A proposed framework for managing river flows to support implementation of the NPS-FM

Prepared for Ministry for the Environment

July 2022

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NIWA CLIENT REPORT No: 2022130CH
Report date: July 2022
NIWA Project: MFE22505

Revision	Description	Date
Version 1.0	Draft Report for external review	1 June 2022
Version 1.1	Revised Report for review	28 June 2022
Version 1.2	Final Report	14 July 2022

Quality Assurance Statement		
	Reviewed by:	Neale Hudson
	Formatting checked by:	Rachel Wright
	Approved for release by:	Scott Larned

Contents

Tables

Figures

Executive summary

River flows are a master variable that are linked to various physical, chemical, and ecological states that are in-turn linked to ecosystem health, human health, cultural wellbeing, landscape character, recreation, and water supply for out-of-stream use. Local authorities must prepare regional plans and action plans that give effect to the National Policy Statement for Freshwater Management 2020 (NPS-FM). River flows are an essential and legitimate consideration for all 15 NPS-FM policies and many of the values described in NPS-FM Appendix 1. The NPS-FM Te Mana o te Wai hierarchy of obligations prioritises first the health and well-being of water bodies and freshwater ecosystems, second health needs of people, and third the ability of people and communities to provide for their social, economic, and cultural well-being. The Te Mana o te Wai hierarchy of obligations is relevant to all freshwater management, including river flow management.

Two of the most important technical terms relating to river flow management within the NPS-FM are “environmental flows and levels” and “take limits”. The NPS-FM does not define environmental flows, but the take limit interpretation is “a limit on the amount of water that can be taken from an FMU or part of an FMU, as set under clause 3.17”. In this report, we interpret the terms as follows:

- **Environmental flows** describe the aspirational state of river flow regimes required to achieve the environmental outcomes described in the NPS-FM. Environmental flows should be thought of as environmental flow regimes that describe the main features of a long-term river flow time-series required to achieve environmental outcomes. Environmental levels are the equivalent to environmental flows, but environmental levels apply to water levels in aquifers (groundwater levels), lakes and wetlands.
- **Take limits** are sets of rules in regional plans that constrain water use to restrict the degree of hydrological alteration arising from collective operation of flow-altering activities. Take limits can be thought of as predefined rules that guide authorities to deliver environmental flows by controlling flow-altering activities. Take limits also clarify water availability for out-of-stream use.

We propose a framework that can be used to facilitate an approach to managing river flows to achieve environmental outcomes defined under the NPS-FM (Figure 1-1; See Figure 3-2 on page 35 for full version). The framework sets out a transparent approach for linking environmental flow regimes to ecosystem states that represent ecosystem health through controls on flow-altering activities. The framework comprises a cascade of steps which:

- starts with a broad definition of environmental flow regimes;
- includes consideration of climate change;
- incorporates a loop for monitoring and adaptive management; and
- ends with controls on flow-altering activities.

We demonstrate how this framework can be operated in a manner consistent with the NPS-FM by mapping each flow-related NPS-FM clause to a step in the framework.

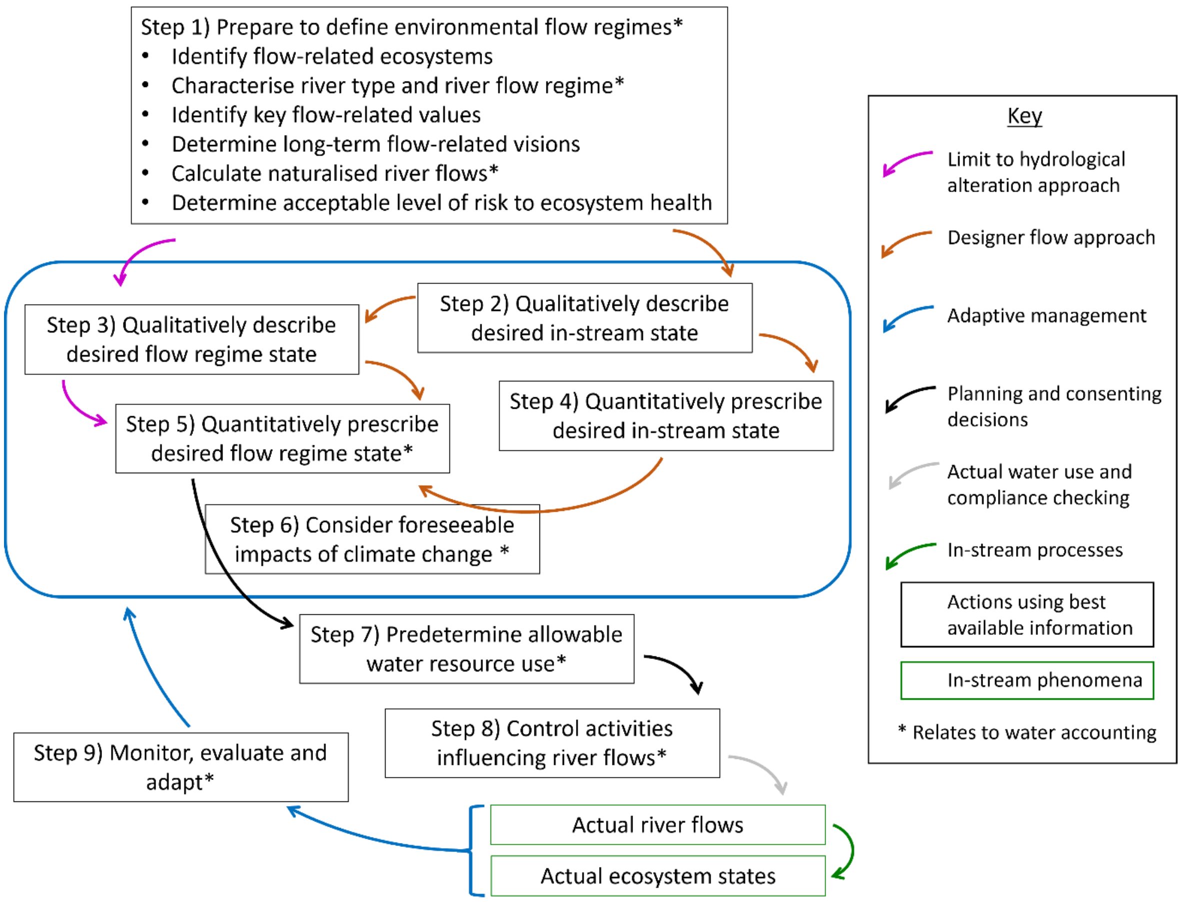

Figure 1-1: Simplified depiction of a proposed framework for river flow management. See Figure 3-2 on page 35 for full version including descriptions of each step.

The foundational principles behind this framework are summarised in the following points.

1. There is a strong theoretical basis for links between river flow characteristics and the freshwater environments, ecological functions, and ecosystem values they support. Aspects of ecosystem health (including periphyton, benthic invertebrates and fish communities) are linked with aspects of river flow. Flow-ecology relationships are therefore often needed to inform river flow management decisions. However, development of quantitative flow-ecology relationships is hampered by lack of data, confounding effects of non-flow stressors, and natural variability through time. Furthermore, flow-ecology relationships are likely to vary spatially due to landscape-scale differences in climate-hydrology-geomorphology-ecology.

2. River flow regimes are multifaceted characterisations of the main features of a river flow time-series when viewed over the long-term. River flow regimes vary naturally across the landscape because of differences in climate, geology, soil properties and vegetation cover. Features typically used to characterise flow regimes include the magnitude and duration of low flows, magnitude and frequency of medium and high flows, and degree of seasonality.

3. Sets of many hydrological indices have been proposed to represent various features of river flow regimes and also to describe environmental flow regimes. Knowledge about how a single hydrological index fits within the wider flow regime is required to avoid unintended outcomes for river flow management. Each individual index represents a particular characteristic of the regime, such as drought duration, flood magnitude, or

seasonality. Hydrological indices have been associated with geomorphological conditions, ecosystem processes, or water availability. For example, habitat conditions at low flows are commonly associated with mean annual low flow (MALF) and flushing flows associated with frequency of events that exceeds three times the median flow (FRE3). Because they are often related to each other, several hydrological indices may also correlate with an ecological metric. Although statistical redundancy occurs when hydrological indices are correlated, this does not necessarily equate to functional redundancy between hydrological indices with respect to links to in-stream values.

4. River flow regimes vary widely across Aotearoa-New Zealand. Expected spatial patterns under reasonably natural conditions can be represented as hydrological classifications or maps of predicted hydrological indices. However, currently available classifications of New Zealand's river network were not specifically designed to set environmental flows or take limits across FMUs and are yet to be tested for these purposes.

5. River flow regimes can be altered by a complex and interrelated combination of local human activities and climate change. River flow regimes can be altered directly by engineered manipulation of groundwater or surface water (e.g., abstraction, diversion, damming). River flow regimes can also be altered indirectly when water fluxes are modified by any combination of the following:

   - drainage modification (e.g., tile drainage, drainage ditches);
   - river channel modification (e.g., channel straightening);
   - urbanisation (e.g., increased impermeable surfaces);
   - intentional changes in landcover (e.g., deforestation or afforestation);
   - unintentional shifts in landcover (e.g., invasive vegetation such as wilding pines, climate-driven change in tree line);
   - primary physical effects of climate change (e.g., reduced precipitation); and
   - climate-driven changes in water demand (e.g., irrigation).

6. Approaches to setting environmental flow regimes range from specifying a default allowable deviation from natural flow regimes to evidence-based design of flow components to meet the needs of specified in-stream values. The appropriateness of any environmental flow setting approach will depend on data availability, degree of hydrological alteration, and type of in-stream value.

7. Environmental flows and take limits should be considered as spatially distributed phenomena, rather than applying to single sites. Environmental flows must account for spatial variations in in-stream values and flow-ecology relationships. Flow alteration will vary in space due to cumulative effects and the connected hierarchical nature of river networks. The number, spatial configuration, and strategy for implementing water takes to meet environmental flows and take limits is therefore important for delivering environmental outcomes across a Freshwater Management Unit (FMU). If spatial considerations are ignored, some implementation strategies could ensure that take limits are met at a downstream monitoring point, but not complied with elsewhere across an FMU.

1 Introduction

1.1 Purpose

This report provides information about the National Policy Statement for Freshwater Management 2020 (NPS-FM). It is not part of the NPS-FM 2020 and it does not have statutory weight. The primary purpose of this report is to help regional councils understand and effectively implement the objectives and policies in the NPS-FM 2020 that pertain to management of river flows to support ecosystem health. This report may also be of use to tangata whenua, stakeholders, or community members who are participating in a regional freshwater planning process.

1.2 Aim

The aim of this report is to set out foundational principles and a general framework to facilitate a credible approach to managing river flows to sustain ecosystem health in a manner that is consistent with the NPS-FM. Examples of technical methods are mentioned. However, a comprehensive set of prescriptive instructions is not provided. Provision of a general framework, rather than prescriptive instructions for technical methodologies, is consistent with the NPS-FM because the NPS-FM allows for flexibility in the methods used to give effect to its objectives and policies. Allowance for flexibility is appropriate given regional/catchment variability in climate, topography, geology, ecology, demand for water use, data availability, and values proposed by tangata whenua and communities. Flexibility in technical methods is also appropriate because improvements in knowledge, monitoring and models should occur over time. Indeed, the NPS-FM (Clause 1.6) recognises that complete and scientifically robust data are not currently in place to adequately meet all the needs of the NPS-FM in all locations. In the absence of complete and scientifically robust data, the best information may include that obtained from modelling, as well as partial data, local knowledge, and information obtained from other sources. One role of a general framework is to help highlight scientific advancements needed to give effect to the NPS-FM (e.g., monitoring data, knowledge, and modelling).

1.3 Scope

This report concentrates on management of river flows in support of flow-driven in-stream values relating to ecosystem health. Human activities influencing hydrological conditions in aquifers are in scope because there can be strong interconnections between groundwater manipulation and river flows. The scope of this report is confined to river environments including river mouth openings, estuaries and hāpua. It is recognised that hydrological conditions influence physical, chemical and ecological states in wetlands, lakes and aquifers. Although wetlands, lakes and aquifers are not considered explicitly here, recommendations for river flow management provided here can be adapted for application to these environments.

It is likely that many flow-driven aspects of cultural, recreational, and aesthetic values are intertwined with ecosystem health (e.g., Harmsworth et al., 2011). We acknowledge that in-stream values associated with cultural, recreational, or aesthetic perspectives are important for river flow management but are not considered explicitly in this report. With respect to cultural values, we refer to Crow et al. (2018) who indicated the importance of cultural flow assessments being “undertaken by mandated representatives of the hapū or iwi, who have a history of interacting with the wetlands, streams and rivers within their rohe.” This is important because Crow et al., (2018) also stated that: “From the perspective of Māori cultural values, beliefs and practices supported by fresh water can be seen to compete with these economic uses [irrigation and hydroelectric generation]. If the interests of Māori are to be weighed alongside the many other uses, and if environmental streamflow assessments and allocative decision-making are to benefit from the knowledge of whanau, hapū and iwi, new techniques are needed to assess the appropriateness of streamflows in culturally sensitive ways". This need is clearly identified within the NPS-FM because it recognises the importance of identifying tangata whenua values that collectively recognise the significance of fresh water. We refer readers to the work of Harmsworth et al. (2016), Tipa et al. (2016), Ataria et al. (2018), Clapcott et al. (2018), Morgan et al. (2021), Taylor et al. (2021), Tadaki et al. (2022) and others on cultural aspects of freshwater management that link to the right to exercise kawanatanga (governance) in a manner consistent with the principle of partnership, and the duty to protect rangatiratanga (sovereignty) in relation to taonga katoa (treasures) as these important issues are not dealt with here because they are outside the scope of this report.

