Flow requirements of Te Arai and Waipaoa Rivers

Prepared for Gisborne District Council

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Councils must define 'environmental flow regimes' (EFRs) that are expected to support instream values to meet the requirements of the National Policy Statement for Freshwater Management (NPSFM 2020). The mechanism by which councils achieve EFRs is by setting 'take limits' in regional plans. The NPSFM directs councils to set take limits that prioritise river health over non-environmental uses of water, hence limits that are 'environmentally conservative'.

Where low flows are a concern, councils should define a 'cease-to-take flow' (CTTF), *the flow rate at which 'Block A' consented takes must cease*. Block A limits apply when river flows are relatively low. Of all the water allocation blocks applying to a river, Block A consents have the lowest CTTFs. Block A limits do not affect permitted takes and discretionary activities. In accordance with the NPSFM, the CTTF of a river—as a component of take limits—should be based on the planned EFR for that river. It follows that, where irrigation is likely to affect low flow hydrology, an EFR may include a 'critical low flow' (CLF). We define the CLF of a river as *the rate of river flow below which the environmental values we wish to maintain are threatened if that flow is experienced for prolonged periods*.

In summary:

- CLF is the flow that we want to avoid happening because it is likely to be harmful to the environment.
- CTTF is the flow that will trigger the Block A abstractions to turn off.

The CLF is a component of an environmental flow regime and a response to Clause 3.16 of the NPSFM 2020. The CTTF is an operational flow; a component of a river's take limits and a response to Clause 3.17 of the NPSFM 2020. It follows that differentiation of the CLF and the CTTF is consistent with the NPSFM. Further, we argue that defining both a CLF and a CTTF helps reduce the risk of undesirable environmental outcomes by explicitly accounting for the lag between reaching a CTTF (notifying those with consented takes that CTTF has been reached) and the response by consented water users to that CTTF (cessation of water takes).

Gisborne District Council (GDC) require information to support specification of CTTFs. Te Arai River and the Waipaoa River are of particular concern, as these two rivers account for the majority of consented water takes in the district, either directly from surface flows or from associated aquifers. Gisborne District Council contracted NIWA to review the current CTTFs in light of the requirements of the NPSFM. They also requested we participate with GDC staff to review Gisborne's hydrology data and its hydrological monitoring practices.

The outputs of the hydrology review were:

- Identification of periods in the available time series suitable for estimating flow duration curves (FDCs) and hydrological statistics (e.g. MALF) for the Waipaoa River and Te Arai River.
- FDCs and observed (not naturalised) MALF estimates for Te Arai River at the water supply intake and at Pykes Weir, and for the Waipaoa River at Kanakanaia. An estimate of naturalised MALF for Te Arai at the water supply intake (also known as the 'water works') is also provided.

- Estimates of flow gains and losses downstream of key flow monitoring gauges, such that GDC may better understand how CTTFs set and monitored at gauging sites are translated downstream.

- Recommendations for how flow monitoring could be improved within the Gisborne District.

Data and models for understanding how low flows affect environmental outcomes were poor. Little to no flow-dependent data has been collected in the Waipaoa and Te Arai Rivers since 2010. Nevertheless, consistent with NPSFM Clause 3.6 (Transparent decision-making) and Clause 1.6 (Best information) we used the best data and models available to present a transparent assessment of CLFs in the Waipaoa and Te Arai Rivers.

Our assessment of CLFs was undertaken to illustrate how the information presented may be used. We do not 'recommend' any particular CLF or resultant CTTF and understand that the choice made by GDC will represent a balance among the competing objectives of maintaining/improving freshwater values and maintaining outcomes for out-of-stream water use.

We assessed potential instream outcomes of CLFs within three water quantity zones (WQZs) of two freshwater management units (FMUs):

1. The Waipaoa surface WQZ within the Poverty Bay Flats FMU.

2. The Upper Te Arai WQZ within Te Arai FMU.

3. The Lower Te Arai WQZ within Te Arai FMU.

Data used for our assessments come from the Waipaoa River at Kanakanaia, Te Arai at the water supply intake (water works) and Te Arai at Reays Bridge, which respectively correspond to the above three WQZs. Reays Bridge is ca. 3 km downstream of Pykes Weir flow recorder.

Assessment of CLFs was based on flow-response models where responses were (a) habitat availability (weighted usable area) of native fishes, macroinvertebrates and periphyton; and (b) water temperature (Waipaoa River at Kanakanaia only). Trout response to flow was not considered as trout are not a major value in the Gisborne District.

Three CLFs were assessed for the Waipaoa River at Kanakanaia and the Lower Te Arai River. By contrast we offer assessment of only a single CLF for Te Arai at the water works. Te Arai River at the water works was treated differently because (a) a natural flow record was available, enabling what is arguably a more defensible approach to minimum flow setting; (b) there are no substantial water takes above the water works; and (c) the major take below the water works is for domestic water supply and so there is currently no Block A CTTF or allocation cap applied to limit abstraction at the water works.

Critical low flow options considered for the Waipaoa River at Kanakanaia and the Lower Te Arai River were:

1. *Instream values*.

2. Observed mean annual low flow *(Observed MALF)*.

3. *Status quo*.

Option 1—instream values—presents CLFs that, given the limited data and models available, may support high levels of NPSFM values, including all aspects of ecosystem health, threatened species and physical habitat associated with mahinga kai (see Appendix 1A of the NPSFM 2020). Option 1 is used as the point of reference for Options 2 and 3. The potential outcomes from Options 2 and 3 are summarised using a five-point categorical scale relative to Option 1 and under the assumption that Option 1 supports '*high*' values. Relative to '*high'* the other four levels of value maintenance were '*moderate-high*', '*moderate*', '*moderate-low*' and '*low*'.

The outcome of our assessments are summarised in the table below.

Table 1: Critical low flow (CLF) options for the Waipaoa and Te Arai Rivers. CLFs presented in units of litres per second (L/s). An assessment of relative maintenance of instream values given currently available data and models provided in brackets after each minimum flow.

	Option 3 (status quo)	**Option 2 (Observed MALF)**	**Option 1 (instream values)**
Waipaoa @ Kanakanaia	1,300 (moderate)	2,550 (moderate-high)	3,000 (high)
Te Arai @ Reays Bridge	60 (low-moderate)	60 (low-moderate)	150 (high)
			Option 1 (instream values; naturalised MALF default)
Te Arai @ water works			36 (high)

To reduce the risk of dropping below the CLF, CTTFs may be set using a simple equation:

CTTF = CLF + Block A allocation cap (Eqn. 1)

This very simple equation highlights a water-supply trade-off: a larger Block A allocation cap increases Block A water availability while flow is above the CTTF, but it also increases the CTTF, so results in cessation of abstraction at higher flows than would be the case for a smaller Block A allocation cap.

The larger the allocation cap relative to the CTTF the larger the chances of a 'yo-yo effect' in flow as flows fall below the CTTF and then rise above the CTTF on consecutive days because cease-to-take restrictions are triggered and then withdrawn. These fluctuations may have a detrimental effect on instream values. The magnitude of potential fluctuations may be reduced by using a Block A allocation cap that is a relatively low percentage of the CLF (say, 33% of CLF). For illustrative purposes only, in Table 2 we have translated the CLFs of Table 1 into allocation caps and CTTFs.

Table 2: Translation of the example CLFs for the Waipaoa and Te Arai Rivers (in Table 2) into allocation caps and CTTFs. Allocation caps and CTTFs are presented in units of litres per second (L/s). Here, allocation caps are set at 33% of the CLFs in Table 1. CTTFs are then determined using Eqn. 1.

	Option 3 (status quo)		**Option 2 (Observed MALF)**		**Option 1 (instream values)**	
	CTTF	Cap	CTTF	Cap	CTTF	Cap
Waipaoa @ Kanakanaia	1,733	433	3,400	850	4,000	1,000
Te Arai @ Reays Bridge	80	20	80	20	200	50

	Option 3 (status quo)	Option 2 (Observed MALF)	Option 1 (instream values)	
			Option 1 (instream values; naturalised MALF default)	
Te Arai @ water works			48	12

Looking ahead, to improve evidence-based take limits within Gisborne District we recommend:

1. Exploring the use of alternative, mechanistic flow-response models for minimum-flow setting during 2024–2025.
2. Naturalising flow series for the Waipaoa and Te Arai Rivers.
3. Implementing monitoring for adaptive management of river flows.
4. Considering a banded water allocation system with several CTTFs controlling separate groups of abstractions.

1 Introduction

1.1 Policy context

Flow is a 'master' variable exerting a strong influence on most physical and biological processes of rivers (Walker et al., 1995). The 'flow regime[1]' of a river interacts with underlying geology to shape habitat structure at multiple spatial scales. Traits of riverine animal and plant species have coevolved with the river's 'natural flow regime[2]' and the habitat associated with that regime. This dependence of species' population processes (e.g., reproduction, movement, recruitment, mortality) on the natural flow regime is a central tenet of the 'Natural Flow Paradigm' (Lytle and Poff, 2004), which has become one of the most fundamental principles in river ecology and management. Disruption of the natural flow regime threatens the physical and biological processes that support the ecosystem values of rivers.

Aotearoa New Zealand's National Policy Statement for Freshwater Management (NPSFM, 2020) acknowledges the detrimental effects that flow alteration has had on New Zealand's rivers and the values they support (NPSFM Policy 11). The NPSFM directs councils to define 'environmental flow regimes' (EFRs) that are expected to support environmental objectives (NPSFM Clauses 3.9 and 3.16).

Defining an EFR requires an understanding of:

A. environmental values of communities and tangata whenua;

B. which types of water takes require management and how those water takes are affecting—or are likely to affect—a river's flow regime; and

C. how those hydrological effects, in turn, affect a river's geomorphology and ecology, hence its values.

Planned EFRs may vary among rivers, depending on variation in natural flow regimes and environmental objectives among rivers.

The mechanism by which councils achieve EFRs is by setting 'take limits' in regional plans (NPSFM Clause 3.17). The NPSFM states that take limits must be expressed as the total volume and/or a total rate at which water is taken from a river (NPSFM Clause 3.17.2). In practice, however, setting take limits to achieve an EFR at a particular site requires defining when, where and at what rate water can be taken by all consented water takes upstream of that site (Booker et al., 2022).

A fundamental concept underpinning the NPSFM is 'Te Mana o te Wai'. Te Mana o te Wai '*refers to the fundamental importance of water and recognises that protecting the health of freshwater protects the health and well-being of the wider environment. It protects the mauri of the wai. Te Mana o te Wai is about restoring and preserving the balance between the water, the wider environment, and the community*' (Clause 1.3.1 NPSFM, 2020). Subclause 1.3.5 presents a particularly challenging directive to councils; it states that there '*is a hierarchy of obligations in Te Mana o te Wai that prioritises:*

[1] We define the flow regime as a quantifiable representation of the main characteristics of a time series of discharge, calculated over a period spanning many years (ideally > 20 years). The flow regime may present variability at several temporal resolutions (e.g., variability within a year, among seasons, as well as interannual variability in gross features of annual hydrographs).
[2] The natural flow regime is the flow regime of a river whose flows have not been significantly altered by humans. The natural flow regime is primarily shaped by interactions between precipitation (snow, rain,…), climate (affecting evaporation, ice formation, etc.) and geology (e.g., influencing runoff).

A. *first, the health and well-being of water bodies and freshwater ecosystems;*

B. *second, the health needs of people (such as drinking water);*

C. *third, the ability of people and communities to provide for their social, economic, and cultural well-being, now and in the future*.'

The implication of Te Mana o te Wai is that councils must set water take limits that prioritise river health over non-environmental uses of water, hence limits that are 'environmentally conservative.'

1.2 Critical low flows and cease-to-take flows

Recent collaborative work between numerous councils and scientific organisations identified two types of water take[3] most relevant to flow management in New Zealand (Stoffels et al., 2022):

1. Water takes during dry periods that increase the duration, magnitude and/or frequency of low river flows within and among years.

2. Water takes during mid-high discharges for off-channel storage, and subsequent use during dry periods ('flow harvesting'). Flow harvesting may decrease the frequency of mid-high discharges within and among years.

This categorisation of water take types is consistent with the report of Hickford et al. (2023) that refers to run-of-river takes and high-flow harvesting takes.

Low flows are of particular concern to many councils. Where low flows are a concern, EFRs should include specification of a 'cease-to-take flow' (CTTF), the flow rate at which 'Block A' consented takes must cease. Block A limits apply when river flows are at their lowest. Block A limits do not affect permitted takes and discretionary activities (see next section). In accordance with the NPSFM, the CTTF of a river—as a component of take limits—should be based on the planned EFR for that river. It follows that, where irrigation is likely to affect low flow hydrology, an EFR may include a 'critical low flow' (CLF). We define the CLF of a river as *the rate of discharge below which the environmental values we wish to maintain are threatened*[4]. Included in this definition of CLF are cultural values such as natural form/character, swimming, boating and transport (tauranga waka; Appendix 1B of the NPSFM 2020).

Note that the CLF is an environmental flow and a response to Clause 3.16 of the NPSFM 2020. By contrast, the CTTF is an operational flow; a component of a river's take limits and a response to Clause 3.17 of the NPSFM 2020. It follows that differentiation between the CLF and the CTTF is consistent with the NPSFM. Further, we argue that defining both a CLF and a CTTF helps reduce the risk of undesirable environmental outcomes by explicitly accounting for the lag between reaching a CTTF and responding to that CTTF (water abstraction ceasing), as explained in Figure 1-1. By reducing the risk of undesirable outcomes, differentiation of the CLF and a CTTF is consistent with Te Mana o te Wai.

