High-flow harvesting

Part 1: influence on New Zealand in-stream values

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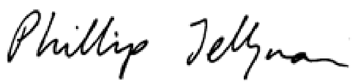	Reviewed by:	Phillip Jellyman
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Executive summary

River flow is a master variable that is 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 various uses. While using water for irrigation, industrial, and domestic purposes can generate important human health and economic benefits, abstractions also alter the magnitude and timing of river flows thereby causing potentially detrimental environmental consequences. Competing uses for water therefore present a challenge for environmental managers. This challenge is recognised within various clauses of the National Policy Statement for Freshwater Management 2020 (NPS-FM) that relate to the role of river flow management in safeguarding ecosystem health.

The fundamental concept of Te Mana o te Wai, which informs the NPS-FM and its implementation, encompasses six principles concerning to the roles of tangata whenua and other New Zealanders in the management of fresh water. The six principles are: Mana whakahaere; Kaitiakitanga; Manaakitanga; Governance; Stewardship; and Care and respect. 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. Te Mana o te Wai hierarchy of obligations is relevant to all aspects of freshwater management, including river flow management. Although general guidance on river flow management under the NPS-FM is available, there is no set recipe for how to conform with the six principles or give effect to the hierarchy of obligations under Te Mana o te Wai with respect to river flow management.

High-flow harvesting has been suggested as an option for economic development through operation of water use that could meet the requirements of the NPS-FM and Te Mana o te Wai, particularly in situations where low flows are fully allocated. One justification for utilising high-flow harvesting is to limit hydrological alteration to parts of the flow regimes that are hypothesised as being functionally redundant from a physical, chemical, or ecological perspective, and thereby reduce alteration to lower river flows that are often hypothesised as being a bottleneck for ecosystem health and other in-stream values. However, environmental effects of high-flow harvesting are possible. The aims of this report are firstly to define high-flow harvesting, secondly to outline parts of the NPS-FM that related to high-flow harvesting, and thirdly to systematically document the potential environmental effects of high-flow harvesting in the New Zealand context by drawing on the domestic and international literature.

We define high-flow harvesting as a situation where water is taken from the natural environment during times of relatively high flows in rivers or high groundwater levels in unconfined shallow aquifers, stored temporarily, and then used later. High-flow harvesting contrasts with run-of-river water takes that we define as a situation where water is taken from the natural environment, transported to the location of use, and then used immediately. Water is taken at a higher rate for shorter periods for high-flow harvesting in comparison to run-of-river takes given the same overall level of water demand. Because water taken under high-flow harvesting does not have to be used immediately, it may be possible to provide the same overall level of water supply and have less impact on in-stream values by taking water during higher flows compared to run-of-river water takes.

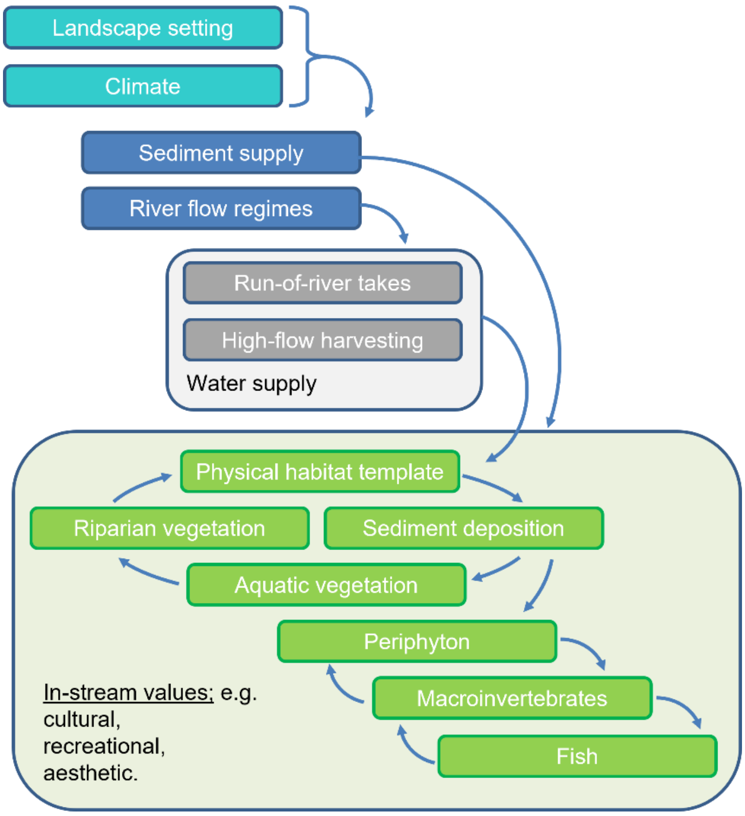

Figure 0-1: Diagrammatic representation of how high-flow harvesting relates to various components of river ecosystems.

The report draws on many sources from the international and New Zealand literature to provide the background rationale for the linkages between high-flow harvesting and various in-stream values, including ecological and cultural values, via flow regime alteration. The hydrological impacts associated with high-flow harvesting will be determined by interactions between river flow, storage size, water demands, water allocation rules, and consent conditions. However, the general effects of high-flow harvesting on in-stream values can be viewed as an interlinked cascade (Figure 0-1).

Māori have an intricate, holistic, and interconnected relationship with te taiao (the environment) that is based upon mātauranga Māori (generational knowledge), whakapapa (genealogy) and whānaungatanga (relationships). Wai (water) is one of the key components that supports the intricate relationships Māori have with te taiao, and the spiritual and cultural significance of fresh water can only be determined by the tangata whenua who have traditional rights over it. High-flow harvesting, and water abstraction in general, can affect cultural landscapes in varying ways; however, cultural landscape values are seldom evaluated alongside standard scientific approaches in freshwater management and Māori face the challenge of conveying to decision makers how environmental flows affect their cultural interests. Not only does abstraction of water often directly impact the natural resources supporting Māori culture, but it can also indirectly impact on cultural landscapes and many other aspects of Māori health and wellbeing (e.g., knowledge loss about the sites, access, and linkages to surrounding areas).

High flows are critical to river geomorphology because of the role they play in contributing to the balance between sediment supply and stream power. The physical consequences of high-flow harvesting via geomorphology effects are relatively easy to identify. However, the magnitude and nature of geomorphological consequences of changes in high flows are likely to be difficult to predict due to differences in the type of alteration to flow regimes, variability in time-scales of responses to disruptions, external factors such as increases in sediment from landcover changes, and climate change driven alteration of extreme events.

Reductions in the magnitude or frequency of high-flow events are likely to be associated with an increased likelihood of changes in composition of riparian vegetation accompanied by an alteration to river channel morphology. Similarly, there is potential for a reduction in periphyton-removing high flow events to directly alter periphyton biomass and composition, or indirectly alter periphyton communities through changes to channel geomorphology or grazing macroinvertebrates.

Native fishes possess unique and specialised life history traits that have been shaped to take advantage of predictable variability in flows and associated in-channel and flood plain habitats. There is potential for high-flow harvesting to impact multiple life history stages of native freshwater fishes by modifying critical habitats, altering food webs, and removing essential food sources, or disrupting key migration pathways.

High-flow harvesting could have impacts throughout a catchment, but it is possible that the cumulative effects will be seen most strongly in estuarine ecosystems of some catchments, with disruptions to geomorphological and biogeochemical processes, and changes to key habitats.

In many cases, it is possible to make conceptual links between high-flow harvesting and in-stream values, however, it should be noted that it is very difficult to test hypotheses about flow-ecology relationships for any part of the flow regime in the absence of appropriate datasets or controlled experiments required to parameterise and test predictive models. Consequently, quantifying the impact of high-flow harvesting on in-stream values is difficult and will depend on several interacting factors such as the size of the river, the characteristics of the flow regime, the size of the water storage, the level of water demand, and the nature of in-stream values.

1 Introduction

1.1 International background

There is a wide body of international literature on the influence of river flow regimes on river hydraulic conditions, water quality, channel geomorphology, and stream ecology. Within the international literature, river flow has been described 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). It is therefore widely recognised internationally that water use should be managed within the constraints of maintaining healthy river systems (Poff et al. 2010) and the sustainability of groundwater aquifers (Gleeson et al. 2010). Competing uses for water present a challenge for environmental managers because, while using water for irrigation, industrial, and power generation purposes can generate important economic benefits, abstractions also alter the magnitude and timing of river flows thereby causing potentially detrimental environmental consequences (Carlisle et al. 2011).

One purpose of studying the potential physical, social, cultural, and economic effects of changes in river flow relates to setting and testing the effectiveness of environmental flow regimes. Several authors have provided broad definitions of environmental flow regimes, but differences between definitions within the international literature means that a global coherent definition is lacking (see summary by Hayes et al. 2018). One commonly used definition of environmental flows in the international literature is provided by the Brisbane Declaration (2007): "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."

The international literature on environmental flows is very broad because interest in river flow management spans many topics including hydraulics, geomorphology, stream ecology, economics, social values, and the cultural importance of rivers. General overviews of many fundamental issues are provided by Whiting (2002) and also Falkenmark and Rockström (2004).

Many overarching environmental flow setting issues of international relevance are covered in the informative papers of:

- Acreman et al. (2014) on managing river systems in highly altered settings where a return to natural flow regimes or physical conditions may not be feasible
- Arthington et al. (2018) on challenges for environmental flow science and management
- Bertassello et al. (2021) on linking ecohydrology to socio-hydrology
- Horne et al. (2019) on the challenge of modelling flow-ecology relationships such that the effects of non-stationarity associated with climate change can be captured

- Lapides et al. (2022) in relation to streamflow depletion resulting from alteration of groundwater systems
- Olden et al. (2012) on many pertinent issues relating to flow regimes characterisation for ecohydrological research and environmental flow setting purposes
- Poff (2018) on the call to employ ecological theory and field observations to target ecologically important parts of the flow regime, and also account for non-stationary climate and the influence of additional environmental stressors such as temperature and sediment
- Poff et al. (2010) on the importance of stating and testing hypotheses about flow-ecology relationships within the environmental flow setting process
- Sun et al. (2017) for an international review in relation to human altered river systems.

Despite the useful material contained within the international literature, it should be noted that there is currently a lack of universally accepted ecohydrological methods and nature-based solutions for river flow management or environmental flow setting. The absence of universal solutions is partly because water-resource management solutions require advances in the science of ecohydrology, and because current understanding is limited by a shortage of observational data and theories that synthesise complex processes across scales ranging from micro-scales (millimetres) to catchment-scales (tens of kilometres) (Guswa et al. 2020).

1.2 New Zealand background

In New Zealand, key aspects of stream ecology, river habitat, and river geomorphology that are known to be influenced directly by river flows and river flow management include periphyton (e.g., Biggs et al. 1999), benthic invertebrates (e.g., Greenwood and Booker 2015), and fish communities (e.g., Crow et al. 2013). Biodiversity and ecological integrity are themselves important values within the New Zealand context (McGlone et al. 2020), but many flow-driven aspects of cultural, recreational, and aesthetic landscape-scale values are also intertwined with ecosystem health (e.g., Harmsworth et al. 2011). River flow-driven ecological values, landscape values, recreation values, and Māori customary and traditional in-stream values are often referred to collectively as “in-stream values” following the Ministry for the Environment (MfE) 1998 guidelines for in-stream values (Snelder et al. 1998). The MfE 1998 guidelines also referred to “out-of-stream values” that comprised values associated with the use of water outside of the river system, including hydro-electric power production, that are frequently associated with an economic value. This terminology can be confusing because: a) wetland or floodplain habitats may be considered a flow-driven in-stream value despite not being in stream channels; and b) hydropower generation from dams may be considered an out-of-stream value despite being located in stream channels.

Demand for water for farming, domestic and industrial uses is high in locations in Aotearoa-New Zealand (Li et al. 2011) where there is high abstraction demand for irrigation purposes (Clark et al. 2007) and power production (Herath et al. 2011). The benefits of irrigation for agricultural production across New Zealand are well established, with water abstracted from rivers and aquifers (e.g., Srinivasan and Duncan 2012). An expanding population (Stats NZ 2022) and the effects of climate change (Collins 2020) will continue to impact on the quantity of available fresh water into the future.

The National Policy Statement for Freshwater Management 2020 (NPS-FM), the Resource Management Act 1990 (RMA), and National Environmental Standards provide the primary mechanisms for managing competing uses for fresh water in New Zealand. National legislation is implemented at the regional level through various planning instruments employed by local authorities (typically regional councils or unitary authorities). Several technical requirements associated with water management are contained within the RMA that states that no person can take, use, dam, or divert water, or discharge contaminants into it, unless allowed by a rule in a regional plan or a resource consent. The NPS-FM also contains various technical requirements that relate strongly to river flow management, such as water quantity being named as one of five biophysical components that contribute to freshwater ecosystem health. Taking a holistic view of the RMA and the NPS-FM, the goal of water resource management within New Zealand has been broadly described as wise use of water to meet the economic, cultural, and environmental needs of society, both currently and into the future (Kaye-Blake et al. 2014; Ministry for the Environment 2020).

1.3 Definition of high-flow harvesting and run-of-river water takes

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

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

Issue	Run-of-river	High-flow harvesting
Operational controls	Timing of take is controlled by a cease-to-take condition that allows water to be always taken except during periods of relatively low flows or groundwater levels. Rate of take is controlled by a maximum rate of take that allows water to be taken at a relatively low rate.	Timing of take is controlled by a cease-to-take condition that allows water to be taken only during periods of relatively high flows or groundwater levels. Rate of take is controlled by a maximum rate of take that allows water to be taken at a relatively high rate.
Possibly hydrological effects	Reduction of low to medium parts of the hydrograph for prolonged periods of time during period of high demand.	Reduction of medium to higher parts of the hydrograph at any time of year independent of immediate water demands and are therefore likely to have different environmental effects compared with run-of-river water takes
Possible environmental considerations	Decreases in wetted area, decreases in habitat quality, higher temperatures, dissolved oxygen depletion, reduced fish passage, increased nutrient concentrations, etc.	Changes in river sediment transport and deposition, reduce removal of nuisance algae, alteration of fish migration cues, etc.
Physical infrastructure	Requires physical infrastructure for taking water from the environment and transporting water to location of use	Requires additional physical infrastructure for water storage and sediment deposition, in comparison to run-of-river takes, because high-flow harvesting involves temporary storage of water followed by later distribution and use
Physical limitations for taking water	Water availability at location of take. Maximum rate at which the water can be used	Maximum rate at which water can be taken from the natural environment, transported to the storage, and filled into the storage. Maximum capacity of the storage. Consideration of suspended sediment load during high flows because high sediment loads may spoil equipment and clog ponds/canals etc.
Water losses and water use efficiency	Potential losses when transporting water from point of take to point of use but some schemes are shifting to partially or fully piped networks that reduce water loss and pumping costs if actively maintained	Additional losses due to leakage from storage and evaporation from storage
Possibility of enhancement of baseflows	In the case of irrigation, river flow augmentation should only be a possibility if the water is being used inefficiently	Offers the possibility of partial return of water to the river to enhance baseflows, but the environmental benefits of using stored water to enhance baseflow must consider the relative size of the storage compared to river flows, and the detrimental effects on water supply.

Definitions and discussion of run-of-river and high-flow harvesting provided above used general, rather than technical, phrasing. General phrasing within the definitions is beneficial because easily understood definitions provide a starting point for further sections in this report about the potential influences of high-flow harvesting on various in-stream values.

1.4 Aim and structure of this report

The aim of this report is to help inform regional council staff and other parties involved in river flow management and environmental flow setting by summarising numerous sources of information about the potential effects of high-flow harvesting on various aspects of in-stream values. Although this report primarily relates to high-flow harvesting, it is recognised that high-flow harvesting would most likely be operated in combination with run-of-river water takes.

Each section of this report relates to an entity with the potential to be influenced by high-flow harvesting. The sections are arranged into three main groups.

1. People and legislation: Section 2 describes parts of the NPS-FM that relate to river flow management and high-flow harvesting. Section 3 describes cultural values, beliefs, and practises associated with water that are required to be supported through the duty of partnership under Te Tiriti o Waitangi.

2. Physical-chemical: Sections 4 and 5 describe the importance of hydrological and river geomorphology in setting physical habitat templates for in-stream values, and the potential for physical impacts of high-flow harvesting. Sections 6 and 7 are topics that transition from physical aspects to flow-driven ecological aspects. Section 6 describes potential impacts on the co-dependent relationship between fine sediment and aquatic vegetation. Section 7 describes potential impacts on riparian vegetation.

3. Ecology: Sections 8 to 10 describes flow-driven aspects of ecological states, functions, and health of periphyton, macroinvertebrates, and fish. Both direct and indirect effects of high-flow harvesting on these various trophic levels are discussed within these sections. Section 11 relates to flow requirements in estuaries, which have contrasting physical and ecological characteristics in comparison with those of rivers.

This report is not the only source of material on river flow management in the New Zealand context. For example, Biggs et al. (2008) provide an overview of methods and issues when attempting to determine flow regimes for protection of in-stream values. A summary of advances in environmental flows research in the New Zealand context was previously provided by and Booker et al. (2016). Stoffels et al. (2022) provides a description of the possible in-stream effects of reducing low flows and proposes methods that would be deployed under a nationally-coordinated strategy for monitoring and evaluating the effects of reduced low flow. The MfE 2022 river flow management guidance (Booker et al. 2022) provides material on several aspects that relate to work presented in this report, including:

- a proposed framework for managing river flows to support implementation of the NPS-FM
- an overview of some fundamental principles for river flow management
- a description of links between river flow regimes and in-stream ecological conditions in the New Zealand context

- a description of how various components of the NPS-FM relate to river flow management
- the recommendation that 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.

Several sections of this report borrow heavily from Booker et al. (2022) and Stoffels et al. (2022) due to the overlapping nature of the topics addressed in those reports and to maintain consistency in language and recommended approaches to river flow management.

For the purposes of this work, and to be consistent with current guidance from MfE, the definition provided by Booker et al. (2022) is used: “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.”

