applied across sites.

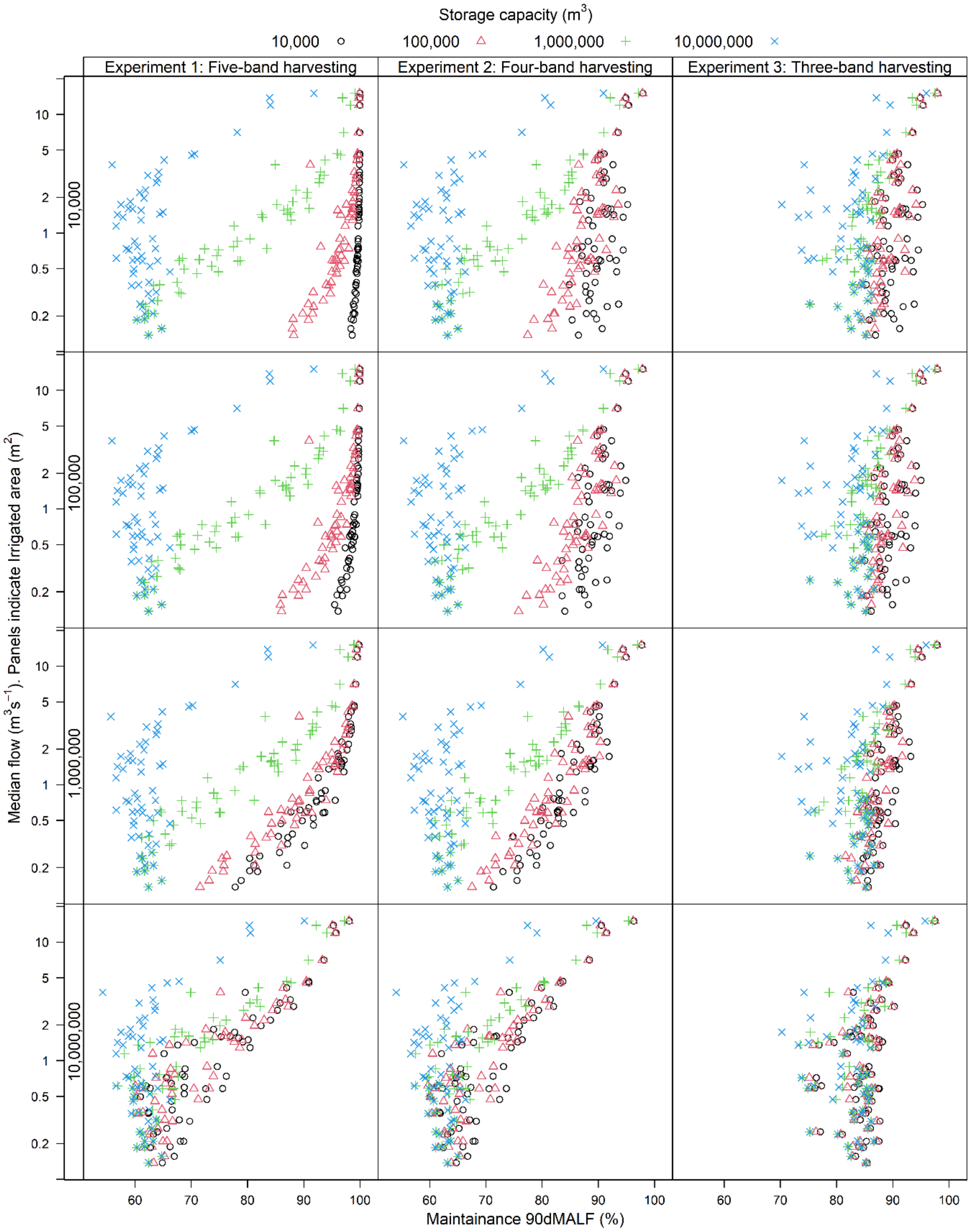

Figure 3-35: Change in 90dMALF against unaltered median flow when different band configurations, irrigated areas, and storage capacities are applied across sites.