Freshwater accounting systems are required by the NPS-FM. However, technical methods for producing water accounts are not in scope for this report. We assume that accounting systems will provide baseline information relevant to river flow management, including spatial patterns of the take limit, and the amount of freshwater that is physically available, allocated, and taken regardless of whether for consented, permitted, or other activities. We also assume that freshwater accounting systems will provide observations or estimates of current and naturalised river flows and their associated uncertainties. For freshwater accounting, naturalised river flows are defined as flows estimated in the absence of "all takes and forms of water consumption, whether metered or not, whether subject to a consent or not, and whether authorised or not" (as is consistent with NPS-FM Clause 3.29).

At the time of writing, many regional councils are working towards establishing policies and methods, including rules set in regional plans, by 2024 that will give effect to the NPS-FM. Many councils may have already set rules under the previous NPS-FM 2014, however councils need to review these rules and be confident that existing rules meet the requirements of the NPS-FM 2020, including the fundamental concept of Te Mana o Te Wai. It is envisaged that this report can feed into the development of plans because the framework we present can be used to demonstrate how existing methods and processes are giving effect to flow management aspects of the NPS-FM. This report is also intended to be of use beyond the 2024 deadline because general advice about approaches to river flow management should endure beyond this date, and river flow management should be seen as an on-going undertaking rather than a set and forget situation.

1.4 Positioning

This report was written independently from other guidance pertaining to the NPS-FM. We cannot guarantee consistency between this report and other guidance or material relating to the NPS-FM. This report should be viewed as an independent discussion paper from the authors because it was not co-developed with the Ministry for the Environment (MfE), iwi partners or regional councils due to a short timeframe for its production. This report does not constitute official guidance from MfE and is not a substitute for legal advice. This report does not critique or suggest changes to the published NPS-FM 2020, which we regarded as incontestable for the purposes of this report.

1.5 Structure

This report contains four main sections. The first section is this introduction. In the second section we outline some fundamental principles for river flow management. Many of these principles will be familiar to those involved in river flow management in New Zealand but are provided here for completeness. In the third section we propose a framework for delivering a flow regime to fulfil environment needs whilst allowing for some degree of hydrological alteration and thereby clarify water availability after environmental needs have been met. The framework takes the form of a cascade of steps for linking a broad definition of environmental flow regimes through to methods for controlling human activities that alter river flows. In the fourth section we provide our interpretation of the requirements of the NPS-FM with respect to river flow management and describe where they fit in the proposed framework. This fourth section also provides some suggested working definitions of some technical terms used in the NPS-FM.

1.6 Content

The level of detail provided in Section Two reflects the complexity and difficulties inherent in river flow management. Section Two draws on a wide body of local and international literature which relates to river flow management. The literature on flow-ecology relationships is broad and complex. We provide several references on flow-ecology relationships to help readers further explore the topic. In the interest of brevity, only citations to the most pertinent scientific literature have been included in all other sub-sections. Key points are provided at the start of each sub-section to summarise the content.

The phrases “environmental flow regime” and “environmental flows” are often used, sometimes interchangeably, in the international river flow management literature. In Section Two we use “environmental flow regime” rather than “environmental flows” because the latter term has a particular meaning within the NPS-FM which we then clarify in Section Three.

2 Fundamental principles for river flow management

2.1 Physical and ecological states influenced by river flows

Key points

- The integrity of freshwater systems depends on river flow to determine physical and ecological structure and processes.
- Multiple aspects of ecosystem health, including periphyton, benthic invertebrates and fish communities, are linked with various aspects of river flow.
- The specification of flow-ecology relationships is likely to vary spatially due to differences in a combination of climate, hydrology, geomorphology, and ecology.

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 nutrients, dissolved oxygen 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 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).

River flows interact with sediment supply, valley slope, valley confinement, and vegetation to drive river geomorphological processes and set riverine habitat templates. Channel-forming high flow events are often associated with transport of gravel and lateral bank erosion that influence meso-scale geomorphological character (e.g., braided, pool-riffle, run, etc.) (Blom et al., 2017). Mid-range and lower flows are often associated with transport and deposition of sand and fine sediment that interact with ecological processes to influence micro-scale riverbed characteristics (e.g., bed texture, interstitial spacing, hyporheic processes, etc.) (Wilkes et al., 2019). A variety of river flow magnitudes and event return intervals are therefore important in determining river physical templates (Gurnell et al., 2016) and overall river health (Maddock, 1999) at a range of spatial scales.

Periphyton is a complex mixture of algae, cyanobacteria, heterotrophic microbes and detritus that attach to the riverbed. Most of New Zealand’s riverine food webs have periphyton as a basal energy source, hence periphyton is critical to river ecosystem health. Periphyton species have specific hydraulic (e.g., depth and velocity) preferences (Biggs, 1996). As a result, changes in the hydraulic state of a river can impact periphyton species composition and biomass on a temporal scale of weeks to months, and changes to flow regimes can affect periphyton species composition and biomass on a scale of months to years (Biggs and Gerbeaux, 1993; Biggs and Hickey, 1994, Biggs et. al., 1999; Wu et al., 2009). Periphyton-flow relationships are not spatially uniform due to variations in hydraulics, sediment, nutrient availability, heat, and light (Hoyle et al., 2017).

Several aspects of flow regimes directly affect invertebrate diversity and abundance, which in turn affect food supplies for fish, periphyton abundance and other ecosystem properties (Booker et al., 2016). Responses of invertebrates to reduced flows can be mediated directly through changes in velocity, depth, wetted area, water temperature, and sedimentation, but also indirectly through changes in dissolved oxygen, pH, and nutrient levels (Dewson et al., 2007). Field observations from three New Zealand streams indicated that reduced river flow can limit the distance that individual invertebrates can travel downstream (James et al., 2009). Recent work has demonstrated the mechanistic link between river flows, near bed velocity and drift flux or rate (Hayes et al., 2019). Changes in flow or associated pulses of sediment may provide cues that cause benthic invertebrates to enter the water column, seek refuges, or undergo metamorphosis and emerge as aerial adults (Lytle and Poff 2004; Gibbins et al. 2005). As is the case for periphyton, macroinvertebrates have specific hydraulic preferences (Jowett et al., 1991; Shearer et al., 2015), so changes in flow can alter macroinvertebrate community structure at multiple temporal scales. Benthic macroinvertebrates are removed from substrates by hydraulic forces and by substrate movement during spates and floods (Statzner 2008). Relationships between flow fluctuations and invertebrate communities are not only dependent on the removal of organisms, but also on re-colonisation and community recovery during periods between spates. Recovery rates vary with rates of dispersal and recolonisation, pre-spate diversity (recovery is likely faster for depauperate communities than for diverse communities), the abundance of species that resist spates and the rate of food accumulation (Death, 2008). Recovery periods following moderate-sized (i.e., partial bed mobilisation) spates in some New Zealand rivers ranged from days (Melo et al. 2003) to several months (e.g., Matthaei and Townsend 2000). Several community-level studies of New Zealand river invertebrates have used long-term invertebrate monitoring data to evaluate the roles of flow variability, including mid-range flow fluctuations (Clausen and Biggs 1997; Booker et al. 2014). It has been found that aquatic invertebrate diversity, abundance, and several aspects of community composition, change significantly with time since a flood (Greenwood and Booker, 2014). Booker et al. (2015) also provided a detailed discussion of co-variance between hydrological indices and other factors influencing invertebrates such as land cover, geomorphology and climate.

Fish are recognised as key components of New Zealand river ecosystems and as a component of native biodiversity. Fish are highly valued for customary mahinga kai (food and food gathering) and for recreational sport. Fish are key species in freshwater food webs and influence the structure and function of freshwater ecosystems (Power, 1990). Freshwater fish are present in virtually every river in the country. The distribution and abundance of fish is influenced by several factors, particularly migration and habitat suitability, which are in turn strongly influenced by flow regimes (Crow et al., 2013, Booker et al., 2016). The specific effects of flow regimes on fish migration and habitat suitability are discussed in detail by Closs et al. (2016).

Low flows are important for fish because they play a role in limiting overall habitat availability (Zeiringer et al., 2018), influence habitat fragmentation (Aarts et al., 2004; Fuller et al., 2015) and cause temperature effects (Lessard and Hayes, 2003; Young et al., 2010). Several studies have focused on demographic and behavioural responses of fish to individual, large floods (David and Closs 2002; Jellyman and McIntosh 2010; Hayes et al. 2010; Young et al. 2010). Jellyman et al. (2013) provides much discussion on the role of flow-driven physical disturbance on fish communities. Although salmonids (e.g., brown trout) are non-native species, they are highly valued as a sports fish and habitat for trout is protected under current legislation. Flow requirements of salmonids can strongly influence the outcomes of environmental flow regime assessments and related management decisions (Hayes et al., 2018a). Much has been written about competition between native fish species and invasive salmonids (e.g., Jones and Closs, 2017; Hayes et al., 2018b). Relationships between brown trout and native fish species are influenced by a complex interaction of river size, physical disturbance regime, invertebrate community composition, barriers to fish migration, and predation (Jellyman et al., 2017). McIntosh et al. (2010) presented evidence that habitat conditions at low flows can influence trout-galaxiid interactions and therefore give the misleading appearance that native species favour low flows. Woodford and McIntosh (2010) indicated that small, trout-free tributaries 'leak' Galaxias larvae to mainstem habitats where trout predation (primarily) and habitat instability otherwise limit local reproductive success.

2.2 Flow-driven metrics for ecosystem health

Key points

- Many physical-chemical and ecosystem attributes of interest to river flow management will be influenced by river flows. However, these attributes were not necessarily designed to monitor and evaluate the effectiveness of river flow management.
- A national approach to monitoring and evaluating both flow-ecology relationships and the effectiveness of river flow management is required, which:
  - describes flow-driven metrics of ecosystem health,
  - explains why monitoring of ecological and/or physical conditions need to be paired with river flow gauging sites, and
  - outlines a plan for locating monitoring sites to inform river flow management across landscape settings with different flow-ecology relationships (e.g., lowland, hill-fed and mountain).

We refer readers to the Envirolink report of Stoffels et al. (2022a) for a detailed discussion of how flow-driven metrics of ecosystem health and landscape-scale classifications may be used to assist monitoring and evaluation of river flow management. Above we provide the key points from Stoffels et al. (2022a).

2.3 River flow regimes

Key points

- River flows at a site are not constant, they change through time in response to weather events, seasonal cycles, and climate variability.
- A flow regime describes the main features of river flow when viewed over the long-term.
- The main features used to characterise flow regimes include:
  - magnitude and duration of low flows,
  - magnitude and frequency of medium and high flows, and
  - degree of seasonality.
- Flow regimes are linked to both climate and catchment characteristics.

River flow is the volume of water passing downstream through a river cross-section within a unit of time. The standard unit of flow is m3 s-1, but it can be expressed in any unit of volume per unit of time (e.g., Giga litres per day or litres per second). River flow in natural catchments will vary in time because of weather patterns, and vary in space due to differences in topography, geology, climate, and vegetation conditions across catchments.

"River flow regime" is a phrase often used to describe the collective properties of river flow as it varies through time at a site when viewed over the long-term. The general features of a flow regime have been described as comprising magnitude, frequency, duration, timing, and rate of change, including seasonality. The features of a flow regime are conditioned by the interactions between climate and catchment characteristics.

A flow regime can be characterised using a suite of hydrological metrics, often referred to as indices in hydrological and flow setting literature. See Section 2.4 for a list of commonly used indices and Section 2.6 for examples of aspects of the flow regime that particular indices are intended to represent. Each hydrological index quantifies a different aspect of the flow time-series. Sets of indices are often used to collectively describe the features of a flow regime considered to be ecologically relevant and/or important for setting physical habitat templates. However, no global definition can be applied to all rivers as to which indices should be used to characterise flow regimes. This is partly because there are various reasons for characterising flow regimes, each requiring different (although possibly overlapping) sets of indices. There are also large differences between rivers in total flow ranges, in temporal flow patterns, and in flow-ecology relationships. Furthermore, flow regimes interact with landscape setting (e.g., slope, valley confinement, vegetation, sediment supply) to create different habitat templates; the same flow regime in a different landscape setting will lead to rivers with different hydraulic and ecological characteristics.

2.4 Hydrological indices

Key points

- Many hydrological indices are available, each of which represents a different aspect of a flow regime.
- Many hydrological indices have been empirically linked with the ecological structure and function of rivers.

River flow time-series are measured at gauging stations, often by combining continuous measurements of water level (stage) and stage-flow relationships. However, gauging stations can be expensive to operate, especially at sites influenced by an unstable riverbed or changes in roughness due to macrophyte growth. Missing data within a river flow time-series can occur because of equipment failure or flood damage.

Various hydrological indices can be calculated from flow time-series. Each index is designed to quantify a particular characteristic of the time-series. Sets of hydrological indices can be grouped together to represent the general features of flow regime. For example, the Indicators of Hydrologic Alteration (IHA; Richter et al., 1996) have been used to characterise natural and human modified flow regimes. The IHA originally comprised 32 hydrological indices (and 32 associated measures of variation). Although Richter et al. (1996) suggested that together these 32 indices provided information on the ecologically significant features of surface and ground water regimes, the number of indices was later expanded to 51 (and 51 associated measures of variation) (Table 2-1; Richter et al., 1997).

Table 2-1: Examples of hydrological indices (after Richter et al., 1997).