[3] For the purposes of this report water 'taken' from a flow regime includes all surface and groundwater abstractions, diversions and damming.

[4] Low-flow ecology of New Zealand rivers is poorly understood. Although we have offered a working definition of CLF here, we acknowledge that quantitatively defining a CLF is an ongoing challenge of an evolving discipline.

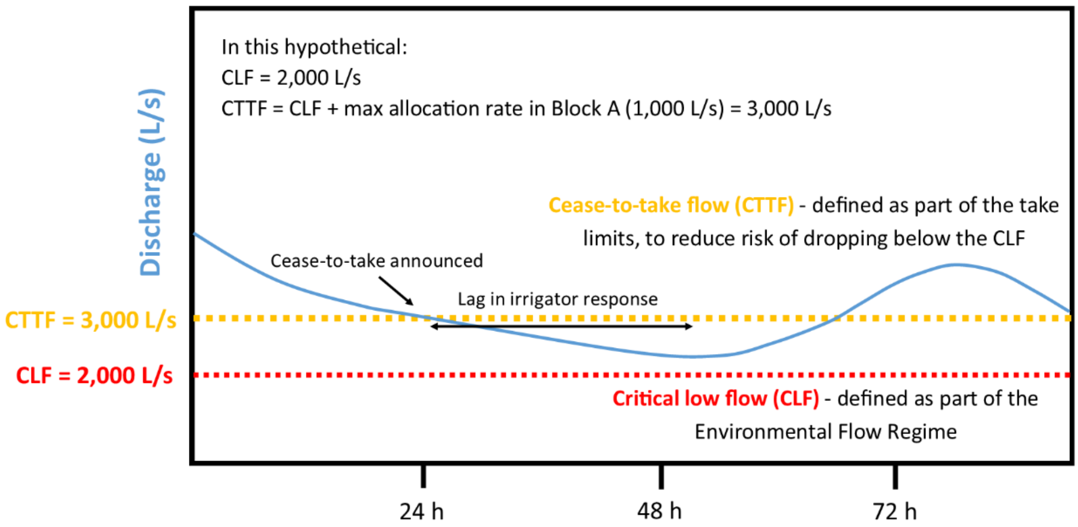


Figure 1-1: Conceptual diagram explaining the difference between the critical low flow and a cease-to-take flow. This figure presents a hypothetical of 2,000 L/s as the CLF, with a maximum allocation rate (referred to as an allocation cap in Gisborne) of 1,000 L/s, hence a CTTF of 2,000 + 1,000 = 3,000 L/s. Lag in irrigator response is only hypothetical.

There is much uncertainty about how low river flows affect environmental outcomes in New Zealand. Despite this uncertainty councils are required to define take limits of rivers subject to abstraction (NPSFM Clause 1.6). We appreciate that riverine values may exhibit a constant positive relationship with flow—no 'threshold' reduction in values may be obvious as flow declines. It follows that defining a CLF may be relatively arbitrary and based on the magnitude of value-loss that a council—in consultation with stakeholders and mana whenua—deems (un)acceptable.

1.3 Project background

Gisborne District Council (GDC) require information to support the design of EFRs. Te Arai and the Waipaoa Rivers are of particular concern, as these two rivers account for the majority of consented water takes in the district, either directly from surface flows or from associated aquifers.

During 2009–2010, GDC contracted NIWA to determine how alternative CLFs may affect availability of physical habitat for aquatic organisms within Te Arai and Waipaoa Rivers (Booker et al., 2010; hereafter referred to as the '2010 report'). Availability of suitable physical habitat as a function of river flow was estimated using physical habitat simulation models (RHYHABSIM; Jowett, 1989). These models were then used to assess the effects of three CTTF options on habitat availability of fishes, *Deleatidium* mayflies and periphyton (Table 1-1).

- Option 1 was based on CTTFs applied by GDC in existing consent conditions at the time, which stated that abstraction below these CLFs is to be at the discretion of the District Conservator.
- Option 2 was based on a default CTTF of either 80% (Waipaoa) or 90% (Te Arai) of the mean annual (7-day), observed[5] low flow (MALF) as set in the National Environmental

[5] In this report we differentiate 'observed' MALF from 'naturalised' MALF. Observed MALF is estimated using a monitored discharge series that has been affected by water abstraction. Naturalised MALF is estimated from a monitored discharge series that is unimpacted by water abstraction or from a modelled discharge series, in which the potential effects of water abstraction have been removed.

Standard (NES) on Ecological Flows and Levels[6]. The MALF used for Option 2 in the 2010 report was estimated from observed flow data, so would have been influenced by historical trends in water abstraction. As such, the MALF of the 2010 report does not reflect MALF under natural flow conditions, and would likely have been an underestimate of naturalised MALF.

- Option 3 was based on maintaining instream ecological values at a higher level, given the data collected, and the models used in the 2010 report.

The 2010 report assessed the relative effect of each CTTF option on instream ecological value using a five-point relative scale: 'Low', 'Low-moderate', 'Moderate', 'Moderate-High' and 'High' level of maintenance of instream habitat for ecological values. Relative maintenance of values was based on (a) the assumption that Option 3 maintained 'high' ecological value; and (b) the relative difference between modelled habitat availabilities under Options 1, 2 and 3.

Table 1-1: Cease-to-take flow (CTTF) options considered in the 2010 report. Cease-to-take flows presented in units of litres per second (L/s). Relative maintenance of instream values provided in brackets after each CTTF.

	Option 1 (status quo)	Option 2 (NES default)	Option 3 (instream values)
Waipaoa @ Kanakanaia	1,300 (moderate)	1,600 (moderate-high)	2,000 (high)
Waipaoa @ Ford Road	1,300 (moderate)	1,600 (moderate-high)	2,000 (high)
Te Arai @ Water Works	No minimum flow (low)	60 (moderate)	150 (high)
Te Arai @ Reays Bridge	15 (low-moderate)	60 (moderate)	150 (high)

Table 1-2: Current cease-to-take flows (CTTFs) and allocation caps for the Waipaoa and Te Arai Rivers. 'Blocks' refer to different subsets of water use consents within the Gisborne District. Of all the water allocation blocks applying to a river, Block A consents have the lowest CTTFs. Permitted Takes include, for example, stock watering. Discretionary activities are water takes where no catchment plan and water quantity limits are in place.

Freshwater management unit	Water quantity zone	Monitoring location	Block A minimum flow	Block A allocation cap	Block B minimum flow	Block B allocation cap
Poverty Bay Flats	Waipaoa surface water	Kanakanaia	1,300 L/s	2,000 L/s	4,000 L/s	2,000 L/s
Waipaoa Hill Country	Waipaoa Hill Country	Kanakanaia	No A block. Permitted Takes only. Discretionary Activity.		4,000 L/s	2,000 L/s
Te Arai	Upper Te Arai	Water supply intake	Restricted Discretionary Activity – City Municipal Supply. All Other takes Discretionary Activity			
Te Arai	Lower Te Arai	Pykes Weir	60 L/s	70 L/s	220 L/s	100 L/s

[6] Ministry for the Environment (2008) Proposed National Environmental Standard on ecological flows and water levels, Discussion document. Wellington: Ministry for the Environment, 868. 61 p. This National Environmental Standard was never ratified. According to the proposed NES 80% of MALF defines minimum flow of 'large rivers' (mean flow ≥ 5 cumecs) while 90% of MALF defines minimum flow of 'small rivers' (mean flow < 5 cumecs).

Following the 2010 report, GDC set the CTTFs and allocation caps (maximum take rates) presented in Table 1-2. The Option 3 'instream values' CTTFs were not adopted by GDC due to economic values being prioritised when the Waipaoa Catchment Plan was developed and notified in 2015[7]. Block A is the block of consents that includes most run-of-river takes (mostly for irrigation purposes) but excludes takes under permitted and/or discretionary activities.

1.4 Objectives, report structure and scope

Gisborne District Council required a review of the current CTTF rules for the Waipaoa and Te Arai rivers (Table 1-2) within the context of the NPSFM 2020. Prior to assessment of the extent to which river flows affect values, GDC requested we collaborate with GDC staff to review flow data from the Waipaoa and Te Arai rivers, and the processes used to monitor flows of those rivers. The objectives of this project were, therefore:

1. Review the analysis of Waipaoa and Te Arai hydrology data recently completed by GDC[8], focusing on:

    1.1 potential inaccuracies in the hydrology data and, if present, how such inaccuracies might be remedied; and

    1.2 estimates of flow gains and losses downstream of key flow monitoring gauges, such that GDC may better understand how minimum flow rules set and monitored at gauging sites are translated downstream.

2. Review options for updating and extending (e.g., new taxa/values) the flow-response model outputs of the 2010 report, based on recent developments presented in the System for Environmental Flow Analysis (SEFA[9]).

3. Either:

    3.1 Update and extend the flow-response model predictions of the 2010 report using the extended capabilities of SEFA; OR

    3.2 if the capabilities of SEFA are unlikely to change the information presented in the 2010 report, then reproduce the flow-response outputs of the 2010 report.

4. Use spatially-coupled river flow, air temperature and water temperature data to analyse the relationship between river discharge, air temperature and water temperature within the Waipaoa River.

5. Present an analysis of the extent to which alternative critical low flow (CLF) choices provide habitat for instream values of the Waipaoa and Te Arai Rivers, especially within the context of the NPSFM 2020.

6. Recommend future work streams to strengthen evidence-based flow allocation rules for rivers of the Gisborne District.

[7] Regional Freshwater & Waipaoa Catchment Plan Review | Gisborne District Council (gdc.govt.nz)
[8] During 2022-2023 GDC undertook an internal review of river flow data monitored within the Waipaoa River at Kanakanaia and Te Arai River at Pykes Weir, as well as river flow monitoring processes and protocols.
[9] sefa.co.nz

Output of Objective 1 comprises Section 2 of this report (**Flow data for the Waipaoa and Te Arai Rivers**). The outputs of Objectives 2-4 comprise Section 3, **Flow-habitat relationships**. The outputs of Objectives 5 and 6 correspond respectively to Sections 4 (**Assessment of alternative critical low flows**) and 5 (**Improving evidence-based take limits in the Gisborne District**) of this report.

Below we list noteworthy elements of scope:

- The hydrology review involved attendance of several online meetings and ad hoc reviews of the outputs and outcomes of the GDC-led hydrology analysis. It follows that a significant component of this work was for NIWA scientist Lawrence Kees to act as an advisor to GDC.
- In this report we present flow-habitat relationships to facilitate CTTF-setting by the GDC. We present an example assessment of alternative CLF choices using the flow-habitat relationships. We do not, however, recommend CLFs or CTTFs for Te Arai and Waipaoa Rivers. We recognise that the GDC is responsible for considering the information presented in this report and setting take limits that balance the numerous—and conflicting—uses of freshwater, in consultation with tangata whenua and other stakeholders.
- Flow-response modelling for trout was out of scope as trout are not a notable value of the Waipaoa and Te Arai Rivers.
- Mechanistic modelling of relationships between flow and native aquatic animal/plant populations was out of scope as such models are currently not available.
- Flow-water temperature modelling for Te Arai River was out of scope as we had no water temperature data from Te Arai River.
- Modelling joint effects of climate change and river flow on instream values was out of scope.

2 Flow data for the Waipaoa and Te Arai Rivers

2.1 Potential inaccuracies in the hydrology data.

2.1.1 Specific aims and approach

The aims of this analysis were:

1. Contribute advice to facilitate GDC's collation and review of river flow data for their fit for river flow management purposes from three sites:

   1.1 Waipaoa River at Kanakanaia;

   1.2 Te Arai River at the Bush Intake Above Weir; and

   1.3 Te Arai River at Pykes Weir.

2. In collaboration with GDC identify periods of flow time series deemed most robust for estimating hydrological statistics, including 7-day observed MALF and flow duration curves (FDCs) for each monitoring site.

3. Using the reliable subsets of flow data from Aim 2, estimate FDCs and observed MALFs for the three monitoring sites listed above.

4. Offer recommendations for how monitoring of river flow data could be improved in the future to inform river flow management, including recommendations for how flow monitoring site infrastructure could be improved.

To meet **Aim 1** a NIWA hydrologist[10] attended nine meetings to discuss data and approaches to GDC's flow data review. Following those meetings NIWA reviewed 10 GDC documents that presented the outcomes and outputs of the GDC-led hydrology review. River flow data are often generated by converting water levels to flows using a level-to-flow rating curve. Rating curves are fitted to paired direct observations of water level and gauged flows measured during site visits. Rating curves can change through time due to changes in river geomorphology at the gauging station. Changes to rating curves are likely to be more frequent in river channels with highly mobile beds such as the Waipaoa River at Kanakanaia (Figure 2-1).

The process of data review undertaken by GDC included the assessment of systematic deviations in the hydrological record, which are indicative of a rating curve change, incorrect rating curve shape or measurement bias. An **outcome of Aim 1** was a set of specific concerns that GDC had about river flow monitoring on Te Arai and Waipaoa Rivers—concerns that influenced subsequent steps in the process of identifying environmental flow regimes and associated take limits.