2 River flow management considerations within the NPS-FM

2.1 Parts of the NPS-FM relating to water storage?

The National Policy Statement for Freshwater Management 2020 (NPS-FM) sets out environmental policies relating to river flow management in Aotearoa-New Zealand. The fundamental concept of Te Mana o te Wai, which informs the NPS-FM and its implementation, encompasses six principles relating to the roles of tangata whenua and other New Zealanders in the management of fresh water. The six principles are:

- mana whakahaere: the power, authority, and obligations of tangata whenua to make decisions that maintain, protect, and sustain the health and well-being of, and their relationship with, fresh water
- kaitiakitanga: the obligation of tangata whenua to preserve, restore, enhance, and sustainably use fresh water for the benefit of present and future generations
- manaakitanga: the process by which tangata whenua show respect, generosity, and care for fresh water and for others
- governance: the responsibility of those with authority for making decisions about freshwater to do so in a way that prioritises the health and well-being of fresh water now and into the future
- stewardship: the obligation of all New Zealanders to manage fresh water in a way that ensures it sustains present and future generations
- care and respect: the responsibility of all New Zealanders to care for fresh water in providing for the health of the nation.

The NPS-FM does not specifically mention water storage for the purposes of water supply outside of Clause 3.31, which relates to large hydro-electric generation schemes specifically. However, the parts of the NPS-FM that relate to river flow management and managing the potential effects of taking water from the natural environment do cover operation of run-of-river and high-flow harvesting water takes despite several differences between high-flow harvesting and run-of-river water takes (Table 1-1). Some important clauses that are relevant to implementation of the NPS-FM in relation to the planning, management, and operation of water storages, as well as run-of-river takes, include the following.

- Clause 3.2.2
  - (a) the need to actively involve tangata whenua in freshwater management (including decision-making processes).
  - (b) engage with communities and tangata whenua to identify long-term visions, environmental outcomes, and other elements of the National Objectives Framework.
  - (c) the fundamental concept of the hierarchy of obligations in Te Mana o te Wai. This hierarchy of obligations prioritises the health and well-being of water bodies and freshwater ecosystems, then the health needs of people, and lastly the ability

of people and communities to provide for their social, economic, and cultural well-being.

- Section 3.7.2
  - (e) set target attribute states, environmental flows and levels, and other criteria to support the achievement of environmental outcomes (clauses 3.11, 3.13, 3.16).
  - (f) set limits as rules and prepare actions plans (as appropriate) to achieve environmental outcomes (clauses 3.12, 3.15, 3.17).
- Clause 3.16 Setting environmental flows and levels
  - Every regional council must include rules in its regional plan(s) that set environmental flows and levels for each FMU and may set different flows and levels for different parts of an FMU.
  - Environmental flows and levels must be set at a level that achieves the environmental outcomes for the values relating to the FMU or relevant part of the FMU and all relevant long-term visions.
  - have regard to the foreseeable impacts of climate change.
  - use the best information available at the time.
- Clause 3.17 Identifying take limits
  - (1) Identify and then include take limits as rules in its regional plan in order to meet environmental flows, and impose conditions on resource consents accordingly (i.e., in line with take limits).
  - (2) Take limits must be expressed as a total volume, a total rate, or both a total volume and a total rate, at which water may be taken.
  - (3.a) Identify the flows and levels at which the allowed taking, damming, or diversion will be restricted or no longer allowed within the plan or resource consent must.
  - (4.a) Provide for flow or level variability that meets the needs of the relevant water body and connected water bodies, and their associated ecosystems.
  - (4.b) Safeguard ecosystem health from the effects of the take limit on the frequency and duration of lowered flows or levels.
  - (4.c) Provide for the life cycle needs of aquatic life.
- Clause 3.24 Rivers
  - (1) Every regional council must include the following policy (or words to the same effect) in its regional plan(s): “The loss of river extent and values is avoided, unless the council is satisfied: that there is a functional need for the activity in that location; and the effects of the activity are managed by applying the effects management hierarchy.”

  - (2) Subclause (3) applies to an application for a consent for an activity: (a) that falls within the exception to the policy described in subclause (1); and (b) would result (directly or indirectly) in the loss of extent or values of a river.
  - (3) "(a) the council is satisfied that the applicant has demonstrated how each step in the effects management hierarchy will be applied to any loss of extent or values of the river (including cumulative effects and loss of potential value), particularly (without limitation) in relation to the values of: ecosystem health, indigenous biodiversity, hydrological functioning, Māori freshwater values, and amenity; and (b) any consent granted is subject to conditions that apply the effects management hierarchy."
- 3.28 Water allocation
  - (2) Every regional council must include methods in its regional plan(s) to encourage the efficient use of water.
- Appendix 1A Compulsory values
  - In a healthy freshwater ecosystem, all five biophysical components (water quality, water quantity, habitat, aquatic life, ecological processes) are managed to be suitable to sustain the indigenous aquatic life expected in the absence of human disturbance or alteration (before providing for other values). The extent and variability in the level or flow of water is specifically referred to with respect to water quantity.

Although the NPS-FM does not specifically mention high-flow harvesting, guidance on the National Objectives Framework of the NPS-FM (MfE 2022) does include some recommendations specifically relating to high-flow harvesting and water storage:

- "It may be environmentally conservative to allow a large rate of take for filling a storage pond during higher flows, in order to limit water abstraction at lower flows."
- "Opportunities to reduce takes could come from more efficient water use (using less water for the same use) or water storage (either from water harvesting at high flows or harvesting and storing rainfall). Councils must consider these options with tangata whenua and their communities."
- "Councils can give direction and assistance, such as relying less on irrigation, or storing water where droughts will become more common, and consent holders will be affected more often."
- "Water storage is an option to use non-critical parts of the flow during low-flow periods when the water body is not stressed, which increases the allocation back to the river. Stored water must not be used to expand or intensify land use that would breach the resource use limits. Councils must clearly set out the limits on total land use and intensity for different land types in a catchment."

The above recommendations generally encourage consideration of high-flow harvesting and water storage as mechanisms for environmentally sustainable water use.

2.2 Challenges associated with the NPS-FM

It should be noted that the NPS-FM is a complicated document that has attracted praise and criticism. The NPS-FM contains prescriptive technical aspects and high-level aspirational statements. The highly technical demands of the NPS-FM are exemplified by 22 attributes within the National Objectives Framework (NOF), each with prescriptive units, measurement methods, and target states. This contrasts with non-technical statements whose implementation is open to interpretation as exemplified by the six principles and hierarchy of obligations associated with Te Mana o te Wai. Some comments on the NPS-FM that highlight the often location-dependent challenges involved in its implementation include the following:

- Larned et al. (2022) stated that “while the potential benefits [of the NPS-FM] are great, the numerous objectives, the requirements to set limits and develop action plans to meet those objectives, and the hierarchy of obligations in Te Mana o te Wai pose an immense challenge for planners and other implementation practitioners, and for scientists”
- White et al. (2020) comment that “New Zealand environmental legislation and Treaty of Waitangi settlements recognise the value of water to Māori and enable their aspirations for a greater role in water management. However, consequent opportunities for iwi, such as the exercise of kaitiakitanga (guardianship), are hampered by barriers including a lack of established methods to transfer traditional Māori knowledge into policy and less than full Māori participation in water management decisions”
- Kirk et al. (2020) indicated that an effect of the NPS-FM has been local governments placing greater emphasis on devising policy and plans at the expense of policy implementation
- Fenemor et al. (2021) comment on “the growing recognition of tangata whenua values in water management alongside belated development of national policy direction on water quality and allocation” in relation to recent freshwater policy development
- The NPS-FM has been criticised for appropriation of te ao Māori, for example Taylor et al. (2021) stated that “the policy language is weak and ambiguous, devaluing Māori rights and interests to mere aspirations whilst making no promises that those aspirations will be provided for. Beneath the bicultural rhetoric there are no meaningful provisions (or penalties) that would recognise and provide for iwi/hapū sovereignty or guarantee equitable co-governance or co-management”.

2.3 NPS-FM summary

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, and therefore high-flow harvesting in combination with run-of-river takes, are an essential and legitimate consideration for all 15 NPS-FM policies and many of the values described in NPS-FM Appendix 1.

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. Te Mana o te Wai hierarchy of obligations is relevant to all freshwater management, including river flow management.

However, there is currently no set ‘recipe’ for how to give effect to Te Mana o te Wai hierarchy of obligations with respect to river flow management or high-flow harvesting. Further information designed to help regional councils interpret and effectively implement the objectives and policies in the NPS-FM that pertain to management of river flows to support ecosystem health can be found in guidance on the National Objectives Framework of the NPS-FM (Ministry for the Environment 2022) and the river flow management guidance of Booker et al. (2022).

3 Māori cultural values, beliefs and practises associated with water

Māori have an intricate, holistic and interconnected relationship with te taiao (the environment) that is based upon mātauranga Māori (generational knowledge), whakapapa (genealogy) and whānaungatanga (relationships) (Harmsworth and Awatere 2013; Fenwick et al. 2018). Wai (water) is one of the key components that supports the intricate relationships Māori have with te taiao, and the spiritual and cultural significance of fresh water can only be determined by the tangata whenua who have traditional rights over it.

Freshwater management where iwi/hapū/whānau (mana whenua) define their cultural values is required through the duty of partnership under Te Tiriti o Waitangi (Waitangi Tribunal 1984, 1991; Tipa and Teirney 2006). This section outlines some key cultural values associated with wai that can be used to understand the cultural risks/opportunities associated with high-flow harvesting. The purpose of this section is not to identify specific cultural values associated with (or at risk from) high-flow harvesting, but to identify themes associated with high-flow harvesting that can be used as the basis for further kōrero (conversation) with mana whenua.

3.1 Te ao Māori and wai

Te ao Māori (the Māori worldview) is based upon an inter-generational knowledge base (mātauranga Māori) and the belief that all living and non-living things are connected/related, that all living things are dependent on each other, and that natural resources must be protected and enhanced for future and past generations (Best 1924; Marsden 1988; Barlow and Wineti 1991; Henare 2001; Harmsworth and Awatere 2013; Mead 2016; Fenwick et al. 2018).

Fresh water is an integral part of Te ao Māori and is considered a taonga tuku iho (treasure passed down) to provide and sustain life (Tipa and Associates 2013; Iwi Advisory Group 2015; Kitson et al. 2018). Iwi and hapū identify themselves through reference to the water source they whakapapa to within their pepeha and mihi (personal introduction and greeting), and this relationship is reinforced through whakataukī (proverbs), waiata (songs), pūrākau (stories) and wāhi ingoa (place names) (Tipa and Associates 2013; Fenwick et al. 2018; Taylor et al. 2021).

Wai is the lifeblood of Papatūānuku (earth Mother), is significant for spiritual health and healing, and has elements from Atua (gods): tapu (sacred), wairua (spiritual force), mauri (essential lifeforce), and mana (authority and reciprocal obligations) (Taylor et al. 2021). Mana whenua (those with territorial rights) have an inherent obligation to their tupuna (ancestors), themselves, and future generations, to ensure the health of their water (Taylor et al. 2021).

3.2 Ki uta ki tai

Concepts such as ki uta ki tai (mountains to the sea) are used by Māori to describe their holistic understanding of fresh water and how it connects to the landscape, atmosphere, surface water, groundwater, land use, water quality, water quantity, and the coast. It is vital that that resource management decision-making processes reflect these connections (Fenwick et al. 2018). The economic, social, environmental, and cultural values of Māori are balanced within the context of ki uta ki tai, therefore, any reduction in the ability of the landscape to support natural resources and cultural use, risks the progressive degradation of Māori aspirations (Durie 1995; Crow et al. 2020). The ki uta ki tai principle is often at odds with current water resource management practices, which are based on council boundaries and western science, so it is important that iwi are enabled to evaluate how high-flow harvesting could affect the health of streams and rivers within their rohe (tribal area) in a way that expresses and accommodates their holistic values and beliefs (Tipa and Teirney 2006; Crow et al. 2018).

3.3 Cultural landscapes

Cultural landscapes can be classified into three categories (Kawharu 2009; UNESCO 2021).

1. Landscapes designed and created by man (e.g., pā/papakāinga (villages), marae (meeting houses), pou paenga (carved posts), tuhituhi neherā (rock art)).
2. Organically evolved landscapes (e.g., ara tawhito (ancient trails), mahinga kai (food gathering areas), maunga (important mountains), tauranga waka (canoe mooring sites), urupa (cemeteries), umu (earth ovens), wāhi kohātu (rock formations), wāhi mahi kohātu (quarry sites), wāhi paripari (cliff areas), wāhi raranga (weaving material sites), repo raupō (wetlands/swamps), puna (springs)).
3. Associative cultural landscapes (e.g., wāhi tapu and wāhi taonga (sacred and treasured places), wāhi ingoa (place names), pūrakau (stories), whakataukī (proverbs), waiata (songs), taniwha (water spirit), whakapapa (genealogy) (Kawharu 2009; Tipa and Associates 2013)).

High-flow harvesting, and water abstraction in general, can affect each of these cultural landscapes in varying ways; however, cultural landscape values are seldom evaluated alongside standard scientific approaches in freshwater management and Māori face the challenge of conveying to decision makers how environmental flows affect their cultural interests (Tipa and Nelson 2012; Kitson et al. 2018). Not only does abstraction of water often directly impact the natural resources supporting Māori culture, but it can also indirectly impact on cultural landscapes and many other aspects of Māori health and wellbeing (e.g., knowledge loss about the sites, access, and linkages to surrounding areas) (Crow et al. 2020).

3.4 Hapū/iwi freshwater management issues

Hapū and iwi across the motu (country) have identified a variety of pressures/issues that impact on their freshwater values, beliefs, and practices (Fenwick et al. 2018). Some of the commonly occurring themes include:

Raupatu (land confiscation)

Land development/modification/degradation (often association with raupatu) has created barriers to freshwater use through the loss of access, loss of aquatic food sources, loss of kaitiakitanga knowledge, and loss of mana associated with the inability to assert rangatiratanga – all factors that directly affect the health and wellbeing of the people (Te Rūnanga o Te Rarawa Iwi Research & Development 2013).

Inappropriate mixing of waters

Contemporary freshwater management options (e.g., artificially augmenting aquifers with water from adjacent catchments) may not align with Māori values, beliefs and practises, because water is classified according to its nature and uses, and the classifications of these waters determines how they may, and may not, be used (Tau et al. 1990).

Water abstraction

Over-abstraction of water can result in degradation of the natural values and character of streams and rivers, and the legacy of past/present management practises is having an impact on the ability of future generations to use and experience the freshwater environment in the ways their tūpuna (ancestors) were able to (Kai Tahu Ki Otago 2017). This is because abstraction has been biased towards supporting economic interests, at the expense of environmental and Māori values, often with very little understanding of the freshwater ecosystem (e.g., hydrology, recharge rates, connectivity) (Ngāi Tūāhuriri Rūnanga et al. 2013).

Water quality contamination

Holistic methods and tools need to be adopted to achieve higher water quality standards. Water quality is often poor in areas where agricultural activity, urban run-off, and/or sewage effluent discharges leach pollutants, which results in the accumulation of contaminants in sensitive freshwater environments (Waikato-Tainui Te Kauhanganui Inc. 2013).

4 River flow

4.1 Flow regimes comprise various components of river flow

River flow in natural catchments varies in time because of weather patterns, and varies 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 at a site as it varies through time when viewed over the long-term. The features of a flow regime have generally been described as comprising magnitude, frequency, duration, timing, and rates of change, including seasonality (Richter et al. 1997). The features of a flow regime are conditioned by the interactions between climate and catchment characteristics. Flow regime features can be identified through visual inspection of hydrographs that represent river flow time-series graphically. For example, Figure 4-1 shows an observed river flow time-series taken from an arbitrarily selected gauging station (Hātea at Whareora Road, Northland) alongside a qualitative description of various flow regime features.

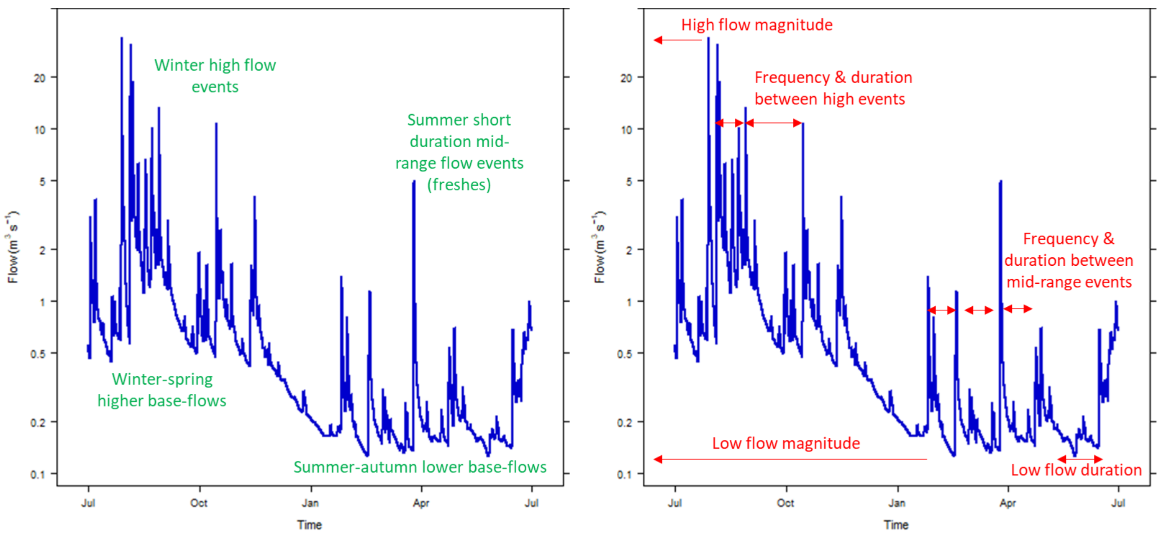

Figure 4-1: Example of the same hydrograph with labels indicating general features of the flow regime. Left-hand labels indicate seasonal features. Right-hand labels indicate features of events. Arbitrarily selected example gauging station (Hātea at Whareora Road, Northland) and hydrological year (1990–1991). Note y-axis is a log scale. Summer flows are very low compared to winter flows.