4 Discussion and guidance

4.1 Assumptions and limitations

We devised a method for simulating the potential effects of different water allocation and consenting scenarios on river flows and water availability within a simplified hypothetical setting. We did not attempt to simulate all real-world physical processes, environmental conditions, or operation of water takes. Several important assumptions should be remembered when interpreting our results:

- We applied a set of simplified water user decisions by assuming:
  - Water users have prefect knowledge about weather and antecedent soil water content.
  - Irrigation decisions are applied on a continuing daily basis during the irrigation season.
  - Water is taken to fill storages on a continuing daily basis during the entire calendar year.
  - Water users always take all water needed to meet a target soil water content, and if excess water is available, then it is used to fill storage if the storage is not full.
  - Water users do not attempt to rationalise their water use to prepare for up-coming shortages in water availability.
- We applied the parameters, settings, and soil water balance algorithms used by Srinivasan et al. (2021), and assumed these represented soil water content adequately.
- We used observed flow data for each site for the period between 1990 and 2021 for which at least five continuous years of record existed, to represent unaltered river flows. We included all sites that did not have significant gaps or suspicious data quality issues. We filled any gaps in the flow data using interpolation. We assessed observed flows for their level of alteration and did not attempt to naturalise the observed flows or assess the effects of real takes on observed flows. It should be noted that changes in the length and quality of flow data as well as any procedure used to naturalise observed flows will influence flow statistics used to defined water allocation bands.
- We used rainfall and PET data from the VCSN to represent the effect of weather patterns on soil water content, and calculated water demands for land by applying the same calculations and assumptions as Srinivasan et al. (2021).
- Losses (e.g., leakage and evaporation) from storage was assumed to be a constant proportion of stored water. Leaked water did not return to the river in our method, although this process could be included if required in future analysis. This approach is consistent with losses via evaporation, but not necessarily consistent with losses via leakage to the ground.
- We did not account for transport of water lost by leakage from river to storage or from storage to land.

- We did not explicitly model the loss of water from storage due to evaporation, or addition to storage due to rain or runoff. Inclusion of these processes would have required assumptions about the configuration (e.g., square planform, angle of sloping sites, maximum depth) of the storage and its surrounding area.
- We concentrated on water used for irrigation purposes. We did not explicitly model water used for industrial, stock-drinking, or domestic purposes. Essentially, we assumed that water used for industrial, stock-drinking, or domestic purposes would be supplied from Band 1 for experiments 2 and 3.
- Storages, takes, and land were located near to gauging stations in our simulations. We did not therefore investigate situations with multiple takes or where takes were located across a catchment.
- No economic considerations were incorporated into our analysis.
- No engineering limitations were considered in relation to storage capacity or equipment needed to fill storages or to supply water to land.

4.2 Future improvements

Although we did not present any analysis that included within-catchment configurations of multiple takes, the methods we applied could also be used to investigate the cumulative effects of multiple takes distributed across catchments to produce spatial variations in river flow alteration. However, analysis of these situations is hampered by lack of data describing spatial patterns in river flows. The utility of using modelled river flow data (which our methods were also able of using as river flow inputs), or spatially transferring observed flow data to ungauged sites could be explored in future research.

Uncertainty in defining target environmental flow regimes often stems from spatial variability in in-stream values, lack of data relating in-stream values to river flows, and the unpredictable nature of river environments. This uncertainty and spatial variability meant that a predefined set of hydrological metrics paired to acceptable degrees of their alteration covering the whole flow regime were not available. Although we were able to quantify simulated flow alteration across all flows (e.g., Figure 3-20), this situation limited our ability to quantify the effects of simulated flow alteration on in-stream values.

We applied the same parameters and settings for soil water balance algorithms to all sites. Use of ubiquitous parameters relating to land had the advantage of simplifying the soil water modelling part of our method. Testing the sensitivity of our results (e.g., Figure 3-33) to changes in soil input parameters, and use of local spatially distributed soil data may provide further insights about spatial patterns, which are likely to eventuate under universal water allocation rules.

We did attempt to validate our analysis by comparing our simulated outcomes against observed or physical experimental outcomes. We suggest that validation of simulated results against observed data would further strengthen our approach in the future. A suitable dataset would have to be available, and a technical approach developed for validation to be applied.