[10] Lawrence Kees

Figure 2-1: Waipaoa River near Kanakanaia in April 2010. Source: Doug Booker, NIWA.

Meeting **Aim 2** involved completing three ad hoc tasks in response to the outcomes of Aim 1:

- For the Waipaoa River at Kanakanaia, compare and contrast (a) FDCs estimated using data from two different flow recorders at this site (GDC vs. NIWA gauge), and (b) the number of gaugings that contribute to flow records coming from each gauge. This comparison shed light on the relative reliability of flow data coming from the GDC and NIWA flow recorders.
- An analysis of stage measurement error for the Waipaoa River at Kanakanaia (GDC data) and Te Arai River at Pykes Weir sites.

The **output of Aim 2** was a set of recommendations concerning which data subsets should be used for hydrological statistics, including the flow assessments in Section 4 of this report.

To complete **Aim 3** the reliable subsets of river data (from Aim 2) were used to estimate FDCs and observed MALFs for all three river flow monitoring sites considered in this report.

Meeting **Aim 4** was straightforward and involved collating several potential problems with flow monitoring noted while completing Aims 1–3, then offering recommendations to help remedy those problems.

2.1.2 Flow data reliability

Comparison of the Waipaoa River flow data from the GDC and NIWA gauges at Kanakanaia

Both NIWA and GDC maintain a flow recorder on the Waipaoa River at Kanakanaia. Flow duration curve comparisons were used to infer whether there were systemic differences in the development of river stage versus flow relationships derived by NIWA and GDC, and at what flows any such differences occur. In the assessment of the reliability of each record at a particular flow, consideration was given to the number of streamflow measurements (gaugings) at each site. A comparison of gaugings applied by NIWA and GDC at the two sites may elucidate what stream flow record is more reliable, and where any differences between flow records may occur. Deviation in flow time-series is important as it may lead to variation in the number of days that irrigation is available to water users, or that habitat is impacted at the higher end of permitted limits.

GDC reviewed flow rating curves estimated using data from their recorder at Kanakanaia from 2003. There is extensive commentary on the gauging data and updated ratings within the spreadsheets supplied to NIWA by GDC and this informed NIWA's analysis. Resources available for the current work did not permit a detailed commentary on every rating curve in the record. To aid the comparison of GDC and NIWA flow data, GDC provided cumulative runoff plots, preliminary FDCs, river streamflow gauging data and the river flow and level relationships (flow ratings) for the GDC Waipaoa at Kanakanaia site and Te Arai River at Pykes Weir.

Comparison between the GDC and NIWA flow duration curves show the greatest deviation at lower flows (3.5 $m^3 s^{-1}$; Figure 2-3), and equates to ~13% at the 95th exceedance percentile and grows to ~18% at the 99th percentile. The period of flow with least differences between NIWA and GDC flow time-series for each site was from 2015 until present. To determine the cause of differences between NIWA and GDC flow time-series, the number of gaugings and the temporal spread of those gaugings was investigated to determine the relationship between measured water level and flow.

There are 1397 gaugings from Waipaoa River at Kanakanaia collected by GDC and NIWA. This number of gaugings reflects the length of record, and the number of gaugings necessary to develop a stage/discharge relationship in a highly mobile stream bed. Of note is the number of gaugings that are made during the period for which a particular rating curve is applied before transitioning to application of a new rating curve (Table 2-1). The higher number of gaugings associated with GDC and the distribution of flow measured by those gaugings suggests that the lower end of the flow record is better characterised by the GDC record (Table 2-1 and Figure 2-3).

GDC has a higher frequency of gauging in summertime and at low flows (Figure 2-4). The gauging frequency reflects the need for accurate flow data to maintain flow by managing water abstractions both upstream and downstream of the Kanakanaia site (Figure 2-4). Consequently the 7-day MALF is better characterised in the GDC data set, although the GDC data does not have the temporal coverage or frequency of higher flow measurements that the NIWA data set has.

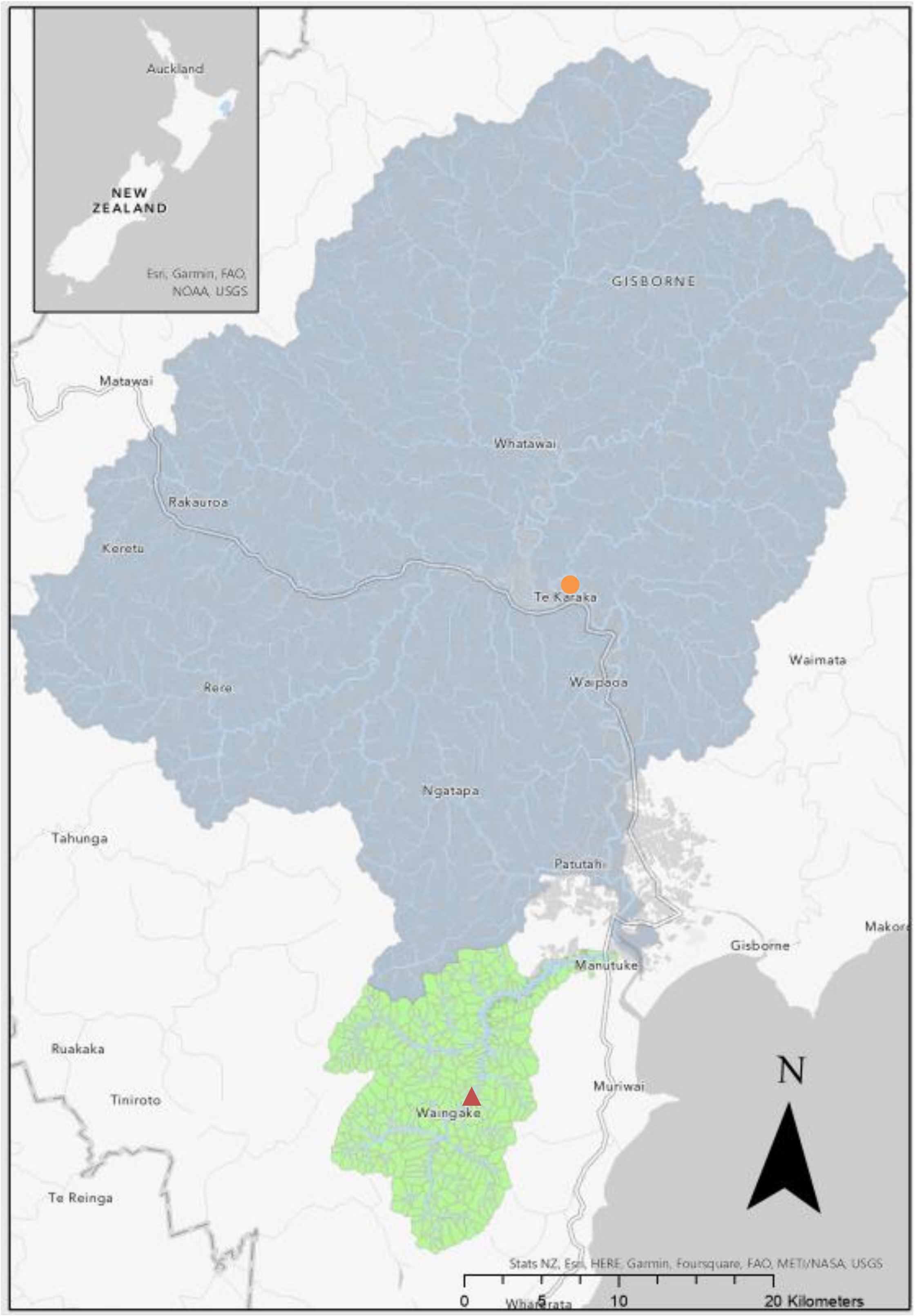


Figure 2-2: Catchments of the Waipaoa River (blue; 1,900 km^2) and Te Arai River (green; 187 km^2). The Waipaoa River at Kanakanaia and Te Arai at Pykes Weir gauges are shown by an orange circle and red triangle respectively.

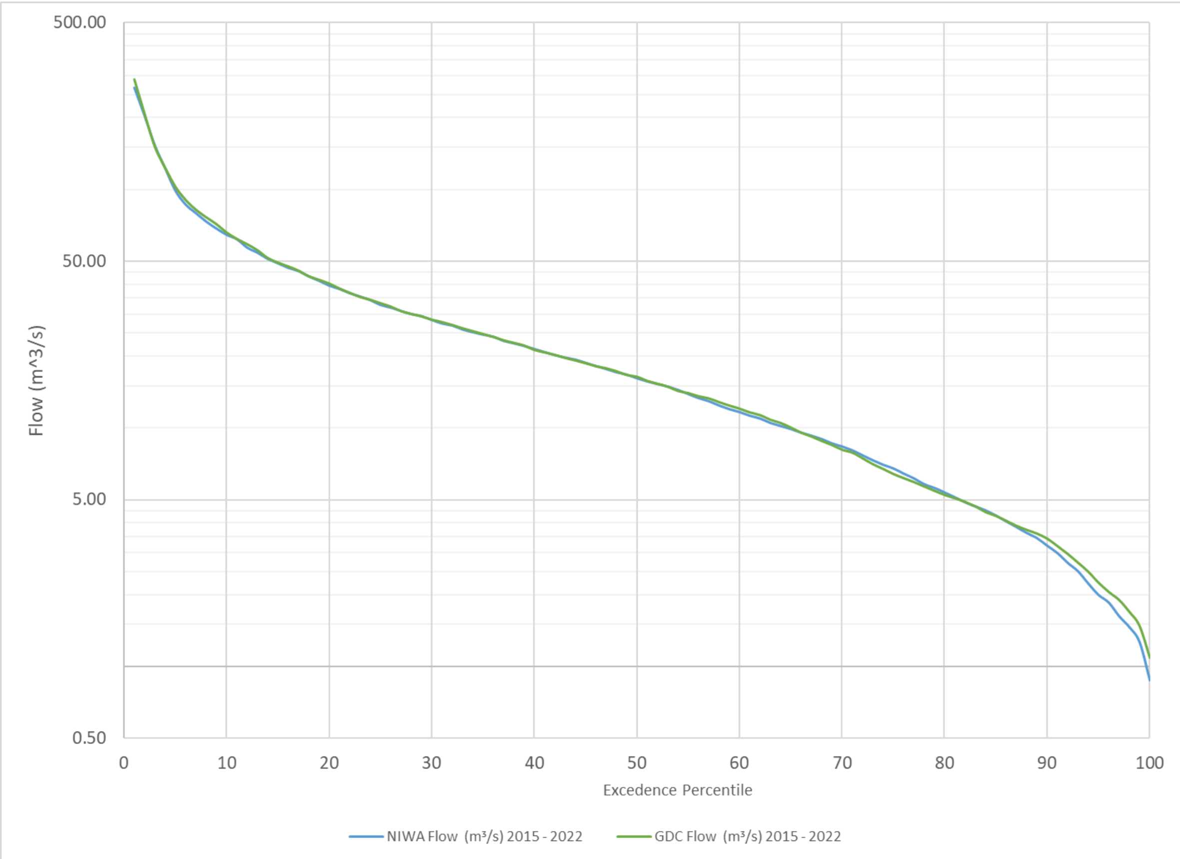


Figure 2-3: Flow duration curves for the Waipaoa River at Kanakanaia estimated using data from both the GDC and NIWA flow recorders.

Table 2-1: Summary of stream flow gaugings per rating change for both GDC's and NIWA's stream flow sites for the Waipaoa River at Kanakanaia.

	GDC	NIWA
From 1980		
No. of rating curves	75	156
No. of gaugings	945	452
Average gaugings per rating change	13	3
From 2010		
No. of rating curves	26	41
No. of gaugings	229	82
Average gaugings per rating change	9	2

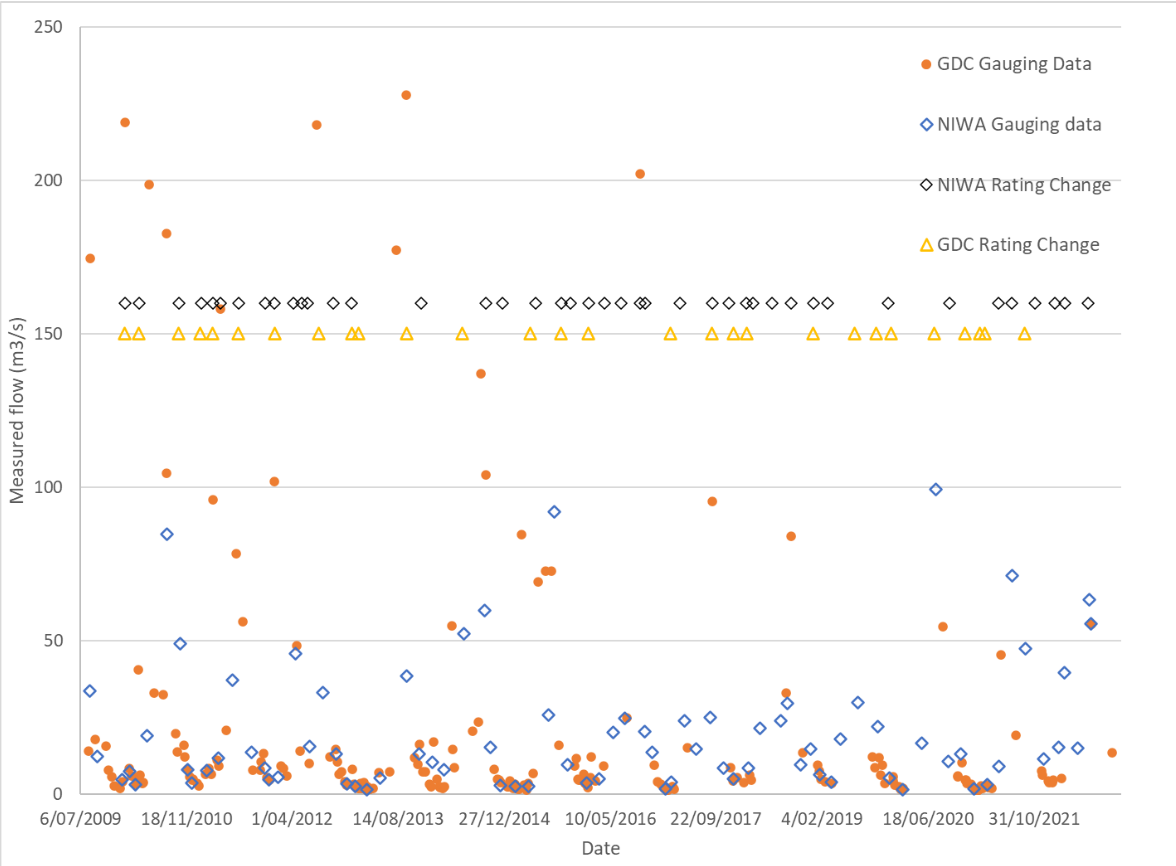


Figure 2-4: The sequences of manual stream flow gaugings and rating changes for the NIWA and GDC flow recorders on the Waipaoa River at Kanakanaia.

