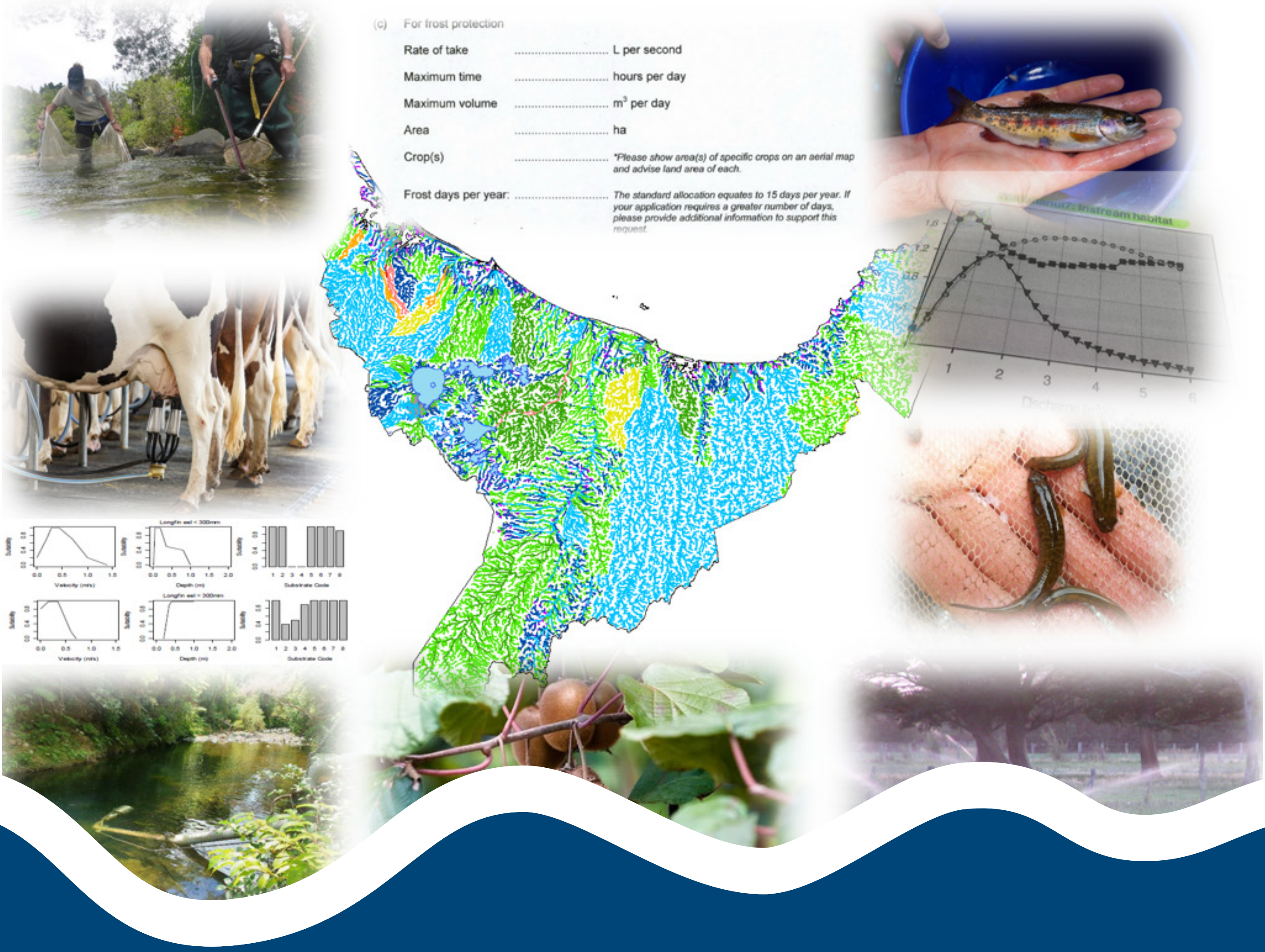

BAY OF PLENTY
REGIONAL COUNCIL
TOI MOANA

Recommended steps to set minimum flows for ecological values in Bay of Plenty waterways

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Prepared by: Alastair Suren

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5 Quay Street
P O Box 364
Whakatāne
NEW ZEALAND

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Executive summary/ Whakarāpopototanga Matua

1 Under the National Policy Statement for Freshwater Management (NPSFM), section 3.16 requires councils to include rules in their regional plans that set environmental flows and levels for each Freshwater Management Unit (FMU). Environmental flows must, amongst other things, be set at a level that achieves desired environmental outcomes for the values relating to the FMU, and environmental flows must be expressed in terms of the water level and flow rate. Section 3.17 also requires councils to identify take limits (as a total volume, total rate or both). This means that councils need to set both a minimum flow limit (Q_{min}, the flow below which taking, damming, or diversion will be restricted, or no longer allowed) and a total allocation limit (ΔQ, the maximum quantity of water available for abstraction).

2 The Bay of Plenty Regional Council (BOPRC) is responsible for setting flow limits in the Bay of Plenty region, and the Regional Natural Resources Plan (RNRP) contains policies, rules and methods to achieve these flows. This report was written to describe a transparent methodology to determine minimum flows to maintain ecological values, which will further inform the final setting of Q_{min} in waterways throughout the region. It contains several recommendations as to how this is to be achieved. For brevity, only the main recommendations that describe important methodological considerations are presented here. Other recommendations of a more technical nature are in either the main body of the report, or the Appendix.

3 There are two flow metrics currently used throughout New Zealand to index minimum flows against: the Q_5 7-day low flow, and the mean annual low flow (MALF). Bay of Plenty Regional Council presently uses the Q_5 7-day, but MALF is used by more regional councils. The first part of this report examined relationships between these two low flow variables to see whether MALF could be used in future plan changes as the preferred flow statistic by which to set Q_{min}. Strong relationships existed between the Q_5 7-day flow and MALF, suggesting that new default rules as part of any future plan changes implementing the NPS-FM could be based on MALF, instead of the current Q_5 7-day flow of the Regional Natural Resources Plan (RNRP). Values of MALF are generally greater than values of the Q_5 7-day flow, meaning that both the Q_{min} and ΔQ would be higher than the current default values that are based on the Q_5 7-day flow if the same percentages were used.

Recommendation 1. Strong relationships exist between Q5 7-day and MALF, based on both measured and modelled data. Given the widespread use of MALF throughout the country, it is suggested that all low flow statistics in the Bay of Plenty are based on MALF in future plan changes.

4 Bay of Plenty Regional Council has also undertaken targeted Instream Flow Incremental Methodology surveys at 53 catchments in the region. A central part of the IFIM methodology is the use of RHYHABSIM (River Hydraulic Habitat Simulations), which calculates an appropriate Q_{min} designed to protect a specific amount of hydraulic habitat for target fish. Similar IFIM studies using RHYHABSIM have also been done by consultants in 13 other streams in the region. Bay of Plenty Regional Council has also made low-flow measurements at 135 monitoring sites, where both the Q_5 7-day flow and MALF have been calculated. However, despite this work, the majority of waterways in the region are ungauged. The only realistic way to set minimum flows in these waterways is to use modelled flow data.

5 This means that there are three potential data sources available for setting minimum flows in streams throughout the region: 1) the IFIM data (representing the most robust, but potentially spatially limiting way to define Q_{min}; 2) measured flow data during summer low flow periods to help estimate flow statistics such as MALF; 3) modelled flow data (representing the least robust, but most regionally extensive way to help estimate statistics such as MALF).

6 Setting minimum flows is traditionally based on a hierarchical approach, with the chosen methodology representing a mixture of the degree of abstraction and the potential ecological values of the particular waterway. The simplest low flow setting methodology is based on setting some defined hydrologically-based minimum flow, such as the need to maintain a specified value (e.g., 70%) of MALF, or maintaining other values requiring minimum flows. More complex methodologies such as IFIM rely on detailed modelled relationships between hydraulic habitat quality and stream flow to protect a defined level of hydraulic habitat for target fish species. In streams with very high ecological values, or streams where the proposed abstraction rates would be high, the more robust IFIM methods should be used. This is because streams with high ecological values need a high degree of hydraulic habitat protection, and streams with high abstraction rates may end up being drawn to, or below their recommended Q_{min} flows for a long period of time. In contrast, it is considered appropriate to use the more generic hydrologically-based models in streams with lower ecological values, or lower abstraction rates.

7 There are over 25,000 individual reaches within the Bay of Plenty, so, in theory minimum flows need to be set for all of these. Development of accurate methodologies to identify minimum flows for ecological values should prioritise those locations with high abstraction pressure. The challenge faced by BOPRC is to set Q_{min} in these priority waterways with the most appropriate methods that is specific to that waterway. This report describes a transparent methodology to determine minimum flows in waterways throughout the region. This methodology is based on a clear hierarchy of questions:

- Has an IFIM survey has been done in the catchment?
- Are target fish species predicted at specific sites?
- Has MALF been measured in the catchment?

Recommendation 2. Make use of the hierarchical decision-making process to inform the methodology of setting appropriate Q_{min} of waterways throughout the region. This hierarchy consists of a dichotomy of:

1) *whether an IFIM survey has been done,*
2) *are target fish expected,*
3) *do we have measured values of MALF,*
4) *is the stream in question large or small? Where target fish do not occur, use default Q_{min} of 70% MALF in small streams, and 60% MALF in larger rivers.*

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8 Where none of the above are applicable, then default values of 70% MALF are suggested for small ($\bar{Q} \leq 5$ m^3/s) streams, and 60% MALF for large (mean flow ($\bar{Q} > 5$ m^3/s) rivers. These default values are intended to provide sufficient hydraulic habitat protection for ecological values other than fish, such as maintenance of healthy invertebrate communities or minimising the chance of excessive periphyton (algal) blooms. The higher Q_{min} in small streams reflects their greater sensitivity to changes in flow that larger rivers, as there is often a greater loss of suitable hydraulic habitat with reduced flows in small rivers.

9 By answering yes or no to these questions, a set of five methods have been identified to set minimum flows throughout the region. Examination of all 25,202 NZReaches showed that the majority of reaches (45.7%) had their Q_{min} based on the IFIM studies, while 24.4% of reaches used the default Q_{min} of 70% MALF in small streams. The fewest number of reaches (0.3%) had a default Q_{min} of only 60% MALF, based on the need to protect ecological values other than fish in larger streams (mean flow of > 5 m3/s).

10 Some of the IFIM sites were in the middle reaches of catchments, so the calculated Q_{min} were initially set to all NZReaches at and above the IFIM site. However, there were often more consented water takes in the lower parts of these catchments, below the IFIM sites. A

manual assessment was consequently made of all NZReaches below an IFIM site, as well as the number of large tributaries flowing into reaches below the IFIM site. These reaches below the IFIM site were subsequently allocated the same Q_{min} if they were close to the initial IFIM site and if no larger tributaries flowed into the reach.

Recommendation 6: Suitable Q_{min} can be based for all NZReaches below the location of an IFIM site, based on the following rules:

1 *Use the value derived from the IFIM survey, as long as no larger tributary streams join the river.*

2 *When the Q_{min} derived from IFIM surveys in upper catchments is lower than Q_{min} derived using other methods in the lower catchments, use the lower IFIM-derived Q_{min} in these lower catchments.*

3 *When the Q_{min} derived from IFIM surveys in upper catchments is higher than Q_{min} derived using other methods in the lower catchments, use the higher IFIM-derived Q_{min} in these lower catchments.*

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11 Following identifying appropriate minimum flows of all NZReaches, freshwater objectives and water resource use limits will be developed, using the identified minimum flows to protect ecological values, and other relevant information when establishing take limits and minimum flow limits. It is also acknowledged that many other reaches have no foreseeable abstraction pressure, despite being identified as having a minimum flow based on this decision hierarchy.

12 This report thus provides a series of transparent and objective steps for BOPRC to use when setting minimum flows as part of the water management process to meet the requirements of the NPS-FM. Once appropriate Q_{min} has been set in waterways throughout the region, other tools such as eFlows Explorer (recently developed by NIWA) can be used to examine the consequences of various Q_{min} allocation regimes on resource use (e.g., the amount of water allocated (ΔQ), and the reliability of supply (R)). In doing so, BOPRC can help achieve the desired outcomes of the NPSFM (2020)

Contents/Rārangi Upoko

Part 1:
Introduction/Kupu Whakataki

1.1 Purpose of this report

The purpose of this report is to identify a transparent and consistent approach to set minimum flows for ecological purposes in waterways throughout the Bay of Plenty. It is intended that this report informs the development of policy regarding minimum flows in future plan changes and supports tangata whenua and community members' understanding of the basis of the preferred flow-setting methodology in relation to stream ecology and the protection of ecological values. It is acknowledged that there are further steps to help define minimum flows for streams; including identification of cultural flow requirements and an understanding of out-of-stream use values that are necessary parts of the overall water-allocation equation, but these are beyond the scope of this report.

1.2 Flow setting objectives

The overall Objective of the National Policy Statement for Freshwater Management (NPS FM 2020) is to ensure that natural and physical resources are managed in a way that prioritises:

1. The health and well-being of water bodies and freshwater ecosystems.
2. The health needs of people (such as drinking water).
3. The ability of people and communities to provide for their social, economic, and cultural well-being, now and in the future.

As part of meeting this overarching Objective, section 3.16 of the NPS FM requires councils to include rules in their regional plans that set environmental flows and levels for each Freshwater Management Unit (FMU). The term "environmental flow" is in itself, a multifaceted concept, and describes the frequency, magnitude and duration of flood flows, and low flows required to sustain freshwater ecosystems, while in turn meeting the needs of human livelihoods and well-being. From an ecological perspective, environmental flows are relevant in ensuring that activities that directly take water from streams, such as abstraction, diversion, or damming, do not result in residual flows that are too low to support desired ecological values, or that flood frequency is reduced to any extent that has unintended adverse ecological or geomorphological effects, such as development of extensive instream plant growth, or the loss of small gravels being transported to the coast.

Section 3.16 (3) states that environmental flows and levels must, amongst other things, be set at a level that achieves the environmental outcomes for the values relating to the FMU (or relevant part of the FMU), and that environmental flows and levels must be expressed in terms of the water level and flow rate. Section 3.17 also requires councils to identify take limits (as a total volume, total rate, or both) so that take limits are (s3.17(4)(b)) able to "safeguard ecosystem health from the effects of the take limit on the frequency and duration of lowered flows or levels" and (s3.17(4)(c)) "provide for the life cycle needs of aquatic life". This means that councils need to set both a minimum flow limit (Q_{min}, the flow below which further water take is restricted or no longer allowed (NPSFM 3.17(3)(a)) and a total allocation limit (ΔQ, the maximum quantity of water available for abstraction).

The idea behind setting a Q_{min} is to help protect specific values within a waterbody. While these values could include ecological, cultural, recreational, or aesthetic, this report only focusses on the requirement to maintain ecological values within waterbodies. Maintenance of ecosystem health in streams is also a compulsory value in the NPS FM.

1.3 Hydrological conditions in the Bay of Plenty

Any investigation into recommending minimum flows to protect ecological values in streams needs to understand the role that stream hydrology has on ecology. There are three main components of a stream's hydrological regime that are fundamental in controlling ecological processes:

- The magnitude, frequency, duration and timing of high flow events (both large floods and smaller "freshes")
- The magnitude, frequency, duration and timing of low flow events
- The nature of the flow hydrograph between low flows and floods (the median flow)

Different ecosystem processes operate at high and low flows: high flows are often characterised as disturbance effects that can remove organisms from the area, and effectively "reset" ecological communities back to early stages of succession, while low flows may result in resource limitation in terms of the maintenance of suitable hydraulic habitat for fish, or maintenance of suitably low temperatures or high instream oxygen levels. This report is focussing only on the low-flow component of the hydrograph. It is, however, important to recognise that any effects of low-flows are heavily influenced by a stream's fundamental characteristics of resource supply, inter-flood velocity, and substrate stability (Suren and Riis 2010), and that streams will respond in different ways to low flow events on the basis of these characteristics (Suren et al. 2003a, b). As such the following discussion considers all aspects, reflecting this interplay of hydrological processes.

The ecological effects of low flows are controlled by the frequency, magnitude and duration of low flow events. While low flows are often described as the Q_5 7-day flow[1], or the mean annual low flow (MALF[2]), another useful flow statistic is the ratio of MALF to median flow[3] (Q_{50}). Streams with a low ratio (i.e., they have a low MALF relative to median flow) have flows (i.e., depths and velocities) at MALF that are significantly lower than the flows that occur for 50% of the time. Therefore, any further reduction in flow is likely to lead to large reductions in hydraulic habitat. These streams are regarded as being sensitive to low flow. In contrast, streams with a high ratio (i.e., they have a high MALF relative to median flow) display comparatively little reduction in depth or velocity at MALF. These could be considered relatively resistant (or less sensitive) to low flow.

Jowett (2018) used the MALF/median flow to describe ecologically relevant hydrological conditions of rivers in Taranaki. He showed that this ratio ranged from 0.2 to 0.4, suggesting that streams there were relatively "sensitive" to low flow. A similar situation exists in the Bay of Plenty where the mean ratio was only 0.26. Examination of spatial patterns showed that streams in the upper catchments in the western and central parts of the region had relatively high ratios (and are therefore potentially more resistant to any

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[1] The Q_5 7-day low flow is the one in 5-year 7-day low flow. This is derived by calculated the rolling 7-day average of mean daily flow during a hydrological year over a 5-year period and selecting the lowest of these average flows.

[2] MALF is usually based on calculating a rolling 7-day average of mean daily flow during a hydrological year (July 1 to June 30). The MALF for a particular year is the lowest of this rolling 7-day average. The MALF for the entire hydrological record is based on the average of each annual MALF that has been calculated.

[3] The term median flow (Q_{50}) refers to the flow that occurs for 50% of the time.

effects of low flows), while lowland coastal streams and many of the mid to upper areas in the west of the Rangitāiki Catchment had low ratios (Figure 1). These streams could be considered more sensitive to any effects of low flows. Co-incidentally streams with low MALF:median ratios are probably where allocation pressures are, since these are typically areas with less reliable summer rainfall, driving greater demand for irrigations and other uses.

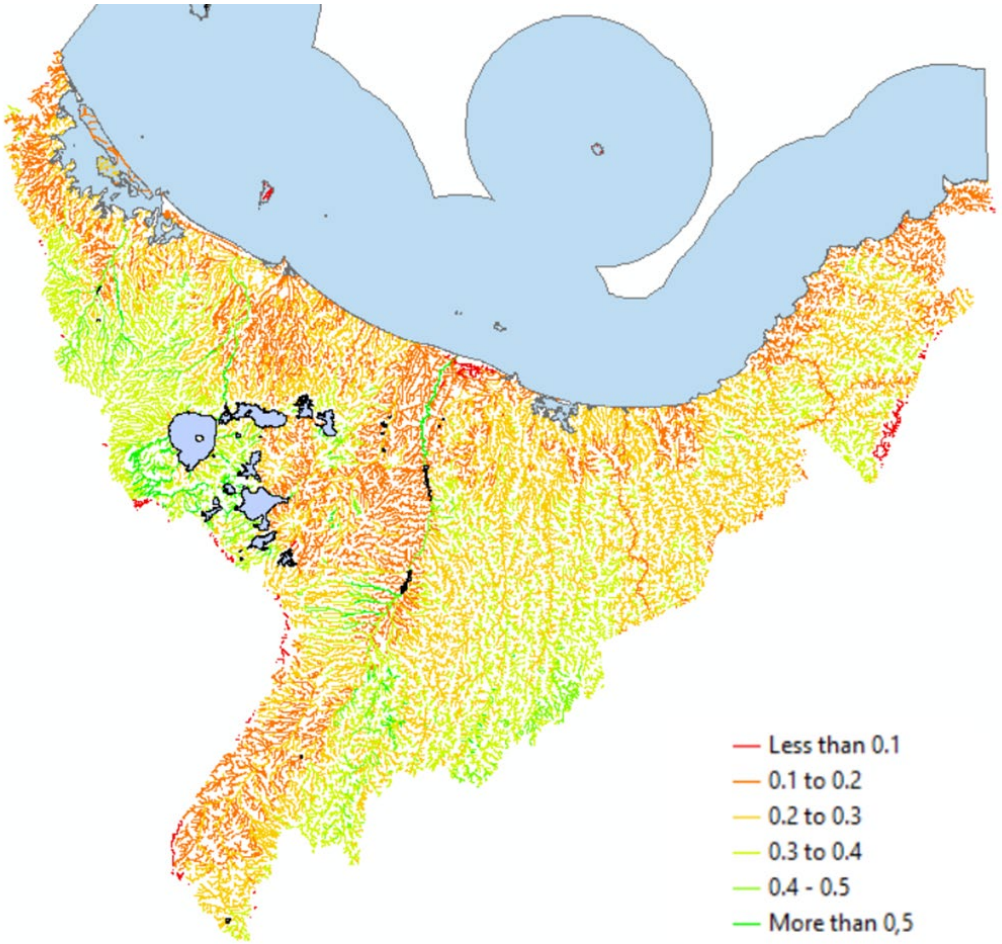

Figure 1 *Map of the ratio of MALF/Q_{50}, based on modelled data from Booker and Woods*

Another hydrologically relevant statistic that determines the effects of low flows is the frequency of flushing events. A common measurement of this is the frequency of flows that are three times the long-term median flow. This measure is called the FRE3. This flow statistic is important as small floods (commonly called “freshes”) can scour periphyton communities from the streambed, helping “cleanse” rivers and remove excess organic material which can often adversely affect both invertebrate communities, and other values such as recreation and fishing (Clausen and Biggs 1997). Arguably, increased abstraction pressure can lead to a reduction in the effective number of FRE3 events, as more water is removed from the stream which effectively reduces the magnitude of these freshes. It seems likely that streams with a high number of FRE3 events would be able to tolerate a higher abstraction demand than streams with a lower number of FRE3 events, as they would likely still maintain a higher degree of flow variability for a give rate of take. In contrast, streams with a low number of FRE3 events may experience even longer periods between freshes, as high abstraction rates may effectively “reduce” the smaller FRE3 events to flows below which any cleansing of the riverbed occurs.

Streams with the lowest FRE3 (< 5) were found in the upper parts of the Rangitāiki Catchment, and streams to the South of the Te Arawa/Rotorua Lakes (Figure 2). Streams with the highest FRE3 (> 15) were in the upper catchments of the Kaimais, and streams to the east of Opotiki. However, the vast majority of streams had a FRE3 of 10–15, so these small freshes would occur on average once a month.

This relatively high frequency of small floods means that extensive blooms of periphyton communities are unlikely to develop, as they may be washed away by these natural flushing events. Indeed, Kilroy et al. (2020) found that long term periphyton communities in the Bay of Plenty were controlled mainly be temperature, FRE2 (i.e., the frequency of slightly smaller floods), and substrate size. This finding has important implications when setting minimum flows for the region, given that excessive periphyton blooms can have detrimental effects to both ecological and other values (Biggs 1985; 1988; Suren et al. 2003a). The relatively high FRE3 throughout the region suggests that many streams may experience multiple “freshes” that help maintain periphyton biomass to relatively low levels (Kilroy et al. 2020). As such, many streams in the region may have a natural “resistance” to potential adverse effects of abstraction that may reduce the number of these small “fresh” events.