We developed an interactive app in order to explore our simulations, devise our five-band rules, and engage with stakeholders for this project. We did not develop a user manual for this app, and the app was not tested by anyone other than the authors of this report. If deployed, this app might be useful to decision makers, but further development to overcome technical challenges and some user testing would be required prior to deployment.

4.3 General interpretations of water allocation rules

A series of experiments was applied to demonstrate the trade-off between water availability and hydrological alteration resulting from interactions between water allocation rules defined by bands, irrigated area, storage capacity, local climate, and local river flows. Both time-series and time-averaged take, storage, land, and river flow conditions were analysed under the following scenarios:

- Experiment 1: All five bands taken to storage.
- Experiment 2: Band 1 used as run-of-river supply for a very large irrigated area not associated with storages (analogous to a fully allocated situation), and Bands 2–5 taken to storage.
- Experiment 3: Band 1 used as run-of-river supply for a very large irrigated area not associated with storages (analogous to a fully allocated situation), and Bands 3-5 taken to storage (Band 2 was not operational).

Some general interpretations of results produced by our idealised experiments for sites across Northland and Gisborne included:

- Spatial patterns in climate created within-region variability in water demands, implying that water demands cannot be assumed to be consistent across each region.
- Between-year climate variability influenced water demand, implying that selection of analysis period is an important consideration when calculating overall water demand.
- Ideally, high quality river flow data covering long periods are required to define rules using bands, and to assess both water availability and hydrological alteration. It should be noted that analysis period can influence estimates of 7dMALF and, to a lesser degree, median flow, as indicated by between-year variability in hydrographs (e.g., Figure 2-4 to Figure 2-7).
- The analysis benefited from river flow data being available for multiple sites, but some river flow time-series were relatively short in duration, some gaps in data were present, and data quality issues were evident at times. Issues with river flow data probably reflect physical challenges of monitoring river flows, technical limitations, and funding constraints.
- Spatial patterns in seasonality of river flows created within-region variability in water supply, implying that water supply cannot be assumed to be consistent across a region, regardless of differences in 7dMALF and median flow.
- Leakage from storage could represent an important source of water demand implying that not all water added to a storage is necessarily available for its intended use, and that leakage should be factored into water demand calculations.
- The use of storage per se does not distinguish the effects of the take on either hydrological alteration or effectiveness of water supply when compared to run-of-river takes. A take supplying a very large irrigated area and using a very small storage will

act like a run-of-river take because demand will be driven by immediate irrigation need, and because demand cannot be satisfied by stored water indefinitely, once supply is restricted.

- A take supplying a very small irrigated area from a very large storage will result in inefficient use of water because there will be a need to take water to mitigate storage losses.
- Irrigation effectiveness (e.g., time for which soil water content is above half PAW) and hydrological alteration (e.g., alteration of 90dMALF) may be predicted, given a specified storage capacity, irrigated area, climate, and river flow regime.
- Variability in irrigation effectiveness and hydrological alteration can arise from variability in climate and river flow regime characteristics, but river flow magnitude (river size) is a strong driving factor of these two outcomes.

4.4 Recommendations for generalised rules to conform with heuristics

In Section 2.6.3, we devised a multi-band form of water allocation rules that could be applied in regional plans. We make the following recommendations and comments after having assessed our multi-band water allocation framework against the heuristics set out in Section 2.2 with respect to joint operation of run-of-river takes and flow harvesting (Table 4-1).

Heuristic 1: practically implementable

A sequence of bands defined by paired cease-to-take thresholds and maximum rates of take can be defined as a function of hydrological metrics (e.g., 7dMALF and median flow) in order to apply universal rules over multiple sites. A multiple band system would conform with the heuristic about practical implementation because it has the same information and operational requirements, and would therefore be as easily implemented as existing low flow water allocation rules. However, the following points should be noted:

- Although it is practically feasible to apply universal rules where no, or very little, hydrological data exist because methods are available to estimate hydrological metrics for ungauged sites, it should be noted that accurate estimation of hydrological metrics at ungauged sites is very challenging, and these estimates are often very uncertain (e.g., Booker and Woods 2014).
- Our analysis assumed that water users can operate their take so as not to drop the flow below the relevant cease-to-take threshold. This assumption somewhat contradicts our heuristic about practicality of implementation because it would require water users to vary their rate of take on a daily basis when observed flow was near to their cease-to-take flow threshold.