A point of interest is the frequency with which each rating period was changed. More frequent changes in rating curves may be needed to reflect frequent changes in river geomorphology. However, more frequent changes in rating curves often means that each curve is less well characterised because fewer gaugings are available to create each rating curve. NIWA changed ratings more often throughout the year. GDC changed ratings associated with the seasonal nature of their streamflow measurement program. In summer this may result in NIWA changing the rating period too often to produce well characterised rating curves, and in winter, GDC not changing the rating period often enough to reflect changes in geomorphology.

Differences between flow records may result in higher MALF estimates derived from GDC's data than NIWA's data during the 1990's and early 2000's (Figure 2-5). This period coincides with the management of the site by an external contractor, with a reduction in deviation between the records since GDC took control of the monitoring site from a contractor in 2015 (Figure 2-5). Observations associated with this assessment are:

- GDC has a reliable flow record from 2015.
- At the same time, there is a reduction in the number of higher flow gaugings, which may be the source of uncertainty in the mid-flow range on GDC data, although this error appears small in the aggregated data of a flow duration curve.
- The GDC flow record is likely more reliable at low flows due to a higher gauging frequency at such flows.

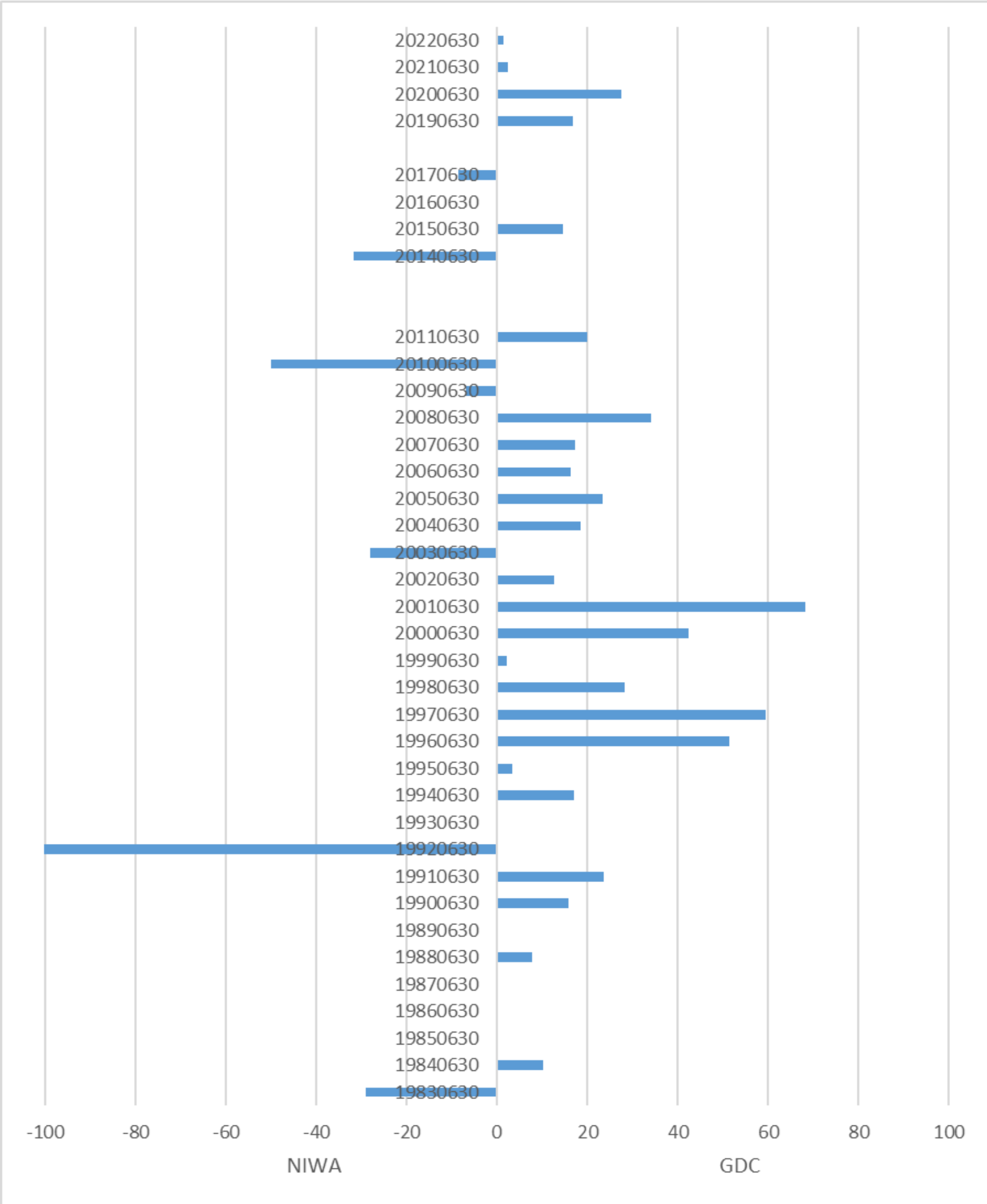


Figure 2-5: Comparison of percent difference of 7-day Annual Low Flow estimated from NIWA and GDC records for the Waipaoa River at Kanakanaia. The hydrological year ending is on the Y-axis. Negative deviation on the x-axis indicates a larger NIWA value, deviation on the positive axis shows a comparatively larger value derived from GDC data.

The difference between 7-day MALF estimates from NIWA and GDC flow records are provided in Table 2-2 and 2-3. To infer changes in data processing procedures over different time periods, the mean annual low flow estimates for the entire record - 1982 – 2003, the reviewed record 2003 to 2022, and the period post 2015 when GDC regained control over data collection and processing from external parties (Table 2-2) are compared. There was a reduction in the difference between the flow records from each organisation from July 2003. GDC have reviewed the flow ratings and record between 2003 and 2023, which has improved the understanding of uncertainties related to the flow record. The 20-year time-period (2003-2022) at Waipaoa River at Kanakanaia provides a good basis for the development of water take limits. The 'like for like' comparison of statistics (Table 2-2) excludes three hydrological years of GDC data (2011-2013, 2017-2018) on the basis that the corresponding NIWA data was not sufficient to form hydrological statistics.

Table 2-2: GDC & NIWA Mean Annual Low Flow (MALF) for the Waipaoa River at Kanakanaia, excluding years with no/limited data. Years not included are 1984–1985, 1985–1986, 1986–1987, 1988–1989, 1992–1993, 2011–2012, 2012–2013, and 2017-2018.

Hydrological year	GDC 7d MALF (m^3/s)	NIWA TIDEDA 7d MALF (m^3/s)	% difference
Jul 1982 – Jun 2022	2.579	2.225	-16
Jul 1982 – Jun 2003	2.748	2.151	-18
Jul 2003 – Jun 2022	2.409	2.192	-9
Jul 2015 – Jun 2022	2.300	2.102	-9

Developing relevant flow statistics from flow record prior to 2003 may be done upon review of the GDC flow data. For certainty of decision making, the inclusion of further years of data would require the data record to have any error associated with data processing and rating development checked and understood in a similar way to the post 2003 data set. However, the entire 20-year record available from 2003, produces a similar value of the 7-day MALF statistic to the entire flow record (Table 2-3). The values in the table below are similar to the 7-day MALF produced for the 1982 – 2022 period (Table 2-2).

Table 2-3: Observed mean annual low flows (MALFs) for the Waipaoa River at Kanakanaia estimated over two different periods / from two organisations.

Hydrological year	GDC 7d MALF (m^3/s)
Jul 1982 – Jun 2022	2.649
Jul 2003 – Jun 2022	2.566

Comparison of the flow records from the two hydrological organisations has been useful in informing the understanding of differences in data processing procedure and reliability of the flow record from NIWA and GDC. For the Waipaoa River at Kanakanaia we recommend using low flow statistics derived from the GDC data presented in Figure 2-3 and Table 2-3. Improvement of the flow record could be made by combining the development of a composite flow record incorporating the discreet flow and stage measurements where gaps in data coverage occur (see recommendations in Section 2.1.4).

2.1.3 Flow data for Te Arai River

GDC supplied flow data for the entire flow record at Te Arai River at Pykes Weir, and for a shorter time period (Nov-2016 to Nov-2022) at Te Arai River Bush Intake Above Weir (also referred to as the 'water works' site in the 2010 report and in Section 3 onwards) and Te Arai River Bush Intake Below Weir.

Flow duration curves and observed MALF

Te Arai River at Bush Intake

Summary data for Te Arai at Bush Creek at sites above and below the weir are presented in this report, The flow at the Bush Intake weir reach is significantly affected by the municipal water supply (Figure 2-6; Figure 2-7). Understanding the effects of the water supply in the Bush Creek reach, and the downstream flow at Pykes Weir are made difficult by the quality of the flow record as a consequence of monitoring frequency, site maintenance and aggregated water abstraction data. Concerns around the supplied flow time series, outlined by GDC, are presented below:

1) Gravel can build up around the water level sensor; when this happens it could artificially raise the water level at the sensor location. As flow is inferred from water level, this could lead to flows which are not representative, particularly at the lower flows (i.e., the actual flow may be lower). The gravel is then cleared out by higher flows.
2) There were gaps in the water level data or the data were very poor from:

   - 3-Jan-2020 to 3-Feb-2020;
   - 24-Aug-2020 to 2-Dec-2020 (issues with the sensor); and
   - 7-Jul-2021 to 23-Feb-2022 (issues with the sensor).

   These water level data were deleted and the gaps filled using regression analysis and water level data from Te Arai River at Pykes Weir.

   There is a gap of two days (24-25 Jun 2019) which has not yet been filled.

   There are also issues with the water level data from Nov-2016 to Feb-2017. These will be reviewed again at a later date.

Some other issues and observations include:

3) The mean daily flow data show that ~30% of flows are higher at the downstream site compared to the upstream site. This is not realistic as there are no tributaries joining Te Arai River between the two sites. It suggests that there could be issues with the water levels and/or rating curves.

4) The flow duration curves at the sites suggest that at the higher flows (from around Q25 to Q0, i.e., when flows are exceeded between 25% and 0% of the time), flows are consistently higher at the downstream site. This could again be related to the rating curves. Gaugings tend to be focused on the medium to lower flows, so there will be uncertainties at the higher flows (Figure 2-6).

5) Using the flow data from 2016-2022, there is no flow below the weir 8 % of the time. This may not be realistic. It also varies according to the years selected (Figure 2-6).

6) There appear to be some errors in the Intake Weir Extraction Rate (e.g., abstraction rates which are unrealistically high), but there are also issues with the flows.

7) The same-day gaugings at Te Arai River Bush Intake Above Weir and Below Weir show that the margin of error in flow measurement can be up to 10% (or greater).

8) The Intake Weir abstraction rates are an average over the day, and may not reflect abstraction rates at the time of the gauging (Table 2-4).

The compounding nature of some of these observations of data quality means that the absolute values of flow from the time series may not be accurate, so it is incumbent on GDC to improve the monitoring at the site to make recommendations of the effect of water takes in Te Arai more reliably. The GDC water level monitoring and flow rating development may not produce a hydrograph well throughout the flow range, time period and difference of aggregated flow data give an indication of the length of time that flow downstream of the weir is affected by abstraction (Figure 2-6). The provided point measurement data (Table 2-4) show that the daily aggregated water take data and measured instantaneous flow can replicate upstream flow data with reasonable accuracy, as well as highlighting some of the concerns listed above, for instance the reduction in flows on the 22/2/2017 and 21/3/2017) does not correspond with water take data. It is also not unreasonable to expect the structure to convey a ~123 L/s abstraction.

Table 2-4: Discharge above and below the Bush Intake Weir, daily mean abstraction rate, and difference between 'extraction + below-weir flows' and above-weir flow. Table supplied by GDC.