Group	Parameter description	Abbreviation
1) Magnitude of monthly flows	Mean value for each calendar month Median value for each calendar month	eg. MeanSep eg. MedianSep
2) Magnitude and duration of annual extremes	Annual minima 1-day means	Mean1DayFlowMins
	Annual minima 3-day means	Mean3DayFlowMins
	Annual minima 7-day means	Mean7DayFlowMins (7d-MALF)
	Annual minima 30-day means	Mean30DayFlowMins
	Annual minima 90-day means	Mean90DayFlowMins
	Annual maxima 1-day means	Mean1DayFlowMaxs
	Annual maxima 3-day means	Mean3DayFlowMaxs
	Annual maxima 7-day means	Mean7DayFlowMaxs
	Annual maxima 30-day means	Mean30DayFlowMaxs
	Annual maxima 90-day means	Mean90DayFlowMaxs
	Number of zero flow days	ZeroFlowDays
	Base flow index	BFI
3) Timing of annual extremes	Julian day of annual maximum	JulianMin
	Julian day of annual minimum	JulianMax
4) Frequency and duration of high and low pulses	Number of low pulses within a year	nPulsesLow
	Mean duration of low pulses	MeanPulseLengthLow
	Median duration of low pulses	MedianPulseLengthLow
	Number of high pulses within a year	nPulsesHigh
	Mean duration of high pulses	MeanPulseLengthHigh
	Median duration of high pulses	MedianPulseLengthHigh
5) Rate and frequency of flow changes	Mean of all positive differences between daily values	meanPos
	Median of all positive differences between daily values	medianPos
	Number of all positive differences between days	nPos
	Mean of all negative differences between daily values	meanNeg
	Median of all negative differences between daily values	medianNeg
	Number of all negative differences between days	nNeg
	Number of hydrologic reversals	Reversals

Many different hydrological indices have been linked to a variety of ecological states and processes in New Zealand. Crow et al. (2013) correlated fish distributions with 47 hydrological indices including those that describe predictability, constancy and contingency of seasonal patterns. Biggs (2000) linked periphyton biomass with nutrient concentrations and a hydrological index defined as the frequency of high flow events exceeding three times the median flow (FRE3). Other studies have used different multiples of the median flow to identify the frequency of events exceeding different ecologically relevant thresholds. For example, Townsend et al. (1997) calculated FRE5 when comparing various metrics of disturbance to macroinvertebrate species traits and species richness. Links between in-stream attributes and particular hydrological indices are discussed further in Section 2.6.

2.5 Calculating and interpreting hydrological indices

Key points

- Many hydrological indices are available.
- Repeatable procedures for calculating of hydrological indices are required to avoid misspecification.
- Several hydrological indices can relate to a single feature of the flow regime (e.g., FRE3, number of reversals and number of high pulses all reflect an aspect of flow variability).
- Because they are often related to each other, several hydrological indices may correlate with an ecological metric.

Hydrological indices are often calculated from mean daily flow time-series. However, they can also be calculated from more frequent observations, such as 15-minute flow data, which are important for characterising high flow conditions (e.g., mean annual flood) and flow variation at sub-daily time-scales (e.g., hydropeaking associated with hydroelectric power generation).

Observed flow time-series are only available where a gauging station continuously measures flow or stage (water height), which is then converted to flow through a stage-flow relationship. Flow time-series can be "donated" from a gauging station site to a site of interest where correlation of flows measured on the same day allow conversion from the donor site to the site of interest. Hydrological models have also been used to estimate flow time-series or particular hydrological indices (Booker and Woods, 2014). However, estimates of flow derived through the application of uncalibrated flow models to ungauged sites across New Zealand are subject to considerable predictive uncertainties (McMillan et al., 2016). Calibration of hydrological models reduces uncertainties in calculated flows but observed flow data are needed to apply a calibration.

For most hydrological indices it is possible to compute a value for each year of record. Both the central tendency and variation of annual values can subsequently be calculated. For example, the lowest flow can be computed for each year of a multi-year time-series. The mean and standard deviation of annual low flows (known as MALF) can be reported because both the average and variability are potentially important characteristics of flow regimes. Long-term means may be of interest when comparing flow regimes between sites or between scenarios of flow alteration. Inter-annual variation may be of interest because, in a natural situation, it can be used to characterise the range of natural variation experienced by organisms living in the river. The mean and standard deviation are appropriate representations of central tendency and variability of normally distributed inter-annual series. However, inter-annual series of hydrological indices can be highly skewed, in which case median and interquartile range are more appropriate representations of central tendency and variability.

The length of flow time-series is important when calculating hydrological indices because there may be large between-year differences in calculated annual values, and because the inter-annual distributions may take skewed distributions. For example, MALF can be strongly affected by the inclusion of data for one particularly low flow year, if calculated from a relatively short record (circa 5 years). Short-term climate oscillations and long-term climate trends within flow time-series can also be a source of uncertainty for calculated hydrological indices. Climate oscillations viewed within a relatively short time-series may result in calculated values that are difference than would be found over the longer-term. Long-term climate-driven and locally-driven trends have been detected in flow time-series from New Zealand (e.g., Booker and Snelder, in press). Flow trends may result in different values for calculated hydrological indices depending on the period for which data are available. The suitable length of time-series will depend on the purpose of the analysis, the type of hydrological index, and river catchment characteristics. For example, Hannaford and Buys (2012) used a minimum of 20 years in a study of trends in seasonal river flow regimes in the UK because their analysis indicated that shorter periods were likely to be influenced by short-term climatic oscillations.

The effect of river size is often removed prior to calculation of hydrological indices. This helps when making comparisons between sites. The impact of river size may be removed by dividing the flow time-series by its long-term mean or by catchment area. This process is known as “standardisation” or sometimes (incorrectly) “normalisation”.

Various software is available for calculating sets of hydrological indices. Bespoke programmes or spreadsheet formulas can also be used to calculate these indices. However, care must be taken when applying such calculations because subtle decisions about how each index is defined and the algorithms employed can lead to considerable differences in calculated values (e.g., how missing data are dealt with or whether “water years” are used instead of calendar years). Booker (2013) discussed these points with respect to calculation of FRE3; the frequency of events that exceeds three times the median flow.

A subset of hydrologic indices need to be selected from those available to reduce computational effort and index redundancy prior to characterising flow regimes, assessing flow alteration scenarios, or setting desired river flow regimes. This task is further complicated because many indices calculated from the same time-series are highly correlated (Figure 2-1). For example, in Figure 2-1 the duration of high pulses (DPHigh) is strongly positively related to the duration of low pulses (DPLow) and negatively related to the frequency of events that exceed three times the median flow (FRE3). To assist with the selection process, hydrological indices may be organised into groups designed to represent similar aspects of flow regimes (e.g., Table 2-1). For example, Olden and Poff (2003) grouped 171 previously published hydrological indices into five categories. These included categories that represent the magnitude (n = 94), frequency (n = 14), duration (n = 44), timing (n = 10) and rate of change (n = 9) in flow events. “Magnitudes” were subsequently further divided into average (n = 45), low (n = 22) and high (n = 27) categories, “frequency” into low (n = 3) and high (n = 11) categories, and “duration” into low (n = 20) and high (n = 24) categories. Multivariate methods can also be used to reduce large numbers of indices calculated for natural flow time-series to a small number of independent indices. Olden and Poff (2003) explored application of principle components analysis (PCA) methods to help reduce redundancy amongst many available hydrological indices. Use of synthetic variables exported directly from PCA (e.g., PCA-axis1) is problematic because they are not recognisable to decision makers and are conditioned by the list of indices used to produce the PCA. Furthermore, synthetic PCA variables do not have units of measurement, which makes it hard to assess their alteration under different flow management scenarios. However, PCA can help to identify a representative sub-set of the original suite of hydrological indices by selecting the dominant indices associated with the significant principal-component axes. Olden and Pott (2003) did conclude that, where possible, PCA should be used in conjugation with more intuitive index selection criteria based on the particular question of interest.

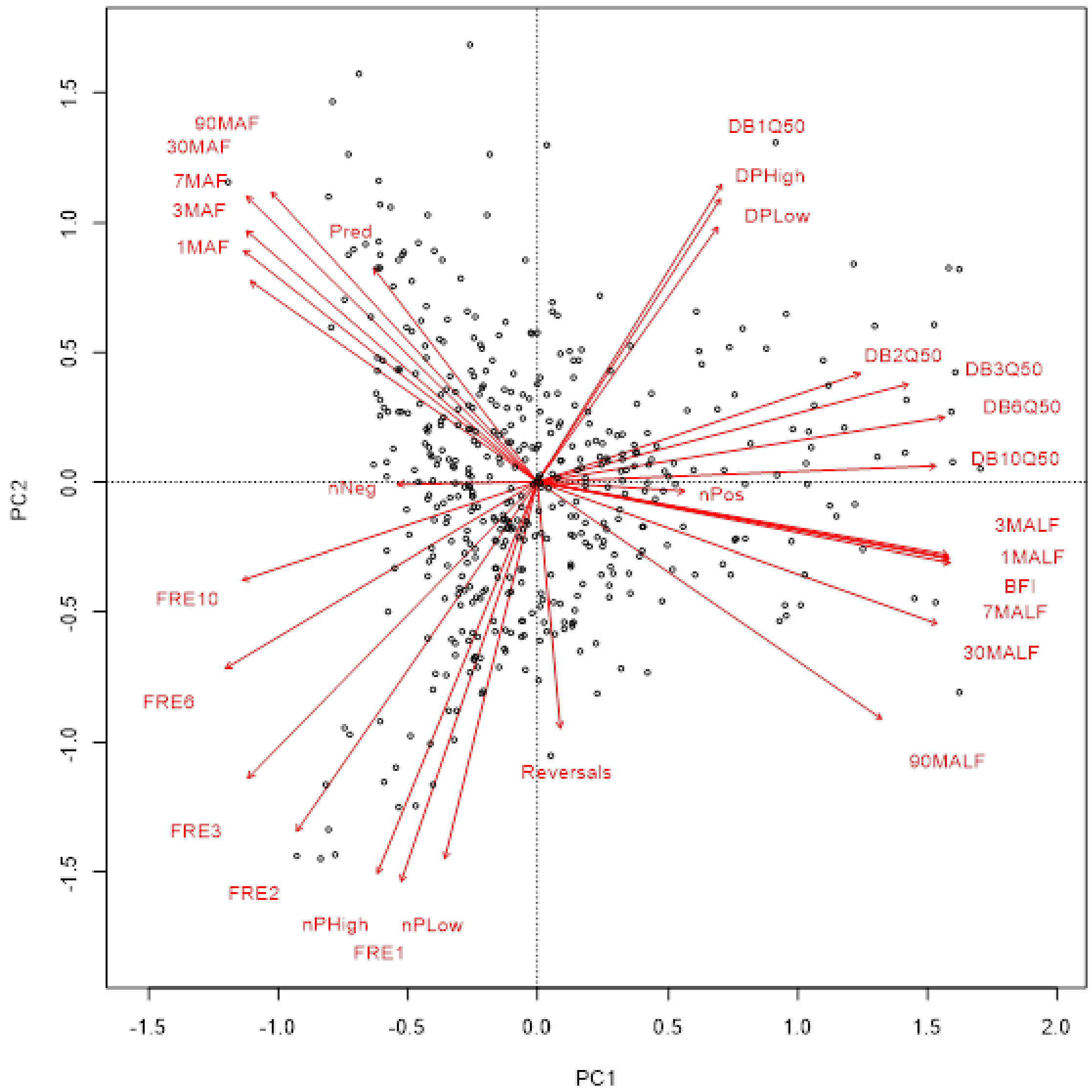

Figure 2-1: PCA ordination of 25 hydrological indices, using daily flow records from 438 river gauging stations distributed across New Zealand. Circles: scores of gauging stations on two principal components. Arrows: strengths of correlations between indices and the first two principal components. Arrows plotting near to each other are highly positively correlated. Arrows plotting in opposite directions are highly negatively correlated. Arrows plotting perpendicular to each other are independent.

2.6 Choosing hydrological indices to inform river flow management

Key points

- Qualitative or quantitative links between flow indices and in-stream values can be useful for managing river flows because they can be used to demonstrate potential impact of river flow alteration on in-stream values such as ecosystem health.
- Knowledge about how a single hydrological index fits within the wider flow regime is required to avoid unintended outcomes for river flow management.

Poff et al. (2010) suggested that three criteria be considered when selecting hydrological indices to inform river flow management (in their case, building a landscape-scale classification for river flow management purposes).

1. If possible, flow indices should collectively describe the full range of natural hydrologic variability, including the magnitude, frequency, duration, timing, and rate of change of flow events.
2. Indices must be ecologically relevant, i.e., they are known to have some demonstrated or measurable ecological influence or can reliably be extrapolated from ecological principles and hence, will be important in assessing ecological responses to hydrologic alteration. For application in the New Zealand context, this could be interpreted as meaning that there should be some theoretical, demonstrated, or measurable link between the hydrological index and an objective that has been set for a specified attribute of a particular in-stream value. See Table 2-2 for examples.
3. The indices should be amenable to management, so that water managers can develop environmental flow standards using these hydrological indices and evaluate the effect of water uses in the catchment on these indices.

Table 2-2: Hypothetical examples of links between in-stream values and hydrological indices. Note, a setting may be associated with multiple in-stream values.