Flow regime features can be quantified by calculating various hydrological metrics that are often referred to as indices in the hydrological and environmental flow setting literature. Each hydrological index quantifies a different aspect of the flow time-series. Sets of indices can be used to describe the general features of a flow regime, and many different hydrological indices have been linked to a variety of ecological states and processes in New Zealand. For example, Crow et al. (2013) correlated fish distributions with 47 hydrological indices including those that describe predictability, constancy, and contingency of seasonal patterns. However, there is no global consensus about which indices should be used to characterise flow regimes. This lack of consensus is partly due to the various reasons for characterising flow regimes (e.g., for river classification, for water availability, or for ecological modelling purposes) each requiring different, although possibly overlapping, sets of indices. The lack of consensus about what constitutes a flow regime may also arise because: a) the selection of hydrological indices that are ecologically-relevant and/or important for setting physical habitat templates varies depends on location and species of interest; b) there can be a high degree of correlation between various hydrological indices resulting in two different indices that are equally valid representations of the same hydrological aspect (Olden and Poff 2003).

Consideration of flow intermittence (zero flows) is one example of how location and river size can influence methods relating to river flow regime characterisation. In many wetter locations zero flows (e.g., represented by the average number of zero flow days per year) are not included when characterising flow regimes because they are not relevant to permanently flowing rivers. However, understanding patterns in flow intermittence has been identified as an important consideration for effective river management in some locations, both globally (Messager et al. 2021) and in New Zealand (Arscott et al. 2010), because the duration and frequency of zero-flow periods are associated with the ecological characteristics of rivers and have important implications for water resources management (Datry et al. 2014). Snelder et al. (2013) indicated that intermittence is partially controlled by processes, such as groundwater-table fluctuations and seepage through permeable channels, that are more relevant to river flows in smaller catchments than larger catchments. The importance of flow intermittence in characterisation of flow regimes may have been underplayed due to underrepresentation of small catchments in datasets of river flows. See Booker and Snelder (2012) for some further discussion of available river flow time-series data.

Difficulties in characterising hydrological regimes arise because there are 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.

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.

It should be noted that hydrographs often exhibit common patterns between years but can also show important differences between years. For example, visual inspection of an example hydrograph over several years (Figure 4-2) indicates that 1992 experienced a much drier summer than 1991 whereas the summer of 1993 experienced low flow for a less extended period than the previous two years. Each summer low flow period was interceded by short duration freshes (a term often used to describe flow events with sharp rises and falls that are not floods because they peak in the mid-range flow magnitude). Figure 4-2 indicates that the summer of 1993 only experienced three summer freshes whereas other years experienced more frequent freshes during the summer low flow period.

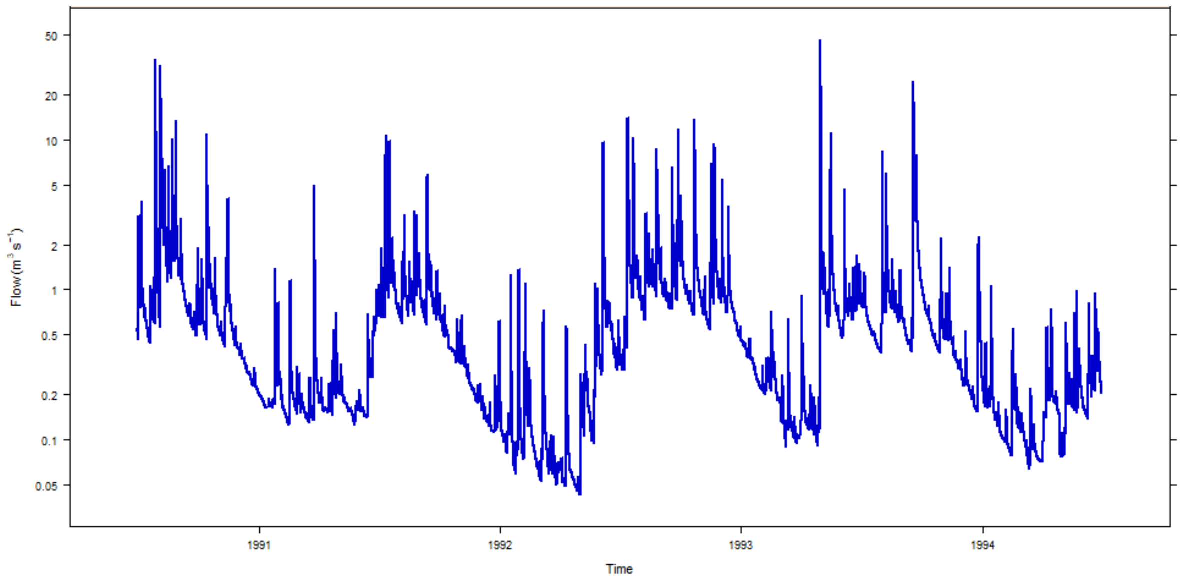

Figure 4-2: Example of a four-year long hydrograph. Arbitrarily selected example gauging station (Hātea at Whareora Road, Northland) and hydrological years (1990–1994). Note y-axis is a log scale. Summer flows fall to different magnitudes in each year.

4.2 Implications of flow regimes for water storage operation

Visual inspection of various hydrographs including Figure 4-1 and Figure 4-2 indicates that seasonality and flashiness are two particularly noteworthy aspects that are likely to be important for water supply and hydrological impacts when considering high-flow harvesting.

Figure 4-2 shows strong flow seasonality; winter base flows are around five times higher than summer base flows due to seasonality in rainfall and evaporation. Seasonality is relevant to high-flow harvesting because it is a driver of synchroneity (or lack of synchroneity) between water availability and water demand. A strongly seasonal flow regime may contain summer flows of low magnitude and long duration. Lack of water availability during times of high demand due to low river flows (possibly in combination with environmental constraints) will compromise the reliability and volume of water that can be taken under run-of-river takes. Lack of available water during summer may encourage authorities and water users to assess the viability of high-flow harvesting.

Figure 4-2 also shows strong flashiness (high rates of change in flow with time resulting in quick rises and falls of flow); rainfall events in this relatively small catchment trigger river flow to rise and fall rapidly at any time of year, with winter events likely to be of greater magnitude than summer events. A strongly flashy hydrograph will mean that high-to-mid range events are relatively short in duration. Short duration high-to-mid range events carry less total volume of water compared to events of the same peak magnitude that are less flashy.

Seasonality and flashiness are relevant to high-flow harvesting because they are strong drivers of how a hydrograph interacts with water allocation rules and consent conditions to determine how much water is available for high-flow harvesting and at what times. For example, depending on water allocation rules and consent conditions, lack of high-to-mid range events during prolonged low flow periods may provide limited opportunity to replenish water storages, and the presence of short duration events may mean that water is available to fill storages for only short periods.

Three important conclusions follow on from the points made above.

1. Water supply and downstream hydrological impacts associated with high-flow harvesting will be determined by interactions between river flow hydrographs, storage size, water demands, water allocation rules, and consent conditions. The viability of proposed high-flow harvesting within environmental constraints will partly be informed by assessment of these interactions. For more details on this subject see the accompanying report to this work by Booker and Rajanayaka (2022).

2. If high-flow harvesting schemes become operational, their operation and compliance with consent conditions will rely heavily on river flow data. Ideally, high-quality, high-temporal resolution, and near-real-time river flow data must be available to water authorities and water users.

3. Water storage operators may have to respond quickly to rapid changes in river flow in order to operate water storages effectively and within consent conditions. Operation of high-flow harvesting will require greater flexibility in logistical arrangements (when to start taking water and when to stop taking water) and physical infrastructure (at what rate to be taking water) than would be the case for run-of-river takes.

Unfortunately, high quality, long-term river flow data are only available for a limited number of sites known as river flow gauging stations. Models have been used to estimate river flows at ungauged sites across New Zealand but predictive performance is variable and depends on which aspect of the flow regime is of interest, and whether intra-site or inter-site patterns are of interest (e.g., McMillan et al. 2016). 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).

4.3 Hydrological alteration associated with local activities and climate change

River flow regimes in natural catchments are determined by the interplay between climate and various catchment characteristics such as slope, soil, vegetation, and geology. A stable climate and natural catchment will produce a stationary river flow time-series. Stationarity has been described as the idea that natural systems fluctuate within an unchanging envelope of variability. A stationary river flow time-series will have the same general characteristics irrespective of which part of the series is being looked at. However, it has been argued that stationarity cannot be assumed for hydrological conditions because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (Milly et al. 2008; Williams et al. 2020). Furthermore, features of flow regimes can be altered by a combination of local human activities and climate change. For example, Booker and Snelder (2022) detected evidence of long-term climate-driven and locally-driven trends in seasonal patterns of river flows across the Canterbury region.

Local human activities can alter river flows directly by manipulating water in rivers or aquifers (e.g., high-flow harvesting, run-of-river takes, damming, river diversion, etc), or indirectly by altering physical catchment characteristics (e.g., deforestation, afforestation, drainage modification, etc). Climate change has the potential to impact river flows through changes to hydrological processes (e.g., precipitation, evapotranspiration, snow storage-melt). However, the direction and magnitude of effect of climate change on river flows across New Zealand is likely to be spatially variable due to interactions between topography and predominant weather patterns (Collins 2020). Water availability and subsequent impacts on in-stream values will shift in some locations even if water demand, water allocation rules, and consent conditions remain constant (e.g., Poyck et al. 2011). However, 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 or irrigation demand. Climate change is likely to result in shifts in water demand, especially for irrigation purposes since demand is driven by patterns of evaporation and rainfall (Srinivasan et al. 2019). Interacting combinations of climate change impacts and various local human activities are therefore relevant to river flow management. AghaKouchak et al. (2021) provide further discussion of how the dual influences of climate and local activities on river flow regimes combine to confound analysis of observed patterns and introduce uncertainty when predicting future hydrological conditions.

Trends are not the only source of non-stationarity in river flow time-series. Climate oscillations viewed within a relatively short river flow time-series may result in calculated hydrological indices that are different than would be found over the longer-term, irrespective of whether hydrological indices were selected to represent water availability or ecologically relevant aspects of the flow regime. Non-stationarity of hydrological records is an important issue globally (see Bayazit 2015) and in New Zealand where long hydrological time-series are relatively rare, and the signals of interdecadal climate oscillations have been detected within river flow records (McKerchar and Henderson 2003). Flow trends and oscillations may also result in different results for calculated hydrological indices being dependent 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.

Removing human influences from streamflow time-series is a process often referred to as river flow naturalisation. Estimated naturalised flows are often used to indicate hydrological alteration and water availability under current water use or proposed water use scenarios compared to an unaltered baseline. Detailed discussion of naturalisation methods and reasons why estimated naturalised flows should not necessarily be considered as true natural flows are provided by Terrier et al. (2021). To avoid confusion when calculating hydrological alteration for different purposes, Booker et al. (2022) suggested 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.

4.4 Hydrology summary

River flow regimes characterise the collective properties of river flow when viewed over the long term. River flow regimes can be described qualitatively by visual inspection or quantitatively by calculating hydrological indices. Availability and analysis of river flow data is very important when assessing water supply and downstream hydrological effects associated with proposed high-flow harvesting. Unfortunately, high quality, long-term river flow data are only available for a limited number of sites known as river flow gauging stations. Hydrological models or substitute records can be used to estimate river flows where observed data are not available but modelled flow estimates will be associated with prediction uncertainties. Where river flow data are available, careful consideration of the effects of climate change and climate oscillations is required. It may be necessary to estimate naturalised flows to establish a baseline against which flow alteration can be assessed. Hydrological impacts associated with high-flow harvesting will be determined by interactions between river flow hydrographs, storage size, water demands, water allocation rules, and consent conditions.

5 River geomorphology

5.1 The importance of river channel geomorphology

River geomorphology can be broadly described as the physical shape of rivers that results from sediment supply, landscape setting and river flow regimes to determine hydraulic and sediment conditions. River geomorphology drives a range of physical and chemical processes that interact to determine channel morphology, bed conditions and heterogeneity, disturbance regime, and water quality (Wohl et al. 2015). River geomorphology therefore sets the physical habitat template within which local-scale hydraulic, sediment, and water quality conditions operate (Maddock 1999).

River geomorphological conditions are crucial to aquatic and riparian ecosystems in many ways. Hydraulic conditions influence physical habitat and food delivery in rivers (Hayes et al. 2007; Petts 2009). Sediment-related states influence many aquatic and riparian organisms that are dependent on size distributions of riverbed and suspended sediment materials at various life stages (e.g., Kemp et al. 2011; Béjar et al. 2017; Béjar et al. 2020). Ecological states and functions are known to be influenced by general geomorphological conditions (McIntosh 2000) and also the temporal patterns characterised by geomorphological regimes often described in terms of frequency and nature of physical disturbance (e.g., Jellyman et al. 2013).

It has been argued that changes to physical habitat within river channels are as detrimental to river ecosystem health as degraded water quality or quantity (Elosegi and Sabater 2013). The importance of river geomorphological conditions for understanding and manging river ecosystems is indicated by its prominent role in several river ecosystem frameworks (Fuller et al. 2019). River geomorphological conditions feature heavily in the following frameworks:

- the River Continuum Concept (Vannote et al. 1980)
- the Intermediate Disturbance Hypothesis (Connell 1978)
- the Network Dynamics Hypothesis (Benda et al. 2004)
- the Shifting Habitat Mosaic (Stanford et al. 2005)
- the Riverine Ecosystem Synthesis (Thorp et al. 2010)
- the Ecological Limits of Hydrological Alteration (Poff et al. 2010)
- the Stream Evolution Geology-Hydrology-Biology Triangle (Castro and Thorne 2019).

River geomorphology is also an important factor that combines with micro-scale roughness, valley confinement and channel slope to influence flow conveyance (Lane et al. 2007).

5.2 Principles of morphological adjustment in river channels

Theoretical principles in fluvial geomorphology are generally built on continuity equations for water, sediment, and energy. River width, depth, slope, and planform can be expressed as functions of the controlling variables: discharge, sediment supply, and channel bed and bank sediment size (although intermediary factors/processes such as vegetation, and human engineered interventions may also be influential). It follows that river channels adjust based on the rate of water and sediment supplied to them and the resulting magnitude and frequency of erosive forces relative to resistive forces (Knighton 2014). Consequently, the physical state of river channels may oscillate about a long-term mean due to inter-annual variability in hydroclimatic controls, or the topography of river channels may systematically increase or decrease based on changes in water and/or sediment supply. For instance, channels sometimes respond to increased river flows and energy by enlarging (Hawley and Bledsoe 2013). Where channel form is adjustable, incision and widening may increase or decrease channel capacity depending on inputs of sediment from bank failures, in-stream wood, and other debris and its subsequent interaction with infrastructure such as bridges and culverts (Stephens and Bledsoe 2020). Alternatively, land disturbance from urban development and upstream channel erosion can increase aggradation and retention of sediment in the channel and diminish flood conveyance capacity (Bledsoe and Watson 2001) that can overshadow climate and land-use effects of flood stages. Slater et al. (2015) reported that concomitant process of increasing flood frequency and reduced channel capacity has amplified flood inundation at stream gauge locations across the USA. Adjustments of river channels is often studied due to its importance for resistance to water flows and therefore conveyance of flood flows. For example, Call et al. (2017) reported that geomorphic adjustment can influence interannual variability in flood inundation.

Over the very long-term, rivers tend to balance changes in bed material load and size (i.e., the work that needs to be done by the river to move the gravel and sand on its bed) against the changes in river flow and gradient, which determines the energy available to do that work (Lane 1954). However, over time-scales relevant to river management, we should view rivers as constantly adjusting to the water and sediment supplied to them (Wilcock 1997). This is true in gravel bed rivers, and particularly braided rivers, which are inherently dynamic. Under circumstances where the controlling variables remain relatively constant when viewed over several years, any small-scale disturbance to channel morphology will result in processes that return the channel to a relatively stable form (Hickin 1983). Although this assumption is valid over short periods (i.e., a few years), it becomes less defensible over longer periods. The timeframes for geomorphic adjustment in rivers are such that a river can rarely be considered in a steady state. Instead, landscapes should be viewed to be in phases of relative stability for varying intervals of time as they progressively adjust to ongoing perturbations (e.g., Phillips 2003).

Gregory (2006) indicated that river channel enlargement, shrinkage, and metamorphosis have been associated with river channel adjustment, but also added that although the scope of adjustment has been established, it has not always been possible to predict what will happen in a particular location, because of complex response and contingency. Detailed modelling approaches to predicting geomorphic adjustments range from relatively simple 1D equations (e.g., De Rego et al. 2020) to spatially explicit two-dimensional landscape evolution models (e.g., Poeppl et al. 2019). Qualitative relationships describing the manner of channel adjustments associated with, for example, changes in discharge or sediment load (e.g., Schumm 1969) form the basis of predictions of river adjustment. Most generalised relationships in the literature are based on single thread rivers (e.g., Schumm's 1969 work predicting relationships for metrics such as width:depth ratios and sinuosity is based on 36 stable alluvial meandering streams where the bed material comprised <10% gravel). If generalised relationships from the literature are to be used for prediction, they must be based on the type of river under investigation.

5.3 Possible effects of flow regime and landscape changes on channel geomorphology

Several types of anthropogenic disruption to river geomorphology have been widely studied within the international literature including the effects of channelisation (physical re-alignment of a channel; Simon and Rinaldi 2006) and damming (which impedes sediment delivery; Petts and Gurnell 2005). The balance between sediment and stream power means that a reduction in water discharge will result in a reduction in the amount (load) and/or a reduction in grain size of sediment transported by the river. Physical flume experiments can be used to investigate riverbed aggradation and degradation associated with changes in sediment feed or hydraulic conditions (e.g., Elgueta-Astaburuaga and Hassan 2019). However, the degree of change in real-world river morphology will depend on the nature and degree of change in discharge (e.g., whether the change in discharge impacts the magnitude, frequency, or duration of flows above the threshold for bed mobility) and whether the change in discharge is also associated with a change in sediment supply.