	Flow (m^3/s)			
Date	Te Arai River Bush Intake Above Weir	Te Arai River Bush Intake Below Weir	Intake Weir Extraction Rate (m^3/s)*	% Difference of abstraction plus downstream flow to upstream flow
4/11/2016	0.350	0.192	0.123	90
10/11/2016	0.334	0.124	0.113	71
20/02/2017	0.202	0.187	0.000	93
22/02/2017	0.070	0.008	0.015	32
21/03/2017	0.165	0.022	0.000	13
9/03/2018	0.263	0.241	0.048	110
14/12/2018	0.217	0.171	0.044	99
25/06/2019	0.375	0.327	0.056	102
10/09/2021	0.124	0.088	0.055	115
15/06/2022	0.187	0.138	0.041	96
26/08/2022	0.246	0.156	0.073	93
10/10/2022	0.348	0.357	0.052	118
21/10/2022	0.327	0.289	0.064	108

*N.B. This is an average rate for the day.

It is not unreasonable to expect that low flows could be halved from the natural flow by the Bush Intake at a daily scale (Table 2-4 and Figure 2-6), but the sub-daily abstraction effects could well have a greater impact for a shorter period. This statement in no way discounts the real concerns around the flow time series quality and site maintenance at Te Arai upper catchment flow sites.

Flow in the upper catchment can be reduced to zero or near zero flow for approximately 10% of the observation period. The extraction of around 55 L/s for municipal supply in the upper catchment effectively halves the natural flow that might otherwise flow through the Pykes Weir flow station and cause the stream to cease to flow (Figure 2-6). It is likely that the amount of time that flow is that flow ceases below the weir will vary annually.

A comparison of flow upstream and downstream of the weir was made by subtracting the water take data at the weir from the upstream flow record. This comparison shows that the effect of the abstraction is negligible (~10% of flow) at flows above the ~25th exceedance percentile (Figure 2-6). It also shows that the synthetic data set can well reproduce the flow record downstream of the weir between the 25th and 80th flow exceedance percentile, and that error in rating curve shape is in this flow range is at its least significant effect. The comparison also suggests that that low flows may be affected by reduction to zero or near zero flow between the 85th and 100th flow exceedance percentile. It should be reinforced that any error associated with the development of the flow rating above the weir is carried through in this comparison, which adds to the ambiguity of the period of time that stream flow is affected. Although, the mechanical control of the weir affords a reasonable estimate of flow in the mid-range despite the observed concerns with the data record and measurement error. Assessment of the effects of abstraction on instream ecology do weight the importance of good low flow measurement highly, highlighting the need for improved monitoring in this reach given the scale of effects on flow, and of fish passage.

It may be useful for GDC undertake concurrent gaugings from above the intake and the reach above Pykes weir to add to the concurrent data set to see how significant the impact weir abstraction is along the reach. From the one concurrent gauging data point available between the above Bush Intake and Pykes Weir, it appears that there is the ~ 40 L/s being extracted from a 47 L/s +/- stream gauging. This suggests a ~40 L/s gain from the catchment between the Bush Intake and Pykes Weir (Figure 2-11, 13/2/2017).

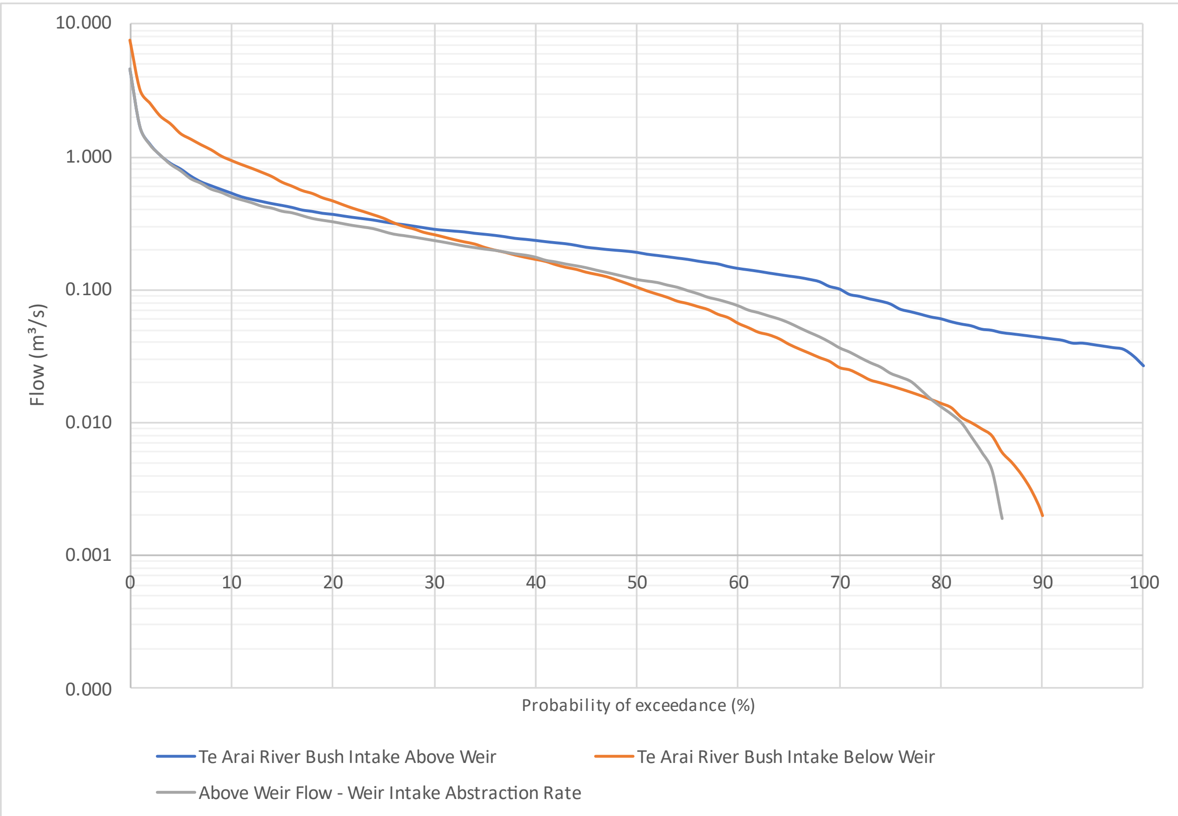


Figure 2-6: Flow duration curves for Te Arai River Bush Intake, above and below the weir/intake (gauge also referred to as water works).

Figure 2-7: Te Arai at Bush Creek intake in April 2010. Source: Doug Booker, NIWA.

Te Arai River at Pykes Weir

With respect to Pykes Weir, 75% of the 642 stream flow measurements have been collected at or below the 7 Day MALF (95th percentile). Measurements are taken throughout the flow range and up to the 99th percentile of flow. Considering the stream flow data alone, Te Arai at Pykes weir could be considered well characterised. The FDC for Te Arai River at Pykes Weir is present in Figure 2-8.

The observed MALF values for each of the three focal sites are presented in Table 2-5. These MALF estimates are based on flow data deemed most reliable for river flow management purposes following the hydrology review.

Table 2-5: Estimates of observed MALF for three sites on the Waipaoa and Te Arai Rivers. Estimates of MALF are calculated from 7-day rolling, daily average discharge. For Te Arai River at the Bush Creek intake, the MALF presented may be a reasonable approximation of naturalised MALF (see Section 4).

Site	MALF	
Waipaoa River at Kanakanaia	2,550 L/s	From GDC (2023)
Te Arai River at the water works / Bush Creek intake	40 L/s	Limited data (2016–2023). Site characteristics result in a flow record with a high degree of uncertainty.
Te Arai River at Pykes Weir	60 L/s	GDC data from 1984 to 2022

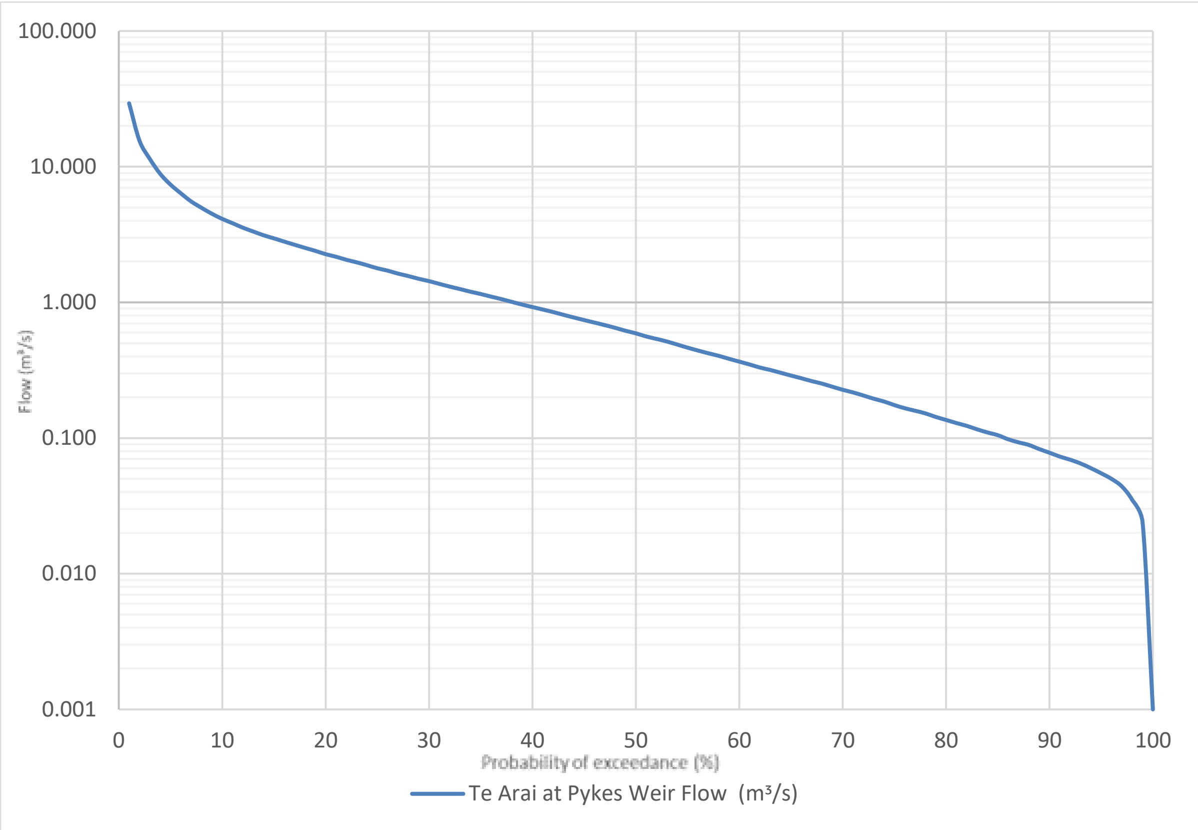


Figure 2-8: Flow duration curve for Te Arai River at Pykes Weir for the period of 1984 to 2022.

2.1.4 Improving river flow monitoring at existing sites on the Waipaoa and Te Arai Rivers

Te Arai River at Pykes Weir represents a stable flow control that can provide a good quality record assuming the appropriate channel maintenance is undertaken.

The comments below relating to the Pykes Weir flow site are valid up until late 2022. Cyclone Gabrielle significantly affected the site, requiring significant remediation works.

Te Arai River at Pikes weir is a shallow v-notch style weir constructed in a concrete channel. Engineered river controls are useful for providing a standard control for flow when estimating streamflow and can be used to estimate flow using theoretical stage to discharge relationships (ratings) for the weir. The shallow weir is useful for controlling river discharge at mid-range flows and low flows, but care must be taken with stage measurement and site maintenance.

Consistency in cross-sectional area is another factor that can affect the performance of theoretical or constructed rating curves. National Environmental Monitoring Standards guidelines suggest that the dimensions of control structures must be measured and recorded:

- at installation and five-yearly intervals thereafter;
- if no significant change is observed in the interim then again at time of site closure; and
- any time the structure is modified.

Channel modification includes the effect of natural processes. The upstream segment of a weir serves the purpose of reducing the velocity of the stream and inducing laminar flow before spilling over the edge of the weir. This process can reduce the ability of the stream to maintain entrainment of sediment and other instream debris, resulting in deposition in the upstream channel altering the cross-sectional area of the weir.

GDC have performed an analysis on the quality of rating curves in a spreadsheet provided to NIWA by GDC titled 'Summary_Rating Curves_Gaugings_&_MALF_Te Arai River at Pykes Weir_V4.xlsx'. In this workbook the following observation was noted:

'The low flow gaugings from 27-Nov-2008 to 5-Feb-2009 all have positive deviations. There seem to be two groups of low flow gaugings which would sit better on different rating curves (these are from 13-Nov-2008 to 22-Dec-2008 & from 7-Jan-2009 to 19-Jan-2009). There are rain events after 22-Dec-2009 which could have caused changes to the channel (and a change in rating) at these lower flows.'

Figure 2-9: Te Arai River at Pykes Weir in December 2008. Source: Mistry and Bosworth (2023)[11].

A potential cause of the deviations in the low flow gaugings is presented in Figure 2-9. In this photograph we see a reduction in cross sectional area upstream of the weir, and deposited branches downstream of the weir which may induce tail water effects at mid-range flows.