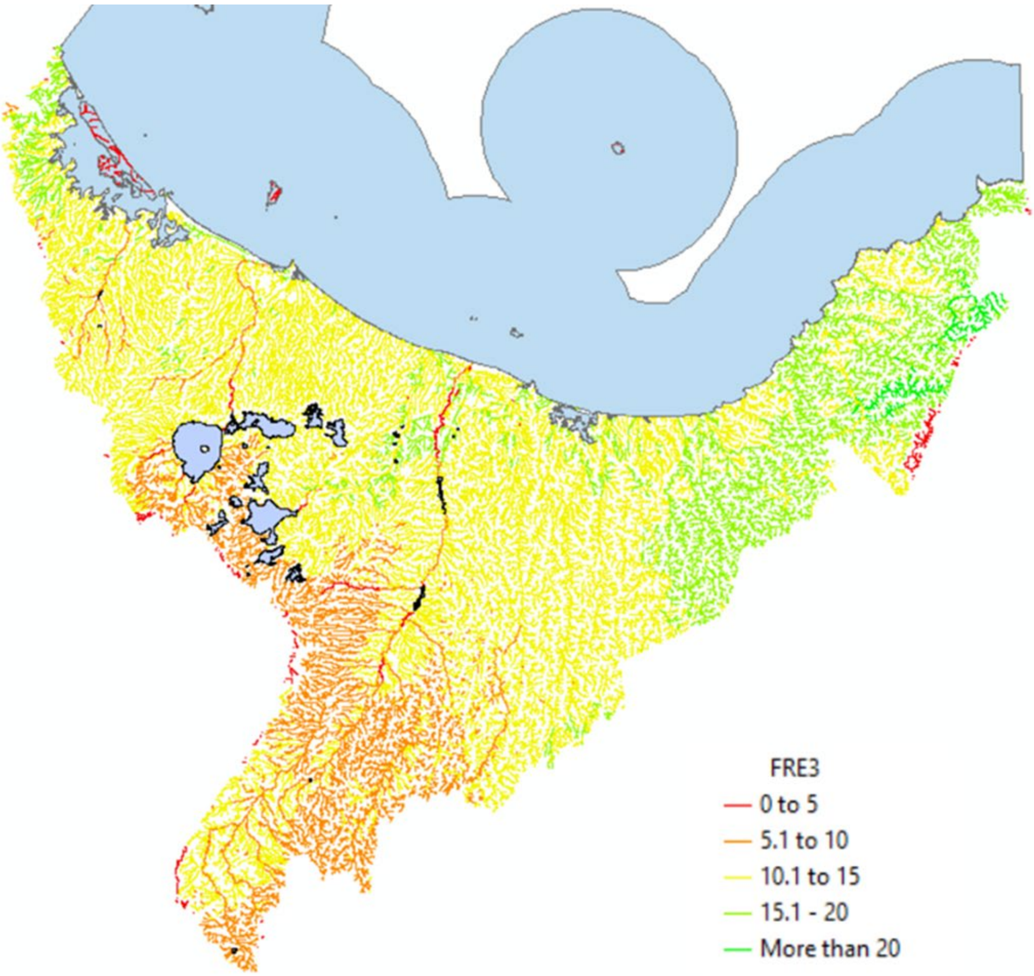

Figure 2 Map of calculated FRE3 throughout the Bay of Plenty, using modelled flow data from Booker and Woods.

1.4 Methods to select ecological flows

Under the NPSFM (2020), councils must set minimum flows and allocation limits at levels that achieve defined environmental outcomes for the values relating to the waterways in an FMU (or part thereof). From an ecological perspective, fish could be considered one of the main values to protect, although it is also clearly recognised that maintenance of overall stream health (commonly measured using freshwater invertebrates) and minimising unwanted algal blooms are also other important ecological values. Fish are arguably the main ecosystem component that are potentially affected by abstraction pressure, and low flows can act as "habitat bottlenecks" for these long-lived species. Indeed, Jowett et al. (2008) showed that fish populations can take several years to recover following low flows which have restricted suitable fish habitat. The recovery of fish populations from losses due to droughts can also vary greatly between species. Trout populations may take up to three years to recover from a drought (Hayes 1995) while native fish are far more resilient and may recover within a year (Jowett et al. 2005), assuming that their connectivity to the sea is still maintained.

Setting minimum flows in streams to protect the hydraulic habitat of fish is an appropriate approach to providing minimum flows that will support ecosystem health. Setting minimum flows is most commonly done through the use of Instream Flow Incremental Methodology (IFIM) surveys and was the recommended approach of Jowett (2013) in his assessment of methods to set ecologically relevant flow requirements in the Bay of Plenty. IFIM surveys rely on using River Habitat Simulation (RHYHABSIM) to model the changes to a stream's hydraulic habitat with reductions in streamflow. Because fish have discrete velocity and depth preferences (Jowett, 1997; Jowett and Boustead, 2001), RHYHABSIM is used to quantify the degree of suitable hydraulic habitat for different fish species and show how this changes with flow. The amount of hydraulic habitat is expressed as "weighted useable area" (WUA), and the instream minimum flow requirement (IMFR) is calculated to protect a specific proportion of the WUA relative to that which occurs at a river's natural mean annual low flow (MALF). It is expected that the fish communities present within a particular stream would be able to tolerate flows as least as low as the MALF, as these naturally occur. Thus, a calculated IMFR would never be more than MALF.

The IFIM methodology (and use of tools such as RHYHABSIM) has been widely used throughout New Zealand, both in setting minimum flows below Hydro Electric Power stations (Ryder 2009; Jowett and Biggs 2006), and for informing regional councils about appropriate minimum flows (e.g., Wilding et al. 2005 (Environment Canterbury); Jowett 2012 (Bay of Plenty); Jowett 2018 (Taranaki)). By calculating the IMFR for specific fish species, we are informing the setting of a $Q_{min,}$ to protect a particular amount of habitat for target fish species, by limiting the reduction in physical habitat naturally occurring at MALF. Setting an objective to protect the instream hydraulic habitat of fish is thus consistent with achieving the fundamental objective of maintaining a stream's ecological values.

Jowett (2018) based his hydraulic habitat models in Taranaki on maintaining sufficient hydraulic habitat for either torrentfish or brown trout at various combinations of Q_{min} and ΔQ, reflecting the interplay between these two attributes. He modelled changes to fish habitat at the 30-day MALF and found that under some abstraction scenarios, fish habitat at the 30-day MALF[4] would be reduced by only 20%. He also noted that such a reduction would probably not be detectable, and that furthermore, any reduction would only occur if the fish population were limited by hydraulic habitat. These points raise a number of important issues to consider when using the IFIM techniques:

- That any modelling comes with a certain degree of statistical variability and inherent uncertainty with the modelled outputs
- That fish densities are normally highly patchy in space and time, making it difficult to accurately monitor and detect relatively small differences in fish density that could arise due to a reduction to hydraulic habitat area
- The central assumption of IFIM models for fish is that a reduction in hydraulic habitat will only translate to a reduction in fish numbers when and where fish are limited by the amount of hydraulic habitat

However, despite these points, the IFIM methodology is still regarded as one of the most defensible methods by which to inform the setting of Q_{min}: indeed, Jowett and Biggs (2006) found that the biological response and retention of desired instream values in streams affected by large-scale hydroelectric developments was achieved using habitat-based methods for Q_{min} in five of the six cases examined.

In addition to fish, minimum flows can also be set to help protect invertebrate communities. For example, Jowett (2018) recommended minimum flows and allocation for rivers in Taranaki based in part on maintaining a specified percentage of invertebrate density, in addition to fish habitat. He developed predictive models for invertebrate density based on maintaining sufficient habitat for high scoring MCI taxa such as mayflies, caddisflies, and stoneflies. Elmid riffle beetles and the crane flies *Aphrophilia* were also used in these models to develop general habitat suitability criteria, as these insects are also common in fast flowing water. Jowett then recommended 2 alternative Q_{min} and ΔQ levels: a Q_{min} of 85% MALF, and ΔQ of 40% MALF, or a Q_{min} of 80% MALF, and ΔQ of 30% MALF. Under both scenarios, densities of these high-scoring benthic invertebrates were thought to be reduced by only 10% to that of densities at MALF. Jowett noted that this slight reduction in density would probably not be detectable.

Jowett's use of high-scoring MCI taxa is based on the fact that these animals prefer faster velocities and live-in riffles. They are also dominant food items for trout. Unfortunately, within the Bay of Plenty, many of these high MCI scoring taxa are not particularly abundant. Indeed, the fauna of waterways in the Bay of Plenty is often dominated by taxa with a much lower MCI score, and also lower velocity preferences (Suren et al. 2017). Furthermore, many of the pumice-dominated streams in the region do not have riffles, as the channels have often cut themselves through the easily eroded pumice, and streams are consequently dominated by runs. As such, a similar modelling process to detect changes in the densities of “flow-sensitive” mayflies, caddisflies and stoneflies would not be as applicable in the Bay of Plenty as in Taranaki.

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[4] The 30-day MALF is based on calculations of a rolling 30-day average of daily flows. Jowett considered the 30-day MALF to be a more appropriate flow statistic for longer lived organisms such as fish.

Of relevance to any discussion on the effects of low flows to invertebrates are the recent results of a survey of invertebrate communities at 17 Western Bay streams during a 5-month drought in the summer and autumn of 2020 (Suren 2021). Flows are continuously monitored at four of these sites, which showed that flows during this time were often between 60 and 80% of MALF (Figure 3). Despite these low flows, invertebrate community composition in the streams changed little. The effects of low flows on invertebrate densities are also ambiguous. Some studies have reported an increase in density after flow reduction (e.g., Wright and Berrie, 1987; Dewson et al., 2007b) while others (e.g., Cowx et al., 1984; McIntosh et al., 2002) have reported either a decrease in density, or else no change (e.g., Cortes et al., 2002; Suren et al., 2003b; Suren and Jowett, 2006). These observations support other New Zealand observations where invertebrate communities appear to be relatively unaffected by low flow events (e.g., Dewson et al., 2003; Suren and Jowett 2008; James and Suren 2009), and large changes in community composition do not occur as a result of periods of low flow. Periphyton is another ecosystem component that is often closely linked to a river's flow regime. During periods of low, stable flow, biomass can increase to levels well in excess of the NPS FW "bottom line" of 200 mg/m$_2$ of chlorophyll. However, biomass is also lost as a result of flood events, as material gets sloughed off the streambed. Biomass is also lost by grazing activities of invertebrates (Suren et al. 2008), and by natural sloughing of algal material as the bottom cells attached to surface of stones die and lose their attachment to the stone. Monitoring periphyton biomass in the Bay of Plenty has shown that biomass in the region is generally low and does not reach levels deemed to have an adverse effect on other values (Carter et al. 2018; Kilroy et al. 2020). One reason for this may reflect the fact that flow regimes in the Bay of Plenty have few long periods of low flows, and many small to medium flushing flows that continually "cleanse" the stream of excess periphyton. Indeed, Kilroy et al. found that variability in periphyton communities at 30 monitored sites in the region was explained mostly by flood frequency and water temperature. Furthermore, no evidence was observed of excessive periphyton blooms (over the NOF guideline values) at the end of the 5-month long drought that occurred in the western Bay of Plenty (Suren 2021), presumably as a result of natural senescence and sloughing processes.

That no adverse effects to invertebrate communities or periphyton were detected in streams in the western bay over a 5-month period, even with extremely low flows (as low as 60% of MALF) suggests a certain degree of resistance in the invertebrate and algal communities in these small streams to low flows. This observation is consistent with conceptual work by Suren and Riis (2010), who postulated that in stream types where algal blooms are unlikely to form, low-flow conditions will cause little or no change to the antecedent plant community because this plant community is structured by top-down grazing pressure. Consequently, benthic invertebrate composition will not change. Based on this finding, it is suggested that the median of the observed low flows in the four sites with monitored flows over the 5-month period (70% of MALF) be used to inform recommended Q_{min} as regional defaults in other streams.

Setting such a default minimum flow also needs to consider the effects of stream size on the sensitivity to abstraction. MfE (2008) highlighted that the risk of abstraction decreasing available habitat depends on stream size and the species present in the stream, with higher risks of deleterious effects in small streams than in larger streams and rivers. They then suggested two different default minimum flows and allocation limits in small streams (mean flow ($\bar{Q}$) < 5 m^3/s), and large streams ($\bar{Q}$ > 5 m^3/s). For simplicity, these same default levels were used to divide streams into "Small" and "Large" classes. Analysis of the REC network showed that the majority of small streams were in orders 1–4, while the majority of large streams were in orders 5 – 8.

Based on the MfE (2008) proposed guidelines it was decided to set a Q_{min} of 70% in small rivers, but a lower Q_{min} of only 60% of MALF in larger rivers, as these are not regarded as being as sensitive to low flows. It is fully acknowledged, however, that this definition between “Small” and “Large” streams was arbitrary, and that a lower level (e.g., $\bar{Q}$ = 2.5 m^3/s) could also have been chosen to separate these size classes.

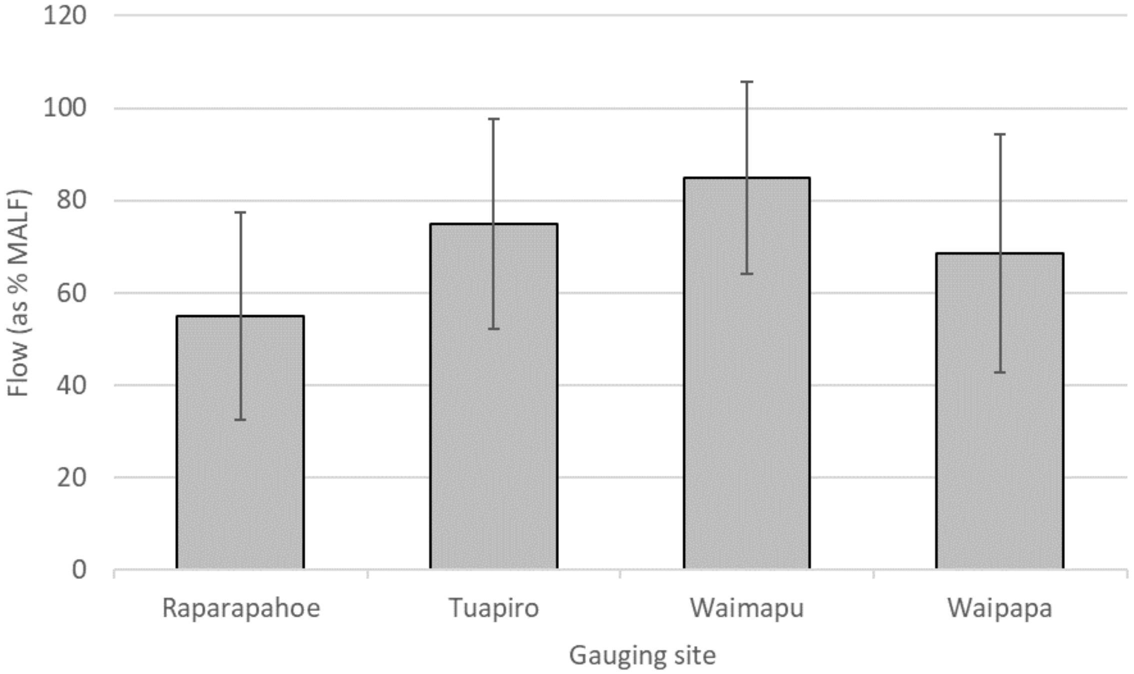

Figure 3 *Box plots of daily flow conditions (mean + 1 SE) from December 2019 to May 2020 at 4 Western Bay hydrological gauging sites.*

Based on these findings, it is expected that these two default minimum flows proposed in streams without target fish is unlikely to pose any ecological risk to invertebrate or periphyton communities in streams in the Bay of Plenty

1.5 Current flow setting in Bay of Plenty

Data obtained from the council’s Accela Database and stored on ARC-GIS (Consent Point - Surface Water Allocation – uploaded 30 January 2021) had 355 records of surface water takes in the region[5]. The majority of these takes were for irrigation for horticulture (predominantly for kiwi fruit, both as irrigation and frost protection), followed by pasture irrigation, commercial-industrial takes, and municipal takes (Figure 4).

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[5] It is acknowledged that this data was correct as downloaded on 30 January 2021. However, as data is added to the consents database, or as data is corrected and recoded, this data is likely to change somewhat.

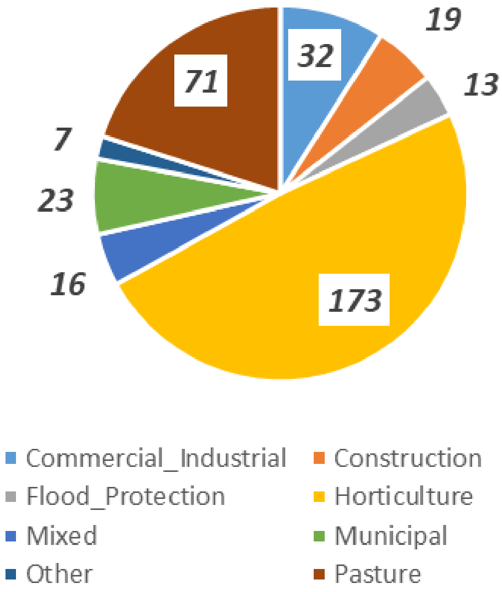

Figure 4 *Summary of the numbers of common types of water takes from surface water in the Bay of Plenty when grouped according to one of eight categories. "Other" includes water for fish hatcheries, discharges into wetlands, and small hydro-power schemes.*

Although many takes were from larger rivers (i.e., fourth order and above), a relatively high number of consents were also from small first and second-order waterways (Figure 5). This emphasises that any methods developed to set Q_{min} need to consider both small streams and large rivers, which is why the two default Q_{min} values were suggested earlier. Interestingly, most water takes come from our definition of "small streams", with a stream order four or less, while takes from larger order five and above are not as common. It is also noted that takes from smaller streams are for lower volumes, whereas takes from larger rivers are for far greater volumes. However, there is still the potential for many small takes from small streams within a catchment to cumulatively add up to a relatively high amount of water being allocated – assuming that all takes are being used at the same time (which is likely to be an over-simplification).

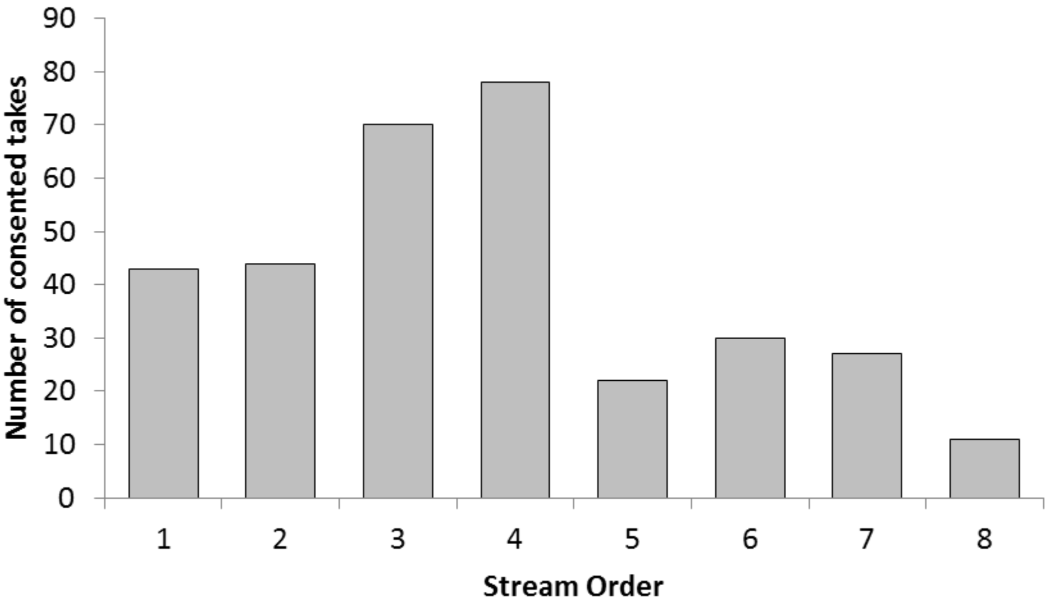

Figure 5 *The number of consented takes within the region from different stream orders*

The take and use of surface waters is managed by BOPRC through implementation of its Operative Regional Natural Resources Plan. Under this plan, a region-wide set default minimum flow, Q_{min} of 90% the Q_5 7-day low flow has been identified, as well as an interim allocation (ΔQ) of 10% of the Q_5 7-day low flow for out-of-stream use. The Q_5 7-day low flow is derived by calculating the lowest of the running 7-day mean daily flows for each year over a 5-year (minimum) record. The lowest of the 7-day mean daily flows over this time (i.e., one in 5 years - or more correctly the 20th percentile) is the Q_5 7-day low flow. The choice of using the Q_5 7-day flow was, presumably, based on reliability of supply objectives set in the regional plan of having water restrictions no more than once in five years on average. It is, therefore, a flow metric for water allocation, but has also been used as a method to derive minimum flows in streams.

The Mean Annual (7-day) Low Flow (MALF) is another flow statistic commonly used throughout the country, including Bay of Plenty for the derivation of minimum flows from RHYHABSIM studies. MALF is calculated as the lowest of the running 7-day mean daily flows for each year. The mean across years is then calculated to give MALF. It does not rely on a minimum of a 5-year period, and so can change on an annual basis. However, as with any flow statistic, more accurate values are calculated with longer hydrological records. MALF will also always be higher than the Q_5 7-day low flow, as the latter is based on the lowest 20th percentile. MALF, or more correctly some proportion of MALF is widely used as a low flow statistic to help set Q_{min} by many councils throughout New Zealand. Finally, proportions of MALF were also recommended as default minimum flows in the proposed National Environmental Standard for Environmental Flows (MfE 2008). Here, small rivers with a mean flow of 5 m^3/s or less had a Q_{min} of 90% MALF and an allocation limit of 30% MALF, while rivers larger than this had a Q_{min} of 80% MALF and an allocation limit of 50% MALF. Although the proposed NES was not adopted, and is not mentioned in the NPSFM, its recommended default minimum flows still have merit for consideration. Consequently, BOPRC could decide to use similar defaults to help set Q_{min} in the region instead of the current 90% Q_5 7-day low flow (which itself also provides for a somewhat arbitrary level of protection, and subsequently treats all waterways as having the same flow needs).

Estimates of MALF can come from sites where BOPRC has continuous flow recording sites (or primary sites) and where MALF is subsequently calculated from this measured flow data, or from secondary sites where summer flow monitoring is done to generate relationships between flows in these catchments and flows in nearby primary catchments. In catchments with no flow recorders, or where there are no secondary sites, the only way to generate values of MALF is to use modelled flow data. Booker and Woods (2014) developed modelled flow data for the Bay of Plenty using random forest models, and these models can be used to calculate MALF in the absence of measured flow data. This modelled flow data was linked to the River Environment Classification (REC), which shows a network of waterways running through valleys defined by a digital elevation model (DEM) with a 20 m contour. This network runs along valleys and contains individual segments (called an NZReach) between in-flowing tributaries. This network is similar to the blue lines that show streams on a standard 1:50,000 topographic map. This means that we can easily estimate specific hydrological flow statistics such as MALF, or the Q_5 7-day flow in any reach of the waterway network in the region if we know its REC NZReach number.