Setting	In-stream value	Attribute representing in-stream value	Objective	Important hydrological functioning	Relevant hydrological index	Notes
Hill-fed	Not too much slime (periphyton)	Chlorophyll a	Should not be above x mg m^{-2} for more than 11 out of 12 monthly observations when calculated over a 5-year rolling average	Frequency of events able to mobilize sand which helps remove and limit growth of nuisance periphyton	Frequency of events exceeding three times the naturalised median flow (FRE3)	Interaction with nutrients, light and macroinvertebrate grazers
Lowland	Fish passage for adult salmon	Minimum water depth over shallow cross-sections	Thalweg of riffles should not be shallower than 0.2 m	Flows that provide at the least the minimum water depth for fish passage	Mean of the annual series of low flows after having applied a 7-day running average (7d-MALF)	Interactions with temperature and water quality, flow events for migration may also be influential
Braided-plains	Predator-free bird breading islands	Number of isolated islands	More than x number of islands per km or river length at flow flows	Sufficient flow magnitude to maintain isolation of braid islands during bird breeding season	Median flow during breeding season	Low flow not too low to maintain isolation of islands
Braided-plains	Natural character of braided rather than single-channel	Number of isolated islands	More than x number of islands per km or river length at flow flows	Frequency and duration of vegetation removing flows	Frequency of events exceeding ten times the naturalised median flow (FRE10)	Sufficient "floods" to keep river free of vegetation
Flows to estuaries	Biodiversity linked to fish community	Number of fish species in catchment	Maintain level of biodiversity	Provision of passage, spawning habitat and migration cues	MedianFebruary MeanPulseLengthHigh	Hard to measure attribute directly

Qualitative or quantitative links between flow indices and in-stream values can be used to demonstrate potential impact of flow alteration on values such as ecosystem health. However, knowledge about how a single index fits within the flow regime is needed to avoid unintended outcomes as demonstrated by the two following simplified examples. The first example is maintenance of low flows without delivering important other parts of the flow regime for in-stream values such as flow variability and flushing flow to remove fine sediment and nuisance algae (e.g., Moawhango River after diversion circa 1979, Jowett and Biggs 2006). This situation could arise when a single flow is linked with a single ecological state or process (e.g., minimum flow required for fish passage or minimal provision of physical habitat), but other parts of the flow regime are allowed to be drastically altered, partly because their importance for in-stream values is not recognised. The second example is provision of flushing flows (e.g., flows intended to remove periphyton), without acknowledging uncertainties in flow-ecology relationships such as progressive armouring of the substrate over time, meaning that flushing flows are not effective in the long term (e.g., Tongariro River downstream of the Rangipo Dam, Tonkin and Death, 2014).

The two examples given above demonstrate how attempts to identify hydrological indices that are driven by Poff et al's. (2010) third criterion (amenable to management) and adhere to their second criterion (ecologically relevant) can come at the expense of their first criterion (collectively describe the full range of hydrological variability). This situation leads to a dilemma for people who are managing river flows; they want to link key parts of the flow regime with in-stream values to help sustain ecosystem health and identify water available for out-of-stream use, but at the same time, they don't want to neglect an important part of the flow regime that might play a role in maintaining ecosystem health. For example, if median January flow is strongly correlated with median February flow, it is not necessary to use both indices to represent the flow regime or predict response in a flow-driven in-stream value. Thus, the magnitude of median January flow may be targeted by flow managers because it broadly represents summer flow conditions. However, this does not mean that either index is unimportant to the in-stream value; the imperative to maintain a statistically correlated index cannot be disregarded just because another (correlated) index has been selected to represent a particular aspect of the flow regime.

2.7 Hydrological models and maps

Key points

- Hydrological models and empirical regressions can be used to estimate hydrological conditions in the absence of observed data.
- Model results can be useful for informing river flow management, but are subject to uncertainties.

Spatial patterns in particular hydrological indices have been estimated at ungauged sites across NZ. For example, Booker and Woods (2014) compared and tested various methods for predicting MALF, mean flow and flow duration curves for ungauged sites. Similar studies have been conducted by Booker (2013) for FRE3 and by Singh et al. (2019) for baseflow index, including seasonal components. Predictions from these studies were described as representing “reasonably natural conditions” because the studied databases contained data from sites that were not affected by large engineering projects such as dams, diversions, or substantial abstractions, according to information given by each data provider. These predictions were generally shown to be unbiased but uncertain, with the level of accuracy varying with the index being predicted, and location (see Booker and Whitehead, 2018). The predictions can be used for informing river flow management in locations where little observed hydrological information exists, and where relatively low pressure on water resources occurs. At the time of writing, estimates of various hydrological indices across the national river network such as those shown in Figure 2-2 are available from MfE's data portal and NIWA's nzrivermaps tool (Whitehead and Booker, 2019).

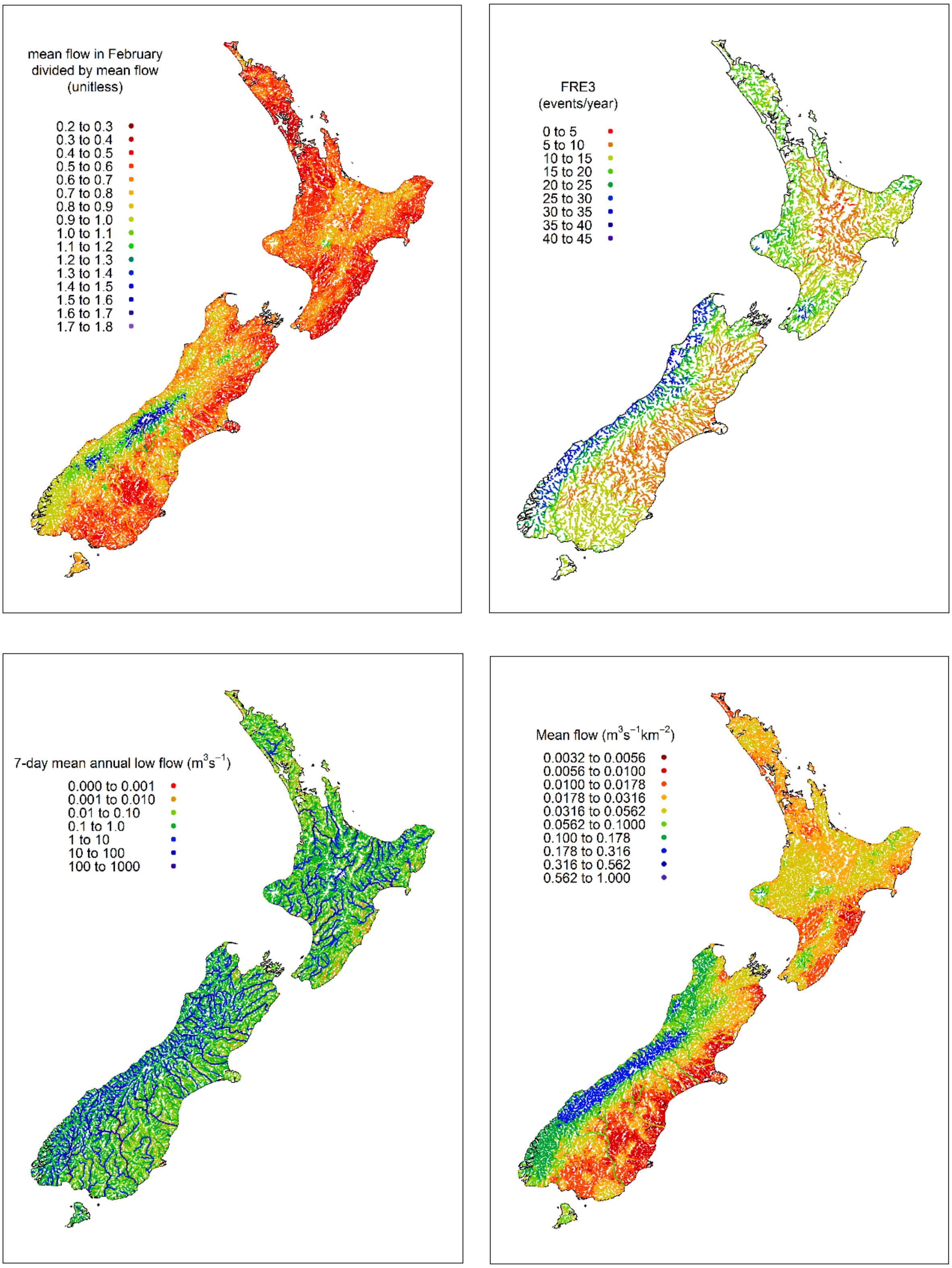

Figure 2-2. Maps of estimated hydrological conditions after Booker (2013) and Booker and Woods (2014).

Models have also been used to estimate river flow time-series at ungauged sites across New Zealand (e.g., McMillan et al., 2016). The key aim of a joint NIWA, GNS Science and Manaaki Whenua project is to enable the prediction of reliable river flows, hydrological fluxes, groundwater levels and transport processes time series. See NZ Water Model for more details. Spatially-distributed time-series models can be calibrated against observed flows to produce more accurate results. Results from these models can be used to calculate any hydrological index. The utility of these models continues to develop, e.g., advancements in process representation of surface water-groundwater interactions (e.g., Yang et al., 2017). Although these models can be used to investigate the future effects of climate change, or of water planning scenarios, they are data hungry (weather, soils and various hydrological parameters are inputs) and require hydrological modelling expertise to run. At the time of writing, NIWA's national hydrological model can be run through a cloud-based tool known as HydroDeskNZ.

2.8 Hydrological classifications

Key points

- Information about which river reaches across the country are likely to have similar flow regimes is available in the form of mapped classes.
- Information about geomorphological and hydraulic conditions likely to be found across the country has also been mapped.

Hydrological classifications attempt to group river sites by characteristics of their flow regimes. Hydrological classifications can be useful when managing river flows because they can be used to provide information that may be applied in several ways:

- Transfer of hydrological information from gauged sites to ungauged sites.
- Development of generic rules for setting limits on hydrological alteration.
- Design of river flow, ecology, geomorphology monitoring networks.
- Delineation of Freshwater Management Units (FMUs).
- Flow naturalization methods.

New Zealand has an existing deductive (i.e., *a priori*-defined) natural flow regime classification known as the River Environment Classification (REC; Snelder and Biggs, 2002), which is mapped onto a digital representation of the river network. The REC is a multi-level classification, with climate at the top level, followed by climate and topography (together), followed by climate, topography and geology (together). A simplified version of this classification forms the basis for regional variation in current deposited and suspended sediment targets within the NPS-FM National Objectives Framework. Snelder and Booker (2012) investigated the utility of the REC as a flow regime classification by defining several inductive (i.e., data-driven) natural flow regime classifications. They found only minor differences in ability to discriminate differences in hydrological indices at gauges between inductive and deductive classifications, and that different choices of classification procedure would not result in significant differences in either performance or correspondence between the inductive classifications. These results suggested that there can be many credible flow regime classifications of the same landscape, and that when considering methods for defining flow regime classifications, aspects other than the discriminative performance, such as flow data requirements and how easily the final classification can be explained, should be considered. For example, the REC is comprised of classes that are contiguously arranged in space with labels such as "cold extremely wet mountain" and "warm dry lowland", whereas the inductive classifications produced non-contiguous classes that were labelled “1b”, “5c” etc. Although classes within the inductive classifications may be associated with particular hydrological characteristics (e.g., type 2b has high MALF and low FRE3), it is difficult for decision makers to conceptualise their hydrological and ecological characteristics when compared to deductive classifications.

It should be noted that the first three levels of the REC classification are independent of human alteration because they do not consider current landcover or engineered forms of hydrological alteration. The REC classification is driven from catchment-scale inputs. It does not attempt to represent reach-scale geomorphological conditions such as river braiding. However, geomorphological and hydraulic conditions such as wetted width (Booker, 2010), depth and velocity (Morel et al. 2019), substrate cover (Haddadchi et al., 2018), and classification of surface–groundwater interactions (Yang et al., 2019) have also been estimated and mapped at the national scale. The classification of Yang et al. (2019) was based on observers experiences of present hydrological conditions and, therefore, does consider current landcover and various other forms of hydrological alteration.

2.9 Flow regime alteration

Key points

- Local human activities can alter flow regimes either directly through abstractions, dams, or diversions, or indirectly through landcover change.
- Climate change can alter flow regimes either directly through precipitation and evaporation, or indirectly through shifts in vegetation type or changes in water demand.
- River flow management needs to account for complex and interrelated dynamics within human-altered hydrological systems that are influenced by interactions between climate and local activities.

Features of flow regimes can be altered by a combination of local human activities and climate change. Local human activities can alter river flows directly by manipulating water in rivers or aquifers (e.g., water abstraction, damming, river diversion), or indirectly by altering physical catchment characteristics (e.g., deforestation, afforestation, drainage modification). Climate change also has the potential to impact river flows. Primary effects of climate change on river flows may result from changes to hydrological processes (e.g., precipitation, evapotranspiration, snow storage-melt). Secondary effects of climate change result from climate-driven changes in local activities that are likely to alter flows, such as changes in electricity demand and water demand. Interacting combinations of climate change impacts and various local human activities are therefore relevant to river flow management (Table 2-3).

Table 2-3: Potential causes of river flow alteration.

- Engineered direct manipulations of water movement
  - Dams
  - Diversions
  - Abstractions
    - Surface water
    - Groundwater
- Engineered alterations to river catchments
  - Drainage modification (e.g., tile drainage, drainage ditches).
  - Urbanisation (e.g., impermeable surfaces)
  - Flood protection works (e.g., embankments)
- Non-engineered alterations to river catchments
  - Intentional landcover change
    - Deforestation
    - Afforestation
    - Urbanisation
    - River bankside planting
  - Unintentional landcover change
    - Invasive vegetation (e.g., wilding pines)
- Climate change
  - Climate conditions
    - Precipitation
    - Temperature
    - Wind
  - Hydrological states and processes
    - Water stored as snow or in aquifers
    - Evapotranspiration
  - Water demand for human uses
    - Irrigation
    - Domestic
    - Industrial
  - Catchment characteristics
    - Vegetation
      - Human adaptation (e.g., changes in crop type)
      - Ecological-driven (e.g., shifting tree line)

The degree to which river flow alteration is present in observed data should be carefully considered when calibrating hydrological models, or when calculating hydrological indices from observed flow data. Observed records may, or may not, represent altered flow regimes, and hydrological models may be calibrated against either true natural, purposefully naturalised (see next sub-section), or known altered flow records.

Hydrological indices cannot be considered as stationary because temporal patterns in climate and/or landcover can cause hydrological indices to trend (exhibit steady or abrupt change through time) or be auto-correlated (exhibit cyclical patterns in time). There is evidence of inter-decadal patterns in some, but not all, hydrological indices for particular regions of New Zealand, but not others (e.g., McKerchar and Henderson, 2003; Booker, 2013). Trends in seasonal river flows have been attributed to both climate-drivers and local human activities (Booker, 2021).