Site hydrology data could be maintained or improved by consistent maintenance throughout the year, which should be possible given the (on average) 14 stream flow measurements per year. The quality of data at the site may also be improved by increased monitoring of the stage and discharge relationship, as affected by changes in the cross section of the stream flow control. This can be done

[11] Mistry and Bosworth (2023) Review of low flow data for the Waipaoa River at Kanakanaia and Te Arai River at Pykes Weir. GDC report for NIWA (20/03/2023).

by comparing the rated flow time-series at the Pykes Weir site with one or a combination of the alternative methods of flow measurement suggestions below:

- Real-time flow measurement using acoustic doppler velocity or current profilers to continuously monitor stage and velocity relationships at low flows could help detect change in channel shape.
- Space Time Image Velocity methods may be useful to estimate flows, and the upper portion of the rating curve when sediment loads impede acoustic doppler measurements. This method also has the benefit of providing a visual representation of any change in channel shape.
- Plotting the theoretical rating-based flow time-series over constructed time series may assist with the timing of rating changes.
- Development of a correlation of stream flow measurement at Pykes Weir with another time series from a catchment with similar hydrological characteristics.

With respect to the Waipaoa River at Kanakanaia site:

- It is recommended that a composite stream gauging data set is formed combining the most reliable data subsets of the NIWA and GDC records. Ratings should be reviewed in light of this composite record to better constrain stage-discharge relationships, and to reduce the ambiguity associated with the application period of each stage-discharge relationship.
- The timing of rating changes should be reviewed to cross-check decisions for the timing of rating changes between NIWA and GDC.

2.2 Spatial distribution of river flow data

2.2.1 Specific aims and approach

CTTFs set with respect to a gauging station should operate to be protective of instream values locally, and both upstream and downstream. The minimum flow set with respect to a gauging station may not have a consistent level of effectiveness in terms of protection of instream values along the reach of the river. Additions of flow from tributaries, changes in river channel shape along the length of the river, downstream water takes and exchanges between surface water and groundwater can influence the effectiveness of spatial extrapolation of CTTFs.

When managing water takes at low flows it is important to consider the spatial distribution of natural gains and losses between surface and groundwater, and their associated seasonal variation. Natural gains to streamflow during low-flow periods result from the inputs of tributaries and groundwater. Gains to streamflows during low flow conditions can also be derived from the drainage of near surface valley bottom (or near channel) storages such as more permanently wetted channel bank soils, alluvial valley fills and wetland areas. The Waipaoa and Te Arai catchments include significant portions of each catchment confined in valleys before flowing through alluvial plains where groundwater losses and gains may be substantial. Both catchments considered in this report display evidence of transmission potential transmission losses outside of the confined valley flow.

Groundwater abstraction within the sub-surface drainage area affects the level of phreatic surfaces and therefore the potential for groundwater re-emergence in stream channels. Localised reductions in the level of the water table may affect either hydraulic gradients or the length of channel that intersects the phreatic surface. The effects of groundwater pumping near the head of a perennial river may result in groundwater table depletion through interception of recharge water and induced recharge of the aquifer from the river itself.

The **aims of this analysis** were:

1. Collate available data describing longitudinal patterns in flow for the Waipaoa and Te Arai Rivers and examine longitudinal losses and gains in flow below:

    1.1 the Waipaoa River at Kanakanaia;

    1.2 Te Arai River at the water work /Bush Creek; and

    1.3 Te Arai River at Pykes Weir.

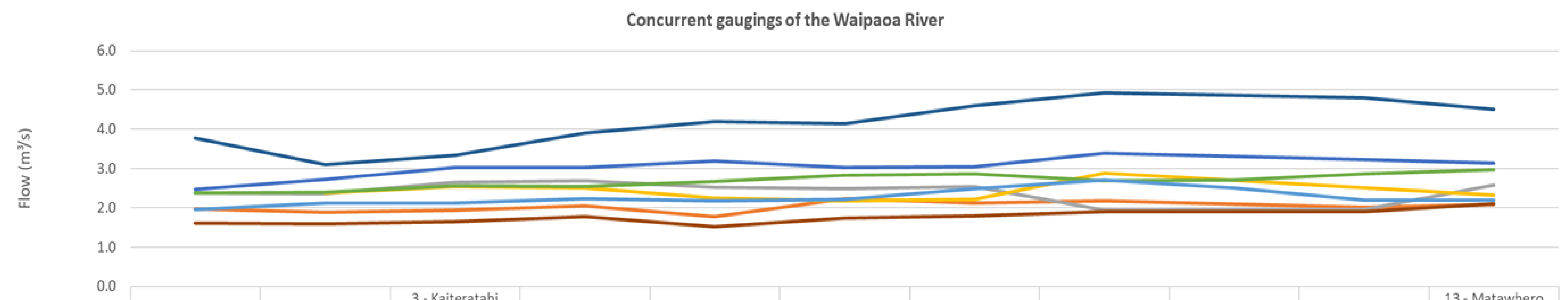
2. Provide recommendations for improving our understanding and monitoring of longitudinal patterns in flow in the Waipaoa and Te Arai Rivers.

To meet Aim 1, we collated GDC data that presented multiple estimates of river flow on the same day, along the courses of Te Arai and Waipaoa Rivers, then plotted discharge as a function of distance downstream. Concurrent estimates of discharge were available for 11 sites along the Waipaoa River between Kanakanaia and Matawhero Bridge. For Te Arai River, concurrent estimates of discharge were available for eight sites between the Water Works and Whakatere Road. For both rivers concurrent discharge estimates were only available for a subset of the sites during each day of measurement.

2.2.2 Longitudinal changes in river flow

Within the Waipaoa River transmission losses occur between Whitmore Road and Ford Road, and between Brown and Tietjens Road (Figure 2-10). These reaches are downstream of the confines of the valley-bound mid-catchment and on the productive plains. Observed losses and gains in flow along the Waipaoa River can be as great as ca. 600 L/s (Figure 2-10; see series from 22/03/2013) and such losses can extend for over 10 km of river length (Figure 2-10). This magnitude of loss is approximately 30% of the current A-Block allocation. It must be noted that the cause and frequency of losses of this magnitude are unknown. The observed losses occurred when surface flow at Kanakanaia was ca. 1000 L/s above the Block A minimum flow (1300 L/s) and ca. 300 L/s over the Block A allocation cap (2000 L/s). (Figure 2-10). When flow at Kanakanaia is close to the CTTF (26/2/13; 6/3/15; 14/2/17) flows downstream tends to be either generally stable or generally increasing. Further investigation should be made to help determine anthropogenic or geomorphic causes of the reduction in surface flows.

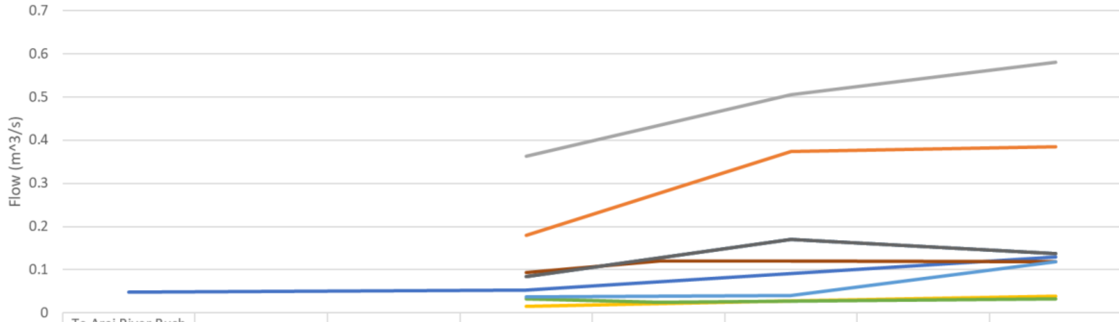
Stream flow measurements taken along Te Arai River on the same day show variable gains and losses along the length of the river (Figure 2-11). These gains and losses are most pronounced downstream of the SH61 bridge where the stream is less bound by hill country and through an area of irrigated land. Gains in river flow are common below Pykes Weir, with flow between Pykes Weir and Whakatere Road (ca. 17 km of river) often doubling (Figure 2-11).



	1 - Kanakanaia	2 - J Clarke	3 - Kaiteratahi Bridge	4 - Whitmore Rd	5 - Ford Rd	6 - Bruce Rd	7 - Brown Rd	9 - Teitjens	10 - Bolitho Rd	12 - Bloomfield Rd	13 - Matawhero Bridge
	0.0	8.8	13.0	21.0	26.5	27.5	28.0	33.0	33.5	37.0	40.0
26/02/2013	1.976	1.877	1.926	2.042	1.766	2.220	2.108	2.178		2.000	2.084
22/03/2013	2.370	2.357	2.649	2.690	2.522	2.488	2.544	1.943		1.953	2.574
26/02/2014		2.378	2.531	2.501	2.239	2.164	2.216	2.875			2.314
16/01/2015	2.456	2.710	3.025	3.027	3.197	3.035	3.054	3.400		3.236	3.146
17/01/2014	2.366	2.384	2.561	2.538	2.671	2.837	2.860	2.691	2.696	2.872	2.981
23/01/2015	3.781	3.095	3.332	3.904	4.201	4.143	4.592	4.932		4.806	4.515
6/03/2015	1.604	1.585	1.642	1.771	1.521	1.731	1.791	1.902		1.902	2.098
14/02/2017	1.955	2.116	2.122	2.231	2.178	2.204	2.474	2.692	2.494	2.183	2.185

Gauging site and distance downstream from Kanakania Bridge

Figure 2-10: Concurrent flow estimates showing longitudinal gains and losses from the Waipaoa River between Kanakanaia and Matawhero Bridge. Numbers directly under site names denote distance downstream; sites span 40 km of river length.



	Te Arai River Bush Intake Above Weir 0	Te Arai River Bush Intake Below Weir 0.025	Te Arai River at Waingake 4.4	Te Arai River at Pykes Weir 7.7	Te Arai River at Reays Br 14.2	Te Arai River at Site 61 14.5	Te Arai River at 304 Waingake Rd 24.5	Te Arai River at Whakatere Rd 24.8
13/02/2017	0.049			0.053				0.129
5/02/2009				0.016		0.028		0.039
10/02/2009				0.033	0.025			0.033
13/01/2010				0.084		0.171		0.138
21/01/2013				0.094	0.12	0.12		0.118
25/03/2013				0.037		0.041		0.119
26/11/2013				0.179		0.373		0.384
15/11/2013				0.363		0.505		0.58
13/01/2010				0.084		0.171		0.138

Figure 2-11: Concurrent flow estimates showing longitudinal gains and losses from Te Arai River between the water works and Whakatere Road. Numbers directly under site names denote distance downstream; sites span 24.8 km of river length.

2.2.3 Improving understanding and monitoring of longitudinal patterns in river flow

To enhance the utility of flow management sites upstream of water allocations, it is possible to develop correlations between flow series at management sites and streamflow gauging sites downstream. Doing so can provide a time-series of expected flows at other sites of interest that can be used to assess the influence of water take rules at monitored sites on downstream locations. In developing stream-flow correlations, the data used should represent natural flow conditions in the catchments. It is important to undertake data collection under hydrologically similar conditions.

Along the Waipaoa River there are three stream flow gauging sites on the Waipaoa river that have sufficient data to develop stream flow correlations: Kaiteratahi Bridge (22 measurements), Bolitho Rd (16 measurements) and Matawhero Bridge (23 measurements). Along Te Arai River there are two stream flow gauging sites that have sufficient data to develop stream flow correlations: at Site 61 (37) and Whakatere Rd (149).

The magnitude, extent and duration of flow gains and losses need to be better understood to address the relative influence of natural and anthropogenic gains and losses on the water body.

If we are to better understand the influence of interactions between groundwater and surface water on stream flows:

- Undertake sufficient streamflow gaugings during winter (when there should be little to no irrigation) and in summer during periods of low to no irrigation to develop correlated flow estimates at sites with variable flow.
- Determine the fraction of stream depleting groundwater and surface water takes at each REC segment in the catchment.
- Collect, collate, and analyse water take data to aid streamflow depletion estimation.

3 Flow-habitat relationships

3.1 Effects of low river flows on ecology

Before describing the approaches we used to determine how river flows affect instream values, it is useful to clarify (a) how water abstraction during summer-autumn affects river hydrology; and (b) how altered hydrology may then affect physical and ecological patterns and processes. This conceptual understanding of the problem is essential to understand the strengths and weaknesses of the models used in this report. This material was recently presented by Stoffels et al. (2022), so it is convenient to reproduce that material below.

Hydrological stressors resulting from low flows are well studied (Smakhtin, 2001) and include the following:

1. *Duration of a low flow event*. The number of days during which discharge is below the *low flow threshold*[12] (Figure 3-1).
2. The *within-year frequency of low flow events*. The frequency with which discharge drops below the low flow threshold (Figure 3-1).
3. The *magnitude of a low flow event*. The difference between the low flow threshold and the minimum discharge observed during a low flow event (Figure 3-1).
4. The *rate of decline in discharge* during a low flow event. The per-day rate at which discharge declines during a low flow event (Figure 3-1).

Water takes during dry periods exacerbate all four of the above hydrological stressors (Figure 3-1).