The general geomorphology literature (e.g., Lane 1954) tells us that even a proportionally small take of flood water can alter the balance between bed material supply and transport capacity. Over time, this can induce a long-term change in riverbed morphology and therefore the associated physical habitat template. The expectations of reductions to high flows are a fining of the riverbed surface material, reduction in channel relief, and ultimately, if the take is large, riverbed aggradation. Floods also naturally help control riverbed woody vegetation, which, if left unchecked, can begin to take control of river morphology (see Section 7 for further details). Such geomorphic responses can change the physical habitat template (velocity, depth, substrate) with consequent effects on river biota (Owens et al. 2005).

Caskey et al. (2015) and references therein stated that various studies have demonstrated that river flow diversions may:

- reduce the cross-sectional area of flow (McKay and King 2006)
- reduce channel width by allowing encroachment of riparian vegetation (Ryan 1997)
- result in morphological simplification of the channel (Stamp and Schmidt 2006)
- increase the abundance of patches of fine sediment and low-velocity habitats (Baker et al. 2011)
- alter water chemistry (Kagawa 1992)
- reduce the richness, abundance, and diversity of macroinvertebrate functional feeding groups (Englund and Malmqvist 1996; Rader and Belish 1999; McIntosh et al. 2002; McCarthy 2008).

However, potential impacts of high-flow harvesting should be interpreted within the context of possible combinations of human activities that may disrupt fluvial responses. The importance of considering multiplicative drivers on river channel characteristics at the catchment-scale is highlighted by a framework for characterising and classifying human impact on river systems proposed by Macklin and Lewin (2019) (Figure 5-1).

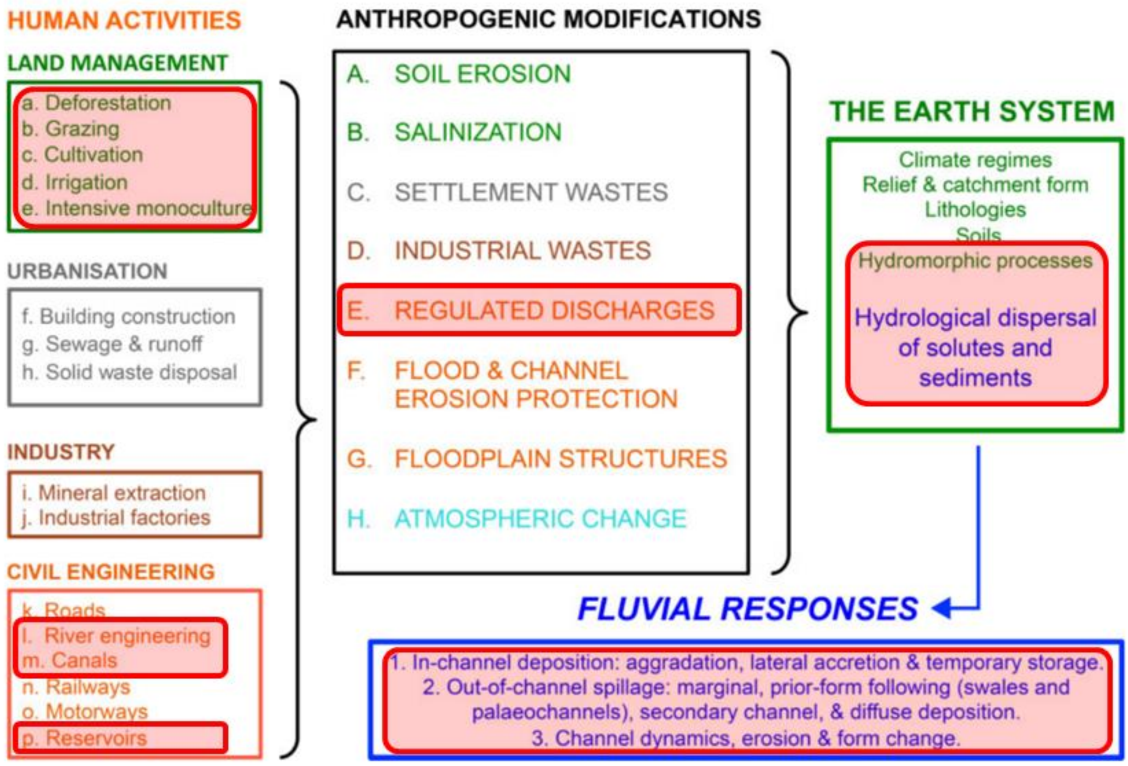

Figure 5-1: Human activities leading to fluvial responses via input modifications to the Earth system (after Macklin and Lewin" 2019). Phrases highlighted in red indicate potential influences of high-flow harvesting.

There are many published studies of anthropogenic disruption or alteration to river geomorphology within the international literature (e.g., Church 1995; Brierley et al. 1999; Stein et al. 2002; Kuriqi et al. 2021). For example, the classic paper of Williams and Wolman (1984) describes general empirical trends in timing and magnitude of downstream channel adjustments, particularly bed degradation and channel narrowing, following dam construction. However, Williams and Wolman (1984) also stated that variability in downstream response is high, and noted many exogenous factors to particular anthropogenic activities, such as vegetation or bedrock, that can affect these general trends.

There have been several studies relating river geomorphology to anthropogenic activities in New Zealand. A summary of findings of two general studies and four case studies are as follows:

- Hicks et al. (2021) describe the overall pressures on braided river systems in New Zealand as increasing due to anthropogenic stresses such as demand for irrigation water (particularly from the alp-fed rivers), braid plain conversion to farmland and invasive vegetation, as well as extreme natural events associated with earthquakes and climate change. They also highlighted the importance of delivery of sediment by rivers in influencing physical and ecological states and processes at river mouths (hāpua)
- Fuller et al. (2015) presented a meta-analysis of the history of river activity across New Zealand (see references within Fuller et al. (2015) for many details). They concluded that recent history has seen strong regional and temporal variability in rates of erosion and deposition, but concluded that:

  - “The clearest evidence for Polynesian impact is found in Northland's catchments in the form of increased floodplain sedimentation…considered to equate with Māori occupation…with further augmentation associated with European settlement in the 1800s and 1900s.”
  - “Farther east, in the East Coast Region of the North Island…European clearance of indigenous vegetation in the Waipaoa and Waiapu catchments exposed a highly erodible terrain to a range of erosion processes, which resulted in erosion rates exceeding by an order of magnitude those estimated at the end of the Last Glacial Maximum.”
  - “The clearest evidence for human disturbance is found in the East Coast Region, where a regime change in system behaviour is evident and the natural processes here have been overwhelmed.”
- Poeppl et al. (2020) described the situation in the Waiapu River, Gisborne. Some relevant quotes include:
  - “The trunk stream and tributaries of the Waiapu River have experienced a complex history of response to exceptional rates of sediment recruitment from mass wasting processes over the last 120 years.”
  - “An extensive record of valley-scale cross-sections shows remarkable rates of channel aggradation across differing parts of this catchment since Cyclone Bola in 1988.”
  - “Ongoing land clearance and forestry operations may temporarily accentuate the delivery of material to the river system, particularly in the absence of riparian margins, in the interval between tree removal and uptake of new growth on hillsides.”
  - “While high sediment yields may persist for years after afforestation, vegetating these slopes very effectively arrests shallow landslides and slopewash from susceptible terrain in the long term.”
  - “It is difficult to deliver truly sustainable results without considering additional knock-on effects, and often conflicting stake-holder interests.”
  - “Another strategy has been to take away gravel via industrial extraction. This can be effective in aggrading systems if carried out carefully and managed in an adaptive manner.”
- Richardson et al. (2014) described the situation in the Kaeo River, Northland. They stated that:
  - “post-settlement floodplain aggradation, equating to over 4 m of interbedded sand and silt alluvium in a partly-confined valley setting, has created considerable contemporary flooding issues.”
  - The “floodplain has accumulated at a faster average rate (8–13.5 mm yr^{-1}) in the last several hundred years in response to anthropogenic catchment disturbance following Māori and European settlement. This response mirrors the general

trend for Northland floodplains, where there has been rapid accumulation of floodplains (3–10 mm yr^{-1}) in the last 1000 years."

  - "In Kaeo, extensive deforestation associated with European settlement has had the greatest impact on floodplain dynamics, with the Kaeo lowland floodplain now a major sediment accumulation zone."
  - "Any flood protection measures or land-use decisions in the Kaeo area should consider the potential implications of ongoing high rates of floodplain aggradation and the potential for the reworking of sediment stored within the fluvial system, coupled with predictions of increased frequency of extreme hydrologic events."

- Jones and Preston (2012) described the situation in the Waipaoa catchment, Gisborne. They commented on how the temporal pattern in sediment delivery ratios supports the context of evolving catchments in response to deforestation, and stated that:
  - "The Waipaoa catchment in New Zealand has one of the highest measured specific suspended sediment yields measured in New Zealand compared to basins of comparable size."

5.4 River geomorphology summary

River geomorphology is an integral part of river ecosystems because it sets the physical template within which local habitat conditions and water quality influence various in-stream values. High flows are critical to river geomorphology because of the role they play in contributing to the quasi-equilibrium balance between sediment supply and stream power. Physical consequences of high-flow harvesting via geomorphology effects are relatively easy to identify, for example possible increases in downstream deposited fine sediment (Figure 5-1). However, the magnitude and nature of geomorphological consequences of changes in high flows are likely to be difficult to predict in space and time due to differences in the type of alteration to flow regimes, variability in time-scales of responses to disruptions, the chaotic nature of river channel evolution, external factors such as increases in sediment from landcover changes, the impacts of earthquakes, climate change driven alteration of extreme events, and interactions with invasive vegetation.

6 Fine sediment and aquatic vegetation

6.1 The importance of deposited and suspended fine sediment in gravel bed rivers

The grain-size composition of gravel bed rivers has been the subject of many international studies (see Karna et al. 2015). Research into deposited and suspended fine sediment has partly been driven by the importance of sediment on macroinvertebrate community composition (e.g., Mathers and Wood 2016), suitability of habitat for fish spawning (especially for salmonid species; e.g., Wildhaber et al. 2014), and fish growth and survival (especially for salmonid species; e.g., Suttle et al. 2004). Figure 6-1 provides a graphical representation of the processes by which increased deposited and suspended sediment inputs can influence various trophic levels of a river ecosystem to influence ecological states.

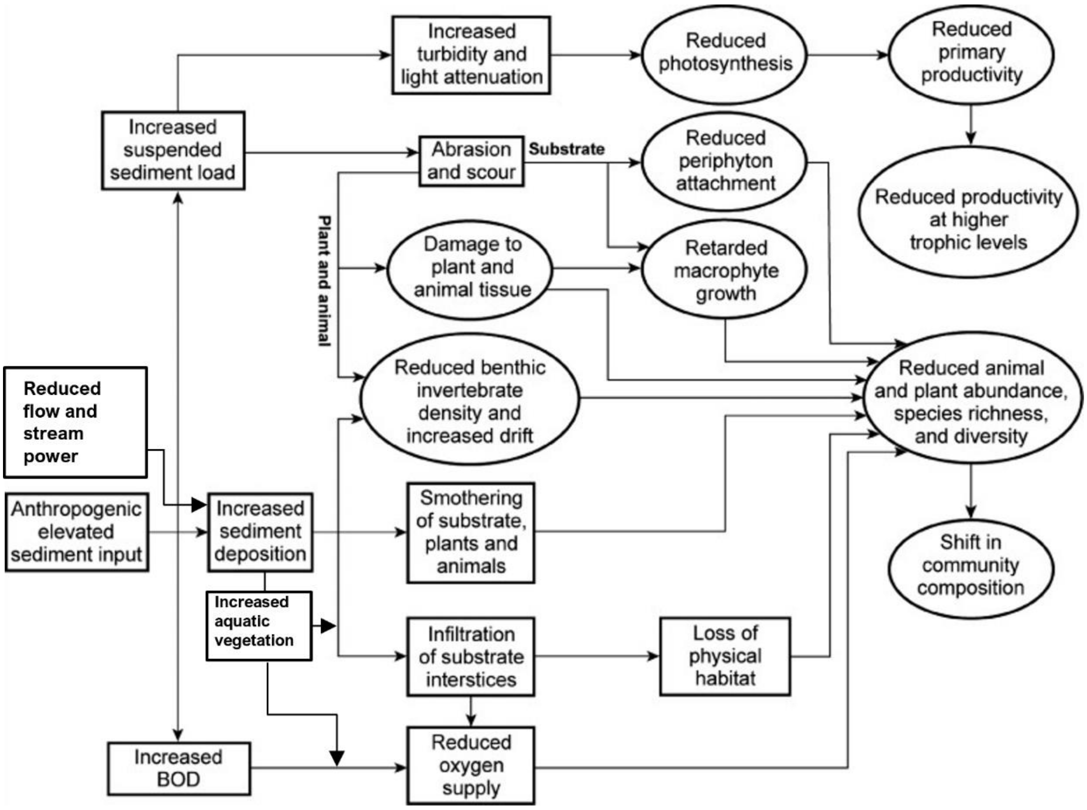

Figure 6-1: Negative impacts of anthropogenically enhanced sediment input to river aquatic systems on lower trophic levels; modified from Kemp et al. (2011). Rectangles and ovals respectively denote physicochemical effects and direct and long-term biological and ecological responses.

6.2 Interactions between fine sediment and aquatic vegetation

There is an inter-dependence between fine sediment and aquatic vegetation (macrophytes) because establishment of aquatic vegetation often requires patches of fine sediment, and there is a tendency for aquatic vegetation to trap fine sediments and therefore alter physical habitats (Clarke 2002). Transport and deposition of fine sediment is therefore often studied in tandem with aquatic vegetation in rivers.

Various studies have considered the role of aquatic and riparian vegetation in trapping finer sediments, building landforms, and influencing the morphodynamics of river channels (e.g., Corenblit et al. 2007; Gurnell et al. 2012). In this respect, aquatic vegetation in rivers can be viewed as acting like physical ecosystem engineers (Licci et al. 2019) but their effects are context-specific because macrophytes cannot establish in high-energy environments (Chambers et al. 1999; Jesson et al. 2000). Gurnell and Bertoldi (2022) stated that, in gravel bed rivers, the ability of vegetation to influence river geomorphology and physical habitat conditions depends on the retention and stabilisation of sand and finer sediments to build landforms within active river channels. Several authors have commented on the importance of patch size of vegetation in trapping fine sediment. Laboratory (e.g., Yamasaki et al. 2019) and numerical (e.g., Yamasaki et al. 2021) experiments have investigated the reinforcing feedbacks that are important in the relationship between sediment and macrophytes.

From a simple physical perspective, fine sediment is trapped and stored within stands of aquatic vegetation because of decreases in velocity and turbulent fluctuations associated with a blocking effect of aquatic vegetation (Zong and Nepf 2010). However, Wilkes et al. (2019) recognised many different situations may arise since particular plant types, materials and species are key to interactions between riparian vegetation and fluvial processes that result in sediment retention, with emergent and submerged aquatic macrophytes, dead and living deposited trees, tree fragments, and accumulations of fragments all acting to trap sediment.

Batalla and Vericat (2009) investigated the effectiveness of artificial flushing flows for removal of excess macrophytes in a large Mediterranean River in Spain. They indicated that artificial flow events can have different effects on sediment transport/suspension and removal of macrophytes compared to natural flow events because of their relatively high flashiness compared to a natural hydrograph. The work of Batalla and Vericat (2009), and similar studies downstream of dams, are relevant to high-flow harvesting because the same logic can be applied to reduction of natural flows resulting from water takes as that applied to design of artificial flushing flows delivered from dams on regulated rivers.

The role of invasive macrophytes species may be important for habitat and river ecosystem alteration, especially if acting in combination with changes in flow or sediment delivery regime (Hofstra et al. 2020). From an international perspective, the effects of invasive macrophyte species as ecosystem engineers in freshwater systems have been described as varied and often being context dependent, with effects of invasion on biodiversity or native ecosystems often shown to be negative (Emery-Butcher et al. 2020). However, not all effects associated with invasive macrophyte species are deleterious to native species. For instance, some invasive ecosystem engineers support native species through the provision of food or refuges (Schultz and Dibble 2012).

The detection, prevention, eradication, and control of invasive plants across various environments in New Zealand has received a great deal of attention (e.g., Fowler et al. 2000; Timmins and Braithwaite 2002; Ashraf et al. 2010; Champion 2018; Collins et al. 2019; Hulme 2020). Several studies have reported the effects of macrophyte invasions in New Zealand lakes. For example, Bickel and Closs (2008) reported on the effects on an invasive macrophyte on common bully in the littoral zone of Lake Dunstan, Otago. There appears to be less information on the effects of invasive macrophytes in New Zealand rivers and streams. However, see Mouton et al. (2019) for insights into relationships between macrophytes and physical disturbance, and Kankanamge et al. (2019) for a study of the establishment and colonization success of three non-native macrophyte species. The potential effect of high-flow harvesting is relevant to the establishment and colonisation success of native and non-native macrophytes because of the role of high flows in causing physical disturbance that removes macrophytes.

6.3 Fine sediment deposition on mesoscale habitat areas

In gravel bed rivers, fine sediments can be deposited within the voids between gravels (interstices) or on top of the gravel as surface deposition. Fine sediments can partially or fully fill interstitial spaces (hiding places for biota) in the gravel framework of riverbeds. If the volume of deposited fine material exceeds the storage capacity of the interstitial spaces, then fine sediment is deposited as surficial patches on the riverbed. A comprehensive review of the international literature by Wood and Armitage (1997) indicated that the causes and negative effects of increased deposited fine sediment on the physical environment and the flora and fauna in rivers is highly variable, reflecting the different sediment sources, types of sediment, and factors influencing fine sediment transport and deposition. Wood and Armitage (1997) also indicated that: a) although sedimentation is a naturally occurring process, land-use changes have resulted in an increase in anthropogenically-induced fine sediment deposition; and b) in addition to elevated inputs of sediment, increased deposition also occurs as a result of altered river flow regimes, for example due to water abstraction or impoundment.