Although the current hydrologically-based water allocation rules are easy to calculate, there are more robust methods to help set more ecologically relevant values of Q_{min} such as derived from detailed IFIM surveys. Site specific assessments of minimum flows for ecological purposes have been made using RHYHABSIM as part of IFIM surveys in 60 streams throughout the region, between 2001 and 2013 (Wilding 2002a, 2002b, 2002c, 2003, 2004; Bloxham 2005, 2008). Sites were chosen for a variety of reasons, such as:

- Streams in the East Cape, Whakatāne and Ōhope areas with either current or anticipated abstraction pressure, or regionally significant trout fisheries (Bloxham 2008)
- Streams in Rotorua that containing regionally significant trout or native fisheries, and the need to protect these from current or anticipated abstraction pressure (Bloxham 2005)
- Overallocation of water in streams in the Galatea Plains, and increased demand for more takes (Wilding 2002)
- Streams in the Kaimais subject to significant abstraction pressure (Wilding 2002)
- The Waitahanui Stream, which was already over-allocated, and where there was a desire to define an appropriate Qmin (Wilding 2000)

The IFIM methodology was subsequently used to propose Instream Minimum Flow Requirements (IMFRs) as the Q_{min} necessary to protect instream hydraulic habitat for selected fish species at these sites. A slight mistake in the wording of the original IMFR methodology meant that some IMFRs were calculated to be greater than a river's MALF. Establishing an IMFR higher than MALF means that abstractors would need to restrict or cease abstraction at flows above MALF. Doing this at such high flows would, however, unlikely have any demonstrable ecological benefits, as stream flows would naturally decline to the lower MALF. Jowett (2012) thus reviewed the initial methodology and argued that new IMFRs be calculated to retain a *percentage of habitat at the MALF*, and to omit consideration of habitat at median flow from the method. New IMFRs have subsequently been recalculated at 53 of these sites using the original IFIM data (Suren 2019). The final IMFR for each stream was selected based on the highest flow needed to protect a specified amount of the hydraulic habitat for different fish species. By selecting the highest flow, it is assumed that species with lower flow preferences would also be protected. The different fish species identified in this analysis included 6 native species (torrent fish, banded kokopu, common and redfin bully, smelt and inanga) and trout (rainbow or brown). These eight species are hereafter referred to as “target fish”, reflecting their common distribution throughout the region, and often high flow preferences (See Appendix 1).

Significant relationships were found between the IMFR and MALF, although IMFRs derived for trout were significantly higher for a given MALF than IMFRs derived for native fish. This emphasises the greater flow requirements of trout than native fish. Suren (2019) suggested that the strong relationships between calculated IMFRs and MALF meant that IMFRs could be calculated for other streams where IFIM surveys had not been done but where target fish were expected, based on these observed regression equations. Any IMFRs calculated from these regressions only needed to consider whether a minimum flow was being set for native fish or trout as the management objective. A similar procedure had already been recommended by Wilding (2003) for streams in the Tauranga area. Although this appears a relatively simple process, it may be somewhat complicated by the need to decide whether a stream is to be managed for either trout or native fish. However, a more generalised regression exists between fish IMFRs and MALF irrespective of fish species (See Section 3 in Appendix 1), and this generalised regression can also be used to calculate an appropriate minimum flow to protect hydraulic habitat for fish, based on its measured or modelled values of MALF.

This report was written to address three major questions:

1 *What are the relationships between the Q_5 7-day low flow and MALF?*

   This was addressed using data from two sources:

   (a) Modelled data using NIWA hydrological statistics from Booker and Woods.
   (b) Measured data at council's low-flow monitoring sites.

2 *What are the best ways to set Q_{min} in streams?*

   There are four methods for this:

   (a) The historic IFIM surveys to provide data to set new IMFRs in all catchments above the individual IFIM sites. These catchments cover about 40% of the region's land area.
   (b) The observed regressions between IMFRs and MALF for native fish and trout, based on Suren (2019). An alternative regression could also be developed for a generalised relationship between IFMR and MALF.
   (c) Regional defaults, based on a percentage of measured MALF as a regional default in streams where flows are measured
   (d) Regional defaults, based on a percentage of modelled MALF as a regional default in ungauged streams

It is emphasised that this report only considers setting minimum flows to protect ecological values from run of river takes without large reservoirs. It is also acknowledged that setting a Q_{min} is only one part of the water allocation puzzle. Other relevant parameters to consider are both the amount of water that can be allocated (ΔQ), as well as the reliability of supply (R). However, both these components are outside the scope of this present work, although it is acknowledged that setting a specific Q_{min} has large consequences for both overall availability and reliability as well as the residual flows that determine in-stream effects.

Part 2:
Methods and Results/Huarahi Ngā Otinga

2.1 What are the relationships between measured and modelled flow data?

Booker and Woods (2014) used a random forest model to generate modelled flow statistics in ungauged streams throughout New Zealand. The resultant dataset was used to extract modelled flow statistics for all 28,385 NZReaches throughout the Bay of Plenty. To check the accuracy of this modelled random forest data, a regression was done between modelled MALF and measured MALF at 119 sites monitored by EDS, as well as additional 69 IFIM sites where we had data for measured MALF, gleaned from the relevant reports describing these studies. These sites were spread throughout the region (Figure *6*).

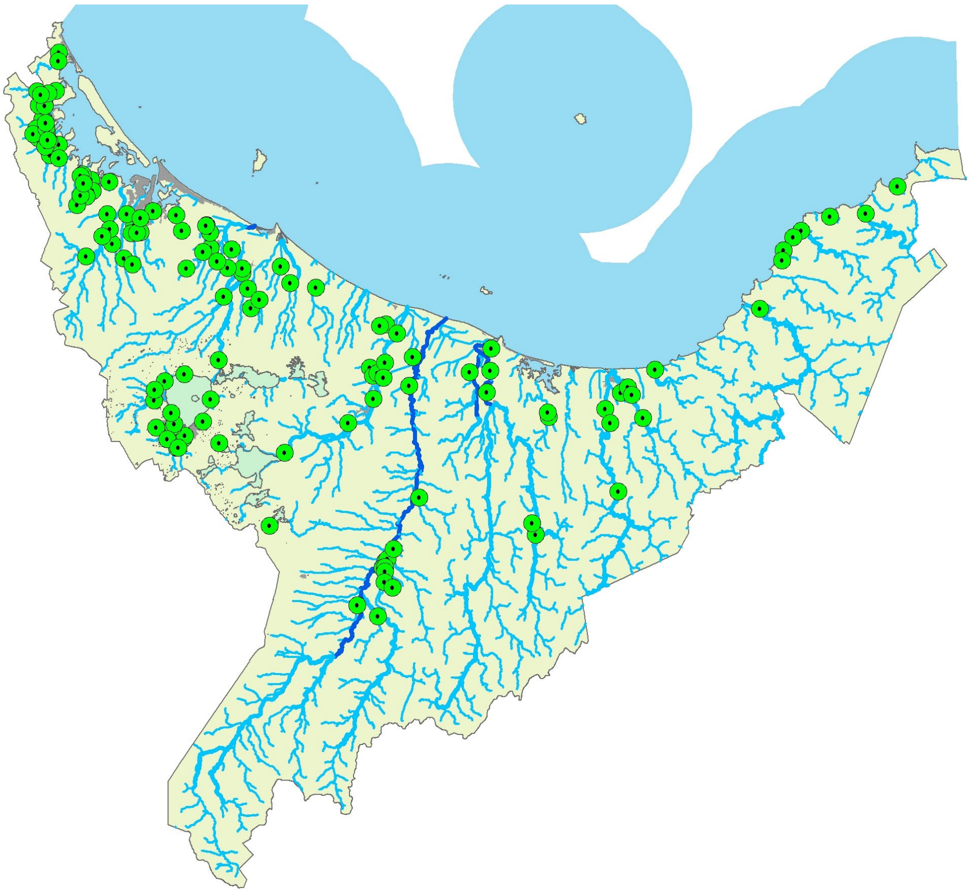

Figure 6 Map showing the location of the 203 sites throughout the region where we had estimates of MALF based on site measurements. Of these, 18 sites were omitted as they were either spring fed or affected by hydro-power schemes.

Examination of the full data set revealed some large inconsistencies between modelled and measured values of both MALF and Q_5. Three reasons were apparent for this. Firstly, some sites were below large, well-known springs, which effectively increased flow from upstream groundwater resources that were far larger than the upstream surface catchment alone. For example, the Awahou Stream, Hamurana Stream, and Mangaone Stream all had measured flows that were respectively 7.6, 70.1, and 10.5 times higher than their modelled flows, which were standardised by their catchment areas. Secondly, two sites on the Tarawera River (Tarawera at Awakaponga, and Tarawera at SH30) had higher measured flows than modelled reflecting the fact that the Tarawera River is lake fed. Lastly, two sites were affected by hydro-power generation, and had much lower measured flow indices than modelled. Because of this, 18 sites were omitted from further analysis, leaving 170 sites for this initial comparison.

With these outliers omitted, the regression analysis showed a significant relationship ($P<0.001$) between measured and modelled values of MALF (Figure 7), giving us confidence that the modelled flows from Booker and Woods (2014) were reasonable, at least at sites that were not spring fed or lake fed, or affected by hydro-schemes. Indeed, 126 sites (or 75%) had modelled MALF values to within + 20% of the measured values. It is acknowledged that our ability to accurately predict the location of waterways with a significant groundwater component is limited at this stage, so we will need to rely on actual measured flows from these waterways until our model performance has improved to spatially identify springs and estimate their flow. Fortunately, BOPRC is currently implementing a spring monitoring programme (Green 2108) that is expected to add considerably to our knowledge of not only where springs are, but also their flow regimes.

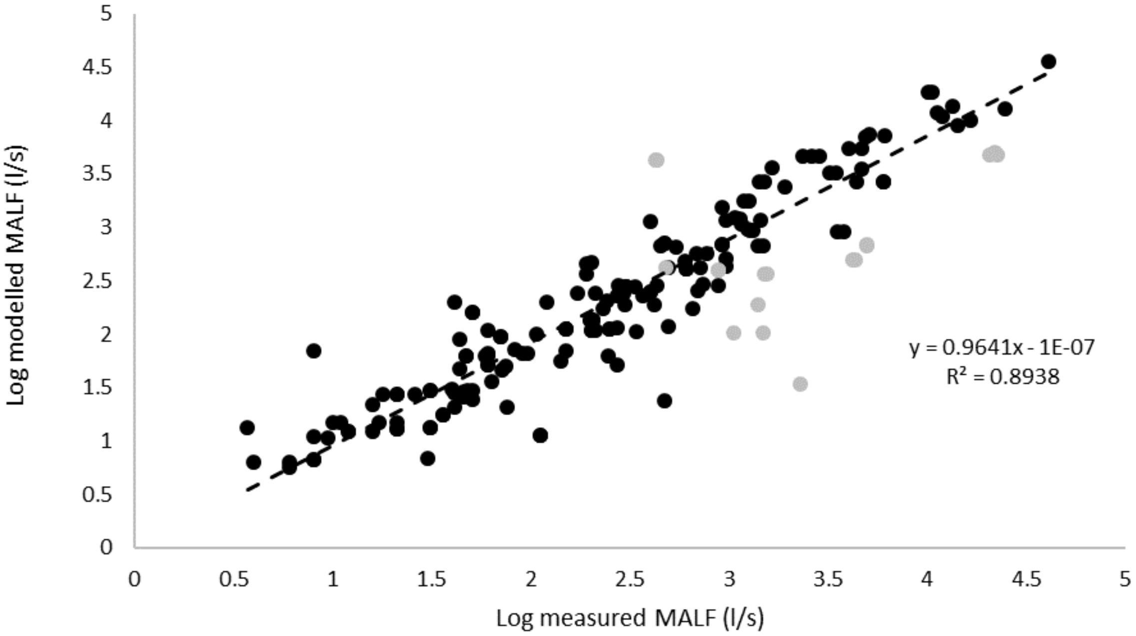

Figure 7 *Regressions between modelled MALF and measured MALF in 170 sites throughout the Bay of Plenty. Grey symbols indicate sits removed from the regression as these were from springs, lake fed rivers, or in rivers affected by hydro-schemes. Their measured flows were usually much higher than their modelled flows.*

2.2 What are the relationships between *Q_5* and MALF?

Following this analysis, relationships between MALF and the Q_5 7-day low flow were investigated, using data from two sources: measured data from the council's Environmental Data Services (EDS) team to give estimates of both the Q_5 and MALF, and modelled data from Booker and Woods (2014) for the Q_5 and MALF. Examination of measured flow data showed highly significant ($P<0.001$) relationships existed between the measured MALF and measured Q_5 7-day flows at the sites monitored by the EDS team (Figure 8).

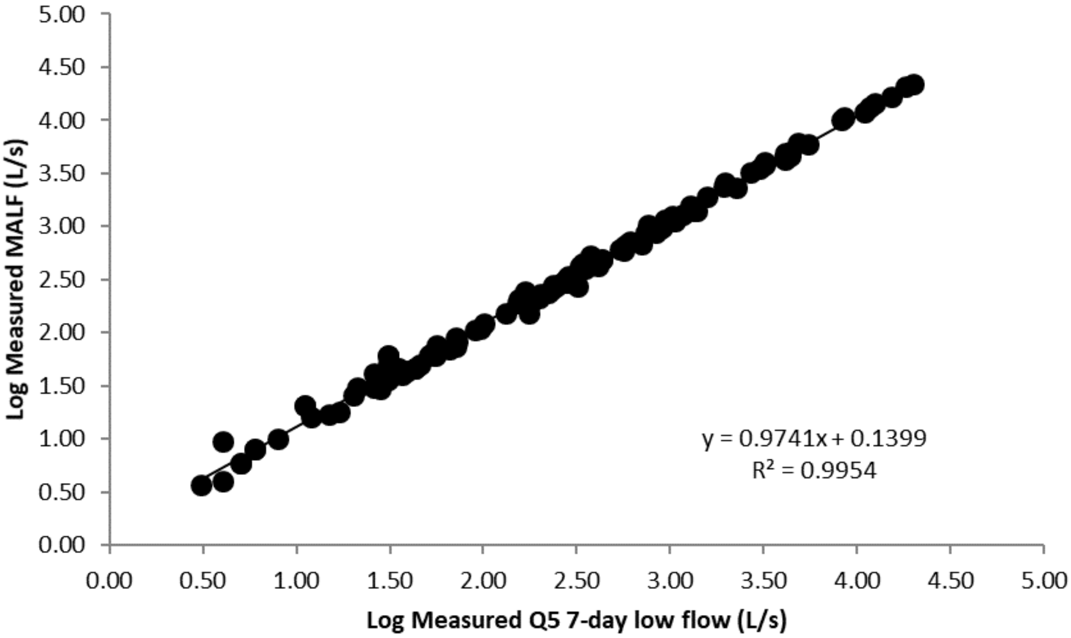

Figure 8 *Regressions between measured MALF and Q_5 7-day low flows in 123 sites throughout the Bay of Plenty. Note that both flow indices were log transformed, as the untransformed data was skewed, with many small sites and fewer larger sites. Such skewness violates many assumptions of data analysis and can distort analytical results.*

Similarly, highly significant regressions were observed between modelled MALF and Q_5 statistics for all 28,385 NZReaches throughout the Bay of Plenty (Figure 9).

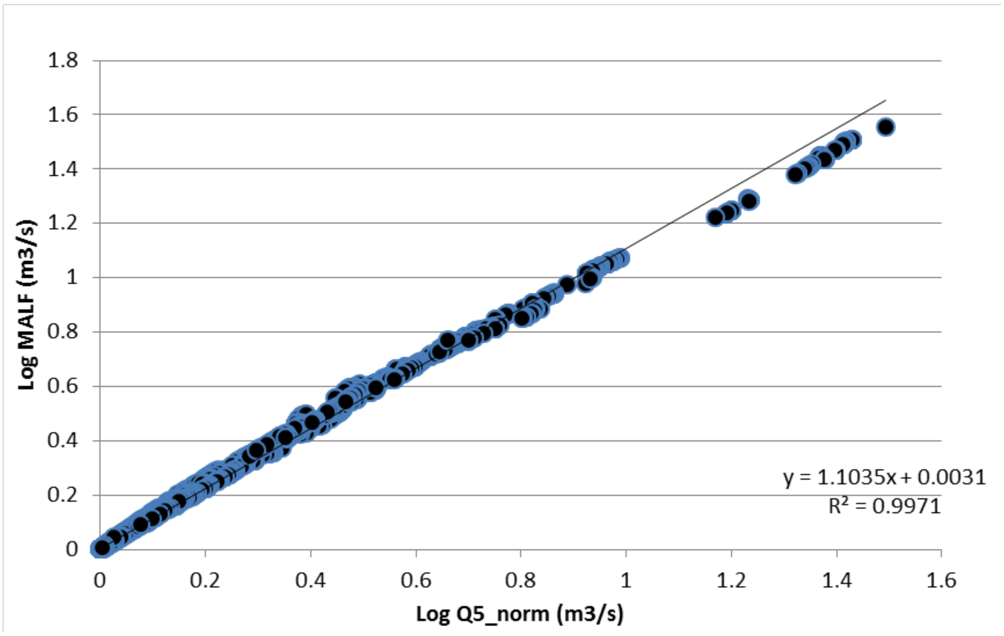

Figure 9 *Regressions between modelled MALF and Q_5 7-day low flows in 28,358 NZReaches throughout the Bay of Plenty. Again, all values have been log transformed for normality.*

Both regression models were in the form of:

$MALF = a \times Q_5 + b$

Where *a* is the slope of the regression, and *b* is the y-intercept. The fact that the slope from both regressions was close to 1 suggests that values of MALF were very similar to values of the Q_5. The y-intercept in both regressions was also higher than 0, indicating that values of MALF at a particular site were slightly higher than values of the Q_5. This is simply a reflection of the ways that each flow statistic is derived. These significant relationships can give us a high degree of confidence that MALF could be used as an alternative low flow statistic as the Q_5 7-day flow. This second analysis was based on modelled flow data from the Bay of Plenty region, using random forest models (Booker and Woods 2014). Although Booker (2014) found that that calibrated TopNet models represented the best available method for calculating mean flow, MALF and the proportion of flow in February at ungauged sites across the Bay of Plenty region, the calibrated TopNet data was only available for part of the region, mostly in the east. As such we had to rely on the random-forest models to generate flow statistics from all NZReaches in the region for use in this report.

The effect of switching from Q5 7-day flow to MALF will vary depending on the flow characteristics of the stream. Values of Q5 were only 82.9 ± 11.4% of those of MALF. This means that a hydrologically based default IMFR based on using some percentage of MALF will effectively increase the resultant Q_{min}, as well as increasing the actual amount of water that is allocated (ΔQ) if this is also set at some percentage of MALF. Any changes in ΔQ value and Q_{min} may then have unintended effects on the reliability of supply. Any effects of potential changes in Q_{min} and ΔQ value arising from using MALF as the flow-setting hydrological statistic needs to be assessed with running a few scenarios in appropriate modelling packages, such as the recently released eFLows from NIWA.

Recommendation 1. Strong relationships exist between Q5 7-day and MALF, based on both measured and modelled data. Given the widespread use of MALF throughout the country, it is suggested that all low flow statistics in the Bay of Plenty are in future plan changes based on MALF.

2.3 What are the best ways to set Q_{min} in streams?

The current hydrological default of setting regional Q_{min} values of 90% the Q_5 7-day low flow has several limitations. Firstly, a simple hydrologically-based rule to create a Q_{min} may miss subtle nuances between streams that support different fish communities, and may not give enough protection to some streams where highly valued fish occur. It may also “over-protect” streams where fish are absent, as such streams may be able to tolerate lower base flows and still maintain healthy ecosystems. Lastly, other low flow statistics such as MALF are used by councils throughout New Zealand and is also consistent with the proposed NES for Environmental Flows (MfE 2008). Because of this, a more nuanced approach to creating Q_{min} was deemed appropriate.

Given the inherent tensions between the need to maximise ecosystem health (by, for not allowing, or severely restricting takes) or maximise the amount of water available for allocation (by, for example, allowing streams to fall well below recommended Q_{min} values: see Figure 1), any decisions about setting minimum flows need to be based on a clear hierarchy of data reliability. This approach is similar to the one outlined in the proposed NES for Environmental Flows (MfE 2008), where increasingly accurate methods at assessing ecological flow requirements are made for given combinations of degrees of hydrological alteration (Low, medium and high) and significance of instream values (low, medium and high). In situations with high instream values, two or more complementary methods are recommended, because of the potentially greater risks to stream ecology of making an incorrect ecological flow decision.

A similar hierarchical approach is recommended here but focussed mainly on inherent methodological and data accuracy. Firstly, the IFIM methodology is a more robust method for defining Q_{min} in rivers to protect a specific amount of hydraulic habitat for target fish species, compared to a simpler defined percentage of Q_5 (Jowett et al. 2012; 2018). Therefore, results of the IFIM surveys should take precedence over simpler methods. Such a methodology would be suitable in streams of high ecological value, and where a high rate of abstraction is proposed, or occurring. Secondly, measured values of MALF[6] would take precedence over modelled values as they are regarded as being more robust. This is particularly true in many of the spring fed systems found throughout in the region, the locations of which are hard to accurately model. Thirdly, the strong relationships observed by Suren (2019) between a river’s IMFR and either measured or modelled MALF suggest that regression equations to predict an IMFR would be more robust than simply using the value of either measured or modelled MALF. Finally, in the absence of other data, modelled values of MALF can be used to help inform an appropriate Q_{min} as some form of regional default. This hierarchy can be used to help develop a transparent system to set Q_{min} of all waterways throughout the Bay of Plenty.

Note, however, that any methods designed to protect a specified amount of hydraulic habitat for fish are not applicable to streams where fish are absent. Because of this, it is suggested that one of the important steps in setting Q_{min} in waterways would be to determine whether a specific waterway supports target fish.

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[6] Assuming that these measurements were made to meet current hydrological gauging standards.

If they do not, then any resultant Q_{min} need not be based on protecting the hydraulic habitat for these fish, but instead could be based on protecting other attributes that are indicators of stream ecosystem health like periphyton or invertebrate communities. Given that periphyton proliferations appear uncommon in the region (Kilroy et al. 2020), and that invertebrate communities are only weakly structured by low flows (see section 1.4), it is assumed that adequate ecological protection of streams would still be maintained by using some other consistent hydrological default not based on protecting the hydraulic habitat of the target fish.

A hierarchical process is consequently suggested to help create a transparent process by which to select an appropriate method for establishing a Q_{min} in waterways throughout the Bay of Plenty region. It can be summarised below in the form of a “dichotomous key”, where the YES or NO answer to each question takes us to the next step in the process:

1 Has an IFIM survey been undertaken in the catchment?

YES – use the IMFR (as %MALF) as the Q_{min}. Go to 2
NO – go to 4

2 Is the IFIM site a large river ($\bar{Q}$ > 5 m3/s)?

YES – go to 3
NO – use the IMFR (as % MALF) throughout the catchment

3 Are other NZReaches above the IFIM site large rivers $\bar{Q}$ > 5 m3/s)?

YES - use the calculated IMFR in all large rivers ($\bar{Q}$ > 5 m3/s))
NO – use regression equations between IMFR and measured MALF

4 Are target fish expected in any reaches affected by the proposed take?

YES - go to 5
NO – go to 6

5 Are there measured values of MALF?

YES - use regression equation between IMFR and measured MALF
NO - use regression equation between IMFR and modelled values (Booker and Woods 2014) of MALF

6 Is the NZReach a large river ($\bar{Q}$ > 5 m3/s)?

YES --- use regional default Qmin of 60% MALF
NO – use regional default Qmin of 70% MALF

In an earlier report, Suren (2019) proposed a decision support diagram to explain links between the different tools available for setting Q_{min}, such as use of regional defaults and the IFIM methodology. However, this earlier suggested methodology did not explicitly require an assessment of whether target fish were within a stream, did not explicitly distinguish between large and small rivers, and did not clearly articulate a methodology to decide whether to use measured or modelled data for MALF. The newer hierarchical process outlined above is thus far more nuanced that that outlined in an earlier report (Suren 2019). It also recognises the fact that measured estimates of MALF are more robust than modelled estimates. It is thus suggested that this new decision support flowchart be used instead of the earlier one.