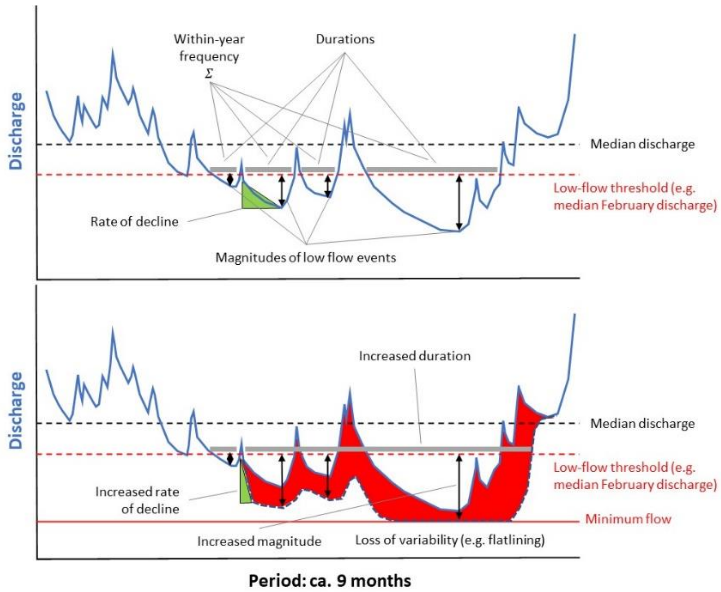


Figure 3-1: Conceptualisation of the impact of water takes during dry periods on a hydrograph and resultant hydrological stressors. Solid and dashed lines indicate hydrographs without and with water takes, respectively. Red filled region indicates volume of water taken away from natural hydrograph.

[12] The level of discharge that defines the low-flow threshold is arbitrary. That is, the low-flow threshold could be defined in several ways (e.g., median February discharge, or perhaps MALF) and is a convenient construct to operationalise the concepts of low-flow hydrology and ecology.

A conceptualisation of the effects of low flows on metrics within runoff-fed rivers is presented in Figure 3-2, which is structured by the NPSFM components of ecosystem health (water quantity, water quality, habitat, aquatic life and ecological processes). The conceptual model was based on research summarised in Smakhtin (2001), Dewson et al. (2007b), Rolls et al. (2012) and King et al. (2015).

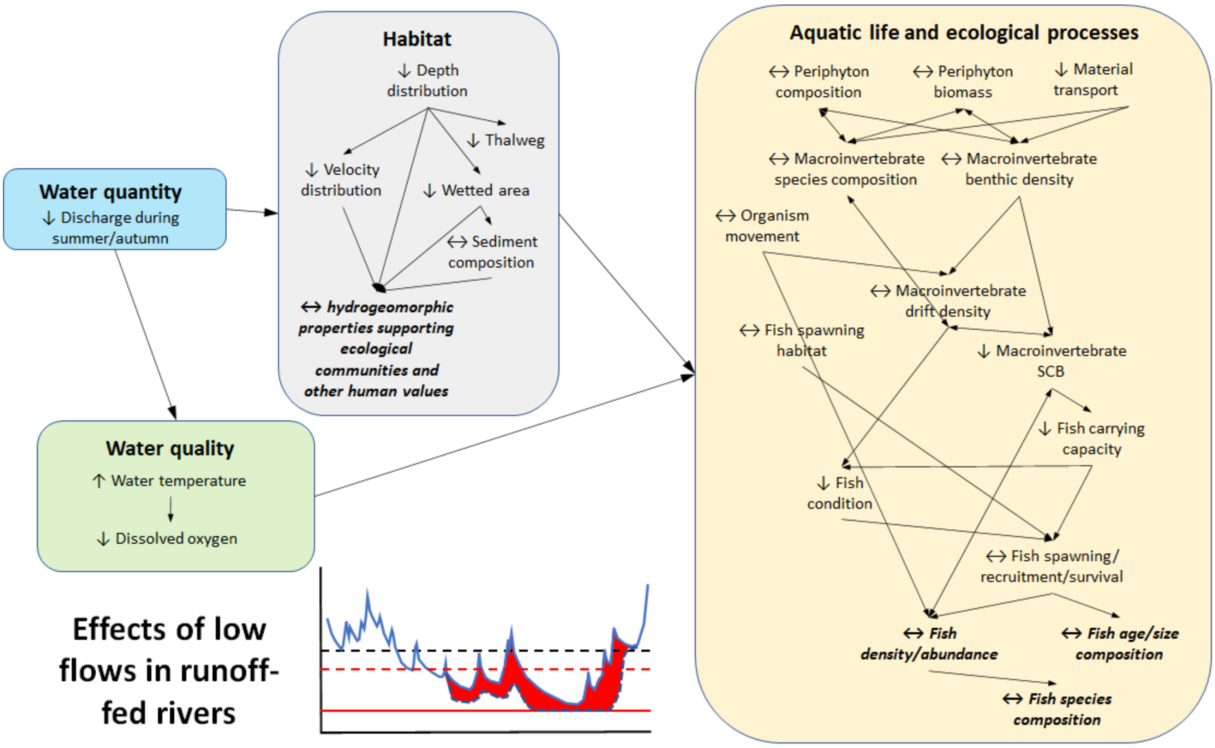


Figure 3-2: Conceptual model of the effects of low river flows on metrics within runoff-fed rivers grouped by water quality, physical habitat, and aquatic life and ecological processes. Up- and down-arrows denote increasing and decreasing respectively. Bidirectional lateral arrows denote change; either increase or decrease, depending on the specific low-flow hydrological stressor considered, its timing, duration and magnitude. Arrows between metrics in different components (boxes) were not included; including them resulted in a very high density of arrows throughout the diagram that did more to obfuscate than clarify.

Low flows may have the following effects on **physical habitat,** resulting in changes in the hydrogeomorphic properties of a river reach that directly (e.g., swimming; boating) and indirectly (support of aquatic life and ecological processes) support focal values (Figure 3-2):

- Reduced discharge will reduce mean depth of the water column throughout a river reach, and may change other statistical properties of the depth distribution of a reach (maximum depth, range, variance, etc.).
- Reduced mean depth may change the thalweg[13] of a river reach.
- Reduced depth will generally reduce reach wetted area. As flow decreases, the magnitude of reduction in wetted area will depend on reach morphometry; the

[13] The thalweg of a river reach is the longitudinal profile of maximum depth along a river reach.

shallower the gradient of the stream bottom, the greater the reduction in wetted area per unit change in depth.

- Mean water velocity of a river reach generally decreases as discharge is reduced.
- As mean water depth and wetted area decline, the sediment size composition of the benthos may also change (Hakala and Hartman, 2004).

Low flows may have the following effects on **water quality** (Figure 3-2):

- Reduced river discharge can increase water temperature (Booker and Whitehead, 2022; Caissie, 2006).
- Higher water temperatures and reduced mixing of the water column may decrease dissolved oxygen in specific rivers where/when ecosystem respiration is high (e.g., in rivers with lots of organic matter, hence high rates of microbial decomposition) (Diaz and Breitburg, 2009).

Flow-mediated effects on physical habitat and water quality will interact to affect **aquatic life and ecological processes** supporting fish populations (Figure 3-2):

- Broad periphyton types (such as thin films or long filaments) tend to be associated with specific depths and velocities (Biggs and Hickey, 1994; Biggs and Stockseth, 1996), so changed hydraulics during low flows may also change the periphyton composition of a river reach, as well as the biomass (mass per unit area) of periphyton as measured by Chl-*a* concentration (Suren et al., 2003b). Increased water temperature during low flows will also interact with changed hydraulics to affect periphyton composition and biomass (Miller et al., 2007).
- Reduced velocity and discharge will reduce rates of organic matter transport downstream, increasing retention of organic matter (Boulton and Lake, 1992; Dewson et al., 2007a).
- Changes in periphyton composition and biomass, organic matter retention and water quality will affect macroinvertebrate species composition and biomass (per unit area) (Brooks et al., 2011; Haxton and Findlay, 2008; Suren et al., 2003a).
- Reductions in wetted area may change the composition of benthic sediment/ substrata. Macroinvertebrates and types of periphyton have specific substrate preferences, hence a change in substrate composition is likely to change the composition of the benthic community (Biggs et al., 1999; Hoyle et al., 2017; Quinn and Hickey, 1990; Shearer et al., 2015). A change in the size composition of benthic sediment may also affect the availability of spawning and refuge habitat of fishes, in turn affecting population survival rates and, ultimately, population size (Davey et al., 2006; Magoulick and Kobza, 2003).
- Changes in the macroinvertebrate community, as well as reduced velocity and discharge will also change the composition and density of drifting macroinvertebrates (Sotiropoulos et al., 2006).
- Although we know that magnitude and duration of low flows affect periphyton and macroinvertebrate species composition and biomass, the direction and magnitude of

effects depends on the spatial context of the river reach (land-use, riparian habitat, etc), and the states of the four low flow hydrological stressors identified earlier in Section 3.1. The states of the four low flow stressors will vary in time, throughout the summer-autumn period. It follows that the directions and magnitudes of effects on periphyton and macroinvertebrates will be dynamic during low flow events (Rolls et al., 2012).

- Despite the dynamic effects of low flows on macroinvertebrate density and species composition at relatively small scales (e.g., within particular channel units (riffles, runs, etc.) and microhabitats (e.g., patches within riffles) (Fausch et al., 2002)), at larger spatial scales we can expect a reduction reach-wide, total standing crop biomass of macroinvertebrates, as a consequence of the reduction in wetted area of the reach (Walters and Post, 2011).
- The effects outlined above combine to reduce fish carrying capacity at the reach scale (Hakala and Hartman, 2004), with the greatest reductions in carrying capacity occurring for large-bodied fishes at higher trophic levels (McCann et al., 2005). Reduced fish carrying capacity will lower condition of individuals in fish populations and in turn lead to reduced survival and recruitment (Cowx et al., 1984), with the end result being reduced fish abundance and changed fish population/community structure (Figure 3-2).
- Increased water temperatures during low flows can affect fish populations via direct and indirect mechanisms, with the direction of the effects (positive/negative) dependent on the magnitude of heating relative to the species' thermal tolerances.

3.2 Approach

3.2.1 Flow-response models, transparent decision-making and best information

The use of models to determine how alternative flow management decisions affect environmental outcomes is considered best practice in flow management (Poff et al., 2010). Models are encoded in computer scripts and functions and accept data as input. These features of models can increase the transparency of decision-making processes in several ways:

- The assumptions that were made when designing a model and/or generating predictions are made explicit[14].
- Model design and assumptions—both explicit and hidden—can be interrogated by independent parties.
- The data that serves as input to the models can be reviewed and analysed for potential biases and imprecisions.
- The output of models can be reproduced.

Given models can increase the transparency of decision-making, use of models to inform decision-making is **consistent with NPSFM Clause 3.6 (Transparent decision-making)**.

[14] We acknowledge that many scientists fail to disclose assumptions, leaving them 'hidden', but that is not consistent with best practice in mathematical modelling.

Ideally, models used to support flow management decisions should be mechanistic, in that they explicitly represent the mechanisms that link environmental outcomes to hydrology (Poff et al., 2010). In the context of low flow management, models should be designed to capture the biophysical mechanistic pathways outlined in Section 3.1, above. When mechanistic models are used to predict environmental responses to flows, the chances of spurious predictions—hence ineffective flow management decisions—is reduced[15] (Lancaster and Downes, 2010b).

When validated mechanistic models are not available, other forms of information should be used to guide flow management decisions (Poff et al., 2010). Correlational models capture associations between environmental responses and hydrological variation in space and/or time, and are not designed to account for variation in the response variable due to known or hypothesised mechanisms[16]. Correlational models may be used to support transparent decision making. However, two variables that are correlated with each other may not be causally linked. Because correlation can not be equated with causation, correlational models have the potential to yield inaccurate information. Table 3-1 presents a very brief comparison of mechanistic and correlational models in terms of their strengths and weaknesses for setting EFRs.

Table 3-1: Strengths and weaknesses of alternative modelling approaches used for designing environmental flow regimes. Footnote 16 applies here.

	Strengths	Weakness
Mechanistic	**Potentially higher accuracy.** Because the models are designed to capture known or hypothesised mechanisms linking hydrology to ecology, there is a lower chance of spurious relationships, hence false predictions. Mechanistic models may be particularly useful when extrapolations outside of the observed bounds are required.	**Development is resource-intensive.** Estimating the parameters of mechanistic models is usually more laborious and takes longer. This increases cost of model development, and delays model implementation. Development of mechanistic models requires more advanced model-building and analysis capabilities; capabilities that are often in short supply. Mechanistic flow-ecology models are rarely available in an easy-to-use software package.
Correlational	**Development is less resource-intensive.** When compared with mechanistic models, parameter estimation is relatively straightforward and less time consuming. Software packages are available for implementing correlational flow-ecology models.	**Potentially lower accuracy.** Correlations between response variables (e.g., fish abundance) and hydrological variables may be confounded by other environmental variables that covary with hydrology. Correlations may be an artefact of sampling methodology and/or strongly biased by choice of sampling method. If correlations between response and hydrology are not consistent with our mechanistic understanding of the system, stakeholder[17] confidence in the model will be low. In short, correlational models may be misleading, and not accurately reflect effects of flow on environmental values.

[15] For a fuller and more general discussion of the need to understand mechanisms to avoid drawing false inferences and/or making false predictions see McElreath, R., 2016. Statstical Rethinking: A Bayesian Course with Examples in R and Stan. CRC Press, Boca Raton, Florida.
[16] Our characterisation of the differences between mechanistic and correlational models as a dichotomy is convenient in that it facilitates explanation but it is, in truth, artificial—environmental models fall along a continuum of types, with highly detailed, dynamical-system, process-based models at one end, and very coarse correlations at the other end.
[17] Including scientists.