Heuristic 2: environmental sustainability

A multi-band configuration can be devised in which cease-to-take thresholds and maximum rates of take are used to define an initial set of water allocation rules in which the lowest band (Band 1) corresponds to rules for run-of-river takes. We used five bands that were defined relative to river flows, using hydrological metrics (7dMALF and median flow) as a basis for rules that would apply to a continuum of run-of-river and flow harvesting takes. A multiple band system would conform with the heuristic about environmental sustainability because the rules could be operationalised to produce predictable hydrological alterations. Alignment of a predictable level of hydrological alteration against specified environmental flow regimes (to achieve environmental outcomes) could also be achieved by declining consent applications or assigning consents (or parts of consents) to different bands depending on the level of current allocation for each band, and other considerations (e.g., efficient irrigation) factored into water allocation decisions.

- A more environmentally conservative application of the base set of rules could be applied by choosing to not assign any consents to particular bands, as was the case for our three-band harvesting experiment; our results showed that altered higher flows were near to being within 80% of unaltered higher flows for our example site (Figure 3-20).
- The same base set of multi-band rules could be applied across a region (or nationally), with decision makers selecting which bands to utilise in particular FMUs. Thus water allocation for all flows across all FMUs would be characterised by a table where rows are bands, columns are FMUs, and each cell represent whether that band is to be allocated as indicated by either true/false or a percentage.
- As an alternative to the point above, a different number and configuration of bands could be used for different catchments or FMUs depending on the flow patterns, community values, level of protection needed for ecosystem health and/or practical limitations. We used multiples of 7dMALF and median flow to set the position of bands. Similar selections could be achieved by defining bands from positions on the flow duration curve (or summer flow duration curve specifically, depending on outcomes to be achieved).
- A multi-band system could cover the continuum from run-of-river takes to high-flow harvesting. It is important to provide adequate protection to river flows across the spectrum of flows (e.g., low flow and flushing flows) from change in daily flow. In theory, if flow harvesting is operated within sustainable limits, it could represent an option for water use that is broadly consistent with the Te Mana o te Wai hierarchy of obligations and other clauses associated with safeguarding ecosystem health laid out in the 2020 NPS-FM.
- It should be noted that the NPS-FM implies adaptive management can be applied to alter water allocation rules and associated consents, but (from an economic and social perspective) it might be very hard to “claw back” high flow harvesting consents once they are in place. This is partly because building and operating storage is costly. Difficulty with clawing back overallocation situations reinforces the need to apply an environmentally conservative approach to water allocation in line with the Te Mana o te Wai hierarchy of obligations outlined in the NPS-FM.
- Implementation of any rules should ideally be accompanied by careful monitoring of effectiveness for water supply, and to identify potential undesirable ecosystem effects, as would be required for effective adaptive management (see Stoffels et al. 2022a).

Heuristic 3: water efficient

Our results demonstrated that rules defined by bands interact with irrigated area, storage capacity, local climate, and river size to influence irrigation effectiveness in a predictable way. The multiple band system could therefore conform with the heuristic about using water efficiently because Figure 3-33 (or similar) can be used to look-up the likely consequences of a combination of factors defined by given irrigated area, storage capacity, and river size, on irrigation effectiveness.

- Possible sources of uncertainty in our analysis and the implications of the assumptions set out in Section 4.1 should be carefully considered if using Figure 3-33 and Figure 3-35 (or similar) to better understand the likely consequences on irrigation effectiveness.

Heuristic 4: spatial consistent

A multiple band system could conform with the heuristic about consideration of spatial issues because analysis shown in Figure 3-33 and Figure 3-35 (or similar) can be used to look-up the likely consequences of a given irrigated area, storage capacity, and river size on relevant outcomes. However, the following points apply.