By answering yes or no to these six questions, a set of five methodologies have been identified as being the most appropriate method to use to set minimum flows throughout the region. The steps in this flowchart (Figure 10) are as follows:

1. Has an IFIM survey been undertaken in the catchment? If so, then the Q_{min} is the calculated IMFR at the IFIM site, expressed as a percentage of MALF. This then becomes the Q_{min} for all NZReaches above the location of the IFIM site (but see Point 2, below). All IFIM sites where measured values of MALF were available, so all this data is based on the best available hydrological data as well.

2. Some IFIM sites were on large rivers, which are less sensitive to low flows than smaller rivers. Calculated IMFR's may thus be only a relatively small percentage of MALF at these sites. To impose such a low Q_{min} throughout the catchment in smaller streams cannot be justified from an ecological perspective. The second step to the flowchart is thus to determine whether the ***IFIM site*** is a large river ($\bar{Q} > 5$ m^3/s) or not. If flows at the IFIM site are < 5 m^3/s, then all upstream reaches will have the same Q_{min} as derived from the IFIM survey (expressed as a % of MALF).

3. If flows at the IFIM site are > 5 m^3/s, then the calculated IMFR at the site will be maintained throughout all large rivers in the catchment ($\geq$ 5 m^3/s). The third step is to thus determine whether each individual NZReach ***above the IFIM site*** is a large river ($\bar{Q} > 5$ m^3/s) or not. If so, then this NZReach will have the same Q_{min} as derived from the IFIM survey. If not, then all smaller NZReaches in the catchment will have their Q_{min} calculated on the basis of the generalised regression equation between IMFR and measured MALF.

4. If an IFIM survey has not been undertaken, then the fourth step is to determine whether target fish are expected at each NZReach. If target fish are expected, then the Q_{min} will be calculated on the basis of the generalised regression equation between IMFR and MALF. Use of the generalised regression equation avoids the added complexity of deciding whether a specific NZReach is to be managed for either the target native fish, or trout.

5. The fifth step is to determine whether there are measured values of MALF in the catchment. If there are, then MALF can be calculated in all NZReaches above the flow site based on catchment area. Q_{min} is subsequently calculated based on the generalised regression between measured MALF and IMFR. If MALF is not measured, then use the modelled values of MALF based on Booker and Woods (2014) in the regression equations to calculate Q_{min}.

6. Finally, if an IFIM survey has not been undertaken, and target fish are not expected at the NZReach, then IMFRs are based on regional defaults aimed at protecting other ecosystem components such as invertebrate and periphyton communities. If flow at an individual NZReach is > 5 m^3/s, then the regional default if 60% MALF is used (Large River), otherwise the regional default of 70% MALF is used (Small Stream).

Recommendation 2. Make use of the hierarchical decision-making process to inform the methodology of setting appropriate Q_{min} of waterways throughout the region. This hierarchy consists of a dichotomy of: 1) whether an IFIM survey has been done; 2) are target fish expected; 3) do we have measured values of MALF; 4) is the stream in question large or small? Where target fish do not occur, use default Q_{min} of 70% MALF in small streams, and 60% MALF in larger rivers.

Many of the IFIM sites were located in the middle reaches of catchments, so the calculated Q_{min} were initially set to all NZReaches at and above the IFIM site. This decision was made to reduce the potential “granularity” of the resultant low flow maps, as the method used to set a Q_{min} would change as we moved up the catchment, and as fish were no longer predicted to occur. When this occurred, the default flow limit would instead be used. This would likely lead to an overly complex set of multiple low flow limits within individual catchments, with follow on implications for planning and compliance efficiencies. A final step in this process was to determine whether the same Q_{min} could be applied to reaches below the IFIM site. This was an important step, as there were more consented water takes in the lower parts of many of these catchments. A manual assessment was consequently made of all NZReaches below an IFIM site, as well as the number of large tributaries flowing into reaches below the IFIM site. These reaches below the IFIM site were subsequently allocated the same Q_{min} if they were close to the initial IFIM site and if no larger tributaries flowed into the reach.

Recommendation 3. Extend the values of Q_{min} (as a % of MALF) to sites below an IFIM survey, as outlined by the steps in Section 1.4 in Appendix 1.

These interlinked steps are discussed in more detail in Appendix 1. By using these steps, the recommended Q_{min} of all 25202 NZReaches in the region was calculated. This assessment included all the new IMFR calculations from the IFIM sites identified in the Suren (2019) report, as well as 13 other IMFRs derived from IFIM surveys conducted throughout the region as part of consent applications. Of these 13 IFIM surveys, three were in the western Bay of Plenty, while the other 10 surveys were located to the east of Opotiki.

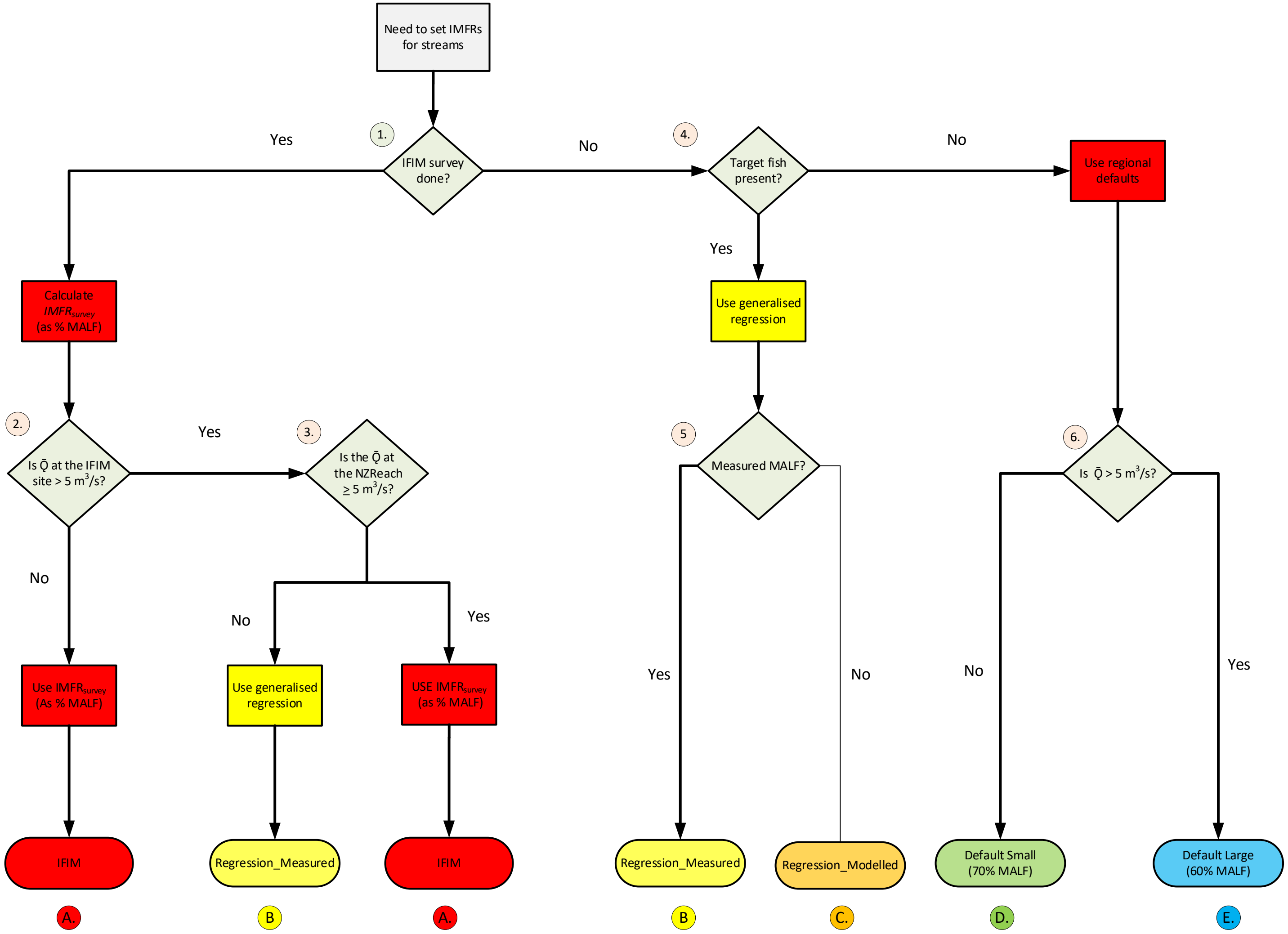

Figure 10 *Flowchart summarising the necessary steps taken to decide which methodology should be used to help set Q_{min} in the region's waterways.*

Examination of all 25,202 NZReaches showed that the majority of reaches (45.7%) would have their Q_{min} calculated based on the IMFR values derived at a result of the IFIM surveys (Table 1). The fewest number of reaches (0.3%) would have their Q_{min} based on the default value of 60% MALF, aimed at protecting ecological values in large rivers.

Table 1 The number and percentage of NZReaches in the region where Q_{min} is set using each of the five different methodologies to obtain low flow statistics.

Flow assessment methodology	Flow statistic	Number of NZReaches	Percentage of NZReaches
A	$IMFR_{surveys}$	11527	45.7
B	$Regression_{\_measured}$	2720	10.8
C	$Regression_{\_modelled}$	4706	18.7
D	Default 70% MALF	6169	24.5
E	Default 60% MALF	80	0.3

Examination of the spatial distribution of the different flow setting methods showed that $IMFR_{survey}$ methodology was found throughout the region, reflecting the large number of IFIM studies done by both BOPRC and consultants (Figure 11). Most of the IFIM studies were done in catchments with a high allocation pressure, such as in the Western Bay and Te Puke area, Rotorua, Galatea Plains, and Eastern Bay sites near Omaio. Indeed, of 335 consented water takes from surface water, just under 50% were in catchments where IFIM surveys had been undertaken. Another 30% of consents were from catchments where Q_{min} was calculated based on the generalised regression method using modelled flow data. Only 11% of consents were from areas where the Q_{min} would be set using regional defaults, suggesting that our hierarchical method was indeed applying more robust methods where abstraction pressure was high, and applying less stringent rules where abstraction pressure was low.

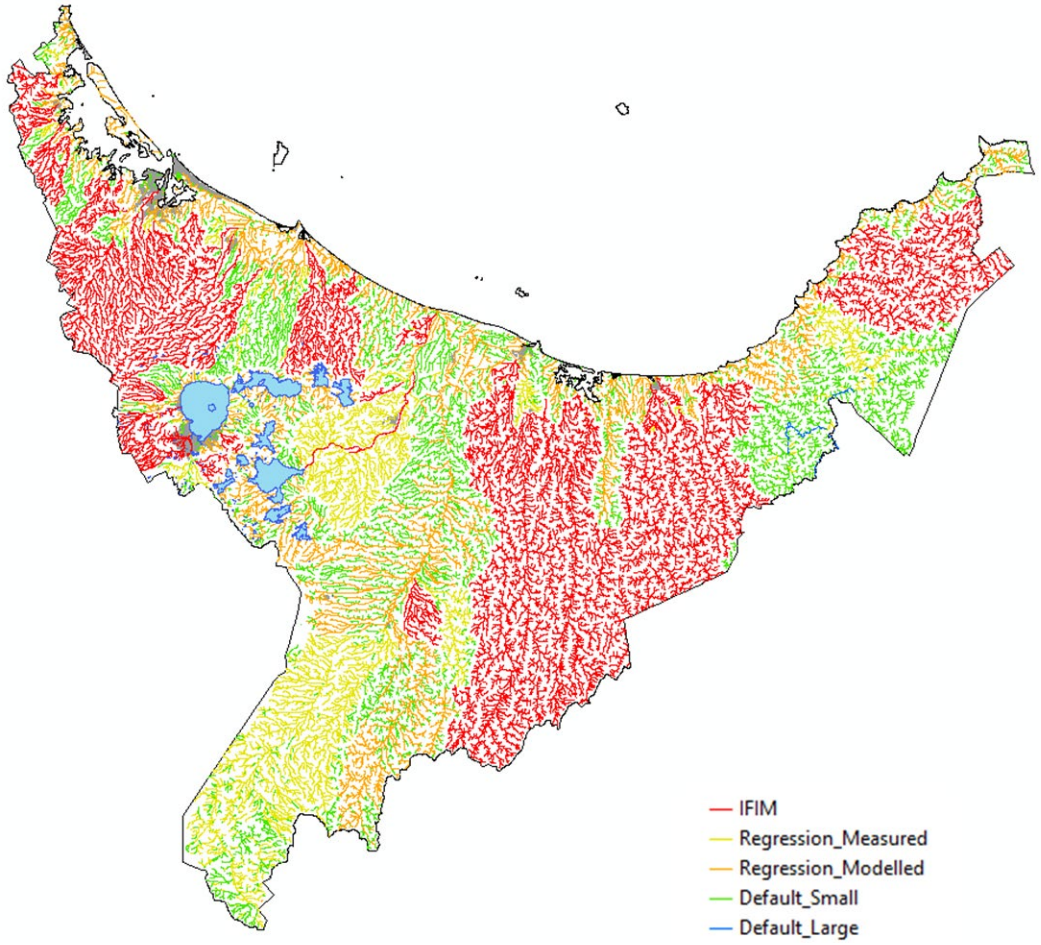

Figure 11 Spatial distribution of waterways throughout the region showing the recommended method used to calculate minimum flows.

IFIM surveys were absent from a number of areas including:

- The central Kaituna Plains, including the Pokopopko, Puanene and Wharere Streams.
- Streams around the Matata area.
- The Rangitaiki River.
- The Waiotahi Valley.
- Large eastern Bay rivers such as the Motu River.

In these areas, Q_{min} was calculated based on either the use of regression equations (for streams where target fish were predicted to occur), or on generalised defaults of 60% or 70% MALF to protect other ecological values of waterways where the target fish were not predicted to occur.

The Rangitaiki Catchment is unusual in that, although an IFIM has in fact been derived for flows in the lower Rangitaiki below the Matahina Dam (Ryder 2009), this was not selected as the appropriate Q_{min}. The IFIM surveys in the Ryder study showed that the flow of only 10m^3/s provided near optimal habitat for native fish, and for small brown and rainbow trout. Flows of only 20 m^3/s provided maximum habitat for adult rainbow trout, as well as maximising food producing habitat (i.e., invertebrate densities). However, flows this low would have resulted in a large upstream movement of the saltwater wedge, adversely affecting many irrigators in the lower Rangitāiki. As such, the ecologically relevant Q_{min}

was deemed inappropriate for this river, and instead another Q_{min} was selected to protect other values. It is recognised that a similar decision may also be made for some of the other recommended Q_{min} values in this report, which are based purely on maintenance of ecological values.

The vast majority of Q_{min} estimated using the decision tree throughout the region were either 90% or 70% of MALF, although some Q_{min} values were as low as 30% or 50% of MALF (Figure 12). The majority of IFIM reaches had a Q_{min} of 90% MALF, although some sites had as high as 95% MALF, or as low as 30% MALF (Figure 13). Q_{min} derived from the generalised regression using measured flow data were either 70% or 80% MALF, while Q_{min} derived from the generalised regression using modelled flow data were either 90%, 95%, or 100 %MALF.

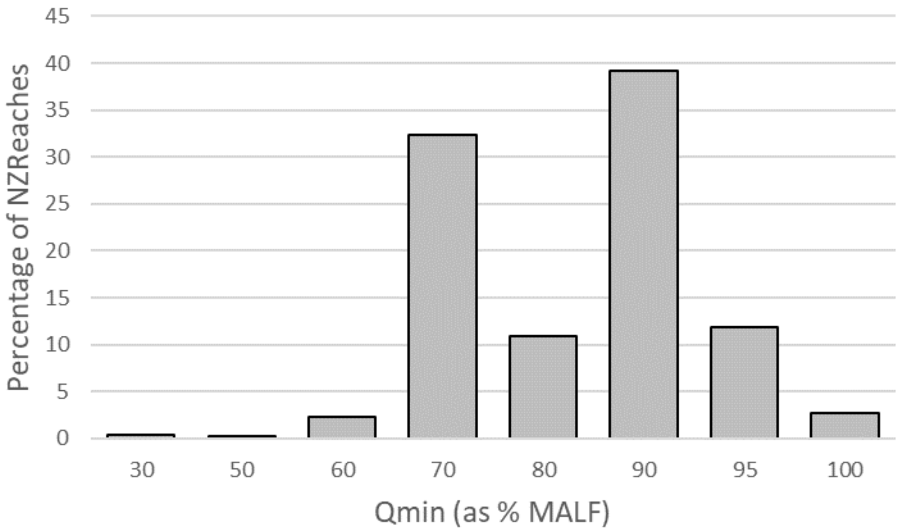

Figure 12 Bar chart showing the percentage of NZ reaches with different Qmin (as a % of MALF) as derived using one of the five methods.

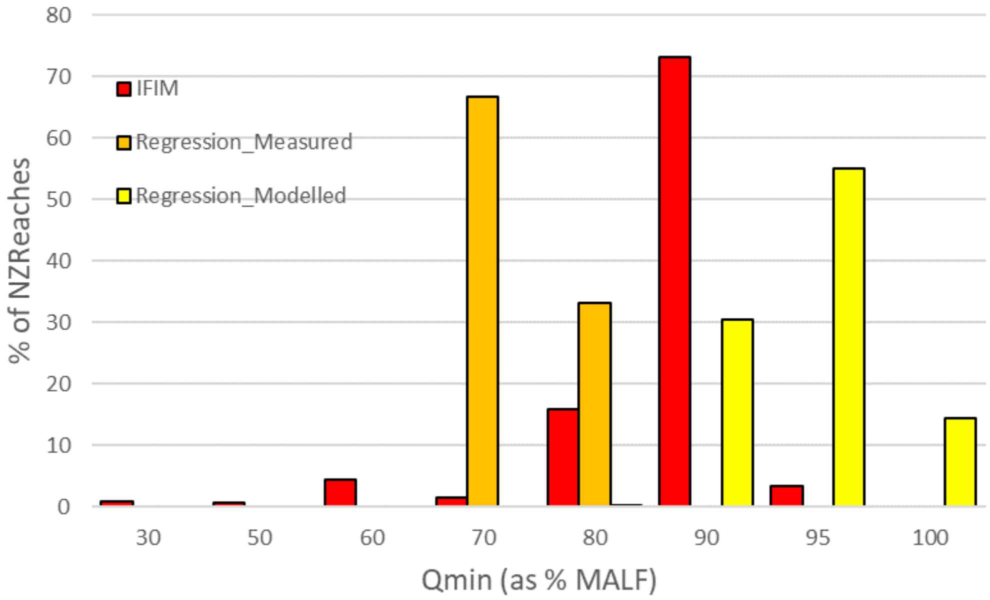

Figure 13 Bar chart showing the percentage of NZ reaches with different Qmin as derived using either the IFIM methodology, or the generalised fish regression for either measured or modelled MALF.

The spatial distribution of the different recommended Q_{min} is shown in (Figure 14). Note the very low Q_{min} ($\leq$ 30% MALF) in three streams: Joyce Stream, Waiorohi Stream, and the Tarawera River. The IFIM for Joyce Stream was conducted by Wilding (2003) as part of low flow investigations in streams around Tauranga. The low IMFR here was calculated to protect the hydraulic habitat for banded kokopu. The IFIM survey of the Waiorohi Stream was done by Baker and Jowett (2001) as part of a study into establishing a Q_{min} for a water treatment plant, and their resultant IMFR was designed to protect the hydraulic habitat of common and redfin bullies. The Tarawera IFIM study was conducted by Bloxham (2008) and was designed to protect the hydraulic habitat for rainbow trout. The resultant low Q_{min} in the Tarawera River River highlights the fact that larger rivers often have large areas of unsuitable hydraulic habitat of fish at high flows, and that this hydraulic habitat becomes more suitable as flows reduce. This is one reason why this low Q_{min} was not recommended for other smaller catchments that flowed into the Tarawera River. Instead, Q_{min} in these smaller waterways was derived based on the regression equations.

Other relatively low Q_{min} values were found in the Waioho Catchment that flows into the Whakatane River, the Waiari Stream (Q_{min} of 60% MALF), and Whakatao and Te Puna streams that flow into the Tauranga Harbour (Q_{min} of 50% MALF). The fact that these values (derived from IFIM surveys) were less than the proposed default Q_{min} for small streams (70% MALF), highlights that in some cases Q_{min} can be less than these defaults and still protect the hydraulic habitat for fish.

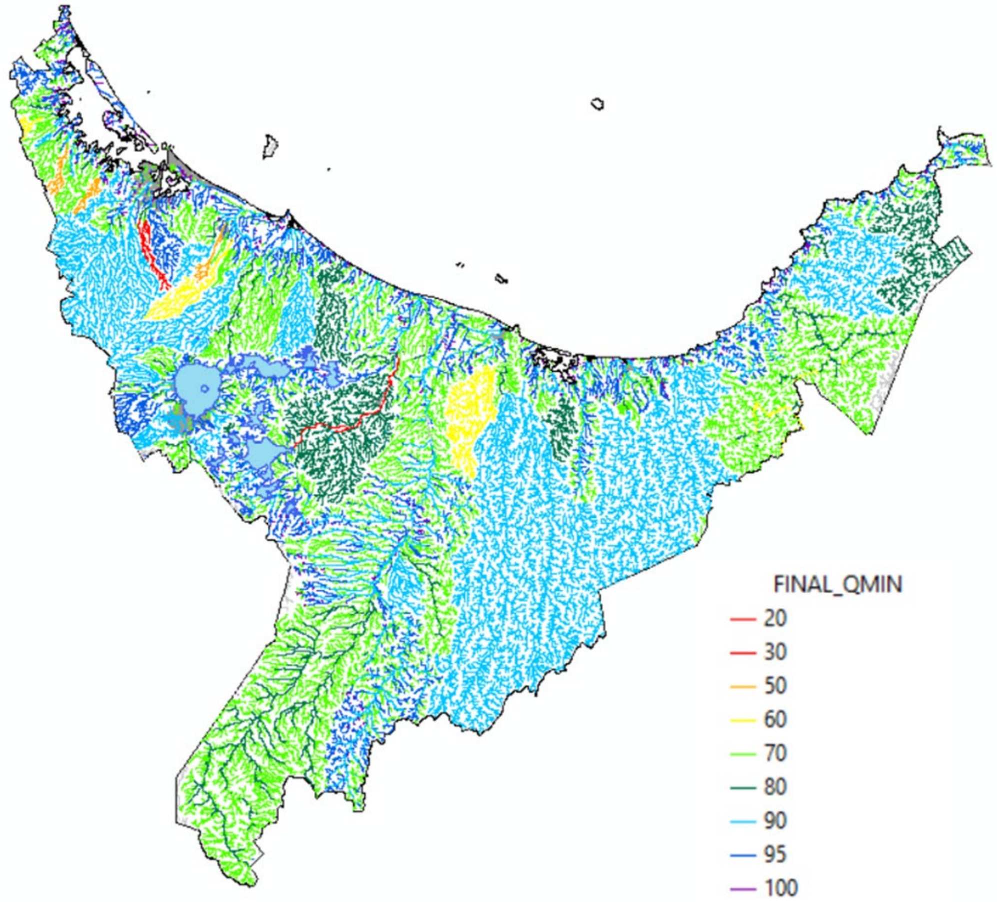

Figure 14 The spatial distribution of the different recommended Q_{min} values in all NZReaches within the Bay of Plenty.