Deposited fine sediment patches are highly mobile and are transported in intermittent suspension through a river system. They are the first materials to be entrained at the start of flood events (Vericat et al. 2008). Fine sediment deposition can span a range of particle sizes from clay and very fine silt to coarse sand and fine gravels. These sediments can be selectively transported from gravel riverbeds depending on the magnitude of river flow that translates to stream power, the rate and characteristics of sediment supply, macro-habitat characteristics (e.g., channel slope, pool-riffle morphology, etc), and micro-habitat characteristics (e.g., gravel grain sizes, degree of sorting, bed armouring etc).

Deposited fine sediment will lift into the water column when stream power increases above the entrainment threshold for a specific size of sediment. The magnitude and duration of floods are, therefore, important hydrological factors to flush fine sediments from riverbeds. In addition, the frequency and magnitude of flow events can play an important role in winnowing (removing) fine sediments away from patches with mixed sediment sizes (Mrokowska and Rowiński 2019).

Some mesoscale habitat morphologies (e.g., pools) are more vulnerable to fine sediment deposition in gravel bed rivers compared to others (e.g., riffles). Suspended sediments overpass immobilised gravel armours where shear stress remains locally high and are carried into low-shear stress zones where particles settle out and accumulate as fine patches (Wiele et al. 1996; Wilcock 1996; Lisle and Hilton 1999). Common observed mesoscale habitat morphologies are water behind cobbles, boulders and logs, voids of the bed framework of coarser gravel, pools, backwaters and embayments. Within braided gravel-bed rivers, river planform has a strong influence on mesoscale habitat morphologies and sediment deposition. High energy environments, such as main braids and riffles, experience very little fine sediment deposition compared to low energy environments, such as minor braids, backwaters, and pools.

Although the purpose of high-flow harvesting into offline storage may be similar to online storage by damming rivers, the effects on sediment and river morphology are different. Dams alter two critical elements of the geomorphic system; the ability of the river to transport sediment and the amount of sediment available for transport. Damming rivers therefore intercepts river sediment resulting in bed degradation and armouring (defined in Section 6.4) downstream (Grant et al. 2003). High-flow harvesting modifies the downstream flow regime, with a much smaller direct effect on sediment supply (although depending on the intake design it may trap and remove some sediment that may need to be periodically flushed back into the river channel). Nevertheless, methods developed to assess the effects of dams on downstream balance between sediment supply and transport capacity (e.g., Schmidt and Wilcock 2008) may be transferable to high-flow harvesting situations.

Many studies have been published in the international literature about river ecosystem responses to in-river dams that disrupt the timing of river flows and starve downstream reaches of sediment supply. The effects of starvation of sediment downstream of hydroelectric dams has been well studied in particular (e.g., Braatne et al. 2008; Kondolf et al. 2014; Mbaka and Wanjiru Mwaniki 2015). However, flow abstraction for hydroelectric generation can also occur at intakes where the water is transferred laterally within the same valley for eventual release downstream or to another valley; a situation similar to high-flow harvesting. Gabbud and Lane (2016) outlined key research questions relating to water take management to reduce downstream ecological impacts in alpine catchments. They commented on the potential ecological effects of water takes that often result in prolonged periods of reduced flows interrupted by artificial higher flow events needed to purge trapped sediment. Gabbud and Lane (2016) concluded that simply redesigning river flows to address sediment management will be ineffective because a natural sediment regime will not be restored, and other approaches are likely to be required if stream ecology in such systems is to be improved.

6.4 The effect of transport capacity on sediment deposition

By examining the effects of flow and sediment-regime changes on channel morphology, the relationships between the control variables (water discharge and sediment load) and the response variables (channel characteristics) can be explored. This information would also provide a basis for predicting the future evolution of river systems. Brandt (2000) anticipated river morphology changes due to changed input of water and sediment. Based on sediment load and transport capacity of rivers, reduction of water flow input from upstream would be expected to lead to three conditions.

1. With higher transport capacity than sediment load, some degradation may occur if the bed material is fine-grained, but it is also likely that reduced river flows are not able to erode and transport the material present before flow regime alteration. However, the finest material may still be available for transport, resulting in armouring; the surface becomes relatively coarser than the underlying material. In this condition, excess fine bed material is winnowed from high shear stress areas with immobilised gravel armours and both erosion and deposition occur in slow-flowing habitats.

2. In equilibrium conditions where sediment load carried matches the carrying capacity, degradation and armouring are not likely to occur, and deposition would be expected to increase in slow-flowing habitats.

3. By overloading of flow (i.e., sediment load exceeds transport capacity), increased deposition rates would be expected, both in-between river-bed gravel armours and within slow-flowing habitats. The locations where deposition would be expected to occur depends largely on the grain size of transported sediment.

6.5 Possible effects of flow regime changes on fine sediment deposition

Experimental flume studies on the effects of water diversion from small mountain streams has shown that floodwater extraction can cause deposition of fine sediment, and that increased extraction causes increased deposition (Parker et al. 2003). Hydraulic conductivity is expected to reduce with increases in river flow takes due to substrate clogging (Schälchli 1992). Significant increase in the abundance of fine sediment patches were observed by Baker et al. (2011) for reaches below diversion structures as compared to geomorphologically similar reference reaches within a study of 13 streams of the Rocky Mountains, USA. Baker et al. (2011) reported that diverted reaches had significantly more slow-zone habitats compared to non-diverted reference reaches. Wang et al. (2007) predicted that sediment deposition would develop along the whole reach, in the long term, downstream of large water diversions in the Lower Yellow River, China. Wang and Xu (2016) found increase sediment deposition downstream of the Mississippi River diversion.

Analysis of paired reaches upstream and downstream of diversion dams on small mountain streams in the United States found that reaches downstream of diversions do contain significantly more fine sediment (Baker et al. 2011). Whilst these studies of small streams demonstrate that floodwater diversion causes fine sediment deposition, the diversions investigated represent a very significant proportion of flood flow. For example, Parker et al. (2003) simulated diversions extracting all flow above 30% of bankfull flow up to a high-flow cut-off ranging from 60% to 100% of bankfull.

Several studies have investigated the interactions between diversions and downstream stream gradient on fine sediment depositions, but with different findings between studies. For example, Ryan (1997) found that low-gradient channel segments exhibit statistically significant geomorphic changes in response to diversions compared to higher gradient channels by studying diversion systems of the subalpine environment of Colorado. Wesche et al. (1988) found that low gradient channels (<1.5%) were susceptible to fine sediment deposition but steeper rivers were not. Similar results were found by Baker et al. (2011), who reported significantly higher fine sediment in channels with <3% slope and no significant differences for steeper channels (>3%). However, Bohn and King (2000) found no correlation between stream gradient and sediment deposition change.

6.6 Mechanisms for flow abstraction effects on fine sediment deposition

Water withdrawal for irrigation, particularly for high-flow harvesting, reduces river flow. In situations where sediment concentration is equal between river water and abstracted water, flow abstraction will decrease shear stress in downstream river reaches without changing sediment concentration. Shear stress during the recession of floods and freshes will approach the critical shear stress value for deposition of a range of fine sediment sizes (fine gravel to fine silt) under artificially reduced river flows in comparison with the flow without diversion. This will increase the likelihood of sediment deposition downstream of the water abstraction site.

In theory, deposited fine sediments should have a slightly coarser particle size distribution compared to depositions above diversions (Figure 6-2). This is because the critical flow for deposition of coarser fine sediments (i.e., coarse sand and fine gravel) is higher than for finer materials, and reduction of flow during periods of elevated suspended sediment concentration will increase the likelihood of their settling on the riverbed. This mechanism of deposition below diversions is more significant in braided rivers compared to single channel rivers because braided channels have more slow-flowing habitat areas such as pools, littoral zones, backwaters and embayments, especially in side-braids, which were once large main braids but due to the channel shifts their inflows were reduced.

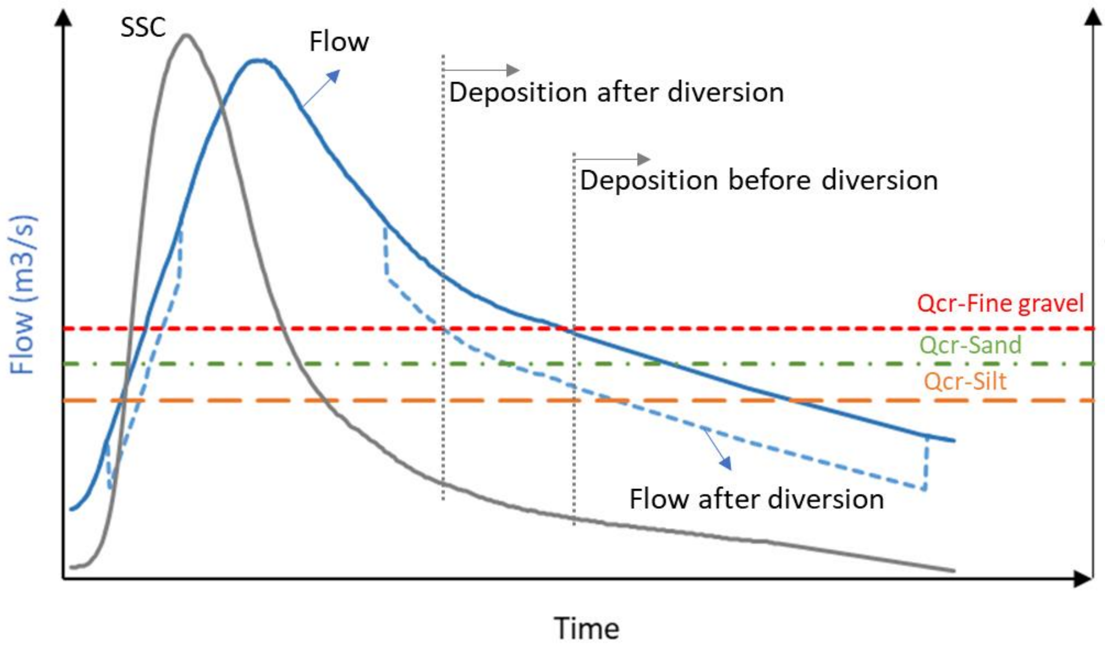

Figure 6-2: Schematic plot showing idealised mechanisms of fine sediment deposition during recession of flow for different particle sizes. Colour coded dashed-lines show critical flow (Qcr) for particles with different sizes. Vertical dashed-lines indicate start of deposition in reaches after and before flow diversion.

One aspect that is missing from previous studies that have focused on the effects of diversions on downstream channel morphology and sediment deposition is the importance of hysteresis patterns between flow and suspended sediment concentration upstream of water abstraction. Since fine sediment deposition occurs during floods with relatively high sediment concentrations late during event recessions (Lisle and Hilton 1999; Park and Hunt 2018), the shape and direction of sediment rating curves can affect the availability of fine sediments during flow recessions. Generally, lower mass of sediment is available during flow recessions in clockwise patterns. Whereas in anticlockwise events, the river carries more significant concentrations of suspended sediment in the falling part of the event that results in increased rates of fine sediment settling onto the riverbed. See Haddadchi and Hicks (2021) for more information on how the hysteresis relationship between suspended sediment concentration and river flow during runoff events relates to event hydrology and catchment characteristics. Analysis of hydrological and sediment-related variables collected from 17 catchments across New Zealand by Haddadchi and Hicks (2021) showed that the main variables controlling the hysteresis patterns within each catchment were flood total runoff and flood duration.

Figure 6-3 shows two example events with similar total discharge-weighted sediment concentration relationships during flood events, but clockwise and anticlockwise hysteresis patterns between flow and suspended sediment concentration. In this hypothetical example, water take was 15 $m^3 s^{-1}$ when river flow was between 40 and 100 $m^3 s^{-1}$. Critical flow for fine sediment entrainment was considered as 60 $m^3 s^{-1}$. For anticlockwise hysteresis, deposited fine sediments during the recession increased by 2.2 times after flow diversion, whereas for clockwise hysteresis, sediment load after diversion increased by 1.9 times.

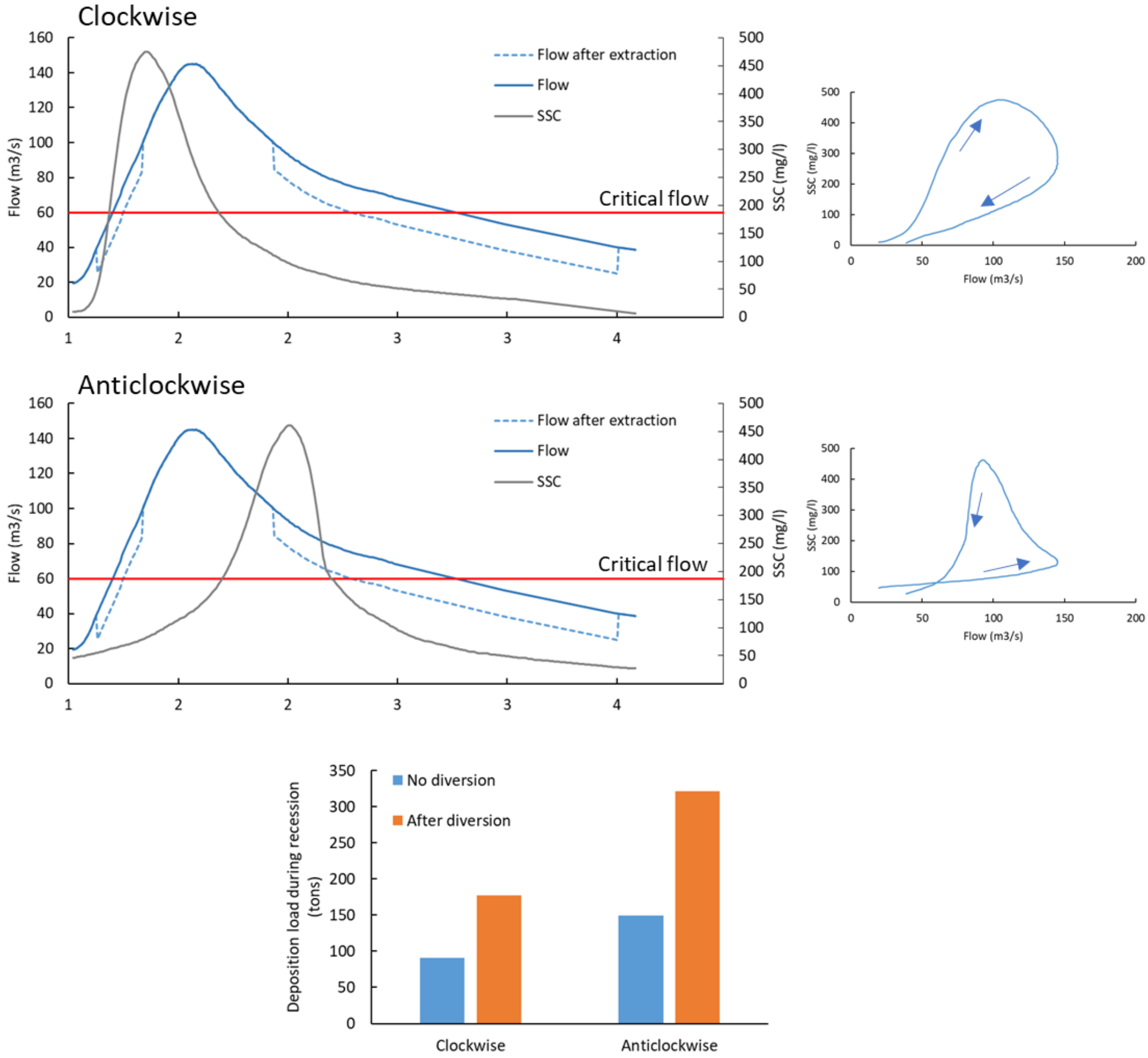

Figure 6-3: The effect of flow-SSC hysteresis pattern on fine sediment deposition after flow diversion. Dashed blue line indicate flow downstream of water intake. Redline shows hypothetical critical flow for fine sediment entrainment (Qcr =60 m^3/s). Arrows in sediment rating curves indicate direction through time.

6.7 Sediment summary

The transport of suspended sediment, and the balance between sediment deposition and entrainment are conditioned by a complex interaction between sediment supply, local channel characteristics, aquatic vegetation, and river flow. Fine sediment retention and storage by aquatic vegetation is potentially an important component of within-channel sediment processes and budgets as well as contributing to the hydrological, geomorphological, and ecological functioning of rivers. The timing and magnitude of high-to-mid range flows are an important input that drives sediment dynamics and disturbance of aquatic vegetation. Changes to the frequency, magnitude, and duration of high-to-mid range flows, which could result from large-scale high-flow harvesting, should be accompanied by an assessment of effects on suspended sediment, deposited fine sediment, and disturbance regime for aquatic vegetation.

7 Riparian vegetation

7.1 The importance of riparian vegetation for river geomorphology and ecosystems

Plants and trees that grow along the margins and banks of rivers, lakes and wetlands are collectively referred to as riparian vegetation. Riparian vegetation consists of diverse and dynamic plant communities that play an important role within the aquatic environment and their biotic communities (such as aquatic plants, fish and invertebrates) providing organic matter and energy, habitat, spawning, and nursery areas (Aguiar et al. 2018). The riparian system is disproportionately plant species-rich compared to surrounding ecosystems because it is located in the transition zone between land and water ecosystems (Nilsson and Svedmark 2002).

Riparian vegetation is beneficial to river ecosystems by providing habitat diversity (Richardson et al. 2007) and supporting ecological diversity (Sabo et al. 2005), but negative effects and control of nuisance vegetation can also be problematic in some situations (Gran et al. 2015). The issue of nuisance vegetation is often complicated by the presence of invasive plant species that outcompete native species to colonise disturbed environments and therefore alter channel morphology. For example, riparian vegetation in many braided river floodplains and catchments disturbed by human activities includes invasive plant species that may constitute a large proportion of the vegetative cover and threaten ecological integrity within these ecosystems (Shafroth et al. 2002; Caruso 2006).