- Our analysis indicated that river size was particularly important in determining spatial variations in outcomes when universal rules were applied.
- Our results indicated that it must be accepted that universal rules will not necessarily result in universal outcomes in terms of hydrological alteration or water supply due to spatial variations in flow regimes and water demands. This is especially relevant with regard to temporary water storage because the size of storage will interact with consent conditions to determine the degree of hydrological alteration.
- In situations with very large storages, it cannot be assumed that hydrological impact will be limited because taking will cease once the storage is full; water take needs to be continued to match losses from the storage even when there is no demand for irrigation.

In Section 2.2 we defined some resource management challenges, as well as principles and heuristics to identify how high flow harvesting and related planning and consenting may be approached. This report describes a model process that was developed to give effect to these principles, guided by heuristics, from which a set of reasonably simple rules were derived. Having applied these theoretically derived rules to idealised situations but using real climate and flow data from across two regions of NZ, we reflect back on how these rules relate to the issues originally identified in Table 4-1.

Table 4-1: How multi-band water allocation rules would align with issues, principles, and heuristics.

Arising issue: what issues prompt the principle?	Principle (piece of knowledge): what should happen?	Heuristic (ways to apply the principle): what needs to happen to apply what should happen?	How a multi-band system aligns with issues, principles, and heuristics
Water allocation systems need to be functional.	Be clear about how much water is available for current water users and potential new water users.	Use rules and consent conditions that are practical and implementable.	Applies the same information, practical, and operational requirements as current low flow water allocation rules.
Sustain ecosystem health by delivering environmental flows.	Hydrological impacts of allowable water use should be predictable and deliver environmental flow regimes.	Assess delivery of environmental flows by take limits.	Assuming that environmental flows have been predefined, assignment of consents to bands can be adjusted so that the worst-case-scenario for consented water use delivers environmental flows. See Figure 3-20 for an example of how this may be achieved.
Use water efficiently.	Don't give access to more water than is needed for efficient use.	Ensure water allocation does not exceed reasonable water demand.	Results shown here demonstrate that rules defined by bands interact with irrigated area, storage capacity, local climate, and river size to influence irrigation effectiveness in a predictable way. See Figure 3-33 for example.
Consideration of spatial issues.	Consider local and catchment-wide hydrological consequences of water use.	Map the hydrological effects of water allocation.	Results shown here demonstrate that rules defined by bands interact with irrigated area, storage capacity, local climate, and river size to influence flow alteration in a predictable way. See Figure 3-35 for example.

It should be noted that storage requirements to enhance water supply reliability for irrigation vary due to multiple factors, including physical characteristics such as climate and soil-water properties of the irrigated land, and water management policies and rules. In particular, the magnitude and timing of rainfall determines the requirements for out of channel storage so that rainfall may be supplemented to meet target plant water conditions. Therefore, it is unfeasible and potentially inefficient to devise a universal policy for flow harvesting that is suitable for all catchments or regions. Our devised rules and accompanying experiments represent plausible sets of allocation rules and consent conditions that could be further optimised and applied in high-flow harvesting situations to align with the principles and heuristics set out in Section 2.2.

5 Conclusions

Water is taken from the natural environment and used by people for a variety of purposes. Lack of available water during low flow periods is problematic for water users because low flows often coincide with periods of high demand for water uses such as irrigation. Harvesting of water during periods of higher flows, combined with water storage for later use, has therefore been proposed as a viable option for providing access to water whilst minimising the risk of detrimental effects on in-stream values.

River flow regimes encompass the magnitude, frequency, duration, timing, rate of change, and seasonality of river flows when viewed over the long-term. Many aspects of flow regime support cultural, recreational, and aesthetic values, which are intertwined with river ecosystem health. Ecosystem health is vulnerable during prolonged dry periods due to factors such as habitat constriction, decreased habitat quality, high temperatures, dissolved oxygen depletion, and reduced fish passage. There is also a strong rationale for linking high-flow conditions with various in-stream values, including ecological and cultural values through controls on nuisance periphyton, fine sediment, riparian vegetation, and aquatic vegetation (Hickford et al. 2023). However, relationships between various parts of flow regimes and in-stream values are known to be difficult to quantify due to factors such as lack of data, variability in hydrology-hydraulics-ecology across the landscape, and the dynamic nature of river environments. This situation makes setting rules for high-flow harvesting very challenging.