Part 3: Discussion/Matapakitanga

Within the Bay of Plenty, there are over 25,000 individual NZReaches, and minimum flows need to be set for all of these. The challenge faced by BOPRC is to decide which of the many methods can be used to set Q_{min}, and which method is the most relevant for each NZReach. Fortunately, a number of low-flow and water allocation related work has been undertaken throughout the region, including targeted IFIM surveys at 54 catchments, as well as low-flow recording measurements at 134 monitoring sites by BOPRC. A further 15 other IFIM surveys have also been done by consultants as part of resource consent investigations for irrigation or public water supply. This means that Q_{min} derived from IFIM surveys can be identified for waterways in about 45% of the region's land area. However, waterways in the other 55% of the region's area needs to have their Q_{min} set by some other method.

A further challenge with this process reflects the fact that the vast majority of waterways throughout the region are ungauged, so the only realistic way to manage these is by using modelled flow data, such as the random forest data of Booker and Woods (2014). This means that there are three potential data sources available for setting minimum flows in streams throughout the region:

1 The IFIM data (representing the most robust, but spatially limiting way to define minimum flows (Q_{min})).

2 Data from the EDS surveys (which gives us more spatial coverage to assess the magnitude of low flows.

3 Modelled flow data (representing the least robust, but most regionally extensive way to define Q_{min}).

Another complication with setting minimum flows is the fact that water is abstracted from even smaller first and second order streams, as well as the much larger fourth and fifth order rivers. Given that larger rivers are less sensitive to low flows than smaller rivers, the final recommended Q_{min} for a particular waterway is likely to differ based on a waterway size.

The hierarchical methodology outlined above was thus designed to use all this available data in a robust, defensible and transparent manner that is intended to allow the policy and planning team to help set Q_{min} throughout the region to protect ecological values. The decision support hierarchy outlined above is designed to make the best use of all available data in helping to select an appropriate Q_{min}. This is consistent with section 1.6 of the NPSFM (2020), which highlights that decisions need to be based on 1) *the best information available at the time* (i.e., IFIM and measured values of MALF), and 2) *in the absence of complete and scientifically robust later, the best information may include information obtained from modelling* (i.e., the use of generalised relationship between IMFR and MALF to generate the regression curves, and the use of the Booker and Woods (2004) random forest hydrological statistics). Furthermore, the recommended default limits to be used to protect ecosystem values such as invertebrates and periphyton are based on a significant amount of published work in Canterbury (e.g., Suren et al. 2003a, b, Dewson et al. 2007a; James and Suren 2009), as well as more recent observations on the effects of a five-month drought on invertebrate and periphyton communities in the Bay of Plenty. As such, the proposed hierarchical approach does indeed use the best available data.

All calculated Q_{min} from this methodology were further simplified by rounding them into Q_{min} classes to the nearest $\underline{+}$10% increments of MALF, with the exception that flows between 90% and 100% MALF were rounded to the nearest 5%. This exception was in acknowledgement that under the current RNRP, permitted takes are allowed from some streams where the rate of abstraction is less than 2.5 L/s. Therefore, if the Q_{min} classes were set at 90% and 100% MALF, there would be no scope for these small, permitted takes, while setting a Q_{min} at 95% MALF does recognise these.

Rounding the actual Q_{min} values into these discrete classes resulted in far fewer individual classes of Q_{min}, than would have occurred if the actual raw values of Q_{min} were used. Jowett (2018) also provided some justification for this rounding process, where he highlighted that a 10% reduction below MALF would be barely detectable by flow gauging and would result in only small changes in depth and velocity. Moreover, under the NEMS protocols for hydrological gauging (NEMS 2013), the highest quality gauging is acknowledged to be ± 5% the true value. Given this, the decision to round up or down by 5% to the nearest 10% increment of MALF (with the exception of the 95% MALF class) would not have resulted in an unacceptable margin of error to the resultant Q_{min}. Furthermore, by creating fewer minimum flow classes, a simpler plan can be implemented than would have been achieved if rounding had not occurred, or if it was rounded to the nearest 5% increment of MALF. There is an obvious trade-off here between accuracy (using the true calculated value of the Q_{min}), and practicality (the need to have a realistic number of flow classes within the region that can be adequately monitored), and it is recognised that the final choice of a suitable rounding of Q_{min} values will be informed by policy needs.

MfE (2008) advocated for methods whereby selection of an appropriate Q_{min} was informed by a combination of the degree of abstraction and the potential ecological values of the particular waterway. Thus, the simplest low flow setting methodology was based purely on setting some defined hydrologically-based minimum flow such as the need to maintain 90% of MALF (or, in the case of the Operative RNRP, 90% of the Q_5 7-day flow). More complex methodologies such as IFIM were recommended for streams with very high ecological values, or streams where proposed abstraction rates would be high. The finding that just over half the consented water takes that BOPRC manages are from catchments where IFIM surveys have been implemented suggests that the use of the IFIM approach in the region is indeed robust and follows MfE guidance.

An additional challenge reflects the fact that the most robust methodology for assessing low flows in streams (IFIM) is based on protecting hydraulic habitat for selected fish species. However, a defining characteristic of New Zealand freshwater fish is the fact that different species have different abilities to penetrate inland. This means that there is a natural reduction in the presence of fish at NZReaches far inland: indeed, fish may even naturally be absent at some sites. Therefore, one of the main questions within the proposed hierarchy was based on the predicted occurrence of the target fish in a specific site or not: if fish were predicted, then the resultant Q_{min} was based on the regressions developed between a stream's IMFR and MALF. If fish were not predicted at a site, then the more generic default Q_{min} was used, to protect other ecological values. This means that all waterways throughout the region have at least some form of Q_{min} set, irrespective of whether fish are predicted or not.

This hierarchical approach appears to be a novel way within a region to maximise the use of the best-available data to inform setting Q_{min} in a defensible and transparent manner. While other councils (e.g., Otago) may have set Q_{min} in "all rivers" using IFIM surveys, many others have set Q_{min} only in selected catchments using this method. However, IFIM studies have not been done in the majority of streams in many regions, so most councils have opted for some form of default Q_{min}, ranging from either use of the Q_5 7-day flow, or MALF. In terms of setting default Q_{min} values, some councils (e.g., Northland) set Q_{min} based on 100% MALF in outstanding rivers, 90% MALF in coastal rivers and 80% MALF in both large and small streams, while Waikato set default Q_{min} based on 90% (large streams) or 95% (small streams) of the Q_5 7-day. This highlights the variability in approaches throughout the country.

The benefits of the hierarchical method proposed in this study are that successively more restrictive Q_{min} are enabled in streams with increasing ecological value. Thus, in streams where none of the target fish are predicted to occur, a permissive method of setting Q_{min} is advocated, where a general default of 70% MALF (in small streams with mean flow < 5 m^3/s) or 60% MALF (in larger streams with mean flow > 5 m^3/s) is recommended. While this may seem to be very low, especially in comparison to other council defaults, recent investigations into the effects of a long-term drought in the summer and autumn of 2019-2020 showed that flows as low as 60% MALF did not appear to cause adverse ecological effects to either invertebrate or periphyton communities in the four streams studied. Furthermore, it must be remembered that MALF is larger than the Q_5 7-

day flow. This means that a higher volume of water remains in streams when a Q_{min} is set to 90% MALF than when a Qmin was set at 90% of the Q5 (the current Operative Regional Natural Resources Plan). Examination of the % difference between the proposed default 70% MALF for small streams versus the current 90% of the Q5 showed that this proposed low flow was, on average just 4% lower than the current default of 90% of the Q5. Indeed, of the 121 sites where we have both measured MALF and Q5 data, 55 had less than a + 5% difference between the proposed 70%MALF default and the current 90% Q5 flow (Figure 15). This suggests that the new proposed Qmin in streams where no target fish are predicted would in fact confer nearly as much flow protection as the current Qmin of 90% of the Q5 that is set as a minimum flow in the operative Regional Natural Resources Plan.

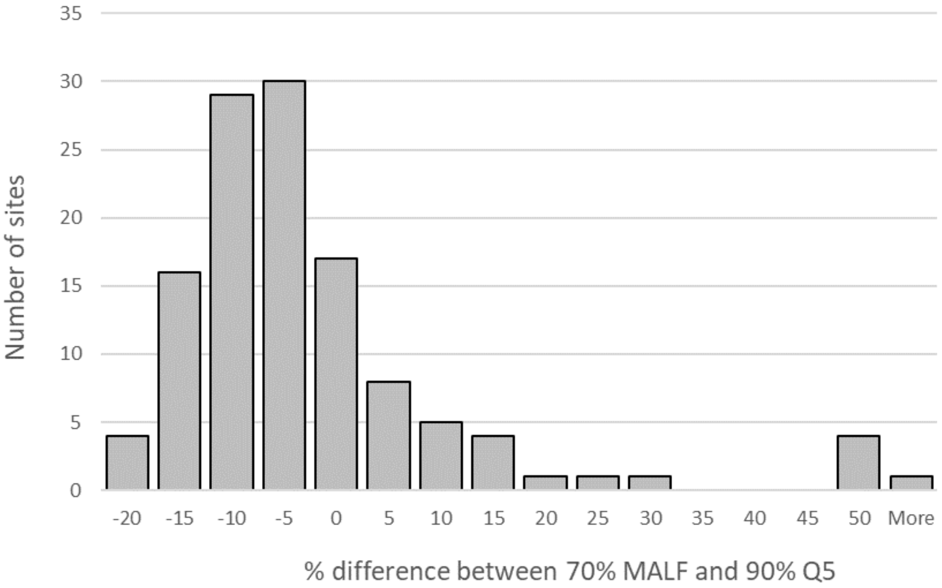

Figure 15 *Histogram showing the difference between Q_{min} calculated as 70% MALF or 90% Q_5 7-day flow and expressed as a percentage of the 90% Q_5 7-day flow, showing the number of sites in each percentage difference class (n = 121).*

Although these defaults are used in streams where target fish are not predicted, the proposed hierarchical approach recognises that higher Q_{min} may be required where target fish are predicted. IFIM surveys have been conducted in many streams with high allocation pressure, and the resultant recommended Q_{min} in these catchments are often higher than the default. Where IFIM has not been conducted, but where target fish are predicted, then Q_{min} has been set based on generalised regressions between a stream's IMFR and either measured or modelled values of MALF. In this way, our minimum flow setting process is more permissive in the absence of target fish species and becomes progressively less permissive in the presence of target fish, and where allocation pressure is high.

Conclusions

The above methodology is recommended as a set of clear, transparent steps to be used throughout the Bay of Plenty when establishing minimum flows for ecological values as a starting point for developing minimum flow limits for the regional plan. It relies on a mixture of current IFIM surveys, measured or modelled values of MALF (depending on what is available), and on predicted fish distributions. The five methods suggested for use in each waterway can be used to determine the Q_{min}. Note that this methodology at this stage has been developed to only consider either hydrologically based Q_{min}, or Q_{min} to protect the hydraulic habitat for selected fish species. However, the same methodology can be used to help set Q_{min} to protect other values such as cultural or recreational flows, if the site location and the desired IMFR to maintain these values is known. Information describing these other values is simply fed into the data schema and a new IMFR generated that shows Q_{min} to protect these values.

Once values of Q_{min} have been calculated, other tools are needed to determine the consequences of the chosen Q_{min} on other values such as reliability of supply and how much water can be allocated. NIWA has recently originally developed EFlows that may provide an accurate assessment as to what the implications of the recommended Q_{min} are on other attributes such as the amount of water that can be abstracted (ΔQ), and on reliability of supply (R). Use of this tool is currently under discussion to the best way to ascertain the implications of the recommended Q_{min} outlined in this document to help BOPRC set robust water allocation limits.

Upgrading to newer version of the REC

The above analysis was undertaken using the REC Version1.0, and the Leathwick et al. (2008) predicted fish distribution models. NIWA has recently released a new version of the REC (version 2.4), and BOPRC have committed to use this latest version. The new REC layer contains about 31,500 NZSegments in the region, as opposed to the roughly 25,200 NZ segments in the REC version 1.0. The higher number of NZSegments reflects a more accurate digital elevation model used to create the waterway network. It also means that it is not a straightforward 1:1 relationship between an individual NZReach and the new NZSegment. This is because a single NZReach in the REC1 may not have “recognised” a small tributary flowing into it, whereas REC2.4 does. This means that this same waterway would in fact have 2 unique NZSegment identifiers, above and below the small tributary.

Crowe (et al.) 2014 have also developed new predictive fish models based on the new REC 2.4 version. One of the important enhancements of this new model was to check and correct the original freshwater fisheries database records that had been assigned to REC1 NZReaches and properly assign them to the new, correct REC2 segment identifier. Crowe et al. (2014) gave an example of this, where the original sampling record (called a “card” in the database) was conducted in a tributary of the Waiotukupuna Stream, and where Leathwick et al. had incorrectly assigned this using the REC1 network to the mainstem of the Waiotukupuna Stream (Figure 16). However, the NZReach that was most representative of the locality sampled in this situation would be the NZReach located immediately upstream of the sampling coordinates, which could only be correctly assigned manually. Correcting these errors in the assignment of REC1 and REC2.4 segment identifiers to the NZFFD cards was thought to have improved the resultant predictive models developed by Crowe et al. for fish distribution throughout the country.

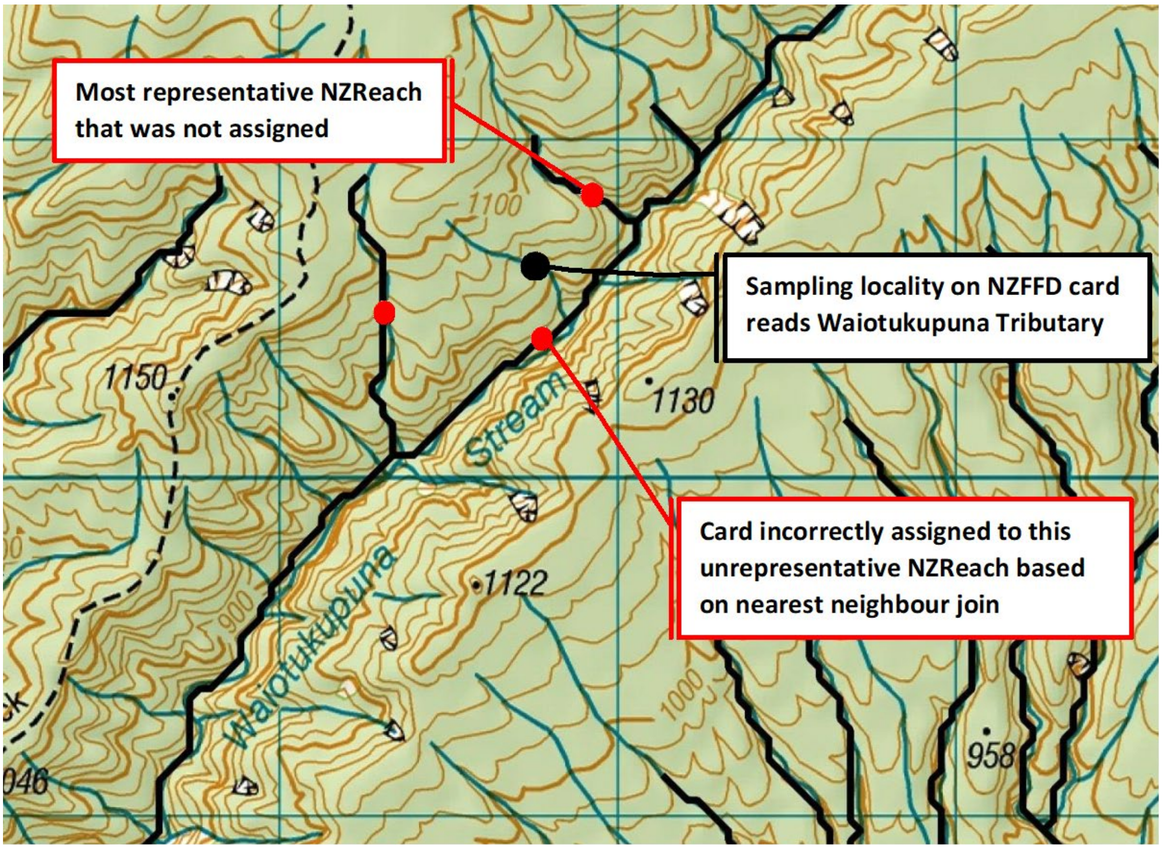

Figure 16 *Example of how the original NZFFD cards could be incorrectly assigned to an NZReach. Here, the coordinates of the sampling locality are shown (black circle) and the REC1 network is shown as black lines. This shows that there was no REC1 network segment present at the sampling locality. The centroid of the three nearest NZReach segment centroids are shown as red circles.*

The original GIS spatial layer representing the recommended minimum flows based on the methodology outlined in section 2.3 was subsequently redone, given the finer resolution of the REC 2.4 river network, and the newer Crowe et al. (2014) fish distribution data. Another enhancement of the new spatial layer involved the removal of any NZ segments that could be classified as artificial watercourses. These were found predominantly in either the Kaituna or Rangitaiki plains and represented by farm drains and land drainage canals. Flows in such waterways are not managed to maintain ecological values, so these waterways were subsequently removed from this assessment.

Comparisons of the resultant Q_{min} when using the newer methods showed a very high degree of similarity to the original methodology, with 84% of NZ reaches having the same Q_{min}. The main differences in the outputs using the two models were related to the fact that the new Crowe et al. (2014) fish distribution models predicted fish in more waterways (65%) than the original Leathwick et al. (2008) models (48%). This meant that target fish were predicted in more waterways using the newer models. Under the hierarchical decision support process outlined in Figure 12, if no target fish were predicted in a stream, then the regional defaults of either 70% MALF in small streams or 60% MALF in large rivers were to be used. If, however, fish were predicted, then the resultant Q_{min} was based on regression equations using either modelled or measured values of MALF. Predicting the presence of fish in more waterways using the Crowe et al. models subsequently resulted in fewer default flows being set, and more flows being set based on either modelled or measured regression equations (Table 2).

Table 2 Comparison of the number (and percentage) of waterways in each of the five methodologies used to develop Q_{min} in waterways throughout the region, using the REC1, and REC2.4 and the different fish distribution models. (Note that the total number of waterways here (22344) is less than the total number of waterways used in the REC1 (25202) reflecting an imperfect one-to-one match between NZReach and NZ segment. This table is therefore showing only REC1 reaches that match to REC2.4 Segments).

	REC 1 and Leathwick et al. fish data		**REC2.4 and Crowe et al. fish data**	
Q_{min} methodology	**Number of NZReaches**	**Percentage of NZReaches**	**Number of NZ segments**	**Percentage of NZ segments**
Default_Large	76	0.3	41	0.2
Default_Small	5128	23.0	4208	18.8
IFIM	10132	45.3	9519	42.6
Regression_Measured	3105	13.9	3661	16.4
Regression_Modelled	3903	17.5	4915	22.0

Resultant maps of recommended Q_{min} developed using the methodology outlined in section 2.3 of this report showed a high degree of similarity at a regional level between the REC 1 and REC 2.4 data (Figure 17). It is therefore recommended that this more up-to-date version of the REC, and the fish distribution models of Crowe et al. (2014) be used for all future work involved setting minimum flows.

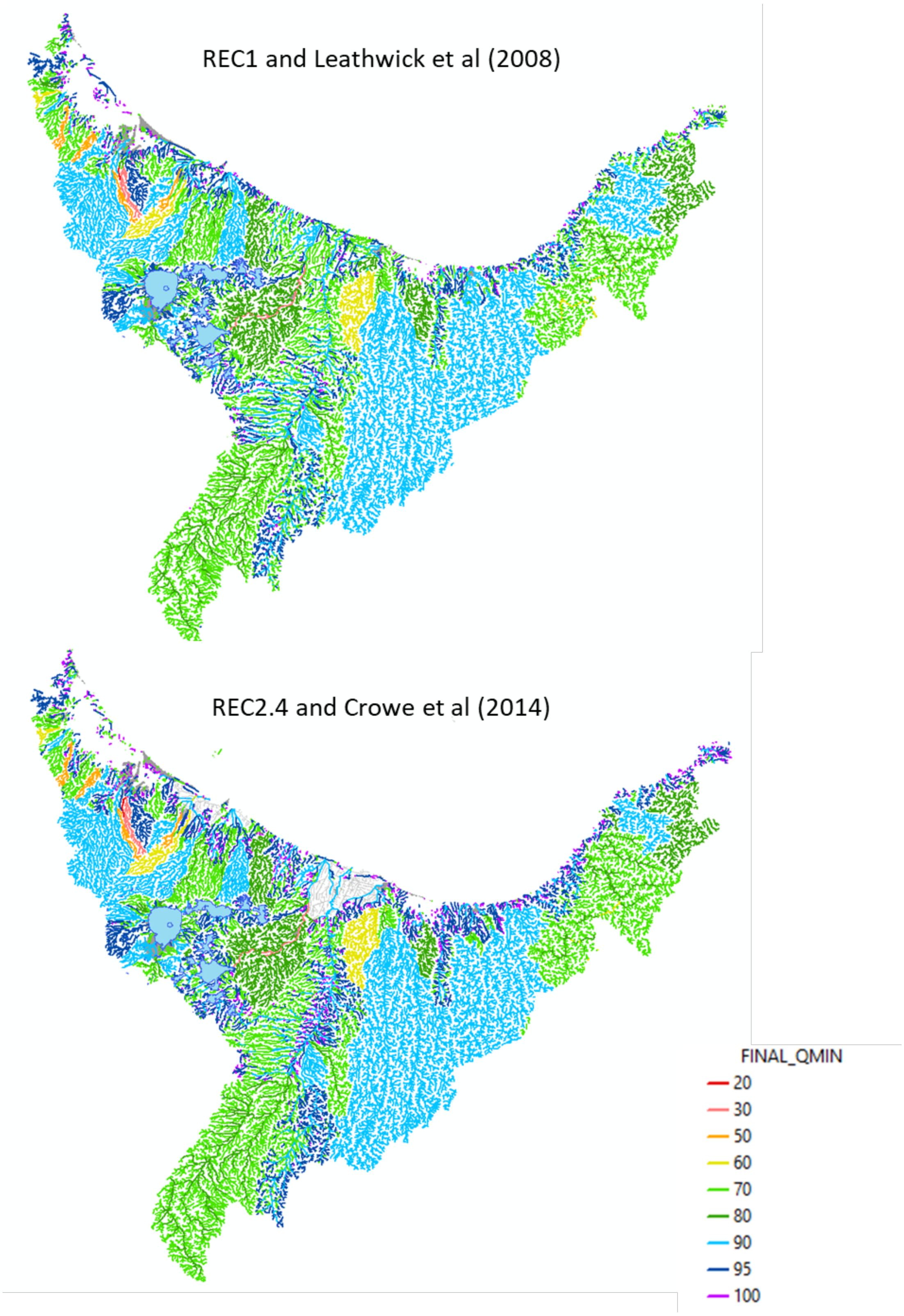

Figure 17 Resultant maps showing the recommended minimum flows using the REC1 (upper map) and REC 2.4 (lower map).

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Appendices/Ngā Āpitihanga

Appendix 1/Āpitihanga 1
Steps to select minimum flows

Based on the hierarchical decision support methodology as outlined in Figure 12, the following major questions are asked. The processes behind answering these questions are outlined in the sections below, which also deals with secondary issues that were addressed as part of making the final decisions as to what the final Q_{min} would be.