2.10 Estimating naturalised flows

Key points

- Clear definitions and statement of methods should accompany presentation of results in relation to naturalised river flows. We suggest the following distinction.
  - “Estimated naturalised river flows” represent estimated flows in the absence of abstractions, dams, or diversions, but with current landcover patterns.
  - “Estimated natural river flows” represent estimated flows with natural landcover patterns and in the absence of abstractions, dams, or diversions.
- Estimating naturalised river flows is challenging and uncertain, but useful for river flow management because they can be used to represent degree of flow regime alteration.

Removing human influences from streamflow time-series is a process often referred to as river flow naturalization. However, clear definition of natural river flow or natural flow regimes is needed because definitions can vary, as shown by two examples below from overseas. The first definition includes the effects of dams, weirs and water abstraction, but excludes the effects of landcover change. The second definition is broad enough that it might include landcover change, depending on interpretation.

1. New South Wales Scientific Committee, Australia, 2002: “Natural flow regimes are determined by the climate, runoff, catchment size and geomorphology without the impacts of dams, weirs, abstraction and river management.”
2. World Meteorological Organization, 2012: “Natural flow corresponds to flow in a stream that would occur under natural conditions.”

Estimates of naturalised flows provide useful information when managing river flows for three main reasons.

1. Naturalised flows are used to indicate the degree of hydrological alteration for current or proposed flows.
2. Naturalised flows are used to indicate impacts of flow alteration on in-stream values where predictive flow-ecology relationships are available.
3. Naturalised flows are used to indicate the upper bound that is possible for flow restoration.

Several methods for flow naturalization have been developed, including adding observed water abstractions to observed river flows, simulation by physically-based models, and substituting and re-scaling observed time-series from a “natural” reference site to a site of interest. Terrier et al. (2021) provide detailed discussion of naturalization methods and why naturalised flows should not necessarily be considered true natural flows. Challenges for accurate flow naturalization beyond those for standard hydrological observation and modelling include:

- Absence of clear definition of naturalization.
- Absence of long observed river flow time-series.
- Absence of accurate historical data on water abstraction or dam operation.
- Inability to apply information from a “natural” reference site with similar catchment characteristics to a site of interest (because no data are available, or because reference sites do not exist).
- Difficulty in estimating the effects of groundwater abstraction on river flows due to uncertainty around connectivity between aquifers and rivers.
- Failure to account for the hydrological effects of landcover changes if these effects are included in the definition of naturalization.
- Where the hydrological effects of landcover changes are incorporated in the definition of naturalization, uncertainty about evapotranspiration rates under different landcover scenarios.
- Difficulties in calculating and expressing associated uncertainties.
- It is difficult to test results against an observed truth because this requires all takes to cease, and groundwater levels to recover where groundwater takes have been active.

As a result of these challenges, naturalised flow estimates should be accompanied with the following:

- A working definition of naturalization.
- The assumptions underlying the method applied.
- Quantification of the associated uncertainties.

Estimates of hydrological alteration may be informative in lieu of estimates of naturalised flows. Methods have been applied for estimating the degree of hydrological alteration at ungauged sites across regions overseas (Sengupta et al., 2018), but not systematically across New Zealand. Methods have been applied to calculate the relative pressure exerted by water resource use consents on median rivers flows across New Zealand (Figure 2-3). See Booker (2018) for full details of methods and results.

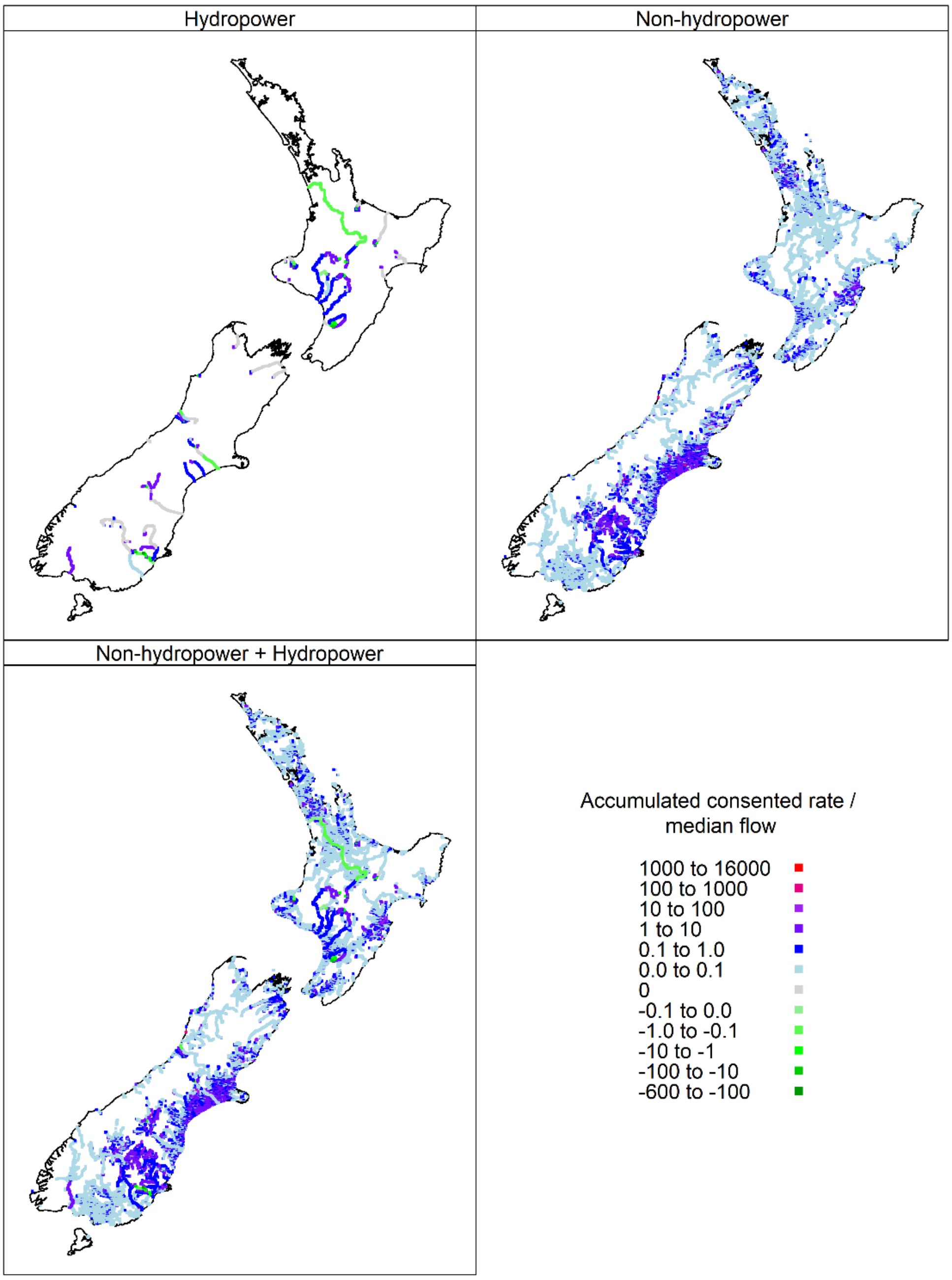

Figure 2-3: Map of accumulated upstream consented takes relative to estimated median flow following the methods of Booker (2018). Blue lines indicate streamflow depletion. Green lines indicate streamflow augmentation.

3 Delivering river flow management

3.1 Broad definitions of environmental flow regimes

Key points

- An environmental flow regime can be broadly defined as the main aspects of a river flow regime that are expected to maintain or improve the structure, functions, processes and resilience of aquatic ecosystems and the human values supported by those ecosystems, including values associated with conservation, culture, recreation, and landscape character.
- This environmental flow regime definition clarifies that the scope of values for which flows are managed includes ecosystems (in rivers as well as aquifers, lakes, wetlands and floodplains where these are linked to river flows), and human values supported by those ecosystems (e.g., conservation, culture, recreation, and landscape character).

Several authors have provided broad definitions of environmental flow regimes, but differences between definitions within the international literature means that a single coherent definition is lacking (see summary by Hayes et al., 2018c). Two common themes that persist amongst these definitions are a description of the hydrological features to be considered, and a description of the things for which flow is being managed. Together these two themes describe the desired general state for a river flow regime and the scope of aquatic ecosystems for which flow-related activities are being managed. For example, two definitions of environmental flow regimes applied in the international flow setting literature are as follows.

- The quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007).
- The quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and the goods and services they provide to people (The Nature Conservancy).

We propose a broad definition of environmental flow regime as "a description of the quantity and timing of river flows required to maintain or improve the structure, functions, processes and resilience of aquatic ecosystems and the human values supported by those ecosystems, including values associated with conservation, culture, recreation, and landscape character". Essentially, an environmental flow regime should be the pattern of river flows left in the river to support in-stream values after the limited takes and other flow altering activities have occurred and affected (often reduced but sometimes increased) the pattern of river flows supplied by the climate and geographical setting. Important features of the environmental flow regime (i.e. water left in the river) for supporting in-stream values can be described qualitatively (e.g. magnitude and duration of low flows, magnitude and frequency of medium and high flows, and degree of seasonality), and quantitively (e.g. using hydrological indices; see Table 2-1), but cannot be easily described by one number or a few simple numbers. Proposed altered flow regimes (e.g., red and amber lines in Figure 3-1) can then be compared to proposed environmental flow regimes (e.g., green zones in Figure 3-1).

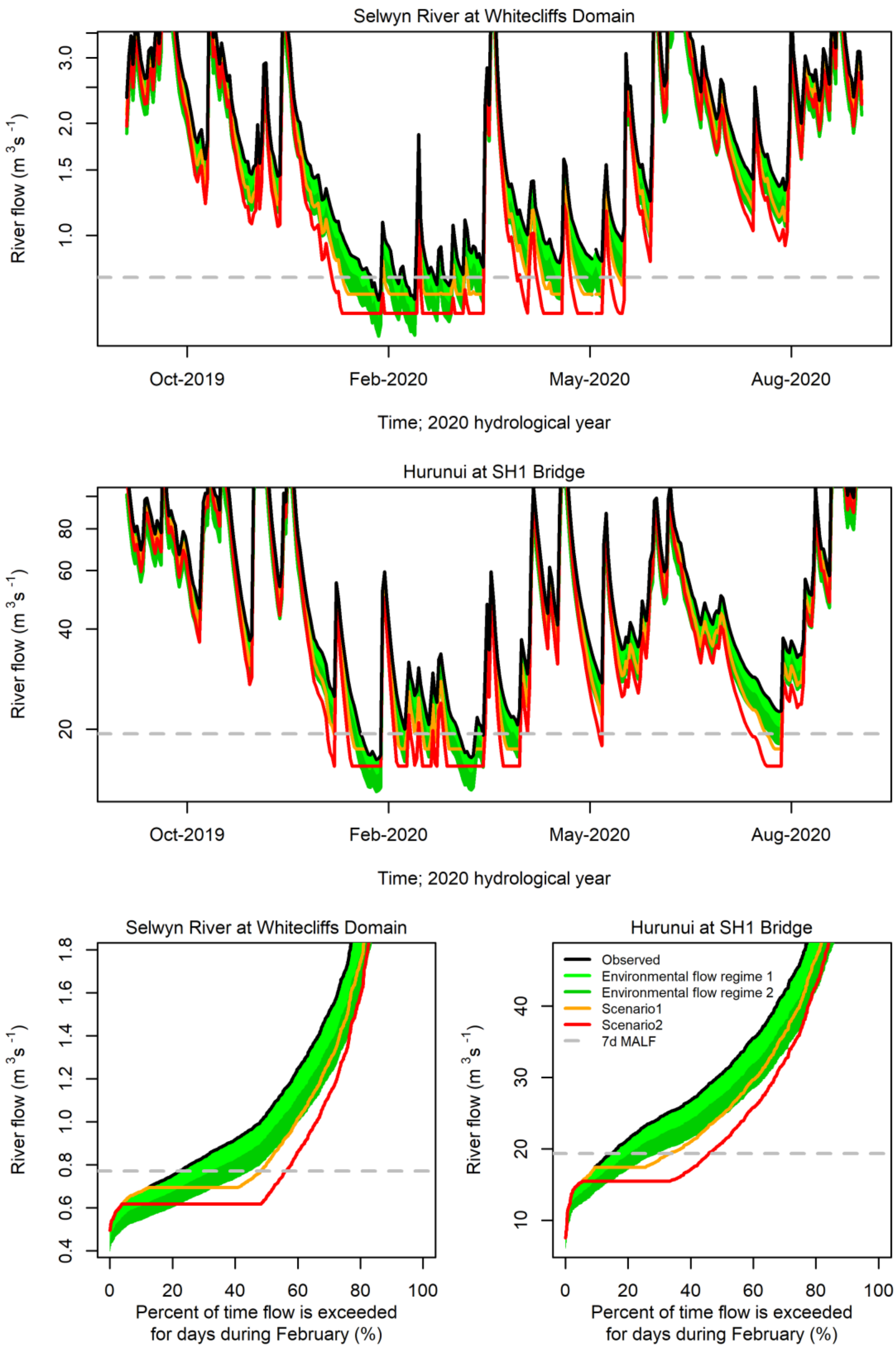

Figure 3-1: Hydrographs (top) and February flow duration curves (bottom) together with hypothetically proposed environmental flow regimes and altered river flows for two example rivers. Environmental flow regime 1 and 2 are the “high level of protection” and “moderate level of protection” from the presumptive standard of Richter et al. (2012) with no flow naturalisation applied. Scenario1 is the “small river” interim default limits of MfE (2008). Scenario2 is the “large river” interim default limits of MfE (2008).