Several New Zealand studies on riparian vegetation have been motivated by attempts to restore vegetation because clearance of native vegetation and development for intensive land uses has degraded the water quality and ecological health of many New Zealand streams (Larned et al. 2016). For example, McKergow et al. (2016) describe tools for the restoration of riparian planting.

7.2 Effects of high-flow harvesting on riparian plant community

Many riparian plant species are adapted to the unique timing, magnitude, and duration of the natural flow regimes within their natural habitats, implying that changes in flooding disturbance and water availability can lead to decreased suitability of habitat and increase susceptibility to invasion by upland and/or exotic species (Bunn and Arthington 2002; Naiman et al. 2005). Thus, changes to flow regimes have the potential to directly alter riparian vegetation through changes in water availability, changes in fine sediment deposition that influence plant establishment (see Sections 5 and 6 above), and by changes in physical disturbance that influence plant removal (Stecca et al. 2022).

The potential role of altered flow regimes in influencing vegetation, and therefore physical habitat and river ecosystems, is shown in Figure 7-1. However, vegetation changes on hydrologically altered river reaches are known to vary between sites depending on the extent of flow regime changes that range from almost permanent stream dewatering on reaches affected by stream diversion and groundwater pumping, to altered timing, frequency, and magnitude of flood flows on reaches downstream of flow-regulating dams (Stromberg et al. 2007). Caskey et al. (2015) stated that results have been mixed among the studies that have examined the effects of river flow diversions on riparian vegetation in the USA. Some studies have found effects in the form of reduced tree growth rates, reduced stomatal conductance and water potential, or reduced stem diameters downstream from diversions, whereas others have not observed effects from diversions. Caskey et al. (2015) also stated that channel morphology and riparian plant communities along low gradient reaches in montane environments in the Colorado Rocky Mountains were influenced by flow diversions, with the net effect of simplifying and narrowing the channel and decreasing riparian diversity and creating a shift towards terrestrial riparian plant communities.

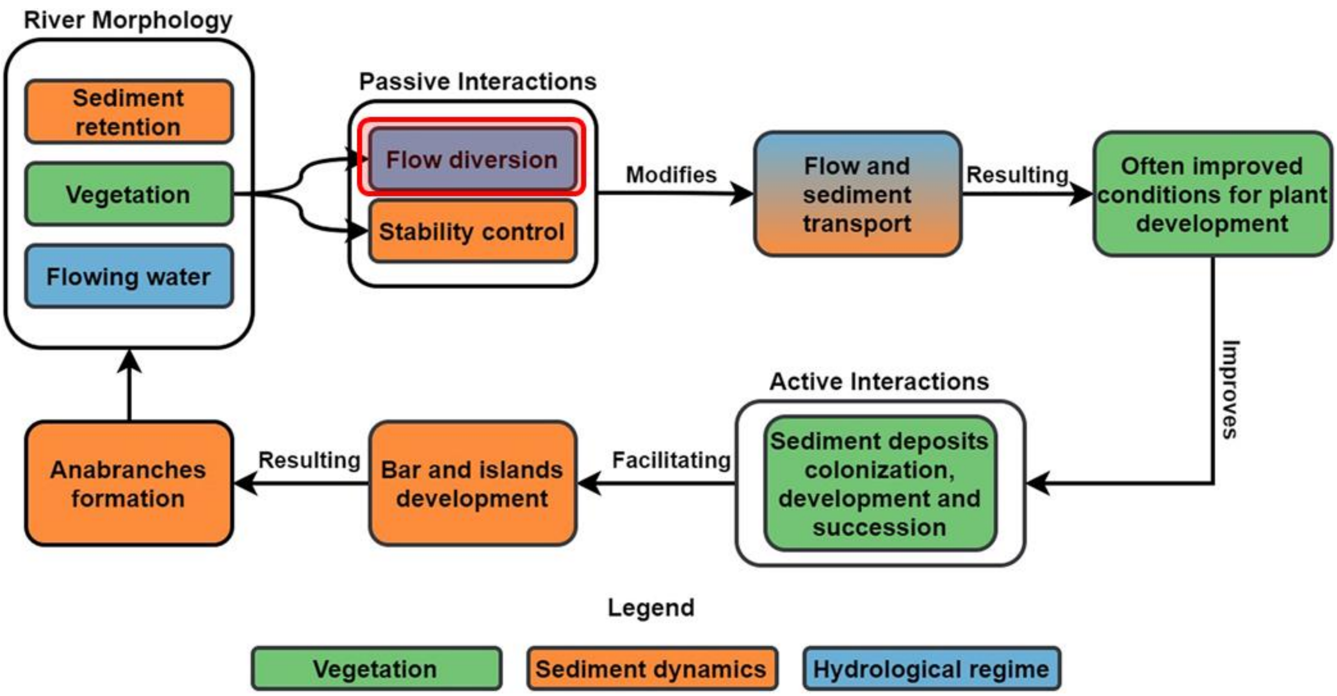

Figure 7-1: Schematic diagram summarising vegetation feedback and its possible interruption as a result of flow diversion affecting river morphology for anabranching river channels after Henriques et al. (2022). Flow diversion is highlighted in red to indicate potential influence of high-flow harvesting.

The importance of high flows for vegetation dynamics was demonstrated by Caruso et al. (2013) for the Ahuriri River in Canterbury where the invasive species crack willow (*Salix fragilis*), Russell lupin (*Lupinus polyphyllus*), gorse (*Ulex europaeus*), broom (*Cytisus scoparius*) and sweet briar (*Rosa rubiginosa*) are of concern (see Caruso 2006 for further details). Historical aerial photographs and long-term flow records show that the flow regime, including flood and high flow pulses, has variable effects on floodplain invasive vegetation, and creates dynamic patch mosaics that demonstrate the concepts of a shifting mosaic steady state and biogeomorphic succession. Table 1 from Caruso et al. (2013) provides a rationale for relating several particular components of the flow regime to riparian plants and their habitats. Overall, their results indicated that peak magnitude of the largest flood, flood frequency, and time since the last flood were correlated with vegetation cover. Caruso et al. (2013) also noted that “as long as seed and propagule sources exist in upstream catchments and tributaries, the natural flow regime and floods will not remove significant amounts of invasive vegetation over the long term, human control of vegetation will continue to be needed as part of management schemes and restoration of braided rivers will be a great challenge.”

River flow time-series data are sometimes not available at the site of a proposed flow alteration (e.g., a high-flow harvesting scheme) yet assessments of hydrological alteration are required to assess potential effects on riparian vegetation. Kondolf et al. (1987) proposed four possible methods for collecting relevant hydrologic data to inform potential impacts on riparian vegetation. The four methods described were: (a) preparing geomorphic maps from aerial photographs, (b) using groundwater level records to evaluate the influence of river flow on the riparian water table, (c) taking spot flow measurements to identify gaining and losing reaches, and (d) analysing river flow time-series from nearby gauges to document seasonal variations in downstream flow losses. It should be noted that these four methods are still relevant with low level remote sensing from drones (Ashraf et al. 2010; Entwistle et al. 2018) and publicly available data (Boothroyd et al. 2021) improving geomorphic mapping capabilities.

7.3 Knock-on effects of changes in riparian vegetation

Riparian vegetation is known to have a complex and interactive relationship with river geomorphology that is mediated by river flow regimes, sediment supply and local topography (Corenblit et al. 2015). Vegetation colonisation of the riverbed, bars, and banks can have a strong stabilising effect on river morphology (Gabbud and Lane 2016; Corenblit et al. 2020). See Section 5 for more details of geomorphology, but we note here that vegetation can have a significant role in modifying or controlling river geomorphology, physical habitat provision, and water quality in various types of rivers through provision of a stabilising effect, for example:

- riparian vegetation has an important effect on riverbank erosion and stability (Thorne 1990) in single channel rivers that are characterised by distinctive banks that may migrate laterally, but within which an active river channel persists
- riparian vegetation stabilises islands in anabranching rivers that are characterised by multiple channels where flow diverges around alluvial islands that can persist for relatively long period of time because they stand approximately at the same elevation as the adjacent floodplain and have banks that are resistant to erosion and capable of supporting mature vegetation (Nanson and Knighton 1996; Henriques et al. 2022)
- riparian vegetation is often relatively free from the active channel of braided rivers that are characterised by a dynamic network of river channels separated by small, often temporary, islands called braid bars (Hicks et al. 2021). However, vegetation on the outer banks of braided channels, as well as the removal and encroachment or vegetation on braid bars (Gurnell et al. 2001) means that vegetation plays a fundamental role in structuring, determining, and maintaining patterns of braided rivers (Räpple et al. 2017).

7.4 Riparian vegetation summary

There is a strongly interacting relationship between riparian vegetation and river geomorphology that is generally characterised by positive feedbacks between increased fine sediment deposition, increased vegetation growth, and increased sediment stability regardless of geomorphological setting. Reductions in the magnitude or frequency of high flows can be associated with an increased likelihood of changes in composition of riparian vegetation accompanied by an alteration of river channel morphology. However, although methods for modelling changes in riparian vegetation resulting from flow alteration at catchment (e.g., Gilbert and Wilcox 2021) and reach scales are available or are under development (e.g., Stecca et al. 2022), precise prediction of the consequence of high-flow harvesting on riparian vegetation (and therefore river channel geomorphology) remains challenging.

8 Periphyton

Periphyton is the green to brown or black slimy growth found on stable substrates in fresh waters. It comprises mainly algae (such as filamentous algae of various types, many species of diatoms that form mats and or filaments, and cyanobacteria), but also includes fungi, bacteria, and other non-photosynthetic micro-organisms. Periphyton accounts for most primary production in hard-bottom (gravel-bed) rivers and, as a key food resource for many grazing macroinvertebrates (Alvarez and Peckarsky 2005), is an essential part of river ecosystems. However, excessive periphyton can lead to ecosystem impairment.[1] The levels and types of periphyton considered problematic are defined in international and national guidelines (Suplee et al. 2009; Ministry for the Environment 2020).

8.1 Direct effects of high-flow harvesting on periphyton

The standing crop or biomass of periphyton at a site is usually measured as concentration of chlorophyll *a* per unit area of bed because all types of algae contain this photosynthetic pigment. Time series of periphyton biomass observations (e.g., monthly observations over multiple years) at most sites show exponential distributions: most observations have relatively low values and a few have high values (Snelder et al. 2014). The highest (peak) biomass recorded over time typically approximate a river's carrying capacity for periphyton (e.g., Biggs et al. 1998), which becomes a problem when carrying capacity exceeds guidelines.

A primary controller of a river's carrying capacity for periphyton biomass is time available for biomass accrual. Most accrual occurs when river flows are stable and low or receding, and the rate of accrual is determined by the combination of algal cell growth and biomass losses. Algal growth rates are influenced by factors such as nutrient supply, light and suitable temperature (Biggs 1996). Simultaneous biomass loss processes – such as grazing by macroinvertebrates (Sturt et al. 2011), and spontaneous sloughing of thick algal mats (Biggs and Stokseth 1996; Hayward 2003; Boulêtreau et al. 2006) – slow down accrual rates. In addition, as periphyton biomass accrues, its composition typically changes from fast-colonising, small, attached diatoms to thicker mats dominated by larger diatoms and other algal taxa and eventually (in suitable enrichment conditions) to communities dominated by filamentous algae (e.g., Hayward 2003; Suren et al. 2003b).

The durations of accrual periods are driven by the frequency of floods large enough to remove periphyton to low levels (Biggs 1995; Biggs 2000). High-flow harvesting – which, by definition, reduces the size of high-flow events – therefore directly affects periphyton by changing the magnitudes of the flow events that would normally remove periphyton and therefore define accrual periods.

The processes responsible for removal of periphyton biomass during high-flow events fall into three categories.

1. Drag: high water velocities tear algae from their attachments to substrate, or cause algae fragments to be detached from larger algal growths.
2. Abrasion: periphyton accumulations are worn off substrata by the action of mobilised sediment particles such as sand or fine gravel.

[1] Examples of impairment are: changes to macroinvertebrate habitat (e.g., from proliferations of filamentous algae) that favour low-quality, more tolerant taxa; and low night-time DO that is harmful to fish. In addition, high biomass can make rivers unattractive or unsuitable for recreational activities such as swimming or angling.

3. Molar action: substrata on which periphyton grow are mobilised and the tumbling action scours off algae (Hoyle et al. 2017).

Drag processes remove least periphyton, although the effect depends on the type of periphyton present (Biggs and Thomsen 1995; Hart et al. 2013). Abrasion typically causes periphyton to be removed to a relatively low biomass in many rivers (Hoyle et al. 2017). Molar action generally removes almost all periphyton (Biggs et al. 1999).

Reducing the magnitude of high-flow events during high-flow harvesting may shift the periphyton removal mechanism associated with those high flows to one that is less effective (e.g., from abrasion to drag), leaving more residual periphyton to start the next accrual period. The abundance and composition of residual periphyton then contributes to the way in which periphyton continues to accrue and may lead to periphyton communities different from those that would have developed under 'normal' accrual. In other words, the site's carrying capacity for periphyton may be altered. Differences may be evident in both biomass and community composition. Contrasting effects on periphyton communities, depending on the type of periphyton removal, have been demonstrated experimentally (Francoeur and Biggs 2006; Davie et al. 2012).

High-flow events are often quantified in multiples of the median flow, which is a useful way to compare flood magnitudes across rivers of different sizes (Booker 2013). For example, the annual frequency of events greater than three times the median flow (FRE3) has been identified as an important metric for representing flow variability in flow – periphyton relationships (Clausen and Biggs 1997) and for defining periphyton accrual periods (Biggs 2000). Nevertheless, analyses of multi-year datasets of periphyton biomass (monthly observations of chlorophyll *a*) against preceding flows have shown that the magnitude of high-flow events capable of removing periphyton to low levels (hereafter periphyton removal flows, PRF) varies across rivers (Kilroy and Stoffels 2019). Variation of PRF across sites is associated with site-specific sediment entrainment characteristics (Hoyle et al. 2017). Consequently, PRF are expected to be predictable at sites where sediment entrainment characteristics can be estimated (Haddadchi et al. 2020).

Site-specific PRF can range between 2 × and at least 15 × median flow (e.g., Kilroy et al. 2020). If high-flow harvesting occurs above flow thresholds substantially higher than the PRF estimated for a site, then the effect on periphyton removal could be negligible because the residual flow events will still remove biomass. High-flow harvesting from events above thresholds that are lower than the PRF is expected to have larger effects because the residual events will be less effective.

Assessments of expected effects of high-flow harvesting have been made as part of resource consent proceedings. For example, long records of simulated and recorded flows for the Lower Waiau River, Southland, have been compared to examine the effects of a proposed increase to the maximum allowable discharge from the Manapōuri Power Station. The flow analysis identified that about one high-flow event every four years, on average, would be reduced so that the accrual period for periphyton was increased. In that case the flow reduction expected to make a difference was determined based on existing data on periphyton and flows. However, documented examples of the *actual* effects of high-flow harvesting on periphyton appear to be rare to non-existent.

8.2 Indirect effects of high-flow harvesting on periphyton

Changes to the magnitudes of high-flow events have direct effects on other parts of the river ecosystem, including river geomorphology (see Section 5.3) and bed substrate composition (see Section 6.5), and macroinvertebrate communities (see Section 9.2). The effects of high-flow harvesting on these other ecosystem components may also have consequences for periphyton. Such consequences will occur in tandem with the more direct effects described above.

River morphology (including bed substrate composition) constantly adjusts in response to the water and sediment supplied from upstream (Wilcock 1997). It therefore follows that consistent reductions of the magnitudes and durations of peak flows can alter this channel-forming process (see Section 5.3), with one potential outcome being gradual changes in substrate composition. Changes in bed substrate composition can affect periphyton because, even in stable flows (i.e., independently of the effect of bed substrate composition on periphyton removal), development of periphyton biomass and community composition is influenced by the type and size of substrate present because the mixture of bed particles present at any site defines the highly variable three-dimensional environment in which algal taxa colonise and grow (Murdock and Dodds 2007). Both periphyton biomass and community composition vary according to rock type (e.g., roughness; Bergey et al. 2010) and particle size. Bed particle size (ranging from sand or silt to boulders) explained a high proportion of the variability in periphyton species composition in stable spring-fed streams (Cantonati and Spitale 2009); and larger bed particles tend to accumulate higher periphyton biomass (per unit area) than smaller substrate (Ledger and Hildrew 1998). At the same time, when bed substrate composition at a site changes in response to flow alteration, the composition shift may also alter the magnitude of the PRF operating at that site (Haddadchi et al. 2020).

Interactions between macroinvertebrates and periphyton are complex and include both top-down effects (e.g., macroinvertebrates reduce periphyton biomass through grazing (Liess and Hillebrand 2004)) and bottom-up effects (e.g., periphyton proliferations driven by extended accrual periods alter macroinvertebrate habitat, leading to shifts in macroinvertebrate community composition from high quality taxa to lower quality taxa (Suren et al. 2003a)). As discussed in Section 9.1, high-flow harvesting may directly affect macroinvertebrate communities by reducing the negative effects of high-flow events on macroinvertebrate density and diversity. Combined with possible reduction of the ability of the same (reduced magnitude) flow events to remove periphyton, the net effect could be both increased residual periphyton biomass and larger residual macroinvertebrate populations.

The ongoing consequences for periphyton of simultaneous effects of high-flow reductions on macroinvertebrates depend on multiple factors (Figure 9-1) and are difficult to predict. For example, one scenario might be that higher-than-expected residual macroinvertebrate populations following a high flow could subsequently exert correspondingly higher-than-expected grazing pressure on accruing periphyton, slowing accrual and leading to lower periphyton biomass carrying capacity at the site. This scenario assumes that the residual periphyton comprises generally early succession diatoms, which are favoured by macroinvertebrate grazers (Fenoglio et al. 2020). An alternative scenario is that when residual periphyton is dominated by taxa that provide a lower quality food resource (e.g., filamentous algae) but favourable habitat for many filter-feeding macroinvertebrates rather than grazers (Tonkin et al. 2014) then the top-down effect of grazing will be reduced, and periphyton biomass carrying capacity may increase.