Overview of the decision-support hierarchy

1 **Has an IFIM survey been done?** This is the major initial question to determine what method is used to recommend a Q_{min}.

1.1 Primary and Secondary IFIM sites

Once an IFIM site has been identified, the spatial location of these sites needs to be investigated, as some IFIM sites are located above other sites. In these cases, a decision needs to be made as to how to deal with 2 potentially different values of Q_{min} calculated from the IFIM surveys.

1.2 Assigning sites below IFIM surveys an appropriate Q_{min}

Many IFIM sites were located in the mid-reaches of some catchments, meaning that a decision was required as to how to select an appropriate Q_{min} below these sites. Where it is decided that the IFIM-derived Q_{min} can be used at NZReaches below the site, a transparent method is required to explain what the appropriate Q_{min} would be in these reaches.

1.3 Increasing habitat protection for tuna

Part of the IFIM methodology is to assign an appropriate level of hydraulic habitat that is to be protected, relative to that at MALF. Jowett (2012) recommended hydraulic habitat protection values for the Bay of Plenty, and these values were used in all calculations to determine the Q_{min} in IFM sites. This means that all the Q_{min} flows calculated as a result of the IFIM surveys are largely controlled by the level of habitat protection, which themselves were somewhat objective, and based on the experience of Jowett in his 2012 report. While the protection levels for some endangered native fish were high (95% hydraulic habitat protection), the protection level for tuna was somewhat lower (75 to 80% hydraulic habitat protection relative to that at MALF for adult and juvenile tuna, respectively). This lower protection level simply reflects that fact that tuna do not “require” as much water as the other species. However, given the taonga status of longfin tuna, it was decided to examine the effect of increasing the hydraulic habitat protection for tuna was on the final calculated Q_{min} value. This was done by recalculating the recommended Q_{min} value to protect 95% of the hydraulic habitat for tuna - the same recommended level of habitat protection for more “flow hungry” fish such as koaro and trout.

2 **Are target fish predicted?** This is the second major question to determine what method should be used to set a Q_{min}. If target fish are predicted, then methods to set Q_{min} are based on more robust and conservative methods, derived from more detailed IFIM surveys. If target fish are not predicted in a specific waterway, then a more generic default flow can be selected, to help protect other ecological components of waterways.

3 **Setting an appropriate Q_{min} where fish are predicted***.* Where target fish are predicted, and where IFIM surveys have not been undertaken, any method to select an appropriate Q_{min} needs to ensure adequate hydraulic habitat is protected for fish. This section describes the

methodology used to generate a generalised regression equation between a stream's Q_{min} and either measured or modelled values of MALF.

4 **Scale of resolution.** The hierarchical decision support system is designed to work on the REC1 waterways layer, with 25 200+ NZ Reaches. Using this methodology, a transparent method has been created to set Q_{min} for all of these reaches. While some catchments in the region are above IFIM sites (and therefore have a single Q_{min}) the recommended Q_{min} is spatially variable in other catchments. This may create problems from a consenting and monitoring perspective. This section describes some potential solutions to this problem of "patchiness", as well as introduces the concept of more catchment-based Management Zones, than the simple classification that has been developed here.

These four issues are discussed in more detail below.

Has an IFIM survey been done?

A total of 69 IFIM surveys have been done by BOPRC, and various consultancies within the region. These studies have all established defined minimum flows based on providing sufficient hydraulic habitat protection for a range of fish species. All the catchments where these studies were done supported "target fish" populations (see Section 2 below), and many had measured flow data to describe MALF. These studies have been conducted throughout the region, and occupy a total of 5551 km^2, or 45% of the total area of the region (12 280 km^2). The derived IMFRs from these surveys have been converted into a Q_{min}, based on the % of MALF at the survey site. These Q_{min} values formed the basis of an initial set of minimum flows throughout the region.

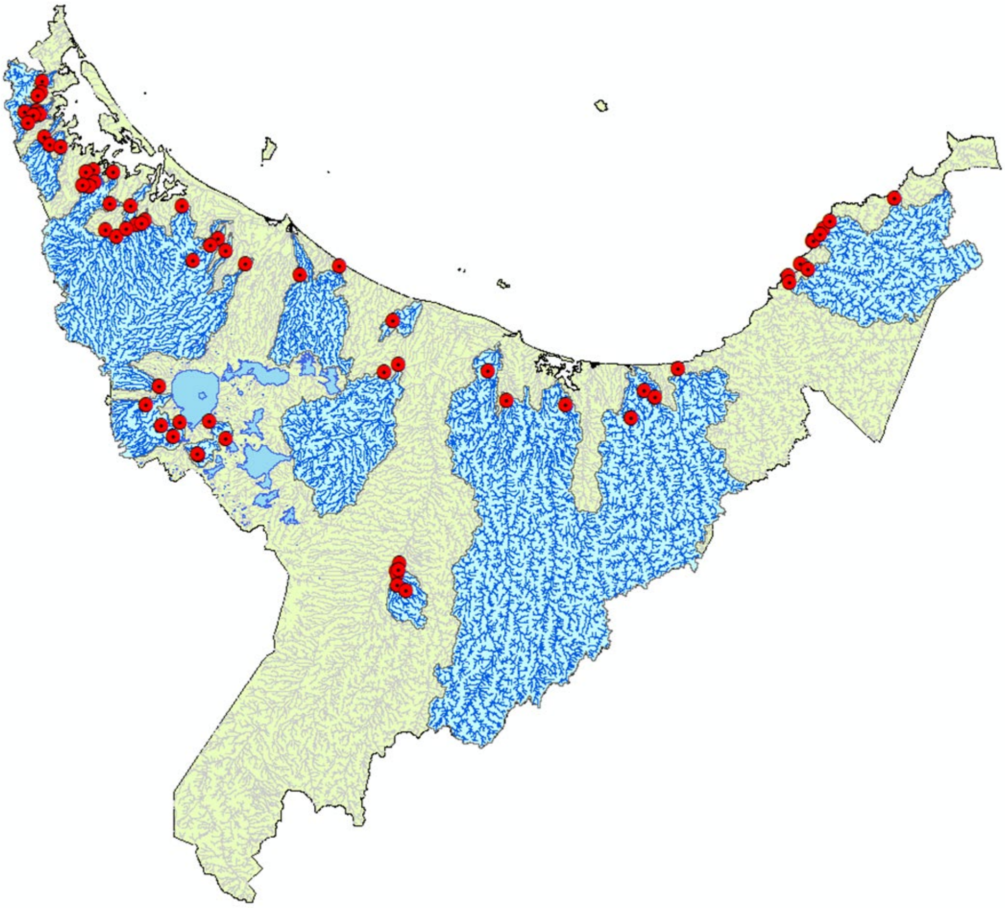


Figure 18 Location of all the IFIM surveys throughout the region (red circles), and their combined upstream catchment areas (blue polygons).

Because a general flow gauging is accurate to only ± 5%, all calculated Q_{min} flows were allocated to specific flow bands, centered around increments of 10%. Thus, Q_{min} values of 66%, 68%, 73% and 75% would all be allocated to a Q_{min} of 70% MALF, as all were within 5% of 70%. The only exception to this was for flows between 96%–99% MALF, which were all allocated to the 95% MALF band. Resultant Q_{min} values ranged from less than 30% MALF at three sites, to 95% of MALF at 12 sites (Figure 19). The median Q_{min} throughout all IFIM studies was 80% of MALF. Note that this is higher than the proposed default Q_{min} values where target fish are not predicted to occur in some catchments, and where the default Q_{min} of 60% or 70% MALF are suggested in small and large waterways, respectively. As such, it highlights those sites where IFIM surveys were done were less permissive for out-of-water takes, to protect the hydraulic habitat of target fish species.

Recommendation 4: Round up or down all flows to the nearest 10% increments of MALF, reflecting the fact that most flow gaugings are only accurate to + 5% of actual flows. Thus, all values of Q_{min} (and of allocatable volume) should not be expressed to a greater implied accuracy than is realistically possible.

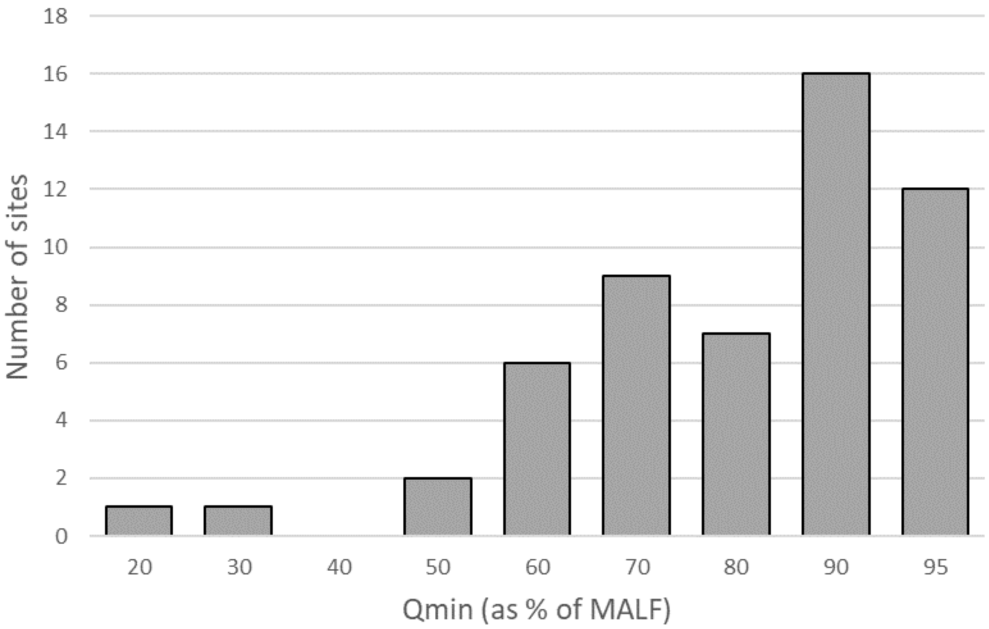


Figure 19 Histogram showing the number of IFIM sites with different values of Q_{min} (as % of MALF).

Once a range of Q_{min} were developed, two further steps were employed to ensure consistency with the method and maximise the use of this data in terms of applying the calculated Q_{min} values to sites below the IFIM reach. These additional steps are discussed below.

Primary and Secondary IFIM sites

Examination of the spatial location of the IFIM studies showed that some areas (especially the Galatea Plains) had catchments where multiple IFIM surveys had been done in smaller streams at increasing distances from the lowermost IFIM site. For clarity, it is suggested that the lowermost IFIM site is called the primary site, while the upper IFIM sites are called secondary sites.

A decision needed to be made as to whether only the lower primary IFIM should inform the Q_{min} at all upstream NZReaches, or whether the individual Q_{min} values in each of the upper sub catchments should be used. Although using secondary IFIM sites is arguably an elegant solution to this situation and makes use of the "best" data available for these sub catchments, it also produces many anomalies. For example, in the Galatea plains there are five IFIM secondary sites above the initial primary site (Haumea at Galatea: Figure 20).

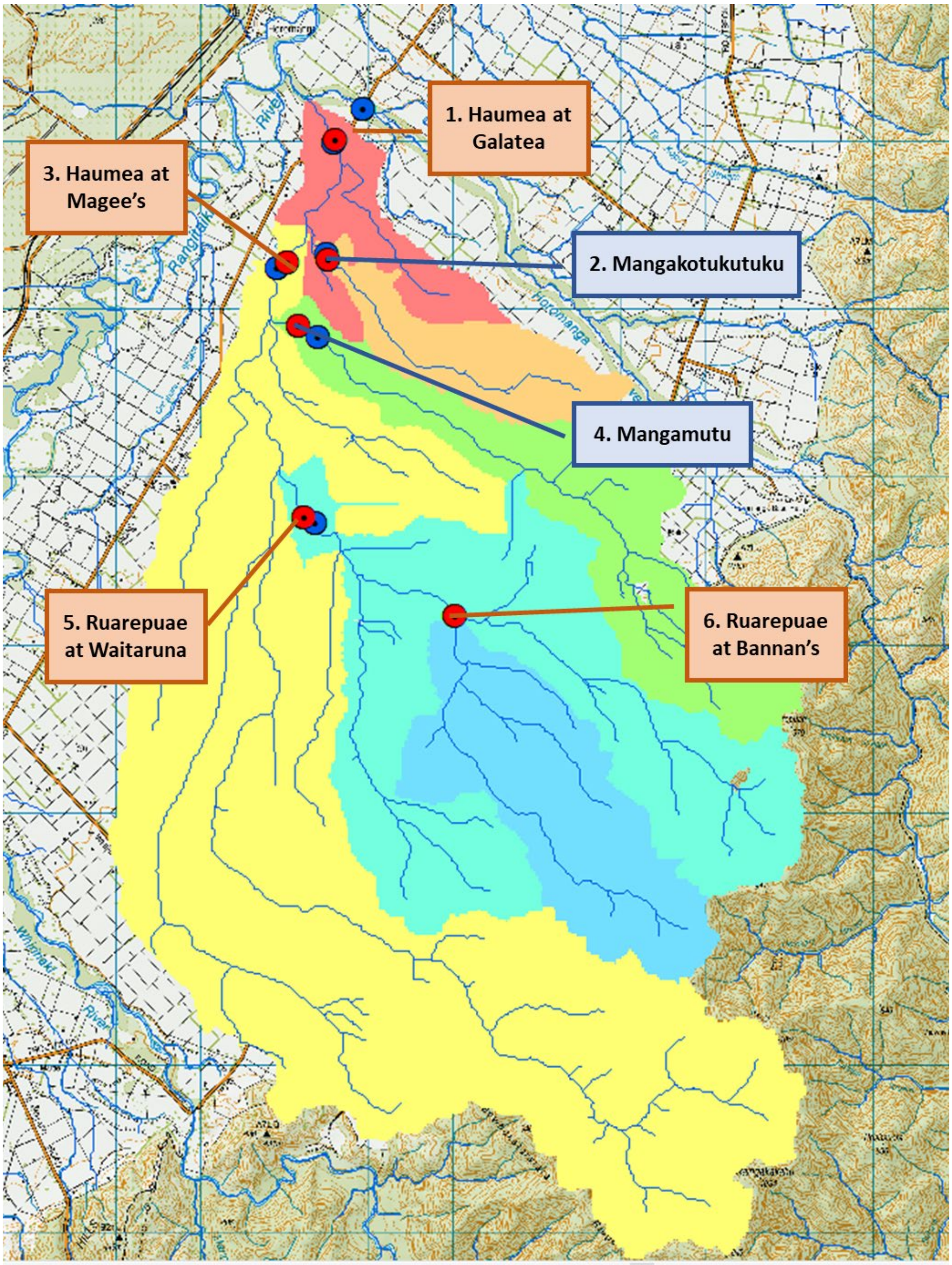


Figure 20 Multiple IFIM surveys had been conducted in the Galatea plains, resulting in potentially six different IMFRs in catchments above each IFIM site.

Using the steps as outlined in Figure 10, the IMFRs were calculated for selected fish species that were present at each site (Table 3). From this, the Q_{min} was calculated for each of the individual IFIM sites, using the measured values of MALF in each of these sub catchments. If we look at the resultant IFIM-derived Q_{min} values (rounded to the nearest 10%), we see large discrepancies between the primary IFIM site (Haumea at Galatea) and secondary IFIM sites (Table 3). For example, at the Haumea at Magee's site, the calculated Q_{min} was only 70% of MALF (i.e., we are being more permissive with the flow takes at this site), which was in sharp contrast to the primary site (Q_{min} = 90% of MALF (i.e., we are being less permissive with flow takes)). This would create a number of anomalies in setting Q_{min} within a relatively small area, which could be problematic to justify from a planning perspective, and difficult to implement.

Table 3 Summary statistics of the mean annual low flow (MALF), in stream minimum flow requirement (IMFR) calculated from the IFIM survey, calculated minimum flow as a percentage of MALF (Calculated Q_{min}), and the selected Q_{min} in the IFIM catchment rounded to the nearest 10% (IFIM_ Q_{min}) in the primary and secondary catchments in the Galatea plains. Also shown are the target fish species selected for each sub catchment, and the Final recommended Q_{min} in these catchments, based on the IFIM_ Q_{min} at the Primary catchment.

Catchment Name	Prim/Sec	MALF	IMFR	Calculated Q_{min}	IFIM_ Q_{min}	Target_Fish	FINAL_ Q_{min}
Haumea at Galatea	Primary	925	850	92%	90%	Trout	90%
Haumea at Magee's	Secondary	475	350	74%	70%	Trout	90%
Mangakotukutuku	Secondary	110	90	82%	80%	Trout	90%
Mangamutu	Secondary	60	50	83%	80%	Trout	90%
Ruarepuae at Bannans Farm	Secondary	50	46	92%	90%	Trout	90%
Ruarepuae at Waitaruna	Secondary	300	276	92%	90%	Shortfin eel	90%

Because of this, it is suggested that the calculated IMFR (and resultant Q_{min} values) from the primary IFIM site is used where we have multiple upstream IFIM surveys. This means, in effect, ignoring IMFR values derived from the IFIM surveys at the secondary sites.

Recommendation 5: Where multiple IFIM studies have been done up, use the IMFR from the lower (primary) site to inform Q_{min} at the upper (secondary) sites, unless there are good reasons to keep the resultant Q_{min} values different at each site.

This situation occurs in seven other catchments in the region (Table 4). While most of these catchments had the same target fish species, the Kopurereroa and Tau Tau Streams had different target fish used in the IFIM models: adult trout in the primary site, and juvenile trout in the secondary site. Given that adult trout are more "flow hungry" than juvenile trout, it is not surprising that the calculated Q_{min} was higher in the primary site (Table 4). The reason that adult trout were not chosen as the target species in the Tau Tau stream reflected the fact that they were not common there, while juvenile trout were. Juvenile trout are much smaller than adults, and so have much lower flow requirements, which is why the Q_{min} is lower in the Tau Tau Stream, meaning it is more permissive to out-of-stream takes. There are three takes from the Tau Tau Stream: two for irrigation (for a total maximum abstraction of 9.7 L/s), and a fourth take for municipal water supply (at a maximum abstraction of 432 L/s). It is highly unlikely that this municipal abstraction could continue if the higher Q_{min} at the primary IFIM site were employed, so this is an example where a pragmatic decision needs to be made to use the calculated IMFR at the secondary site to inform the Q_{min} there, instead of the more general recommendation to use just the primary IFIM site. It is thus a planning decision as to whether to use only the primary IFIM site to inform Q_{min} in the catchment, or the secondary IFIM sites.

Using the primary IFIM sites alone, recommended Q_{min} values were always highest in the primary IFIM site, with the exception of the Te Puna catchment (Table 4), where the Q_{min} value (50% MALF) was less than that derived at the secondary site (60% MALF). The implication here is that these lower sites will be less permissive with the amount of water that they can take in order to protect their higher Q_{min} values. Given the fact that the same target fish species were used in both the primary and secondary IFIM sites, the differences in the calculated IMFRs (and subsequent Q_{min} values) most likely reflects subtle changes in the shape of the greater usable area versus flow curve within each site.

Table 4 Summary statistics of MALF, IMFR, and calculated Q_{min} in the primary and secondary catchments throughout the region. Also shown are the target fish species selected for each sub catchment.

Catchment location	Catchment Name	Prim/Sec	MALF	IMFR	Calculated Q_{min}	IFIM_ Q_{min}	Target_Fish	Final_ Q_{min}
Kopurereroa	Kopurereroa	Primary	1490	1420	95	95	Trout - adult	95
	TauTau	Secondary	430	200	47	50	Trout - juvenile	50
Raparapahoe	Raparapahoe no. 4	Primary	611	562	92	90	Trout	90
	Raparapahoe no. 3	Secondary	300	253	84	80	Trout	90
Te Puna	Te Puna at rapids	Primary	150	74	49	50	Native	50
	Te Puna tributary	Secondary	11	7	64	60	Native	50
Uretara	Uretara at Wharawhara	Primary	210	155	74	70	Native	70
	Uretara at Rea	Secondary	210	155	74	70	Native	70
Utuhina	Utuhina downstream	Primary	1315	1250	95	95	Trout	95
	Utuhina upstream	Secondary	970	890	92	90	Trout	95
Waipapa	Waipapa trib at Plumer Road	Primary	30	20	67	70	Native	70
	Waipapa trib at Jeffco farm	Secondary	7	4	57	60	Native	70

Therefore, maintaining minimum flows in the upper catchments is consistent with the recommendation from the Snelder et al. (2016) report in developing water quantity freshwater management units for the region, where levels are set based on the most sensitive downstream environment.

After employing this approach, the following final recommended Q_{min} for each of the 45 IFIM catchments are presented in Table 5, based on using data from the primary catchments only (with the exception of the Tau Tau Stream). It is, however, a planning decision as to whether this approach is acceptable, and there is nothing to preclude the decision to use the Q_{min} derived from a secondary IFIM catchment if this decision is made.

Table 5 List of recommended Q_{min} (as a % of MALF) as determined from IFIM assessments in 58 catchments where IFIM surveys were done. (Note that this list is based only on calculated Q_{min} values in the Primary IFIM sites, and not any secondary sites above these, with the exception of the Tau Tau Stream, where a decision was made to accept the Q_{min} at the secondary site).