Our broad definition of environmental flow regimes provides a starting point for river flow management. The definition:

- includes ecosystem values and human values supported by flow-influenced ecosystems;
- clarifies that the physical scope of ecosystems for which river flows are being managed includes aquatic ecosystems in rivers, aquifers, lakes, wetlands and floodplains where conditions in these environments are linked to river flows; and
- clarifies the purpose for river flow management by describing the general desired state of flow-driven in-stream values.

3.2 Approaches for setting environmental flow regimes

Key points

- Approaches to setting environmental flow regimes range from specifying a default allowable deviation from natural flow regimes, to evidence-based design of flow components to meet the needs of specified in-stream values.
- A mixture of these two approaches can be applied.
- Any environmental flow setting approach can be applied using an environmentally conservative perspective to be consistent with the Te Mana o Te Wai hierarchy of obligations.

Globally, environmental flow regimes have been proposed and adapted using different approaches, many of which are based on some combination of: 1) limiting alterations from the natural flow baseline to maintain biodiversity and ecological integrity; and/or 2) designing and purposefully manipulating flow regimes to achieve specific ecological and ecosystem service outcomes. Acreman et al. (2014) argued that the former “limit to hydrological alteration” approach is more applicable to natural and semi-natural rivers where the primary objective and opportunity is ecological conservation. The latter “designer” approach is 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 history. In both approaches, environmental flow regimes often intend to mimic naturalised flow patterns and ecological outcomes of the natural flow regime.

The limit to hydrological alteration approach seeks to equate changes to all components of the flow regime from their natural state to desired risk of altering aquatic ecosystems, whereas the designer approach seeks to identify and deliver the parts of the flow regime necessary to uphold desired ecosystem states. Acreman et al. (2014) argued that in a future characterized by altered climates and intensive regulation, where hybrid and novel aquatic ecosystems predominate, the designer approach may be the only feasible option. This conclusion stems from a lack of natural ecosystems from which analogue conditions may be drawn, and the need to support broader socioeconomic benefits and valuable configurations of natural and social capital. However, application of the designer approach requires well known flow-ecology relationships, which is challenging given the complex and dynamic (i.e., unpredictable) nature of flow effects on river ecosystems, or leeway to apply adaptive management principles to alter flow regimes (see Stoffels et al., 2018; Stoffels et al., 2022b).

The “presumptive standard” method of Richter et al. (2012) is an example of a limit to hydrological alteration approach. The “building block” method of De Villiers et al. (2008) is an example of a designer approach. However, a mixture of these two approaches can be applied because flow-ecology relationships used in designer approaches are often derived from hypotheses about, or observations from, near-natural situations. For example, the ecological limits of hydrologic alteration (ELOHA) framework of Poff et al. (2010) mixes the two approaches.

It is important to recognise that any approach can be applied using a more environmentally conservative approach as is required to give effect to the Te Mana o Te Wai hierarchy of obligations. For the limit to hydrological alteration approach, a low limit to hydrological alteration equates to a more environmentally conservative application. For the designer approach, a low threshold for burden of proof for providing an environmental benefit when assigning water to be kept in the river equates to a more environmentally conservative application.

3.3 Spatial variation in environmental flow regimes

Key points

- Although there are legitimate reasons to vary environmental flow regimes according to landscape classifications, no universally accepted landscape-scale classification system exists currently.
- Setting environmental flow regimes at too fine a spatial scale may be untenable due to high complexity in their development, enforcement, and evaluation and adaptation.
- Environmental flows and take limits should be considered as spatially distributed phenomena, rather than single site entities.

Since natural flow regimes, in-stream values, and flow-ecology relationships are all likely to vary across landscape settings, a particular hydrological index may not be associated with the same ecological or geomorphological function in all river locations. It follows that the same level of flow alteration may not equate to the same level of effect on ecosystem health across locations. It also follows that an environmental flow regime may not have to include the same level of protection for different flow regime features for all locations. For example, Haddadchi et al. (2020) demonstrated that the level of flow required to reduce periphyton cover can be determined from estimates of flow required to mobilise sediment. They also demonstrated that the likely range of sediment-based periphyton removal flows would vary with landscape setting across the country due to differences in sediment characteristics and hydraulic conditions.

One way to acknowledge differences in landscape setting is to apply a single approach for setting environmental flow regimes to all locations within each class of a river classification. Basin-scale and regional assessments of flow requirements would then be applied (Arthington et al., 2018). Poff et al. (2010) gave two reasons to use river classifications to apply environmental flow regimes. First, by assigning river segments to a particular type, flow-ecology relationships can be developed from data obtained from a limited set of segments of that type and applied across the entire river type. Second, by strategically placing monitoring sites to capture the range of ecological responses across a gradient of hydrologic alteration for different river types to facilitate efficient monitoring and data analysis. However, application of spatial classifications to river management applications are challenged by lack of data to define and test the classifications, and by the trade-off between attempting to represent real-world spatial heterogeneity in landscape settings and introducing unnecessary complexity to planning decisions. See Stoffels et al. (2021) for detailed discussions on river classifications with respect to management of fine sediment. River flow regime classifications and modelled flow-ecology relationships may be used to devise and/or test possible environmental flow regime classifications. It should be noted that currently available classifications of New Zealand's river network were not specifically designed for assisting river flow management and are yet to be tested for this purpose.

Environmental flows and take limits should be considered as spatially distributed phenomena, rather than applying to single sites. Environmental flows must account for spatial variations in in-stream values and flow-ecology relationships. For example, while some in-stream values are ubiquitous across river networks (e.g., ecosystem health), other in-stream values can be associated with unique locations (e.g., wai tapu). Furthermore, ecological communities vary across river networks (e.g., fish species richness generally declines with distance inland), hence the dominant flow-ecology relationships relevant to defining environmental flows also vary throughout the riverscape. Similarly, flow alteration will vary in space due to cumulative effects and the connected hierarchical nature of river networks. The number, spatial configuration, and strategy for implementing water takes to meet take limits is therefore important for delivering environmental outcomes across a Freshwater Management Unit (FMU). If spatial considerations are ignored, some implementation strategies could ensure that take limits are met at a downstream monitoring point but not met elsewhere across an FMU. Booker et al. (2014) demonstrated how differences in implementation of the same take limits at one location can lead to vastly different outcomes for both water users and the flow regimes across a simulated catchment. However, setting of environmental flow regimes and limits to water use has high demands for collection of observational data, predictive modelling, and planning processes. For example, development of an environmental flow regime requires appropriate physical infrastructure and/or human resources to measure water use, groundwater levels, river flows, and ecosystem responses. Consequently, setting and implementing different environmental flow regimes and limits to water use at a fine spatial scale (e.g., for every tributary separately) is untenable due to the high operational requirements for environmental flow regime development, enforcement, evaluation, and adaptation.

3.4 A proposed framework for delivering environmental flow regimes

Key points

- For desired environmental flow regimes to be delivered, they must be transparently linked to real-world ecosystem states through controls on activities that actually influence river flows.
- There are several challenges to delivering desired river flow regime states stemming from multiple sources of uncertainty.
- The effects of climate change need to be considered to deliver desired future environmental flow regime outcomes.
- We proposed a framework for river flow management comprising a cascade of steps which:
    - starts with a broad definition of environmental flow regimes;
    - includes consideration of climate change;
    - incorporates a loop for monitoring and adaptation; and
    - ends with controls on flow-altering activities.

A goal of water resource management is often to ensure wise use of water to meet the economic, cultural, and environmental needs of society as a whole, today and into the future (Kaye-Blake et al. 2014; Ministry for the Environment 2020). One way of assisting with this goal is to identify and deliver environmental flow regimes as defined in Section 3.1 above. For desired ecosystem outcomes to be realised, regional councils need to be able to control flow-altering activities to produce flow alterations that match predefined environmental flow regimes. A cascade of steps for effective river flow management should therefore start with a broad definition of environmental flow regimes and end at methods for controlling human activities that alter river flows. We propose a framework for completing this cascade of steps (Figure 3-2). The primary purpose of this framework is to deliver a flow regime that fulfils freshwater ecosystem health, whilst allowing some degree of hydrological alteration after environmental needs have been met, in line with the requirements of the NPS-FM (see Table 4-4 that shows how the proposed river flow management framework can be used to give effect to various NPS-FM 2020 clauses, and Table 4-5 that describes the purpose, and gives some hypothetical examples of steps in the proposed framework). The secondary purpose is to assist water resource use planning by clarifying the volume and timing of water available for out-of-stream uses. Transparent descriptions of each step and how they are linked is essential for the framework to effectively fulfil both purposes, regardless of physical setting, type of in-stream value(s), or technical methodologies used. Specifically, mechanisms for controlling flow-altering activities (Step 8; e.g., granting of consents and consent conditions) need to relate back to environmental flow regime descriptions (Step 1) via several intermediary steps. The proposed framework is structured to explicitly consider future climate change and uncertainty. Consideration of climate change is an important step that can be examined using hydrological and ecological models to explore scenarios (Horne et al., 2022). The proposed framework does not set any limitations on the methodological approach used to describe desired states or flow-ecology linkages. The proposed framework also does not preclude the intentional integration of participatory approaches or the inclusion of diverse stakeholders and iwi partners.

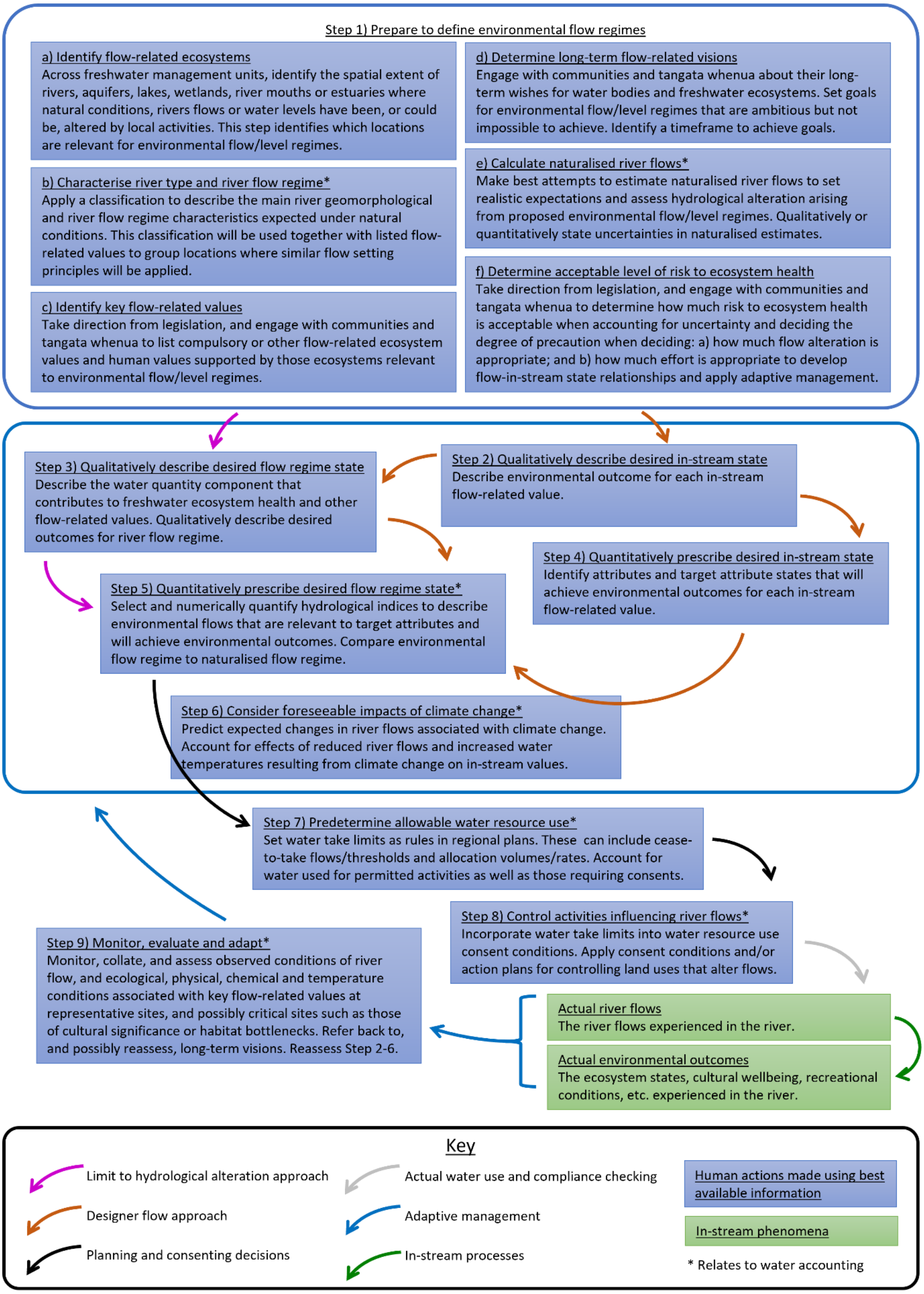

Figure 3-2: A proposed framework for river flow management comprising a cascade of steps. Sub-steps a—f within Step 1 do not have to be applied sequentially. Adaptive management involves repeatedly looping through Steps 2-9. Arrows passing through Step 6 indicate the need to consider climate change.

The link between predefined environmental flow regimes and mechanisms that collectively control flow alteration can be easily predicted when there is one dominant flow-altering activity (e.g., a large dam). However, this link becomes harder to predict as uncertainty between flow-altering activities and their real-world flow altering consequences increases (e.g., as the number and spatial spread of flow-altering activities or the proportion of abstraction from groundwater increases). We recognise that there are many potential complications when attempting to deliver environmental flow regimes:

- Flow altering activities may be controlled through different mechanisms.
  - Activities controlled by water use consents/permits.
  - Activities controlled by land use consents, for example plantation forestry.
  - Activities that are allowable as permitted activities.
  - Activities that are uncontrolled.
- Calculation of naturalised flows may be challenging due to model uncertainties and because data describing water use and flow altering activities may not be available, may contain missing records, or may be of poor quality.
- Impacts of flow altering activities vary according to their type and spatial arrangement.
  - Many activities can combine to have cumulative effects on river flows.
  - Cumulative effects on river flows can increase or decrease in the downstream direction depending on the spatial arrangement of abstractions and natural downstream flow accumulation.
  - Surface water abstraction has an immediate effect on river flow, whereas groundwater abstraction can have a delayed effect on river flows.
  - The magnitude and spatial influence of surface water abstractions on river flows is relatively easy to predict in comparison to predicting the magnitude and spatial influence of groundwater abstractions on river flows.
- The future effects of climate change on the hydrological cycle will vary with location and with time.
- Climate change will alter water demand.