Because water taken under high-flow harvesting does not have to be used immediately, it is possible to take water during short periods during high flows events, and at higher instantaneous rate of take relative to run-of-river water takes. Given the same overall level of water demand, high-flow harvesting would be expected to differ from run-of-river water takes in terms of operational controls, hydrological effects, infrastructure requirements, and water losses via leakage and evaporation.

This report described some overarching requirements for successful water allocation systems related to hydrological knowledge, legislation, regulation, information, management, and engagement that have been suggested in the international literature. These overarching requirements were used to devise principles and heuristics which call for water allocation rules to be practically implementable, environmentally sustainable, water efficient, and spatially consistent.

Overall, our analysis indicated that the same rules for determining water availability would have different outcomes for river flows, water availability, storage viability, and irrigation effectiveness depending on river flow regime, climate, storage capacity and irrigated area. Rules used to specify water availability across the entire flow regime for all sites were derived by defining five bands of water availability using 7dMALF and median flow. The bands were positioned in different positions relevant to local river flows in order to manage all takes along a continuum between run-of-river and high-flow harvesting water takes. Differences in the position of bands (in the form of cease-to-take thresholds and allowable rates of take) relative to a flow duration curve, together with difference in flow regimes and climate, resulted in some between-site differences in both water availability and hydrological impacts. The existence of between-site differences in water availability and hydrological impacts demonstrate that regionwide application of universal rules should not be expected to result in universal impacts on either in-stream values (in the form of flow-driven responses) or out-of-stream values (in the form of water supply). However, outcomes for river flow alteration and irrigation effectiveness were reasonably predictable, given how rules defined by bands interact with irrigated area, storage capacity, local climate, and river size. Consequently, a maximum level of hydrological alteration can be calculated from a set of multi-band water allocation rules, and a viable irrigated area can be calculated for a given river flow regime, set of band rules, and storage capacity.

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7 Glossary of abbreviations and terms

Term	Definition
Storage	A facility for temporarily storing water after it has been taken from the natural environment (usually from surface water from a nearby river) and before it is used for an activity just as irrigation, municipal supply, or industrial use.
Maximum capacity	The maximum volume of water that can be stored in the storage.
Instantaneous capacity	The volume of water that can be added to the storage before storage maximum capacity is reached.
Instantaneous availability	The volume of water that is available from the storage to be used.
Leakage	The rate at which water is lost from the storage specified as a proportion of water currently stored in the storage.
River flow	The volume of water passing through a river cross-section during a specified time.
Unaltered river flow	The river flow in the river before accounting for water that has been taken. Also known as naturalised river flow.
Altered river flow	The river flow remaining in the river after water has been taken form the natural environment.
River flow depletion	The reduction in river flow that results from upstream water takes. Also known as streamflow depletion.
Abstraction	Taking of water from a river (or aquifer in the case of taking from groundwater).
Take point	A location on the river from which water is taken from the natural environment (e.g., river or aquifer).
Control point	A location on the river whose flow is used to restrict or cease taking of water from the natural environment.
Consent	A set of conditions that controls from where water is taken and under what conditions.
Land parcel	A parcel of land to be irrigated.
Demand	Water that is needed to keep soil moisture at its intended level.
Potential evapotranspiration (PET)	The evaporation resulting from a short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water.
River reach	A length of river represented in the digital river network as being a stretch of river located between two river confluences.
Time step	A unit of time over which calculations are made and results are represented.

Term	Definition
River flow augmentation	Water being returned to rivers after it is has been taken. River flow augmentation can be unintentional as in the case of inefficient irrigation practices, or intentional as in the case of flow releases from water storages.
High-flow harvesting water takes	Taking of water that allows the possibility for water to be stored for later use. This type of water take may involve taking at a higher rate and for shorter durations when compared to run-of-river water takes.

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