Final_Q_{min}	**IFIM_Study**	**Total number of NZReaches**
20	Joyce	1
	Waiorohi Stream	55
30	Tarawera	932
40	Tau Tau	27
50	Ohinieangaanga	21
	Te Puna at rapids	21
	Te Rereatukahia	13
	Waioho	392
	Waipapa tributary @ at Jeffco farm	1
	Whatakao	29
60	Tahawai R/B	3
	Waipapa tributary @ Plumer Road	9
	Waiari Stream	107
70	Aongatete	55
	Mangawhai	3
	Ngututuru	3
	Tahawai L/B	7
	Uretara @ Rea	29
	Waitao	53
	Maraetai Stream	1
80	Boyd Trib	7
	Mangakakahi	11
	Miller Road	9
	Nukuhou	182
	Otara	783
	Puremutahuri	23

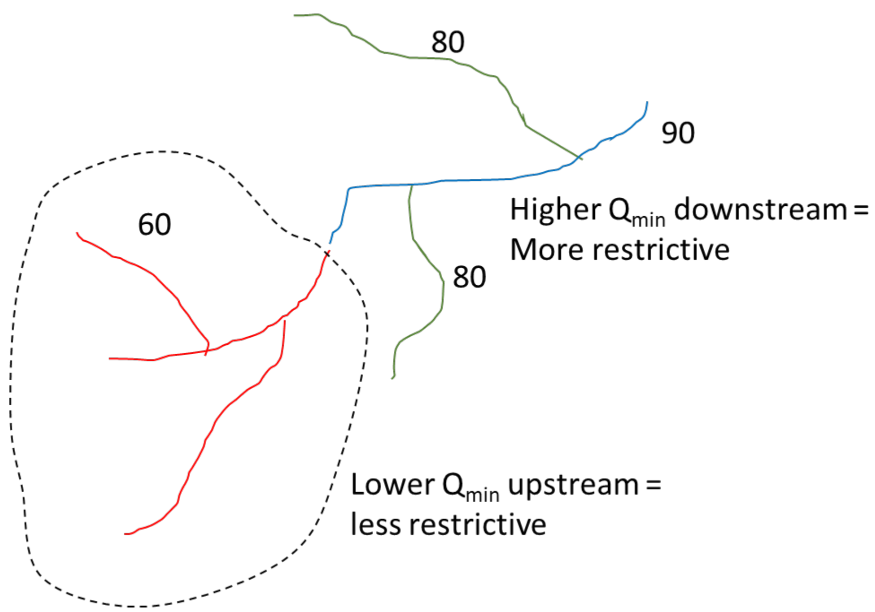
Final_Q_{min}	IFIM_Study	Total number of NZReaches
	Tuapo	11
	Waitahanui	236
	Whakatane	3614
	Waioira Stream	3
	Rerepa Stream	3
	Haparapara River	379
	Orini Stream	3
	Puremutahuri Stream	23
	Raukokore River	790
90	Awakaponga	14
	Haumea @ Galatea	134
	Kopurereroa	83
	Mangaone	25
	Mangorewa	341
	Mill Stream	15
	Ngongotaha	125
	Ohourere	63
	Omanawa	118
	Oturu	19
	Pongakawa	167
	Raparapahoe number four	73
	Tuapiro	87
	Utuhina downstream	110
	Waimapu at McCarrols Farm	141
	Waingaehe	21
	Waioeka	1966
	Waipa	51
	Wairoa	452
	Waitetī	53
	Waiaua River	199
	Pakaranui Stream	9
	Kereu River	298

Assigning sites below IFIM surveys an appropriate Q_{min}

As discussed earlier (Section 2.3), some of the IFIM surveys were in the mid reaches of catchments. Given that the IFIM methodology is the “gold standard” at selecting Q_{min} to protect the hydraulic habitat of fish, it was considered good practice to use the same Q_{min} derived from the IFIM surveys in the mid reaches to these lower sites. However, there were a number of considerations here. Firstly, there could be no major tributary streams (i.e., larger than the stream of interest) with different Q_{min} that flowed into the stream. If this occurred, then hydrological conditions below the two streams may be very different to the conditions within the IFIM catchment. Secondly, a “rule” was required to decide what to do when the Q_{min} values in the lower catchment were greater, or less than the Q_{min} derived from the IFIM survey in the upper catchment. There were two potential options for dealing with this situation. These options are best explained in terms of the implications of different minimum flows to out-of-stream users (i.e., abstractors).

Streams with a low Q_{min} are much less restrictive to abstractors, as the low Q_{min} suggests that relatively large amounts of water can be abstracted without adverse effects. On the other hand, streams with a high Q_{min} are more restrictive to abstractors, as only small amounts of water can be abstracted. Given that IFIM surveys are done to protect the hydraulic habitat for fish, we need to assume that the same target fish will be found at lower sites. This is not unreasonable, especially given the strong migratory behaviour of many New Zealand native fish.

For the situation where there is a low Q_{min} in the upper IFIM catchment, it suggests that adequate hydraulic habitat protection for target fish can be met even though relatively large amounts of water are being abstracted. If a low Q_{min} protects the hydraulic habitat for fish in the upper parts of the catchment, then there are no ecological reasons to have a higher Q_{min} (i.e. being more restrictive) at sites below the IFIM location in the lower catchment. Therefore, where the Q_{min} of reaches below an IFIM site are higher than those above the IFIM site, then the Q_{min} in the lower catchment is reduced the same level to match the Q_{min} within the IFIM catchment (i.e., it becomes less restrictive: Figure 21)



Assuming that the same fish are found downstream, why are we being more restrictive?

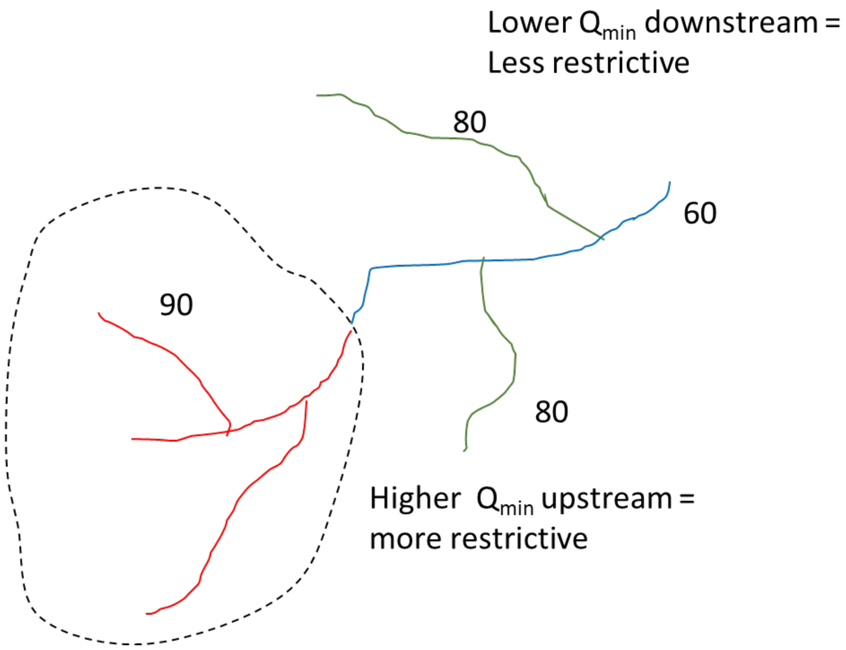
If a Q_{min} of 60% protects fish (which, according to the IFIM modelling it does, then there is no ecological reason to have a higher Q_{min} below the IFIM site

Therefore, CHANGE the Qmin in the lower catchment to be less restrictive here (i.e., Q_{min} gets lower)

Figure 21 Example of the situation where the calculated Q_{min} in catchments where IFIM surveys have been done (red line) is lower than calculated Q_{min} values in the downstream catchments (calculated either by the generalised regression (green line), or the regional defaults (blue line)

In contrast, where a Q_{min} in the IFIM catchment is high, similarly high flows would be needed to protect fish in the lower parts of the catchment. Therefore, if the calculated Q_{min} is lower at sites below the IFIM location, then the Q_{min} at these sites needs to be increased to match the Q_{min} within the IFIM catchment (i.e., it becomes more restrictive: Figure 22). In all cases of multiple NZ reaches below the IFIM site having different values of Q_{min}, then the average Q_{min} of all these reaches was taken as the one to compare with the Q_{min} above the IFIM site.

Finally, this analysis was done for all NZ reaches downstream of the IFIM site but extending only as far as the Coastal Marine Area boundary. NZReaches below here were not considered, as they were very highly likely to be tidally influenced.



Assuming that the same fish are found downstream as upstream, then if the upstream sites need a more restrictive Q_{min}, then the lower sites should also have the same Q_{min}

Thus if a Q_{min} of 90% is needed to protect fish according to the IFIM modelling, then there IS a clear ecological reason to have a higher Q_{min} below the IFIM site

Therefore, flows in the lower catchment become MORE restrictive (i.e., Qmin gets higher)

Figure 22 Example of the situation where the calculated Q_{min} in catchments where IFIM surveys have been done (red line) is higher than calculate Q_{min} values in the downstream catchments (calculated either by the generalised regression (green line), or the regional defaults (blue line)

Recommendation 6: Suitable Q_{min} can be based for all NZReaches below the location of an IFIM site, based on the following rules:

1. *Use the value derived from the IFIM survey, as long as no larger tributary streams join the river.*
2. *When the Q_{min} derived from IFIM surveys in upper catchments is lower than Q_{min} derived using other methods in the lower catchments, use the lower IFIM-derived Q_{min} in these lower catchments.*
3. *When the Q_{min} derived from IFIM surveys in upper catchments is higher than Q_{min} derived using other methods in the lower catchments, use the higher IFIM-derived Q_{min} in these lower catchments.*

Increasing habitat protection for tuna

A key aspect of calculating IMFRs in waterways is based on the requirement to protect a specific amount of suitable hydraulic habitat for target fish species. This hydraulic habitat consists of depth and velocities, as well as (to a lesser extent) substrate size. Different fish have specific preferences for water of different depth and velocity (e.g., Jowett and Richardson, 1995), so the effects of decreased stream flows (and therefore velocity and depth) due to abstraction pressure are not consistent between fish species. For example, shortfin and longfin eel have relatively slow velocity and shallow depth preferences (Figure 24), and so may be relatively unaffected by decreases in these hydraulic parameters as abstraction pressure increases. Other fish species such as koaro and trout prefer faster water, and so are expected to be less common in slower flowing rivers (Figure 24). This means that densities of these more “flow hungry” fish may decline as water velocity decreases because of abstraction. Because of this, the recommended hydraulic habitat protection levels for these species are set relatively high to protect 90%–95% of their hydraulic habitat at MALF (Jowett 2012). In contrast, both shortfin and longfin eel have velocity preferences for slower water and are only rarely found in streams with velocity is greater than 0.5 ms^{-1}. This means that densities of these species are not expected to decrease as much due to reduced velocities associated with high abstraction levels. This means that their recommended hydraulic habitat protection levels are set to a lower level, 75% to 80% MALF for adult and juvenile tuna, respectively (Jowett 2012), as they simply do not “require” as much water as the other species.

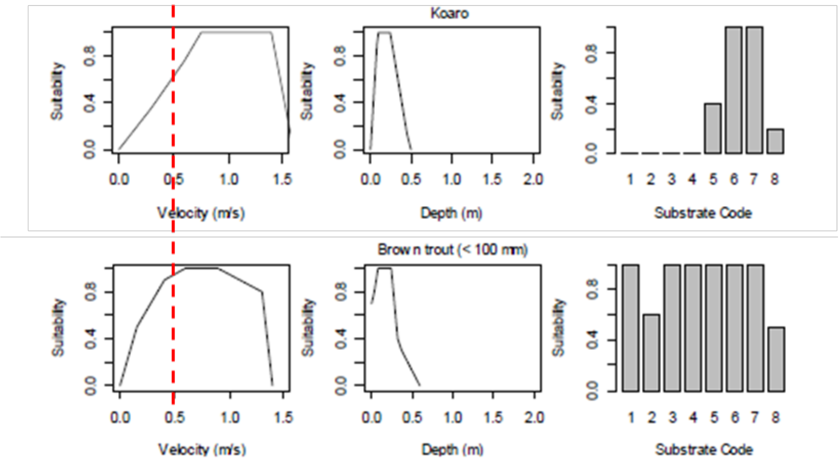


Figure 23 Examples of hydraulic habitat preferences for koaro and brown trout showing the suitability of different velocities, depths and substrate size. Note the preference of these two species to fast flowing water > 0.5 ms^{-1}. (Data from Booker 2015).

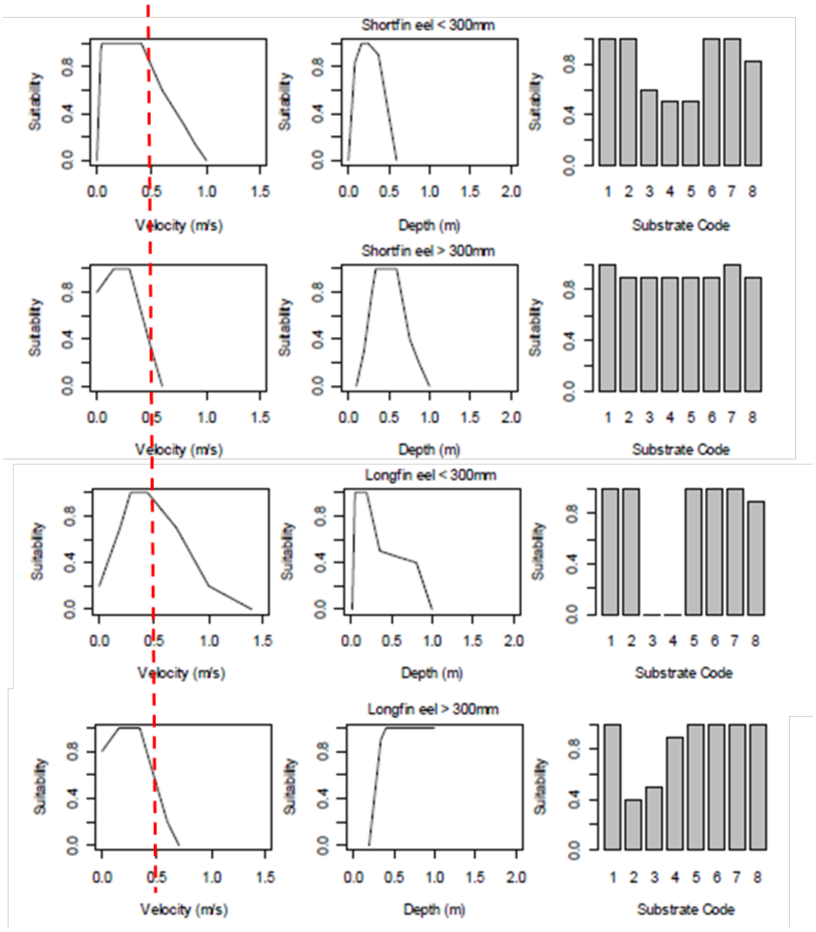


Figure 24 *Examples of hydraulic habitat preferences for adult (> 300 mm) and juvenile (< 300 mm) tuna (longfin and shortfin) showing the suitability of different velocities, depths and substrate size. Note the preference of these species to slow water flowing < 0.5 ms^{-1}. (Data from Booker 2015).*

Any IMFR calculated for a particular stream is thus based on maintaining sufficient hydraulic habitat for the *most flow hungry species* (e.g., trout), with the implication that sufficient hydraulic habitat will still be maintained for less flow hungry species at the same site. Thus, by setting minimum flows to protect the hydraulic habitat of these flow hungry species, species with lower flow requirements will still be left with adequate hydraulic habitat.

However, given the taonga status of tuna, and particular longfin tuna to iwi, it was decided to examine the consequences to the calculated IMFRs if tuna were given a *greater amount* of hydraulic habitat protection. Initially, a 100% level of hydraulic habitat protection for tuna was trailed, but this often ended up with a calculated IMFR either greater than, or equal to the MALF. Having a minimum flow this high may have significant adverse effects on the ability for abstractors to take water and represents an overly restrictive amount of habitat protection, as stream flows naturally fall below this level (e.g., during a natural Q_5 7-day event). Instead of selecting a 100% protection level for tuna, a hydraulic habitat protection level of 95% MALF was assessed. This effectively gave these slow-velocity preference fish the same degree of habitat protection as the more flow hungry species such as trout and koaro.

Of the 53 rivers where IFIM surveys were undertaken and where the RHYHABSIM files were available to reanalyse, increasing the level of hydraulic habitat protection of tuna to 95% resulted in changes to the IMFR in only 15 rivers. It made no change to the resultant recommended Q_{min} in the other 38 rivers. Of these 15 rivers, the new IMFR based on 95% habitat protection at MALF was greater than MALF at one site (Waimapu at McCarrol's Farm). Because it makes no sense to set an IMFR greater than MALF (which the river naturally falls to), this site was omitted from further analysis. Of the remaining 14 streams, the new IMFR was based on retaining 95% of the habitat of longfin tuna at nine sites, and eight sites had a new IMFR based on retaining 95% of the habitat of shortfin tuna. The average increase to the IMFR at these 14 sites was 28.8% of the original IMFR that was chosen by selecting other flow hungry species, but this result was highly skewed by one site – Joyce Creek. Here, a new IMFR based on retaining 95% of the hydraulic habitat for long fin eel (20 L/s) was 185% higher than the original IMFR based on protecting 95% of banded kokopu hydraulic habitat (7 L/s).

Despite the large difference in IMFRs at this single site, the difference between IMFRs at most other sites was small: indeed seven of the 14 sites had an increase of the IMFR of *less than 10%.* This is nearing the margin of error for gauging accuracy. It is thus suggested that there is little to be gained from an ecological standpoint to protect tuna by giving them a higher level of hydraulic habitat protection because:

1. IMFRs calculated by setting a 95% hydraulic habitat protection level only resulted in increases to the IMFR at 14 of 53 sites (26%).
2. Even when protecting 95% of the hydraulic habitat for tuna, the average increase in IMFR (ignoring the unusual result from the Waimapu at Joyce site) was relatively small (median = 14%),

This statement is also made with consideration of the demonstrated lower velocity preferences for both longfin and shortfin tuna (Figure 23, Figure 24), and the argument that protecting more flow hungry species will more than adequately protect tuna. Giving tuna higher hydraulic habitat protection may, however, decrease the amount of water potentially available to abstractors, and this may have significant economic and social consequences, with potentially little ecological benefit. Notwithstanding this, it is clearly possible to alter the degree of hydraulic habitat protection for all fish species if specific groups are interested in applying a higher degree of hydraulic habitat protection.

Recommendation 7: Maintain the current levels of hydraulic habitat protection for all fish as suggested by Jowett (2013). However, where necessary, the amount of hydraulic habitat protection can be increased in cases where this is warranted, although this may result in unintended consequences to abstractors if no water becomes available.

Determine if target fish are predicted

The second step in the decision support hierarchy was to determine whether "target fish" were present in individual NZReaches. Leathwick et al. (2008) developed predictive models for fish distribution throughout the country, based on current environmental conditions. These models give the probability of occurrence of individual fish at any specific NZReach, ranging from zero (no fish predicted) to one (fish always present). The difficulty with these probability values is in deciding on a suitable threshold value for a particular species for it to be considered present at a site. Joy (2013) highlighted that a single probability (e.g., 0.5% or 50% probability) cannot be selected for all species, as the predictive models are not balanced. For example, longfin eels had a much greater range in their probability of occurrence (0.006 to 0.994) than either giant kokopu (0.001 to 0.626), or lamprey (0.001 to 0.450). Thus, a single threshold value (such as 0.5) does not give the best representation of the likelihood of finding a particular species. To circumvent this problem, Joy (2007) calculated best "threshold values" for a range of native species to give the best prediction for their occurrence within an individual NZReach. Based on these threshold values, distribution maps of the likely occurrence of native fish or trout in the region were made.

These predictive models were used to determine the likelihood of occurrence of all six native species used in by Suren (2019) investigating relationships between IMFR and MALF (i.e., banded kokopu, inanga, smelt, redfin bully, common bully and torrentfish), and brown and rainbow trout in all NZReaches in the Bay of Plenty. These fish were the ones selected during the analysis of the data collected from the IFIM surveys to set Q_{min} in selected catchments. Apart from eels (both longfin and shortfin), these eight fish are the most widespread and abundant in the region (Table 6). They also have a wide range of velocity preferences, from slow water (0.04 and 0.05 ms^{-1} for banded kokopu and inanga) to fast water (0.68 to 0.72 ms^{-1} for adult rainbow trout and torrentfish). Given this, these eight fish were deemed appropriate to use in the development of a decision support models created to help council select the most appropriate values of Q_{min} in the region.

Although koaro and bluegill bully also have fast velocity preferences (Table 6), these fish were not as widespread throughout the region, and were found in < 10% of sites where we have records. Furthermore, predictive modelling of fish distributions shows that these two species are restricted to inland areas mainly to the central and east of the region, where abstraction pressure is minimal (see Section 1.5). Including fish with restricted distributions in generally unmodified catchments seemed inconsistent with the development of regional models designed to set minimum flows on the basis of protecting hydraulic habitat for fish in areas with a high demand for water. Finally, it was decided not to include tuna as target fish to help set Q_{min} in streams, as they often have lower hydraulic habitat requirements than other species. Because of this, they have been given a lower degree of hydraulic habitat protection when compared to other fish such as some galaxiads and trout (Jowett 2012). Given their lower hydraulic habitat requirements, it is logical that the flow requirements of fish such as tuna will be protected if the hydraulic flow requirements of more flow hungry species are maintained (but see Section 1.3 for a discussion on the implications of increasing the hydraulic habitat protection levels for tuna).

Table 6 List of all freshwater fish found in the Bay of Plenty, showing the number and percentage of sites (out of 1493) where they have been observed (data extracted from the New Zealand freshwater fisheries database). Species highlighted in yellow have been selected as target fish for use in setting IMFRs. Also shown are the velocity preferences for these species (Jowett and Richardson 2008).

Common name	Scientific name	Number of sites	Percentage of sites	Average velocity preference (m/s)
Longfin eels	*Anguilla dieffenbachii*	773	51.8	0.40
Shortfin eels	*Anguilla australis*	516	34.6	0.28
Rainbow trout[a]	*Oncorhynchus mykiss*	426	28.5	0.53 - 0.68
Redfin bully	*Gobiomorphus huttoni*	374	25.1	0.25
Common bully	*Gobiomorphus cotidianus*	347	23.2	0.35
Inanga	*Galaxias maculatus*	284	19.0	0.05
Brown trout[b]	*Salmo trutta*	322	21.6	0.48
Smelt	*Retropinna retropinna*	192	12.9	0.25
Banded kokopu	*Galaxias fasciatus*	179	12.0	0.04
Unidentified eel	*Anguilla sp*	175	11.7	
Torrentfish	*Cheimarrichthys fosteri*	175	11.7	0.72
Koaro	*Galaxias brevipinnis*	102	6.8	0.64
Bluegill bully	*Gobiomorphus hubbsi*	96	6.4	0.68
Mosquito fish	*Gambusia affinis*	87	5.8	
Giant bully	*Gobiomorphus gobioides*	86	5.8	
Giant kokopu	*Galaxias argenteus*	62	4.2	0.05
Gold fish	*Carassius auratus*	58	3.9	
Shortjaw kokopu	*Galaxias postvectis*	33	2.2	0.18

Common name	**Scientific name**	**Number of sites**	**Percentage of sites**	**Average velocity preference (m/s)**
Unidentified bully	*Gobiomorphus*	32	2.1	
Unidentified galiaxid	*Galaxias sp.*	22	1.5	
Crans bully	*Gobiomorphus basalis*	14	0.9	
Lamprey	*Geotria australis*	12	0.8	0.06
Dwarf galaxias	*Galaxias divergens*	9	0.6	0.43
Cockabully	*Grahamina*	7	0.5	
Grass carp	*Ctenopharyngodon idella*	4	0.3	
Brook char	*Salvelinus fontinalis*	2	0.1	
Tench	*Tinca tinca*	2	0.1	
European carp	*Cyprinus carpio*	1	0.1	
Rudd	*Scardinius erythrophthalmus*	1	0.1	

The resultant map of predicted fish distributions (Figure 25) showed that the six target native fish were mainly relatively low altitude waterways within 20 km of the coast, although some native fish were predicted at sites far inland up the Whakatāne and Tauranga Rivers, as well as many of the larger waterways in the east (Figure 25). These six native fish were predicted in approximately 16.4% of the 25202 NZReaches in the region. Trout were predicted in 25.3% of NZReaches and were found at inland sites at the headwaters of the Wairoa Catchment, around the Rotorua Lakes, and the upper Rangitāiki Catchment above the Matahina Dam (Figure 25). Both native species and trout were predicted together in a further 6.4% of NZReaches in the region. These were many of the larger waterways throughout the region, such as the Tuapiro and Te Rereatukahia in the Western Bay, headwater streams around the Rotoehu Forests, and many mid-sized waterways such as the Whakatāne, Tauranga, Waioeka, and Otara rivers in the central and eastern parts of the region (Figure 25).