Multiple causes of river flow alteration mean that river flow management may have to consider the hydrological effects of several local activities in combination with climate change effects. This is a difficult challenge because whilst regional councils can influence some human activities and acknowledge the impacts of others, they can only anticipate and adapt to the effects of climate change.

4 The NPS-FM with respect to river flow management

4.1 Why do river flows need to be managed under the NPS-FM?

Key points

- Management of water quantity, including river flows and groundwater levels, is a necessary consideration for all 15 NPS-FM policies and all of the values outlined in Appendix 1 of the NPS-FM.
- Regional councils and others with input to river flow management need to take a holistic view of the whole of the NPS-FM and operate under the fundamental concept of Te Mana o te Wai when considering flow management options.
- The state of some attributes requiring limits on resource use from NPS-FM Appendix 2A (e.g., periphyton, dissolved oxygen, suspended fine sediment) and attributes requiring action plans from NPS-FM Appendix 2B (e.g., submerged plants, fish, macroinvertebrates, deposited fine sediment) will be influenced by river flows. However, these attributes were not necessarily designed to monitor and evaluate the effectiveness of river flow management.

Regional councils and others with input to river flow management need to take a holistic view of the NPS-FM because management of water quantity, including river flows and groundwater levels, is a necessary consideration for successfully implementing all 15 policies outlined in the NPS-FM (Table 4-1).

Table 4-1: Reasons why river flows are a necessary consideration for each of 15 NPS-FM 2020 policies.

Policy number	Abbreviated policy description	How consideration of river flows relates to the policy
1	Freshwater is managed in a way that gives effect to Te Mana o te Wai.	River flows are a master variable that are linked to various physical, chemical, ecological states that are in-turn linked to ecosystem health, human health, landscape character, cultural wellbeing, recreation and water supply for out-of-stream use. River flows are an necessary consideration when applying the six Te Mana o te Wai principles of mana whakahaere, kaitiakitanga, manaakitanga, governance, stewardship, and, care and respect. The Te Mana o te Wai hierarchy of obligations applies to river flow management decisions.
2	Involvement of Tangata whenua in freshwater management, identification and provision for Māori freshwater values.	River flows have been linked to cultural values expressed by tangata whenua in various ways depending on local perspectives (e.g., Crow et al. 2018).
3	Integrated freshwater management, consideration of land development on whole catchments, effects on receiving environments.	River flows are important across river environments from tributaries to main stems, to wetlands, lakes, estuaries and river mouths. Changes in river flows in one location can influence ecosystem health attributes in other locations due to cumulative effects of water abstraction and non-uniformity in ecosystem states.

Policy number	Abbreviated policy description	How consideration of river flows relates to the policy
4	Response to climate change.	Changes in precipitation and temperatures resulting from climate change will influence river flows. River flows are also an important determinant of water supply. Also, see answer to 1 above.
5	Maintaining or improving (where it is degraded) health and well-being of water bodies and freshwater ecosystems	See answer to 1 above.
6	Halt loss of wetland extent, protect wetland values, and promote wetland restoration	River flows are linked to wetland hydrology either directly through water supply to wetlands from rivers or indirectly through links between river flows, groundwater levels, and wetland water levels.
7	The loss of river extent and values is avoided to the extent practicable	River flow is a prerequisite for aquatic habitat in rivers. Dry stretches of rivers can also be a barrier to connectivity between river reaches.
8	The significant values of outstanding water bodies are protected	See answer to 1 above.
9	Habitats of indigenous freshwater species are protected	Habitats of indigenous freshwater species particularly fish, invertebrate, periphyton, and macrophyte communities are linked to river flow conditions through provision of suitable habitat, food delivery, temperature control, transport of material etc.
10	The habitat of trout and salmon is protected, insofar as this is consistent with Policy 9	Habitats of trout and salmon are linked to river flow conditions through provision of suitable habitat, food delivery, temperature control etc.
11	Freshwater is allocated and used efficiently, existing over-allocation is phased out, and future over-allocation is avoided.	Physical allocation of freshwater is linked to river flows because damming, diversion, and abstraction of water influences river flows.
12	National targets for water quality improvement is achieved.	River flows are linked to water quality through various processes such as dilution, transport and links with chemical processes such as nutrient uptake.
13	Water bodies and freshwater ecosystems are monitored over time, and action is taken where freshwater is degraded, and to reverse deteriorating trends.	When paired with climate and water use data, river flow (and groundwater level) time-series are an important indicator of human influences on river environments. Paired ecology-hydrology monitoring data is required to improve the effectiveness of river flow management. Actions to maintain or improve freshwater ecosystems may require alteration of take limits and environmental flows and levels over time. Also, see answer to 1 above.

Policy number	Abbreviated policy description	How consideration of river flows relates to the policy
14	The state of water bodies and freshwater ecosystems, and the challenges to their health and well-being, is regularly reported on.	See answer to 1 above.
15	Communities are enabled to provide for their social, economic, and cultural well-being in a way that is consistent with this National Policy Statement.	See answer to 1 above.

Appendix 1A of the NPS-FM sets out compulsory values (ecosystem health, human contact, threatened species, mahinga kai). Water quantity is one biophysical component of ecosystem health that must be managed so that all components are suitable to sustain indigenous aquatic life expected in the absence of human disturbance or alteration. Appendix 1B of the NPS-FM also sets out nine other values that must be considered, all of which are influenced by hydrological regimes as indicated in Table 4-2.

Table 4-2: Values from NPS-FM 2020 Appendices, and how they could relate to river flows.

Nature of value	Label	How related to river flow
Appendix 1A – Compulsory values	Ecosystem health	Water quantity (river flows) is one biophysical component of ecosystem health that must be managed so that all components are suitable to sustain indigenous aquatic life expected in the absence of human disturbance or alteration.
	Human contact	Various ways in which people connect with the river water such as swimming, waka, fishing, and mahinga kai are related to different flows or levels.
	Threatened species	Habitat provision and migration triggers for various threatened fish species are related to river flows.
	Mahinga kai	Freshwater species that have traditionally been used as food, tools, or other resources, as well as the places those species are found and the act of catching or harvesting them are all related to river flows.
Appendix 1B – Other values that must be considered	Natural form and character	River flows are a crucial element in determining the natural character of river environments.
	Drinking water supply	River flows are a supporting element in determining water available for drinking in some situations.
	Wai tapu	River flows are a supporting element of wai tapu as they are explained in Appendix 1B of the NPS-FM.
	Transport and tauranga waka	River flows influence river connectivity, which may be a supporting element for navigation for identified means of transport.
	Fishing	River flows are a supporting element in determining fishing experience in rivers.
	Hydro-electric power generation	River flows are a source of power generation for hydro-electricity schemes.
	Animal drinking water	River flows are a supporting element in determining water available for animal drinking purposes.
	Irrigation, cultivation, and production of food and beverages	River flows are a supporting element in determining water available for these agricultural and horticultural purposes.
	Commercial and industrial use	River flows are a supporting element in determining water available for commercial and industrial purposes.

4.2 Interpretation of Environmental flows and Take limits in the NPS-FM 2020

Key points
▪ Unambiguous definitions of key phrases are required to ensure that desired environmental outcomes will be achieved. ▪ Environmental flows describe the state of flow regimes (the main features of river flows when viewed over the long-term) to achieve environmental management goals. ▪ Take limits are limits set as rules in regional plans that are used to guide control of human activities in order to deliver environmental flows.

Two of the most important technical terms used within the NPS-FM relating to river flow management are “environmental flows and levels” in Clause 3.16 and “take limits” in Clause 3.17. The definition and meaning of these terms can have important implications for river flow management. The NPS-FM does not define environmental flows. The NPS-FM take limit interpretation is given in Table 4-3.

Table 4-3: The description of “take limit” quoted from the 2020 NPS-FM.

▪ **Take limit** means a limit on the amount of water that can be taken from an FMU or part of an FMU, as set under clause 3.17

We suggest that, when interpreting the NPS-FM 2020, best practice would be as follows:

- **Environmental flows** mean the aspirational state of flow regimes required to achieve the environmental outcomes for the values and long-term visions (and therefore uphold Te Mana o te Wai, sustain ecosystem health, etc.). Environmental flows should be thought of as environmental flow regimes that describe the main features of a long-term river flow time-series required to achieve environmental outcomes. Thus “environmental flows” is a synonym for “environmental flow regime” used in our Section Three above. Environmental levels are the equivalent to environmental flows, but environmental levels apply to water levels in aquifers (groundwater levels), lakes and wetlands

Take limits mean sets of rules in regional plans that constrain water use to restrict the degree of hydrological alteration arising from collective operation of flow-altering activities. Take limits guide control of human activities in order to provide environmental flows. Take limits can be thought of as predefined rules that guide authorities to deliver environmental flows by controlling flow-altering activities, and also clarify water availability for out-of-stream use. Thus “take limits” is a synonym for “water resource use limits”. See The NPS-FM does not define environmental flows. The NPS-FM take limit interpretation is given in Table 4-3.

- Table 4-3 for official NPS-FM 2020 definition.

- **Consent conditions** mean conditions that are written into water resource use consents in order to restrict consented activities that influence river flows or groundwater levels.

The word “aspirational” is included in the definition of environmental flows to clarify that environmental flow regime characteristics cannot be expected to be maintained every year because river flows are influenced by climate variability.

4.3 Relating NPS-FM clauses to river flow management

Key points

- Each NPS-FM flow-related clause can fit under the proposed framework for river flow management.
- The proposed framework could be applied differently in different FMUs or landscape settings.

The NPS-FM contains four parts and five appendices. Part 1 describes preliminary provisions. Clause 1.3 on the Fundamental concept of Te Mana o te Wai, and Clause 1.6 on use of best available information are both broadly relevant to river flow management. Part 2 describes objectives and policies (see Table 4-1). Part 3 describes implementation, with Subparts 1, 2 and 3 describing approaches to implementation, the National Objectives Framework (NOF), and specific requirements respectively. Clause 3.16 and 3.17 of Subpart 2 of Part 3 are most pertinent to river flow management because they pertain to setting environmental flows and levels, and identifying water take limits respectively. However, these clauses do not stand alone – they are strongly influenced by many other clauses.

Although the NPS-FM contains requirements that relate to river flow management, it does not offer a framework for delivery of river flow management. Table 4-4 indicates where each relevant NPS-FM 2020 clause would fit under the proposed framework for river flow management shown in Table 4-1.

Table 4-4: Implications for river flow management from several NPS-FM 2020 clauses, and where these fit into the proposed river flow management framework. Steps are shown in Figure 3-2: 1) Prepare to define environmental flow regimes; 2) Qualitatively describe desired in-stream state; 3) Qualitatively describe desired flow regime state; 4) Quantitatively prescribe desired in-stream state; 5) Quantitatively prescribe desired flow regime state; 6) Consider foreseeable impacts of climate change; 7) Predetermine allowable water resource use; 8) Control activities influencing river flows; 9) Monitor, evaluate and adapt. *See NPS-FM 2020 for precise wording. NA = not directly applicable.

Clause	Step	How related to river flow management*
3.2 Te Mana o te Wai	1a, 2, 3, 4, 5, 9	Engage with communities and tangata whenua to identify scope of physical environments for which flows are to be managed in Step 1a. Apply the hierarchy of obligations in Step 5 by applying Step 3 and/or 2 & 4. Noting that any approach should be applied using a environmentally conservative viewpoint. Enable application of mātauranga Māori in Steps 1, 2, 3, 4 & 9.
3.3 Long-term visions for freshwater	1d, 2	Specify long-term visions for flow-driven in-stream values in Step 1d by applying Step 3 and/or 2 & 4.
3.4 Tangata whenua involvement	1c, 2, 6, 7, 9	Work collaboratively with, and enable tangata whenua to identify any flow-driven Māori freshwater values in Step 1c & 2, be actively involved in decision-making in Step 7 & 9, and be actively involved in monitoring in Step 9. Use of mechanisms available under the Act relating to transfers or delegations of power, joint management agreement and mana whakahono a rohe (iwi participation arrangements) in Step 7.
3.5 Integrated management	1a, 7	List the environments for which river flows are being managed (e.g., rivers, wetlands, estuaries, lakes) as described in Step 1a. Incorporate potential cumulative effects of multiple flow-altering activities and consider spatial arrangement of flow alteration in Step 7. Consider influences of landcover changes alongside direct flow-altering effects of dams, abstractions and diversions in Step 7.
3.6 Transparent decision-making	All	Describe sequences of actions taken to fulfil all steps being used. Publish records of matters considered and the reasons for decisions reached in each step that has led to limits set in Step 7 and the controls applied in Step 8.
3.7 NOF process	1c, 2, 4, 9	Identify flow-driven values for each FMU in Step 1c and 2. Set environmental outcomes as objectives for each flow-driven value in Step 4. Monitor and take action if degraded in Step 9.
3.8 Identifying FMUs and special sites and features	1b, 9	Describe how FMUs in the region fit with an environmental flow regime classification in Step 1b. Clarify whether all steps are the same for all FMUs or describe differences in steps between FMUs in Step 1. Monitor river flows, calculated flow alteration and state of flow-driven in-stream values in Step 9. Monitoring sites relating to Māori freshwater values (e.g., cultural flow preferences) determined in collaboration with tangata whenua in Step 9.