8.3 Periphyton summary

In practice, because of the complex factors that influence periphyton standing crop (as biomass or community composition), demonstrating effects on periphyton of high-flow harvesting in isolation is likely to be difficult. Nevertheless, as discussed above, there is clear potential for both direct effects via changes to the magnitude of high flows that remove periphyton and indirect effects via the effects of reduced flow magnitudes on river-bed geomorphology and on macroinvertebrate communities, which themselves independently influence both periphyton biomass and community composition.

9 Macroinvertebrates

New Zealand has over 280 species of freshwater macroinvertebrates that live on or under the plants, stones, wood, or debris in our waterways. These animals include insects such as mayflies, stoneflies and caddisflies, crustaceans including amphipods, ostracods, and freshwater crayfish (kōura or kēwai), molluscs such as snails and freshwater mussels (kākahi, kāeo or torewai), and various types of worms.

Freshwater macroinvertebrates are important components of river ecosystems as they provide food for animals such as fish, birds, spiders, and lizards that forage within the river or adjacent to it (Baxter et al. 2005; McIntosh et al. 2016), they consume and can sometimes reduce periphyton biomass (Alvarez and Peckarsky 2005), and contribute to ecosystem services such as nutrient recycling by processing organic matter.

9.1 Direct effects of high-flow harvesting on macroinvertebrates

High-flow events directly impact macroinvertebrate communities by causing mortality to individuals, generally though movement of the bed substrate or abrasion by suspended sediment rather than the increase in flow itself (Figure 9-1; Townsend et al. 1997b). However, increases in water velocity and suspended sediment load during floods can also cause invertebrates to either passively or actively enter the water column and drift downstream (Statzner 2008; Hayes et al. 2019). Likewise, reduced river flows can limit the distance that individual invertebrates can travel downstream (James et al. 2009). Changes in flow or associated pulses of sediment may also provide cues that cause benthic invertebrates to seek refuges or undergo metamorphosis and emerge as aerial adults (Lytle and Poff 2004; Gibbins et al. 2005). Through a combination of these mechanisms, high-flow events often lead to temporary declines in the density and diversity of macroinvertebrates (Sagar 1986; Lake 2000; Collier and Quinn 2003; McMullen and Lytle 2012).

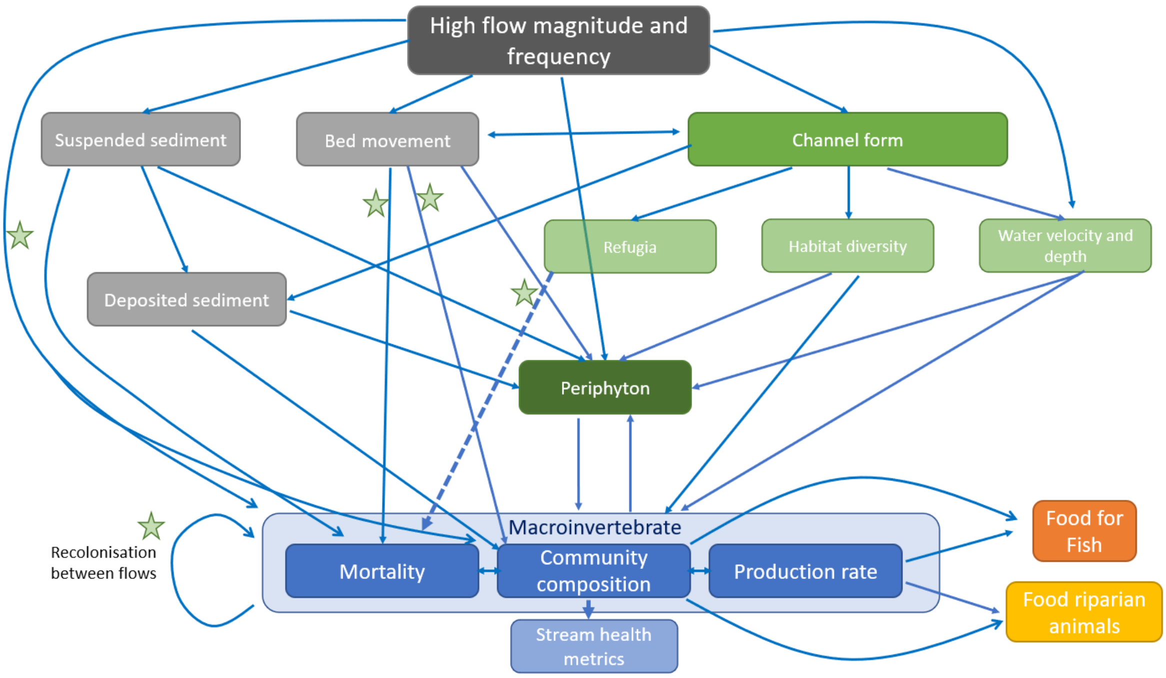

Figure 9-1: Summary diagram of potential influences of high river flows on macroinvertebrates. Green stars indicate pathways which may be mediated by the presence of refugia.

The influence of flow fluctuations on macroinvertebrate communities are not only dependent on the removal or mortality of individuals, but on re-colonisation and community recovery during periods between spates. Recovery rates are often rapid, particularly in depauperate communities, as individuals recolonise from local sources within the river, with those with good dispersal abilities returning first, tracking the availability of different food resources (Mackay 1992; Lepori and Malmqvist 2007). However, recovery time depends on the intensity of the disturbance to the macroinvertebrate community (Lake 2000), the flood history of the site (Lytle 2001), the in-stream habitat (McMullen and Lytle 2012), the rate of food accumulation as well as macroinvertebrates' rates and modes of dispersal (e.g., from refuges within the river or via oviposition from aerial adults), diversity before the high-flow event (recovery is likely faster for depauperate communities than for diverse communities) and the abundance of individuals that survived (Death 2008). Recovery periods following moderate flow events (i.e., partial bed mobilisation) in some New Zealand rivers have ranged from days (Melo et al. 2003) to several months (e.g., Matthaei and Townsend 2000).

The length of time between high-flow events, or time available for recovery, has been shown to significantly impact macroinvertebrate diversity, abundance, and several aspects of community composition within a river during an analysis of long-term monitoring data of more than 60 rivers in New Zealand (Greenwood and Booker 2015). Likewise, the magnitude and timing of recent high-flow events are commonly identified hydrological drivers of differences in community composition between rivers (Robinson et al. 1992; Death and Winterbourn 1995). Rivers with different hydrological regimes often have different macroinvertebrate communities due to velocity, depth and substrate preferences of individual taxa (Shearer et al. 2015; Greenwood et al. 2016), and the traits of these communities to persist during a high-flow event and recolonise afterwards (Mackay 1992). Rivers with repeated high-flow events, particularly flows that cause bed movement, often have more depauperate macroinvertebrate communities than rivers that rarely (Death and Winterbourn 1995; Lake 2000) or periodically (Townsend et al. 1997a) experience high-flow events. Rivers that flood often tend to contain macroinvertebrates with life histories or traits that increase their ability to resist flow disturbances or rapidly recolonise afterwards (Scrimgeour 1991; Mackay 1992; Scarsbrook 2002), such as high adult mobility (i.e., flying adults) and flattened or dome-like shaped larvae (Townsend et al. 1997b).

Flow regime-induced changes to macroinvertebrate community composition may influence higher trophic levels. Taxa that recolonise quickly after a disturbance can be less protected and more edible to in-stream consumers than later colonising taxa due to life-history trade-off (Elger et al. 2004). For example, Greenwood and Booker (2015) observed significant changes to the proportion of individuals that were protected by a case, shell or hardened elytra over time since a flood event , indicating that changes to the timing or frequency of floods could impact higher trophic levels, such as fish, by altering the edibility of potential prey. A controlled flood in a regulated section of the Colorado River significantly reduced aquatic invertebrate biomass but increased production of rainbow trout by almost 200%, likely because the aquatic invertebrate community shifted from dominance by snails to more digestible dipteran larvae (Cross et al. 2011). Many riparian consumers feed on adult aquatic insects in the terrestrial environment (Baxter et al. 2005) and the flow regime-induced changes to the abundance, size or flight behaviour of taxa with winged adults observed by Greenwood and Booker (2016) may also alter the availability of an important food resource to terrestrial predators.

9.2 Indirect effects of high-flow harvesting on macroinvertebrates

High river flows also impact macroinvertebrate communities through indirect effects (Figure 9-1). For example, river flow is a major determinant of physical habitat in rivers, which in turn influences macroinvertebrate community composition (Bunn and Arthington 2002). The river flow regime influences the channel form (See Section 5). Changes to channel form alter spatial patterns of water depth, velocity, and bed substrate, which affects habitat suitability for different macroinvertebrate taxa (Shearer et al. 2015; Greenwood et al. 2016). More diverse physical habitat i.e., riffles, pools, runs, and a varied substrate, often results in a higher diversity of macroinvertebrates across a reach (Gray and Harding 2009). Channel form and bed substrate composition also influence the magnitude of flows that mobilise bed substrate (Haddadchi et al. 2020) and the presence of refugia from high-flow events such as a connected hyperheos, pools or backwaters that do not flood, or interstices between large stable substrate. These refuges reduce mortality and can aid rapid recolonisation and recovery after high-flow events (Scrimgeour et al. 1988). At a larger scale, the proximity of more distant refugia (e.g., drift downstream from unimpacted areas or aerial dispersal from disconnected floodplain habitats) can provide sources of long-distance colonists (Townsend et al. 1997a). Multiple studies have found that the influence of flow variability and floods on macroinvertebrate communities is influenced by the physical habitat as well as overall hydrological regime of a river (e.g., Monk et al. 2008; Dunbar et al. 2010; McMullen and Lytle 2012).

High-flow events can indirectly impact macroinvertebrates by altering the composition and abundance of food resources, such as periphyton. Periphyton composition and biomass are commonly influenced by the length of time between floods of a magnitude that remove or scour the periphyton, as this affects the length of time to accrue or grow between floods (see Section 8.1). Invertebrate community composition can be altered by algal biomass and composition as it is an important food resource for many invertebrates (Lawrence et al. 2002). Likewise, excess periphyton growth, such as the development of thick mats, can smother habitat for macroinvertebrates and alter their community composition (Hart et al. 2013). Therefore, changes to the river flow regime that alter the composition and biomass of periphyton may influence macroinvertebrate community composition. In return, grazing by macroinvertebrates can also alter periphyton composition and occasionally reduce biomass. Complex relationships between river flow, channel form and periphyton and macroinvertebrate composition and biomass or abundance are likely.

Spatial and temporal patterns in riverine macroinvertebrate diversity, abundance and biomass are influenced by high-flow events through multiple mechanisms both directly and indirectly. Many of the impacts on macroinvertebrates depend on how and whether flow events alter the geomorphology of the river and thus bed mobility during spates, physical habitat suitability and presence of refugia. Some broad predictions of community compositional changes are possible based on habitat preferences of different taxa and previous studies, for example reductions in flood magnitude or timing can result in increased periphyton biomass, if light and nutrients are not limiting, and lead to macroinvertebrate communities being dominated by taxa such as snails (Suren et al. 2003a). However, developing generalised flow-macroinvertebrate community relationships to predict ecological responses to flow alteration is challenging (Poff and Zimmerman 2010; Webb et al. 2013). Identifying the impacts of high river flows on macroinvertebrates is difficult, often due to a lack of long-term paired hydrological and macroinvertebrate data sets over a broad spatial range, as well as appropriate measures of potential disturbance to macroinvertebrates, such as the frequency and degree of movement of bed substrate.

Macroinvertebrate communities are influenced by many factors, including river hydrology. Changes in macroinvertebrate community composition have been used to investigate the effects of alterations to the hydrological regime, such as artificially reduced flows below dams (Rehn 2009), increased discharge due to flow restoration (Merigoux et al. 2015) and the effects of flow intermittence (Arscott et al. 2010). However, comparing changes in community composition between sites and communicating the relevance of this to environmental change can be challenging. To summarise macroinvertebrate community change in response to different stressors, many univariate metrics have been designed and are commonly used worldwide. Macroinvertebrates make good indicators of environmental change as they occur in almost all waterways, are affected by local conditions such as water quality, often have relatively well defined taxonomy and ecological preferences and provide a longer-term view of in-stream conditions than variables such as water chemistry (Boothroyd and Stark 2000).

In New Zealand, macroinvertebrate metrics are compulsory ecosystem health attributes that must be monitored by councils under the NPS-FM 2020 (Ministry for the Environment 2020) for national reporting. One of the required metrics is the Macroinvertebrate Community Index (MCI), which is based on the presence and absence of over 280 taxa that have been assigned tolerance values according to their perceived tolerance to organic pollution (Stark and Maxted 2007; Clapcott et al. 2017).

Macroinvertebrate-based metrics that are designed to respond to hydrological changes have been created in Europe, North America and Australia (e.g., Extence et al. 1999; Chessman et al. 2022) and in New Zealand (Greenwood et al. 2016), based on the water velocity preferences of different taxa. The New Zealand metric has not been extensively tested but has been shown to respond more to temporal changes in hydrology than in water quality (Greenwood et al. 2016; Clapcott et al. 2017). An invertebrate metric based on taxa tolerance of bed-movement has also been developed in New Zealand (Schwendel et al. 2011). Internationally, hydrological invertebrate metrics have been used as indicators of the ecological effects of different flow regimes such as changes in flow due to hydroelectric dams (Kairo et al. 2012; Armanini et al. 2014), investigating aquatic invertebrate community composition across river classes (Monk et al. 2006) and identifying ecological responses to both high and low flow events (Monk et al. 2008). In the U.K., the Lotic invertebrate Index for Flow Evaluation (LIFE) is correlated with changes in natural and anthropogenic variations in flow (Extence et al. 1999) and is commonly used in the development of river management plans and to identify sites subjected to hydrological stress (Monk et al. 2008).

In general, invertebrate community metrics will respond to any factor that influences macroinvertebrate community composition (Boothroyd and Stark 2000) and indices that are designed to be sensitive to specific environmental stressors often (e.g., Kairo et al. 2012), but not always (Armanini et al. 2014), show overlap in the parameters that influence their observed values. For example, the MCI and its variants, designed as indicators of water quality (Stark and Maxted 2007), are generally insensitive to local water velocity (Stark 1993) but can be affected by floods and extended periods of low flow (Boothroyd and Stark 2000), particularly in more pristine waterways (Death et al. 2009). Thus, while univariate metrics can indicate change in macroinvertebrate community composition, disentangling the mechanistic cause of changes is difficult due to the joint effects of hydrology, water quality and habitat on invertebrate communities (Chessman and McEvoy 1998).

9.3 Macroinvertebrates summary

New Zealand riverine macroinvertebrates can be described as being generally adapted to our montane environment where the timing of floods is often unpredictable and highly variable within rivers (Winterbourn et al. 1981). However, this does not mean that macroinvertebrate communities are unaffected by changes to the timing or magnitude of river flows. Riverine macroinvertebrates can be impacted by high-flow events through many mechanisms (Figure 9-1), both directly through impacts of high-flow events removing or killing individuals, and indirectly through flow-mediated changes to channel form, water velocity and depth, substrate composition, flow refugia and habitat diversity (Bunn and Arthington 2002).

10 Fishes

New Zealand has more than 60 recognised freshwater fishes (Joy and Death 2013). This diversity includes 21 exotic species that have been introduced to New Zealand (Dunn et al. 2018). The total number of described native species is increasing at an accelerating rate as new species are discovered and new genetic techniques discriminate between morphologically similar species (Waters and Wallis 2000; Wallis et al. 2009). New Zealand's geographic isolation has led to a unique freshwater fish fauna with a high degree of endemism (Lévêque et al. 2007); 92% of New Zealand's described native fish species are found nowhere else in the world (Joy and Death 2013). Regardless, New Zealand's freshwater fish diversity is low compared to other regions globally (Lévêque et al. 2007).

New Zealand's native freshwater fishes have a number of unusual characteristics: most are small, benthic, largely nocturnal, and many are diadromous, migrating between marine and freshwater environments at least once during their life history (Joy and Death 2013). Amphidromy is the most common form of diadromy in New Zealand's native freshwater fishes (McDowall 1998). Larvae of amphidromous species migrate to sea soon after hatching, this is followed by early feeding and growth at sea, and then a migration of post-larval fish from the sea back into fresh water; there is further prolonged feeding in fresh water during which most somatic growth from juvenile to adult stages occurs, as well as maturation and reproduction. It is known that spawning (Hopkins 1979; Mitchell and Penlington 1982; Allibone and Caskey 2000; Charteris 2002), egg hatching (O'Connor and Koehn 1998; Charteris et al. 2003; Franklin et al. 2015), larval migration (Ots and Eldon 1975; O'Connor and Koehn 1998; Charteris and Ritchie 2002) and post-larval migration (McDowall and Eldon 1980) of several native amphidromous species are associated with high-flow events.

10.1 Direct effects of high-flow harvesting on fishes

The ecological integrity of river ecosystems depends on their natural dynamic character (Poff et al. 1997). Hydrologic variability creates and maintains a "predictable diversity" of in-channel and floodplain habitat types (Poff et al. 1997). Dynamic flows promote the evolution of a diverse suite of species that can exploit unique facets of the mosaic of habitats. New Zealand has a highly variable maritime climate, steep, mountainous terrain and many relatively short and unstable rivers (Winterbourn et al. 1981; Jowett and Duncan 1990); disturbance from floods is common in many New Zealand rivers. Many of New Zealand's freshwater fishes have evolved behavioural (David and Closs 2002; McEwan and Joy 2013) and life history (McDowall 1996; Leathwick et al. 2008) traits that enable them to survive and, in some cases, take advantage of living in a disturbed environment.