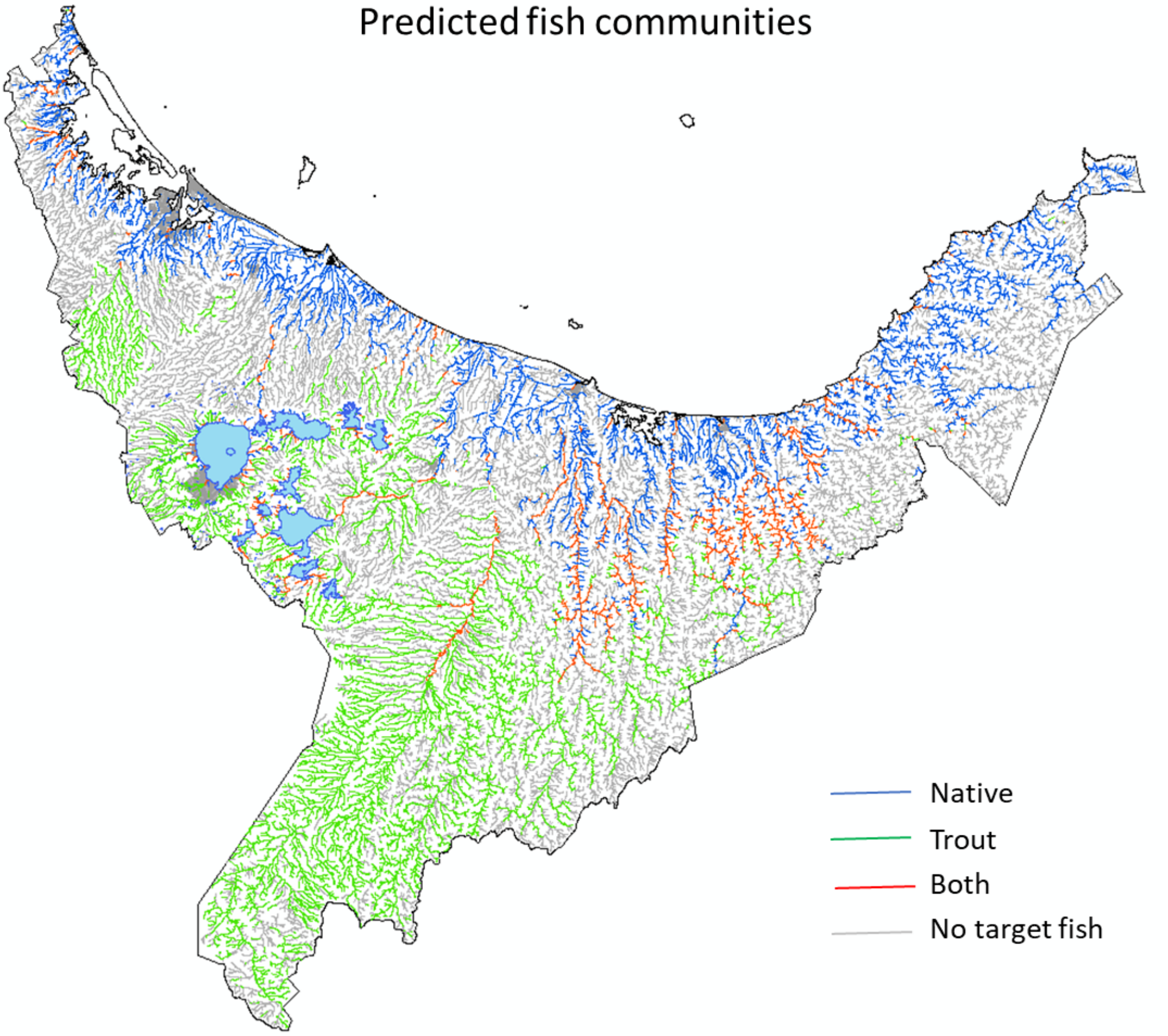


Figure 25 *Map showing the predicted distribution of fish groups in the Bay of Plenty: Native = a mix of common and redfin bully, banded kokopu, inanga, smelt and torrent fish; Both = both native and trout. Note how most of the native fish are restricted to waterways relatively close to the coast, while trout are found at sites much further inland. Where no target fish are predicted, it is recommended to simply use a hydrological default value to set Q_{min}.*

Just over half the NZReaches in the region (51.5%) were not expected to support any of the six native fish or trout (Figure 25). However, this does not imply that other fish do not live in these streams, but rather that they don't support the more "flow hungry" fish used in the IFIM analysis to set Q_{min}, or to develop relationships between IMFR and MALF. For example, eels are widespread throughout the region, and are found in 69% of the 1,531 sites where we have data on fish distribution (Table 6). However, eels generally prefer slower flowing water than many of the native fish or trout used to set minimum flows. As such, they were not used to set minimum flows in streams based on the need to maintain a specific percentage of hydraulic habitat. This is also why eels were given a lower habitat protection level by Jowett (2013) when recommending methods to set minimum flows in the Bay of Plenty using the IFIM methodology. Where none of the target fish are predicted in a stream, a simple hydrological default of either 70% MALF (small streams) or 60% MALF (large rivers) could be used to set Q_{min}, as flows this low are thought to still allow the maintenance of ecological processes in streams.

Setting Q_{min} to protect fish where no IFIM surveys have been done

Bay of Plenty Regional Council has already undertaken 54 IFIM surveys throughout the region to develop IMFRs for target fish species (Suren 2019). A further 14 IFIM surveys have been conducted as part of consent applications for water takes using the IFIM techniques (Baker and Jowett 2001; Jowett 2008, 2010, 2015). These consent-related data were subsequently added to the other IFIM surveys conducted by council to provide IMFRs from 68 rivers. This has given us the ability to set Q_{min} in all NZReaches within these catchments. However, there are many other NZReaches where target fish are predicted to occur, and where Q_{min} needs to protect their hydraulic habitat. A method thus had to be developed to allow a defensible Q_{min} to be set in streams where fish are predicted, but where no IFIM surveys had been done.

Regressions with measured MALF

Suren (2019) found highly significant regressions between IMFRs derived from IFIM studies and measured MALF, and these regressions differed significantly between the six native fish (banded kokopu, inanga, smelt, common and redfin bullies, and torrentfish) and trout, with trout having a higher IMFR for a given MALF (Figure 26). It was suggested that these regressions could be used to calculate the IMFR in all NZReaches where these fish were predicted to occur.

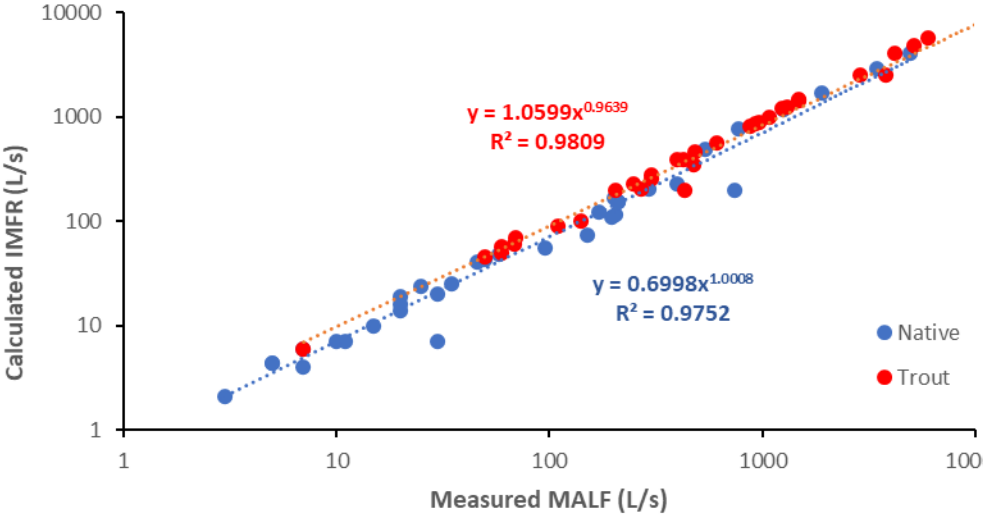


Figure 26 *Relationships between calculated IMFR values (derived from the IFIM surveys) for native fish and trout and measured MALF in 68 selected waterways throughout the region (using log transformed data). Note the different regression lines for trout (red symbols) and native fish (blue symbols). Note that data on both x and y axis have been plotted on a logarithmic scale.*

However, using these regressions is somewhat complicated by the fact that both fish types were predicted to occur in some NZReaches, meaning that a specific management decision would need to be made as to what the target species to protect would be. To simplify this process, a generalised regression was produced that examined the relationship between IMFRs derived from IFIM studies and MALF, irrespective of fish species. The resultant generalised regression was also highly significant (Figure 27), and subsequently used to calculate IMFRs in all NZReaches where any of the target fish were predicted to occur.

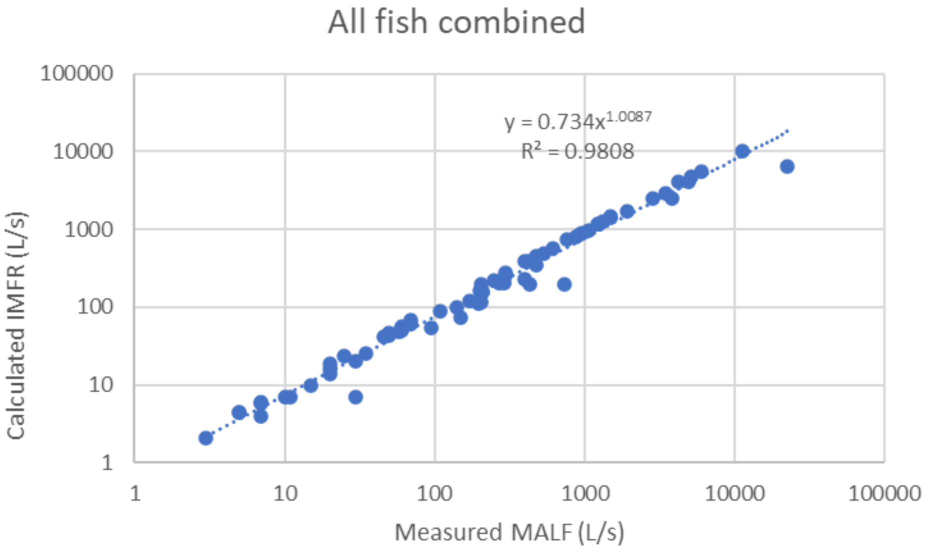


Figure 27 *Relationships between calculated IMFR values (derived from the IFIM surveys) for all fish and measured MALF in 68 selected waterways throughout the region). Note that data on both x and y axis have been plotted on a logarithmic scale.*

The above relationship in Figures 26 and 27 were derived using measured values of MALF. However, measured values of MALF are not available in every waterway in the region, so relationships between calculated IFMRs and modelled values of MALF were also examined. Relatively strong relationships were found between calculated IMFR values and modelled values of MALF (Figure 28), although the strength of these relationships was not as high as between the IMFR and measured values of MALF (Figure 26). Such significant relationships are not surprising given the high degree of correlation between measured MALF and modelled MALF as shown earlier (Figure 7). These findings suggest that the regression equations as shown in Figure 28 can be used to set IMFRs in other waterways throughout the region where MALF is not known, based on these modelled values of MALF (Suren 2019). The resultant IMFR values could then be used to set minimum flows to protect the hydraulic habitat requirements for the target fish species, where they were predicted to occur.

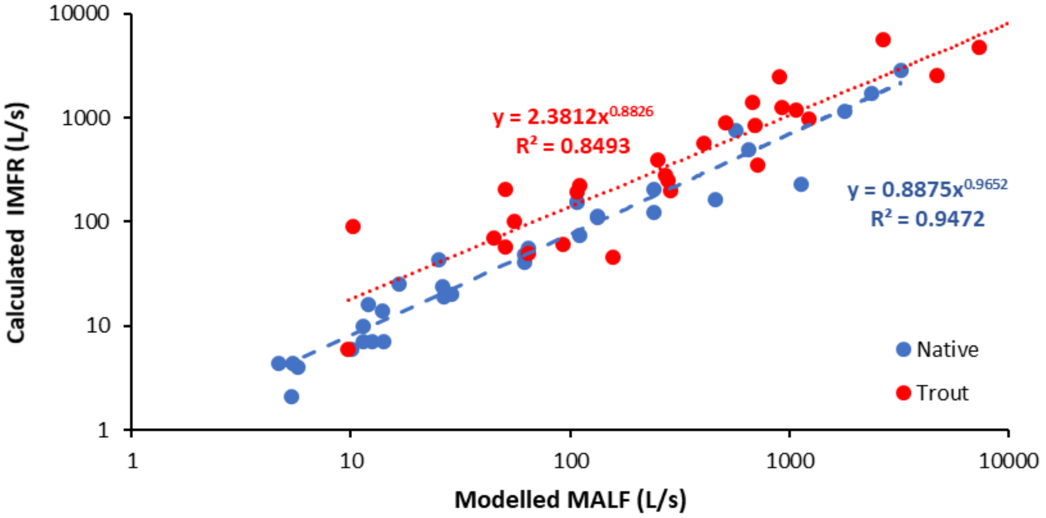


Figure 28 *Relationships between calculated IMFR values (derived from the IFIM surveys) for native fish (banded kokopu, inanga, smelt, common and redfin bullies, and torrentfish) or trout (brown and rainbow trout) and modelled MALF in 68 selected waterways throughout the region. Colours as per Figure 26.*

Regressions with measured MALF

As with the regressions between native fish or trout, and measured MALF, a regression of ALL IMFRs (irrespective of whether they are native or trout) and modelled MALF was also calculated (Figure 29). This generalised regression was used to calculate Q_{min} in all streams where the target fish were predicted to occur, but where only modelled MALF data was available. Use of these generalise regressions represented a pragmatic simplification of the decision to manage a waterway for either native fish, or trout, and would ensure that enough of the hydraulic habitat for these target fish is maintained in a site, relative to the MALF in that waterway.

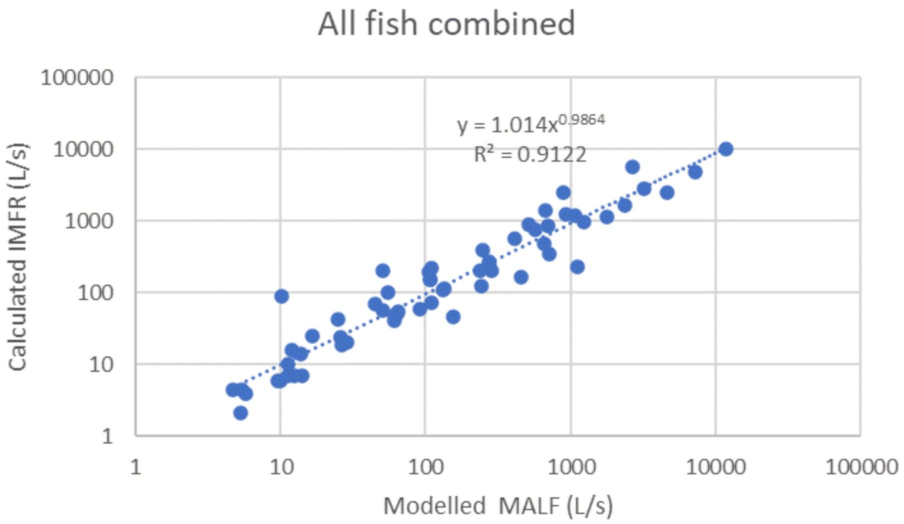


Figure 29 *Relationships between calculated IMFR values (derived from the IFIM surveys) for all fish and measured MALF in 68 selected waterways throughout the region). Note that data on both x and y axis have been plotted on a logarithmic scale.*

Use of generalised regressions

Although there would be differences in IMFRs when calculated using either the regression models developed for native fish and trout, or the generalised models, these differences were relatively small. For example, the average difference between IMFRs calculated using measured MALF with the native fish regression model or the generalised regression model showed that the native fish model underestimated IMFRs by only 4.7% (Table 7). The greatest difference was found between IMFRs calculated using modelled flow data and regression models for trout or the generalised model, where the trout model underestimated IMFRs by 10% those calculated using the generalised model. These differences are comparatively small, so that any disadvantages associated with using the generalised regression model are more that out weighted by the advantages of simplicity with not needing to make a management decision as to what the target fish should be.

Table 7 *Calculated average differences between IMFRs derived from regression equations for native fish, or trout and measured or modelled MALF, and IMFRs derived from the generalised regression equation of all fish combined and measured or modelled MALF.*

Fish group	% Difference – Measured MALF	% Difference – Modelled MALF
Native fish	-4.7%	-5.6%
Trout	-7.9%	-10.2%

IMFRs were thus calculated for all waterways (NZReaches) in the region where fish were predicted, and where IFIM surveys had not been done, based on modelled values of MALF in these waterways.

Recommendation 8. In waterways where target fish are predicted, and where IFIM surveys have not been undertaken, use the generalised regression equations developed between a stream’s IMFR and either measured or modelled MALF.

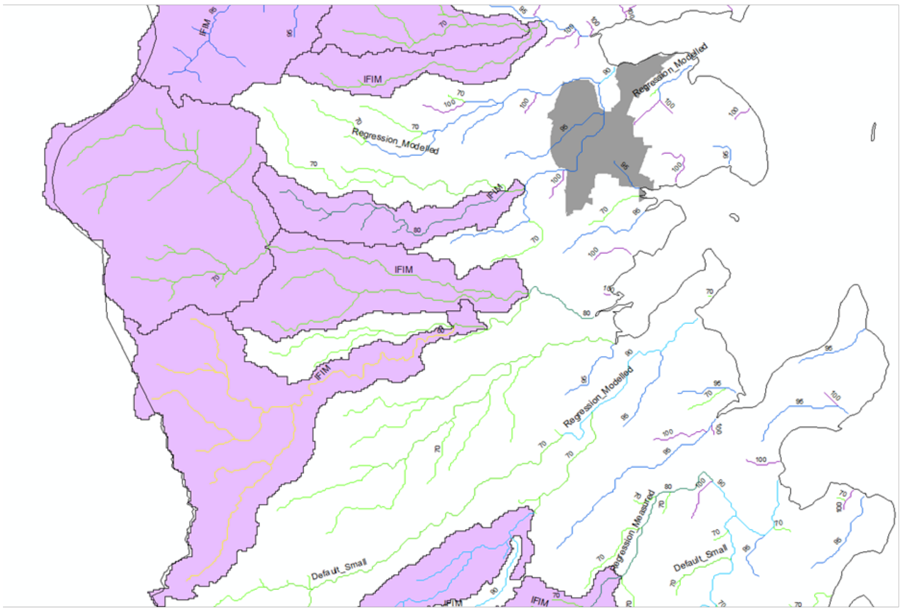
Scale of resolution

Snelder (et al. 2016) defined a potential biophysical framework for the Bay of Plenty to feed into the development of Freshwater Management Units (FMUs). The first step of their work was to classify the region’s rivers for water quality and quantity management, based on individual NZReaches of the REC network. Their M*anagement Classification* was based on methods that broadly discriminated variation in the characteristics of individual NZReaches that were relevant to management such as their values and capacity for resource use. The recommended Q_{min} for all NZReaches in the region (Figure 14) is thus the recommended Management Classification, as it discriminates variation of individual NZReaches on the basis of their Q_{min}.

Although this management classification was developed to set Q_{min} for all NZ reaches throughout the Bay of Plenty, it is important to consider the impact of the scale of resolution of any resultant outputs of this model in terms of planning, implementation and monitoring. The most accurate hierarchical model is developed using all 25,202 NZ reaches, which gives the greatest level of resolution and ability of setting appropriate Q_{min} in all waterways. This may seem a powerful technique, especially as a relatively large number of consented water takes are from small first-order streams. However, this difficulty with this is the potential high level of monitoring that would be required to see whether such minimum flows within each NZReach are being met. Another option would be to ammalgamate all catchments up to larger river orders (e.g., order 3), which greatly reduces the number of potential NZReaches (Figure 30), as well as reduce what would be very variable monitoring requirements that would need to be aplied across the region

This issue was highlighted in Snelder et al. (2016), where small and isolated NZReaches in some management classifications were too small for the practical application of policies. To remove some of this “patchiness”, Snelder et al. merged segments that were less than third order streams with the *management zone* assigned to the next downstream segment, irrespective of their own *management zone* assignment. Figure 30 demonstrates the difference in the *management zones* for stream order of one (all river network reaches included) and a minimum stream order of three.

REC ALL stream orders (25202 NZReaches)



REC stream orders ≥ 3 (6306 NZReaches)

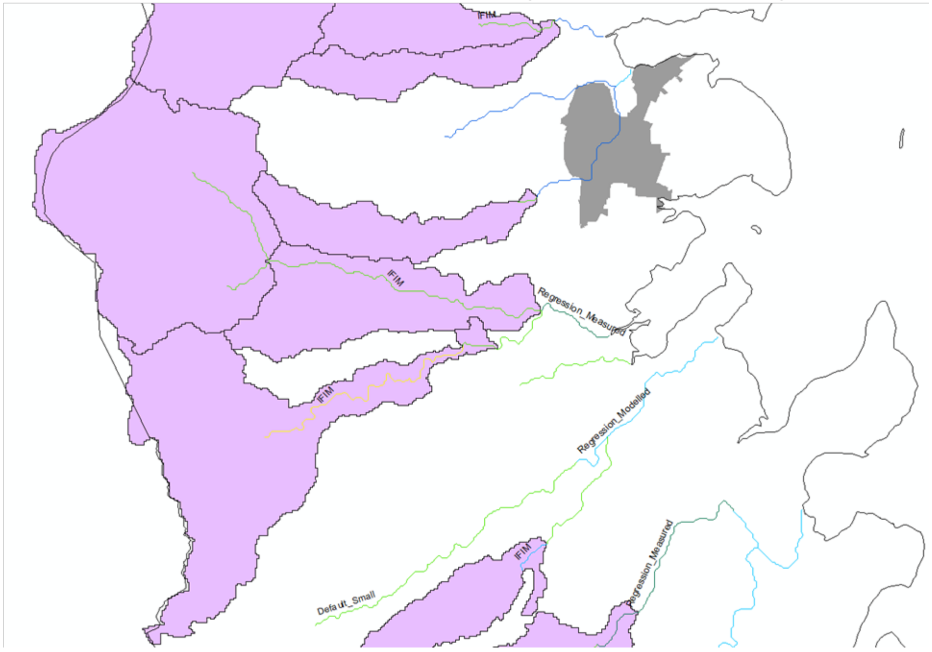


Figure 30 Example of differences in resolution of NZReaches obtained by using either all waterway sizes (First order and greater) or using only larger waterways such as third order and above. Note that fewer number of NZReaches with the latter approach.

The second step of Snelder et al.'s work involved assigning the land surrounding individual NZReaches in their management classification to specific M*anagement Zones*. *Management zones* recognise that many of the management actions (i.e., policies and rules) to achieve objectives apply to land areas (and associated land use and development) that drain to water bodies (although, for the purposes of setting Q_{min}, management actions do apply to the water body itself). Nevertheless, it is convenient to regard that all land areas draining to water bodies belonging to a particular *management class* become a *management zone*. *Management zone*s need to be defined so that management actions and limits that apply to them provide for the achievement of the *most restrictive requirement* (in this case, the most restrictive Q_{min}). For example, in some circumstances an upstream river segment may be relatively insensitive to the effects of abstraction, as fish may not be predicted to occur in it. It will thus have the default Q_{min} of 70% MALF, which is be less restrictive to takes. However, further downstream, target fish may be predicted to occur, meaning that its Q_{min} was based on the generalised regression equations, and the watercourse would be more sensitive to abstraction. Thus, any Q_{min} in the upper areas needs to ensure that any more restrictive flows can be achieved in downstream NZReaches.

As for the *management classes*, small and isolated patches of land in larger management zones would be too small for the practical application of policies, and these could be merged with the surrounding zone. It is thus suggested that further work be undertaken to develop new management zones, or sub-catchments for Q_{min} throughout the region.