Clause	Step	How related to river flow management*
3.9 Identifying values and setting environmental outcomes as objectives	1c, 1f, 2, 4, 5	Describe the environmental outcomes sought in Step 1c, 1f, 2, 4 and possible Step 5.
3.10 Identifying attributes and their baseline states, or other criteria for assessing achievement of environmental outcomes	4, 9	Identify the baseline state of each attribute, using the best information available at the time in Step 4. Assess baseline state as part of monitoring in Step 9.
3.11 Setting target attribute states	4	Set target attribute states in Step 4 in such a way that they will achieve the environmental outcomes for the relevant values by linking them with flow regime state in Step 5 and hydrological alteration in Step 7 and 8.
3.12 Achieving target attribute states and environmental outcomes	7, 8, 9	Identify limits on resource use that will achieve the target attribute state in Step 7. Impose conditions on resource consents to achieve target attribute states in Step 8. Monitor attribute state in Step 9.
3.13 Special provisions for attributes affected by nutrients	1c, 5, 9	Recognise that periphyton and other nutrient-related attributes are also influenced by river flows in Step 1c, 5 and 9.
3.14 Setting limits on resource use	6, 7	Set limits on water resource use in Step 7. Have regard to the foreseeable impacts of climate change in Step 6.
3.15 Preparing action plans	8	Encourage controls on activities that are not controlled by resource consents.
3.16 Setting environmental flows and levels	1d, 3, 5, 6, 7, 8	Set environmental flows and levels to achieve specified environmental outcomes for each FMU or part of an FMU as this relates to the sequence of Steps 1-3-5-7-8. Set and adapt environmental flows and levels over time to take a phased approach (Step 1d) to achieving those environmental outcomes and long-term visions in Step 9. Have regard to the foreseeable impacts of climate change in Step 7.

Clause	Step	How related to river flow management*
3.17 Identifying take limits	7, 8	In order to meet environmental flows and levels, identify take limits and set as rules in regional plans in Step 7. Impose conditions on resource consents specifying when taking, damming, or diversion will be restricted or no longer allowed in Step 8. Impose conditions on resource consents, specifying when a discharge of water (e.g., downstream of a dam) will be required in Step 8. Provide for flow or level variability in (as specified in Step 5) and in Step 8. Safeguard ecosystem health from the effects of the take limit on the frequency and duration of lowered flows or levels (as specified in Step 5) in Step 8.
3.18 Monitoring	9	Establish methods for monitoring progress towards achieving target attributes states and environmental outcomes in Step 9.
3.19 Assessing trends	9	Assess trends in Step 9.
3.20 Responding to degradation	5-9	Take action to halt or reverse the degradation if detected in Step 9 by looping through steps 5-9.
3.21 Definitions relating to wetlands and rivers		NA
3.22 Natural inland wetlands	8	Ensure that an application does not result (directly or indirectly) in the loss of extent or values of a natural inland wetland by including consideration of river flow-driven wetlands in Step 8 (based on Steps 4-9).
3.23 Mapping and monitoring natural inland wetlands	9	Develop and undertake a monitoring plan associated with Step 9 that contains sufficient information to enable the council to assess whether its policies, rules, and methods are ensuring no loss of extent or values of those wetlands by mapping connectivity of water from rivers to wetlands.
3.24 Rivers	All	Include river-related values of ecosystem health, indigenous biodiversity, hydrological functioning, Māori freshwater values, and amenity within Step 1, 2 and 4. Monitor the condition of rivers and assess whether policies, rules, and methods are ensuring no loss of extent or values of the rivers in Step 9.
3.25 Deposited sediment	4	If it is appropriate to return a non-natural soft bottom site to a hard-bottomed state, prepare an action plan for how to do that, possibly by restoring flushing flows in Step 5.
3.26 Fish passage	2, 4	Although this clause mostly relates to engineered physical barriers to fish passage, barriers to fish passage can arise due to low flows, therefore fish passage could be a flow-related in-stream value in Step 2 and 4.

Clause	Step	How related to river flow management*
3.27 Primary contact sites		Although this clause relates mainly to water quality, river flow management should be considered because of the role of river flow in delivery and dilution of pathogens that could be included in Steps 2, 4, and 5.
3.28 Water allocation	7	Set criteria for deciding applications to approve transfers of water take permits in Step 7 and 8. Set criteria for deciding how to improve and maximise the efficient allocation of water in Step 7 and 8.
3.29 Freshwater accounting systems	All	Provide baseline information and methods for calculating naturalised (Step 1e), observed and scenarios of altered river flows and hydrological indices to inform Steps 2, 3, 5, 7 9.
3.30 Assessing and reporting	6, 9	Collect and report data to inform Step 9. Predictions of changes, including the foreseeable effects of climate change in Step 6.
3.31 Large hydro-electric generation schemes	All	Special provisions for 5 hydro-electricity generation schemes may impact all steps but particularly Step 8.
3.32 Naturally occurring processes		NA
3.33 Specified vegetable growing areas		NA

Table 4-5 gives some hypothetical examples of each step in the proposed framework for different types of river or landscape setting. These examples demonstrate how the general framework could be used to show how various technical methods and river types could fit within the sequence of steps outlined in the proposed framework to inform river flow management decisions.

Table 4-5: Label, purpose, and hypothetical examples of steps in the proposed framework for river flow management.

Label	Purpose	Example 1) Regional default	Example 2) Braided river	Example 3) Spring-fed streams
1a) Identify flow-related ecosystems.	Clarifies the physical scope of aquatic ecosystems for which flows are being managed.	Map showing positions of rivers as well as aquifers, lakes, wetlands, and floodplains where these are linked to river flows.	Map showing area of interest.	Same as Example 2.
1b) Characterise river type and river flow regime.	Creates efficiencies by grouping locations.	Apply a landscape-scale classification to assist setting of take limits, monitoring, and evaluation of river flow management. This does not have to coincide with FMUs.	Devise and apply operational definition of braided river.	Devise and apply operational definition of spring-fed streams.
1c) Identify key flow-related values.	Clarifies flow-related values for which flows are being managed.	See NPS-FM Appendix 1A, 1B, 1B, and 2B.	Same as Example 1 plus in-stream values proposed by local communities and tangata whenua	Same as Example 2.
1d) Determine long-term flow-related visions.	Describes long-term goals for freshwater ecosystems.	Set goals in view of six principles and hierarchy of obligations in Te Mana o te Wai.	Same as Example 1.	Same as Example 1.
1e) Calculate naturalised river flows.	Allows comparison of proposed altered flow regimes against naturalised flow regimes. Recognises that flows cannot be higher than those that are naturally available.	Estimate naturalised flow indices.	Same as Example 1 plus estimate naturalised flow time-series.	Same as Example 2.
1f) Determine acceptable level of risk to ecosystem health.	Recognises that the hierarchy of obligations in Te Mana o te Wai applies to river flow management decisions, and that risks to ecosystem health is a function of level of flow alteration and level of effort placed into developing flow-in-stream state relationships and applying adaptive management.	Reduce risk to ecosystem health by applying a high degree of precaution when deciding how much flow alteration is allowable.	Recognise that risk to ecosystem health can be reduced by placing increased effort into developing flow-in-stream state relationships, monitoring, evaluating, and applying adaptive management principles.	Same as Example 2.

Label	Purpose	Example 1) Regional default	Example 2) Braided river	Example 3) Spring-fed streams
2) Qualitatively describe desired in-stream state.	Describes what aspects of in-stream values are being managed for, and their desired state.	Incorporation of NOF objectives or in-stream values proposed by local communities and tangata whenua.	Same as Example 1. Plus, braided character of river channel.	Same as Example 1. Plus, limitation of diurnal dissolved oxygen fluctuations.
3) Qualitatively describe desired flow regime state.	Describes why features of the flow regime are being targeted for river flow management.	Determine acceptable levels of alteration of pre-defined important components of naturalised flow regimes.	Maintenance of low flows to ensure isolation of islands important for nesting bird habitat. Maintenance of channel forming flows to ensure maintenance of braided character through periodic removal of riparian vegetation.	Maintenance of low flows to ensure artificial flow-related oxygen concentration does not drop below levels required to support in-stream values.
4) Quantitatively prescribe desired in-stream state.	Provides quantified description of in-stream values (e.g., descriptions of state of ecosystem health), and their desired state.	NOF objectives. See NPS-FM appendices.	Number of islands per km that are designated as providing safe bird nesting habitat.	A minimum threshold for oxygen concentration percentage.
5) Quantitatively prescribe desired flow regime state.	Provides quantified description of environmental flows against which scenarios of hydrological alteration can be compared.	No more than 10% deviation from pre-defined important components of naturalised flow regimes; Median flow for each month, 7d-MALF, Mean90DayFlowMins, MeanPulseLengthLow, nPulsesHigh.	Low flow of river not to fall below 90% of naturalised MALF unless through natural conditions. Number and average duration of channel forming flows to by X and Y.	Low flow of river not to fall below 90% of naturalised MALF unless through natural conditions.

Label	Purpose	Example 1) Regional default	Example 2) Braided river	Example 3) Spring-fed streams
6) Consider foreseeable impacts of climate change.	Account for the foreseeable impacts of climate change on naturalised flow regimes and ecosystem state where possible.	Estimate impacts of climate change on water demand to indicate whether utilisation of currently allocated water will increase; if yes, there will be a need to update the relationship between take limits and desired flow regime. Estimate naturalised flow regimes under climate change scenarios to investigate whether conditions for in-stream values will alter and/or water availability will decrease regardless of take limits or actual water use, if so, there will be a need to update the relationship between take limits and desired flow regime.	Same as Example 1.	Same as Example 1. Estimate whether climate change driven increases in water temperature will alter flow-ecology relationships; if yes, there will be a need to update flow-ecology relationships.
7) Predetermine allowable water resource use.	Rules in regional plans designed to limit hydrological alteration to fulfil environment needs and allow for some degree of alteration after environmental needs have been met. Clarify water availability for out-of-stream uses.	Total take limits for abstraction of baseflows. Cease-to-take trigger flows for protection of low flows. Clarification of water available for higher flow harvesting for storage schemes.	Same as Example 1.	Total take limits for abstraction of baseflows. Cease-to-take trigger flows for protection of low flows.

Label	Purpose	Example 1) Regional default	Example 2) Braided river	Example 3) Spring-fed streams
8) Control activities influencing river flows.	Mechanisms for controlling flow-altering activities.	Granting or declining of water permits and allowing takes through permitted activities. Cease-to-take trigger flows or conditions matching from Step 7 All takes, including those permitted by regional rules or section 14(3)(b) must be included when quantifying the total take.	Same as Example 1.	Same as Example 1.
9) Monitor, evaluate and adapt.	Obtain information and develop tools required for (a) evaluation and reporting of the impacts of take limits on environmental outcomes within plans; (b) reduce uncertainties about the relationships between take limits and river flow and, in turn, river flow and ecosystem health; and (c) in light of new information, adapt environmental flow regimes and take limits to achieve environmental outcomes.	a) Monitor the relationship between river flow and physical habitat structure at sites within each FMU. b) Monitor the relationship between physical habitat structure and mahinga kai. c) Develop quantitative relationships using data obtained from (a) and (b) above to reduce uncertainty about flow-ecology relationships and adapt environmental flow regimes in plans over time. d) Monitor the quantity and timing of water takes within a catchment, towards quantifying the effects of water takes on observed river hydrology.	Same as Example 1.	Same as Example 1.

5 Summary and recommendations

This report proposes a framework that can be used to facilitate management of river flows to achieve environmental outcomes defined under the NPSFM. The framework sets out a transparent approach for linking environmental flow regimes to real-world ecosystem states through controls on flow-altering activities. Provision of a general framework, rather than prescriptive instructions for technical methodologies, is consistent with the NPS-FM because the NPS-FM allows for flexibility in setting in-stream values and the methods used to give effect to its objectives and policies.

It is important to recognise that the proposed framework does not preclude the intentional integration of participatory approaches or the inclusion of diverse stakeholders and iwi partners in flow management decisions. The proposed framework does not set any limitations on methodological approach used to describe desired states, flow-ecology linkages, cultural values, or cultural attributes.

We suggest that adoption of the proposed framework would provide a regional council with an overall strategy for giving effect to the NPS-FM with respect to river flow management. Adopting the framework would encourage selection of a combination of scientific methods (e.g., monitoring, trend detection, water accounting, ecological models), mātauranga Māori, planning processes (e.g., tangata whenua and community engagement), and consenting mechanisms (e.g., restrictions within consents) to strategically fulfil the requirements of the NPS-FM. In some cases, existing scientific methods, mātauranga Māori, planning processes and consenting mechanisms will be available to populate the framework. In situations where appropriate methods are not readily available, adopting the framework will highlight the need to develop, adapt, or seek scientific methods, mātauranga Māori, planning processes and/or consenting mechanisms because existing knowledge or methods are not readily available to adequately deliver a particular step.

In its current form, this report should be viewed as an independent discussion paper from the authors because it was not co-developed with the Ministry for the Environment (MfE), iwi partners or regional councils due to a short timeframe allowed for its production. We recommend that the proposed approach be tested and refined with regional councils and tangata whenua through a participatory process to increase its credibility and legitimacy. We recommend further development in two areas: 1) the implications of the Te Mana o Te Wai hierarchy for existing water take limits, and 2) co-development of methods to interpret, apply and evaluate the Te Mana o Te Wai hierarchy with respect to river flow management within the proposed framework.

6 Acknowledgements

Many thanks to Robin Holmes (Cawthron Institute), Chris Daughney (NIWA and Te Uru Kahika - Regional and Unitary Councils Aotearoa), Tom Drinan (Dept. of Conservation), Ned Norton (LWP), and various staff from Auckland Council, Bay of Plenty Regional Council, Environment Canterbury and MfE for their helpful reviews of an earlier draft.

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