Buoyant freshwater plumes transport massive quantities of river water into coastal seas, particularly after high intensity rainfall events (O'Callaghan and Stevens 2017). These river plumes are usually only a few metres deep at the ocean's surface (O'Callaghan 2019). In some coastal areas, river plumes disperse quickly but in other areas the plumes are persistent and extensive (O'Callaghan and Stevens 2017; O'Callaghan 2020). River plumes act as a critical interface between estuaries and the ocean for diadromous fishes; juveniles use river plumes to locate river mouths and re-enter the freshwater realm (McDowall and Eldon 1980; McDowall 1990). There is strong evidence that the number of diadromous galaxiids (whitebait) migrating into rivers increases significantly after high-flow events (McDowall and Eldon 1980). Furthermore, the species composition of whitebait runs changes after high-flow events; migrating banded kokopu (*Galaxias fasciatus*) avoid highly turbid water (Rowe et al. 2000; Richardson et al. 2001) and their abundance decreases in catches after high-flow events (McDowall and Eldon 1980). However, other whitebait species (i.e., īnanga, *Galaxias* *maculatus* and banded kōkopu) and the migratory stages of other diadromous species (i.e., longfin elvers, *Anguilla dieffenbachii,* shortfin elvers, *A. australis* and redfin bullies, *Gobiomorphus huttoni*) show no avoidance of high turbidities (Boubée et al. 1997). It is likely that these species use river plumes, particularly during high-flow events, to guide them towards river mouths. If the extent or persistence of freshwater plumes is reduced by high-flow harvesting during key migratory periods the immigration of juveniles into rivers may be hindered and their life cycles disrupted (McDowall 1995, 1999). This could also disrupt the whitebait fishery that is sustained by diadromous galaxiids (Yungnickel et al. 2020).

Diadromous fish species are dependent on unobstructed egress and ingress while migrating through river mouths (McDowall 1988, 1992). The processes that keep river mouths from closing are a complex interplay of river flow, sediment load, wave action and longshore drift (Hart 2007, 2009). River mouth closures are more common during low flow periods (Kirk 1991) and on coasts dominated by coarse-grained sediments, high-flow events are critical for re-opening and aligning river mouths (Kirk 1991; McSweeney et al. 2016). Drought can impact flows in New Zealand rivers at any stage of the year, but it is often most serious during late-summer and autumn (Caloiero 2017). Unfortunately, this is the time when much reproduction and emigration to sea of the larvae of diadromous fishes is occurring (McDowall 1976, 1995), and thus when river mouth closure can potentially cause major larval mortalities. It is also the period of emigration of mature, pre-spawning adults of both New Zealand eel species. However, mature eels have the capacity to cross gravel berms to reach the sea if the river mouth is closed (Hobbs 1947). River mouths, particularly in eastern areas, may also close during spring (Hart 1999) preventing immigration of juveniles (e.g., whitebait), reducing recruitment to adult populations and the abundance of short-lived diadromous species (McDowall 1995; Jowett et al. 2005). If high-flow harvesting reduces the intensity of floods that would otherwise have reopened closed river mouths during either of these critical migration periods, it could have serious consequences for native diadromous fishes.

High-flow harvesting could disrupt the reproductive strategy of four species of diadromous galaxiids (i.e., kōaro, *Galaxias brevipinnis*, shortjaw kōkopu, *G. postvectis*, banded kokopu and giant kōkopu, *G. argenteus*) that, along with īnanga and common smelt (*Retropinna retropinna)*, sustain New Zealand's whitebait fishery (Ots and Eldon 1975; O'Connor and Koehn 1998; Charteris and Ritchie 2002). These four species deposit their eggs amongst riparian vegetation or substrates in forested streams in locations that are only temporarily submerged by a high-flow event (Hopkins 1979; Mitchell and Penlington 1982; Allibone and Caskey 2000; Charteris 2002). The eggs develop in a humid atmosphere and hatch when the egg deposition sites are resubmerged by a subsequent high-flow event (O'Connor and Koehn 1998; Charteris et al. 2003; Franklin et al. 2015). After hatching, elevated flows may also increase the rate of downstream transport of the larvae, facilitating survival during dispersal to sea from spawning sites in streams that may be long distances inland (Ots and Eldon 1975; O'Connor and Koehn 1998; Charteris and Ritchie 2002). Hatching during high-flow events may favour survival of the larvae because turbid flows may provide 'cover' for the larvae as they emigrate to sea (McDowall and Charteris 2006), or the higher flow may transport them to the sea more quickly (Closs et al. 2013). High-flow harvesting is more likely to impact larval transport and dispersal of these species than egg deposition, development, and hatching. It is likely that larvae migrating downstream, which hatched during a high-flow event, will be entrained by harvesting infrastructure. These larvae are very small (<10 mm length; Ots and Eldon 1975; Hopkins 1979; Mitchell and Penlington 1982; McDowall and Suren 1995) and could only be excluded by impractically fine fish screens (e.g., <0.3mm mesh size; MacLean 1986; Charteris 2006).

The reproductive strategy of several other diadromous fishes may also be impacted by high-flow harvesting. Egg hatching of redfin (McDowall 1990) and bluegill bullies (*Gobiomorphus hubbsi*; Jarvis and Closs 2015) is probably stimulated by physical disturbance associated with high-flow events. As with the diadromous galaxiids, the tiny larvae of these diadromous bullies (<3 mm length; McDowall 1965; Jarvis et al. 2018a) are at risk of entrainment by high-flow harvesting infrastructure while they migrate, in some cases more than 10 km (Jarvis et al. 2018a), downstream to sea (Bonnett et al. 2014). Although torrentfish, *Cheimarrichthys fosteri*, are thought to spawn as close to the ocean as possible (Scrimgeour and Eldon 1989; Warburton et al. 2021), their tiny larvae (<3 mm length; Jarvis et al. 2018b) do occur up to 1.5 km from the ocean and are also at risk of entrainment by high-flow harvesting infrastructure in lowland areas (Jarvis et al. 2018b). Diadromous populations of īnanga, the commonest species in the whitebait fishery (Yungnickel et al. 2020), use tidally-induced fluctuations in water level to access their riparian spawning sites (Hickford and Schiel 2011). However, non-migratory populations of īnanga in Australia (Pollard 1971), and New Zealand populations in non-tidal rivers (Orchard and Schiel 2021) depend on water level fluctuations caused by high-flow events to trigger spawning, access riparian vegetation and initiate egg hatching.

10.2 Indirect effect of high-flow harvesting on fishes

High-flow harvesting may indirectly affect native fishes by altering the availability of critical food sources and/or essential habitat. Most of New Zealand's native fishes are opportunistic carnivores (McDowall 1990). They are predominantly insectivorous, feeding on aquatic invertebrates, and terrestrial insects that fall into the water (e.g., Scrimgeour and Winterbourn 1987; Glova and Sagar 1989; Hayes and Rutledge 1991; Sagar and Glova 1994; Sagar and Glova 1998; Rowe et al. 2002; West et al. 2005; Ramezani et al. 2014). New Zealand native fish are mostly benthic (i.e., they live on the bed of rivers), and broadly favour habitats with larger substrate sizes and, thus, larger interstitial spaces (McDowall 1990).

Even a small proportional take of high flow water could alter the balance between sediment inputs and transport capacity (see Section 5). Eventually, it is likely that reductions to high flows will cause a fining of the bed surface material, reduction in channel relief, and ultimately, if the high flow take is large, then bed aggradation may occur (Bakker et al. 2017; Hoyle et al. 2022). These geomorphic responses can change the physical habitat template (see Section 5) with consequent effects on river biota (Owens et al. 2005).

Elevated sediment deposition is widely recognised to negatively impact macroinvertebrate communities, reducing the availability of food for fishes (Ryan 1991; Kemp et al. 2011). This could take the form of an overall decrease in macroinvertebrate abundance, or a change in community composition (see Section 9.1) towards less preferred and more difficult to detect prey, i.e., a reduction in drifting species and an increase in burrowing species (Bilotta and Brazier 2008). A reduction in food quality and supply, combined with reduced feeding efficiency from elevated suspended sediments (Rowe and Dean 1998), can reduce fish growth rates and overall condition (Sagar 1986; Scrimgeour and Winterbourn 1987; Hayes et al. 2000; Collins et al. 2011).

One of the primary mechanisms through which high-flow harvesting may impact fishes is by elevated sediment deposition (see Section 5), particularly elevated levels of fine sediment filtering into the interstitial spaces (gaps) between rocks in the bed (Richardson and Jowett 2002). Interstitial space is an important refuge and foraging habitat for small fishes and juveniles of larger species, and a key spawning site for many species (McDowall 1990; Jowett and Richardson 1995). For example, upland bully (*Gobiomorphus breviceps*; Jowett and Boustead 2001), redfin bully (McEwan and Joy 2014b), bluegill bully (Jowett et al. 1996), torrentfish (Jowett et al. 1996), adult banded kōkopu (Akbaripasand et al. 2011), kōaro (McEwan and Joy 2014a), shortjaw kōkopu (McEwan and Joy 2014a), and dwarf galaxias (*Galaxias divergens*; Jowett et al. 1996) have all been shown to have an association with these habitats and may, therefore, be negatively impacted by infilling of interstitial spaces.

10.3 Fishes summary

The dominance of amphidromy amongst New Zealand freshwater fishes presents the greatest vulnerability to adverse effects from high-flow harvesting. Native fishes possess unique and specialised life history traits that have been shaped to take advantage of predictable variability in flows and associated in-channel and flood plain habitats. There is clear potential for high-flow harvesting, by altering the amplitude and/or duration of high-flow events, to directly and indirectly impact multiple life history stages of native freshwater fishes.

11 Estuarine environments

Estuarine ecosystems are hotspots for productivity, biogeochemical cycling, and biodiversity, with multiple contributions to ecosystem services such as food production, protection, recreation, carbon sequestration, and nutrient cycling (Thrush et al. 2006; Cloern et al. 2014; Douglas et al. 2019). Estuaries are located between the land and the ocean, acting as buffer areas for coastal seas and mitigating nutrient, sediment, and organic matter received from terrestrial sources (Villnäs et al. 2019; O'Meara et al. 2020). However, estuarine habitats are particularly vulnerable to ongoing anthropogenic pressures including coastal development, eutrophication, sediment loads, pollution, climate change, and reduced freshwater inflows (Lotze et al. 2006; Passeri et al. 2015; Lam-Gordillo et al. 2022).

The functioning of estuaries encompasses complex relationships between physical, chemical, and biological processes, mainly relying on the inflow of fresh water (Thrush et al. 2013; Lam-Gordillo et al. 2022). Worldwide, high-flow harvesting has been implemented as an alternative to manage water. Despite the potential benefits of high-flow harvesting for agricultural, domestic, and industrial needs, there are also consequences and impacts on estuarine environments associated with this activity.

11.1 General effects of high-flow harvesting on estuarine environments

Modifications to riverine water flow (e.g., from high-flow harvesting) change the hydrological regime, inducing marked effects on the structure and functioning of estuarine ecosystems. Although the nature of the impacts will depend on the type of system implemented, its duration, and how much water is harvested, global research has identified seven interconnected components of estuarine environments that are impacted by high-flow harvesting (e.g., Copeland 1966; Gillanders and Kingsford 2002; Kennish 2002; McKerchar et al. 2005; Gillanders et al. 2011; Dittmann et al. 2015; Gluckman 2017; Chilton et al. 2021).

1. Hydrodynamics.
2. Salinity.
3. Erosion/deposition.
4. Nutrient cycling.
5. Hydrological connectivity.
6. Biota.
7. Energy transfer.

The water circulation, mixing and flushing within estuaries (i.e., hydrodynamics) are driven by the interaction of fresh water, tides, and, in particular estuaries, wind direction and speed (Goodrich et al. 1987; Scully 2010). Harvesting riverine water decreases the freshwater inflow into estuaries, which changes the circulation and flushing, affecting the distribution of salinity, dissolved oxygen, and resident organisms (Cloern et al. 2017; Fonseca et al. 2020). In general, estuarine salinity is greater during the dry season and lower during the flood season. Several important life cycle events, such as the reproduction and recruitment of fish and shrimp, and the germination of macrophyte seedlings, are triggered by seasonal shifts in salinity (Kim et al. 2013; Sun et al. 2013; Kim et al. 2015; Sun et al. 2015). Decreased freshwater inflow, due to high-flow harvesting, could result in intensified saltwater intrusion into estuaries. This could increase estuarine salinity and reduce the survival of organisms living in these habitats (Copeland 1966; Dittmann et al. 2015; Hallett et al. 2018; Chilton et al. 2021).

Erosion and deposition of sediment in estuaries are related to freshwater inflows. Freshwater inflows shape the geomorphology of estuaries, transporting sediment particles to estuaries and building habitat structure for colonisation by plants and infauna (Le Pape et al. 2013; Adams 2020; Li et al. 2020). A constant supply of sediment is necessary for depositional coasts to form and be maintained. However, reducing inflow could reduce the sediment supply to estuaries and adjacent coastline, accelerating coastal erosion. Alternatively, reduced freshwater inflows could cause deposition of sediment to change. An increase in the accumulation of fine sediment in receiving estuaries could affect the living organisms as well as contribute to erosion of adjacent coastlines (Ryan 1991; McKerchar et al. 2005; Gluckman 2017).

Freshwater inflow into estuaries enhances nutrient cycling and primary production by regulating biogeochemical processes. Overall, the nutrient cycling in estuaries could be affected by high-flow harvesting in two opposite scenarios (Copeland 1966; Wetz and Yoskowitz 2013; Adams 2020).

1. Excess accumulation of nutrients that could result in eutrophication.
2. Limited delivery of nutrients to the estuarine ecosystem and, therefore, decreased primary production.

Freshwater inflow facilitates hydrological connectivity in estuaries, linking the water from the catchment to the ocean, and allowing movement or migration of organisms (e.g., diadromous species) from the ocean to the estuary and *vice versa* (Duggan et al. 2019; Scharler et al. 2020). Freshwater inflow enables connectivity between intertidal habitats and coastal wetlands, with benefits for pelagic and intertidal organisms such as accessibility to habitat and food resources and enhancing benthic primary production (Clark and O'Connor 2019; Raman et al. 2020). High-flow harvesting could impact connectivity in estuarine ecosystems by limiting the access of organisms to the estuary to complete their life cycles or reducing habitat quality or quantity, food sources, or primary productivity.

The biota living in estuarine ecosystems are influenced by riverine inflow. High-flow harvesting will decrease natural inflows into estuaries, impacting the delivery of sediment, nutrient cycling, salinity levels, and limiting connectivity. These alterations could negatively impact estuarine biota by decreasing the biomass of phytoplankton, zooplankton, and benthic organisms (Nichols et al. 1986; Hooper and Austen 2013; Dittmann et al. 2015), limiting the movement of migratory species (Bunn et al. 2014; Chen et al. 2016), changing the structure and composition of living communities (Dittmann et al. 2015; Lam-Gordillo et al. 2022), reducing food sources (Hooper and Austen 2013) or affecting the food chain and energy transfer (McKerchar et al. 2005; Gluckman 2017).

11.2 Effects of high-flow harvesting on New Zealand estuarine environments

Specific knowledge of the consequences of high-flow harvesting on New Zealand estuarine environments is limited. Only six investigations have assessed the potential effects of high-flow harvesting on lowland and estuarine ecosystems. McKerchar et al. (2005) assessed the general implications of harvesting floodwaters across New Zealand. They suggested that because high-flow harvesting only extracts water during flood flows, the effect on normal and low flows should be minimal; however, they identified that high-flow harvesting could alter river channel morphology and sediment flows that may in turn cause effects lower in the catchment. For example, alterations in channel/estuarine morphology and sediment accumulation could affect habitat quality and reduce sediment flow with effects on shoreline erosion (e.g., Ryan 1991; Duncan 2015; Cloern et al. 2017). Similarly, a study in the Waipaoa and Te Arai River showed that increased abstraction (i.e., harvesting) of water flow from the Waipaoa River would likely cause an increased rate of fine sediment deposition in the lower river (Duncan 2015). This aligns with findings in other studies in New Zealand (e.g., review - McKerchar et al. 2005; modelling - Gomez et al. 2009; Prime Minister's Chief Science Advisor's report - Gluckman 2017) and around the world (e.g., Ryan 1991; Adams 2020; Li et al. 2020). These suggest potential impacts of increasing deposition of fine sediment and increasing erosion rates in receiving estuarine habitats that could affect the living communities and change the ecological character of these ecosystems.

In 2017, a report was released reviewing the values, state, trends, and human impacts on New Zealand's fresh waters (Gluckman 2017). This study identified that different water flows are needed as organisms respond in different ways to flow-related variables (e.g., current velocity, water depth, channel geomorphology). In rivers, high-flow events shape the geomorphology, control the vegetation and transport sediment. High-flow harvesting could decrease the sediment and nutrient transport in rivers, which could affect estuarine ecosystems by receiving less sediment and nutrients, with repercussion such as loss of habitat, limiting organisms' migration, erosion of adjacent coast, and in general, a reduction in the provision of ecological services. Similarly, Hicks (2018) found that the harvesting of floodwater is not necessarily free of environmental effects. He suggested that there could be an increase in fine sediment deposition in the Rangitata River because of high-flow harvesting activities. This finding was supported by a recent study in the same river (Hoyle et al. 2022) that also suggested a potential increase of fine sediment deposition in receiving estuarine ecosystems. A review of the general impacts of altering water flow across New Zealand (Ministry for the Environment & Stats NZ 2020) detailed the possible consequences of high-flow harvesting in rivers. Some examples described are restricting organisms' movement or migration, altering river channel and geomorphology, reducing the amount and quality of habitat, potential increases in temperature and algal blooms, which are similarly expected to occur in estuarine ecosystems because of high-flow harvesting as it has been previously described in other studies around the world and in New Zealand.

11.3 Estuarine summary

Overall, previous studies suggest that high-flow harvesting could impact receiving estuarine habitats by altering the quantity, quality, and timing of the inflow water, affecting geomorphological and biogeochemical processes, and the habitats of organisms in estuarine ecosystems.

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