Few mechanistic flow-ecology models are available to support flow management decisions in New Zealand. Hayes (2019; 2016) has developed mechanistic flow-ecology models for trout, but no mechanistic flow-ecology models are currently available to support decisions focused on native species. Nevertheless, **Clause 1.6 of the NPSFM (Best information)** requires councils to advance decision-making despite not having ideal decision-support tools. In the absence of mechanistic models, therefore, use of correlational models to support decision making is consistent with Clause 1.6 of the NPSFM.

3.2.2 Weighted usable area (WUA) models

We used models of weighted usable area (WUA) to determine how variation in flow affected availability of habitat for native fish, the mayfly *Deleatidium* and periphyton. WUA models are correlational models that predict changes in the availability of habitat as a function of flow-induced changes in depth, velocity and substrate composition. Our review of the SEFA software revealed that it would not extend the WUA capabilities beyond those used in the 2010 report. Accordingly, the WUA models used here are exactly the same as those used in the 2010 report. Further, because there has been no further collection of data since the 2010 report, the WUA results presented here are a copy of those presented in the 2010 report.

All details of the WUA methods can be found in Booker et al. (2010). Results from physical habitat modelling are provided in units of square metres of available suitable habitat per metre of river length (m^2/m). Graphs showing relationships between flow and river hydraulics variables (i.e., river width, wetted perimeter, average depth and average velocity) are also presented.

3.2.3 Habitat suitability criteria

Weighted usable area models combine two sub-models to predict how flow affects habitat availability of a taxon:

1. a hydraulic model that is used to predict how a change in discharge affects the spatial distribution and abundance of depths, velocities and substrates within a river reach; and

2. habitat suitability criteria, which are correlations between a taxon's relative abundance[18] and velocity, depth and substrate size.

Table 3-2: Habitat suitability criteria (HSC) used in this study.

Species	HSC name	HSC source
Fish		
Shortfin eel	Shortfin eel < 300mm	Jowett and Richardson (2008)
	Shortfin eel > 300mm	Jowett and Richardson (2008)
Longfin eel	Longfin eel < 300mm	Jowett and Richardson (2008)
	Longfin eel > 300mm	Jowett and Richardson (2008)
Torrentfish	Torrentfish	Jowett and Richardson (2008)
Crans bully	Crans bully	Jowett and Richardson (2008)

[18] Density, relative abundance (e.g., catch per unit area), or occupancy (presence-absence).

Species	HSC name	HSC source
Upland bully	Upland bully	Jowett and Richardson (2008)
Common bully	Common bully	Jowett and Richardson (2008)
Bluegill bully	Bluegill bully	Jowett and Richardson (2008)
Redfin bully	Redfin bully	Jowett and Richardson (2008)
Benthic invertebrates		
All	Food producing	Waters (1976)
Deleatidium	*Deleatidium* mayfly nymphs	Jowett et al. (1991)
Periphyton		
	Short filamentous	unpublished NIWA data
	Long filamentous	unpublished NIWA data
	Thin films	unpublished NIWA data

Some of the most **notable assumptions of habitat suitability criteria** are as follows:

- Habitat suitability criteria are assumed to capture causal relationships between the fundamental processes that shape population dynamics (reproduction, recruitment, growth, survival, maturation) and the microhabitat around them measured at the time and place of sampling.
- It is assumed that the primary mechanism by which flow affects populations is by affecting availability of suitable physical microhabitat.
- They most often assume that the habitat requirements of a species do not vary across life-stages, nor across processes within life-stages (e.g., feeding, hence growth, vs reproduction).
- It is assumed that abundance-microhabitat associations are sampled without bias.

The habitat suitability criteria used in the present analysis are summarised in Table 3-2.

3.2.4 Information used at each site

Two sites were the focus of our WUA modelling: the Waipaoa River at Kanakanaia and Te Arai at Reays Bridge / Pykes Weir (Reays Bridge data are assumed to be representative of flow-response relationships just upstream at Pykes Weir; Figure 3-3). These sites are the key hydrological monitoring sites within our two study catchments.

We did not undertake WUA modelling at the water works site on Te Arai River because naturalised flow series were available for that site which, we argue (in Section 4.4), may be a more defensible basis for CLF setting than application and interpretation of WUA models.

A short water temperature time-series was available for the Waipaoa River at Kanakanaia, so we developed a flow-water temperature model to inform assessment of CLFs at this site.

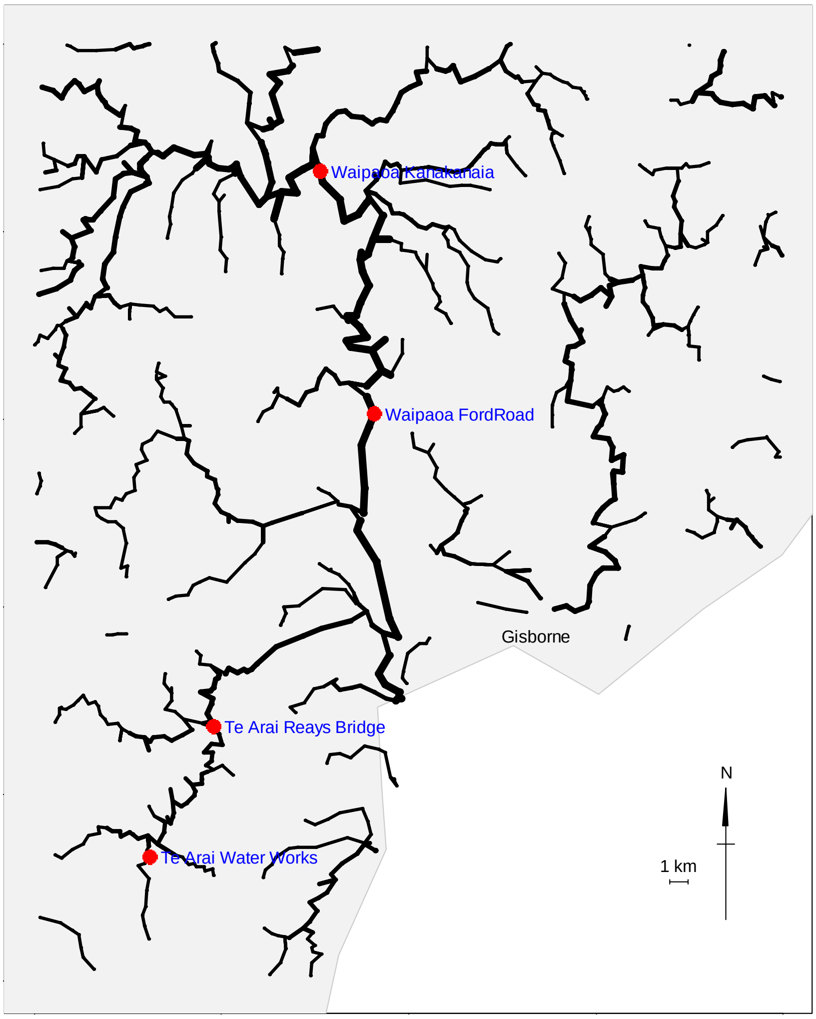


Figure 3-3: Map showing locations of sites from which data were obtained. We did not assess CTTFs or CLFs at the Waipaoa at Ford Rd site – no flow recorded is installed at Ford Rd, so it currently cannot be used for monitoring and enforcing CTTFs.

3.2.5 Water temperature modelling

Low river flows may increase water temperature (Caissie, 2006), which in turn has well-studied, direct and indirect effects on the physiological performance and behaviour of aquatic organisms (Portner and Farrell, 2008), hence on instream values. Thus, models of water temperature as a function of river flow—irrespective of the mathematic approach used—are "building blocks" of mechanistic models of flow-ecology relationships. Both mean and maximum daily water temperature are biologically important. Mean daily water temperature has a strong influence on the metabolic rate of freshwater organisms, which in turn affects growth efficiency and, therefore, maturation, reproduction and survival. Maximum daily water temperature causes mortality when it exceeds the upper thermal limit of a species or life-stage. Both mean and maximum daily water temperature are considered in this report.

As discussed in a more general context above (Section 3.2.1) approaches to modelling water temperature vary along the correlational-mechanistic continuum (Benyahya et al., 2007). Mechanistic models tend to be mathematical depictions of the underlying physics. Correlational models capture relationships between water temperature and predictor variables, usually including air temperature (Caissie, 2006), but do not include terms that account for the physical mechanisms that link ultimate drivers to water temperature.

Here we employed simple correlational approaches to model the relationship between water temperature, air temperature and river discharge in the Waipaoa River. A range of correlational models has been applied to modelling water temperature, including linear regression (Pilgrim et al., 1998), non-linear regression (Mohseni et al., 1998), GAMs (Booker and Whitehead, 2022) and machine learning models (Feigl et al., 2021). These models have shown a close association of water temperature with meteorological variables, particularly air temperature, alongside solar radiation and ground temperature in addition to hydrological variables, such as flow (Booker and Whitehead, 2022; Feigl et al., 2021; Laanaya et al., 2017).

Gisborne District Council provided water temperature & flow data for the Waipaoa River at Kanakanaia (2015-2018). Meteorological data came from the National Climate Database (https://cliflo.niwa.co.nz/[19]). The water data was measured at 10-minute intervals and daily for the meteorological observations.

Before modelling the relationship between water temperature and predictors, the data was split into train and test sets (James et al., 2021). The first two years of data were assigned to a training set, and the third year's data to the test set to evaluate the performance of the models. An exploratory data analysis was carried out on the training set to identify patterns to inform the modelling. A limited amount of analysis was also carried out on the training set to ensure the data was clean, there were no major data gaps, and the training and test datasets appeared to display similar characteristics following a visual comparison.

Five regression approaches were tested with the aim of estimating the mean daily water temperatures: random forests, multiple linear regression, logistic regression, generalised additive models (GAM) and weighted multiple linear regression. The idea of using weighting was to emphasise the more extreme temperature, which only makes up a small fraction of the observed values but is of particular ecological importance. More advanced models using deep learning and autoregressive time series models were not explored given the very small amount of data available. Exploratory data analyses are described in Appendix A. Covariates/predictors of water temperature that we considered were mean air temperature and log-transformed mean daily discharge (Appendix A).

The “best model” was selected on the basis of root mean squared error (RMSE) and predictive bias between the testing data and model predictions. Root mean square error is an estimation of the average absolute error between predictions and observed data (either training or testing data). An RMSE of, for example, 2 would indicate that model predictions are, on the average, out by 2 degrees Celsius. To calculate the direction and magnitude of predictive bias, we estimated “PBIAS” (Moriasi et al., 2015). A PBIAS value of zero indicates that the model fits the testing data perfectly on average although variability between predictions and observations may remain. Positive values of PBIAS indicate that model predictions are, on the average, below the observed values in the testing data, while negative values indicate model predictions are, on the average, higher than observed values in the testing set (Moriasi et al., 2015). Once the best model was identified, the effects of discharge on mean and maximum water temperature were estimated under different air temperature scenarios, including assessment of uncertainty.

[19] Station data from CliFlo: 24976 D87697 30-Nov-2012 04-Apr-2023 100 Gisborne Ews -38.62747 177.9218

The analysis was called out using R version 4.2.2 (R Core Team, 2022) and used the tidyverse (Wickham et al., 2019), GAM (Hastie, 2023), Partial Least Squares (Bjørn-Helge Mevik et al., 2020) and Random Forest (Liaw and Wiener, 2002).

3.3 Results

Much of the results are presented here as figures only, then discussed in Section 4.

3.3.1 Waipaoa River at Kanakanaia

Hydraulics

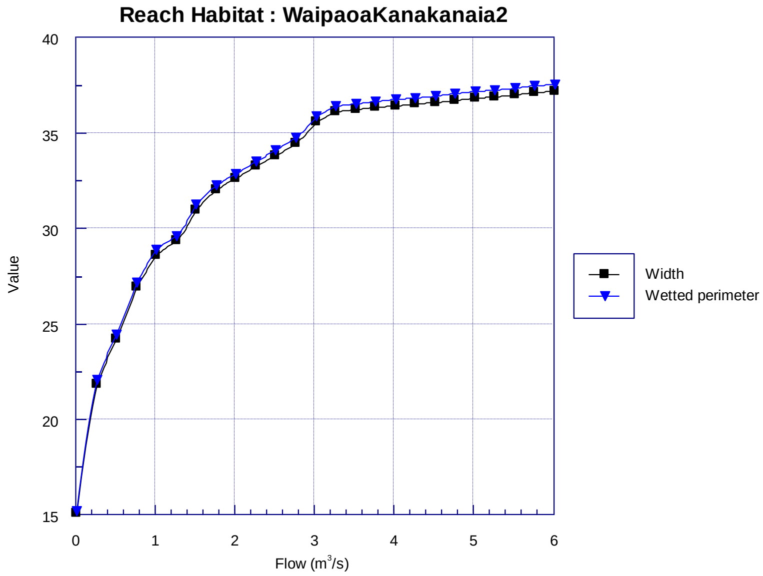


Figure 3-4: Relationships between wetted width (m) and perimeter (m) and flow of the Waipaoa River at Kanakanaia.

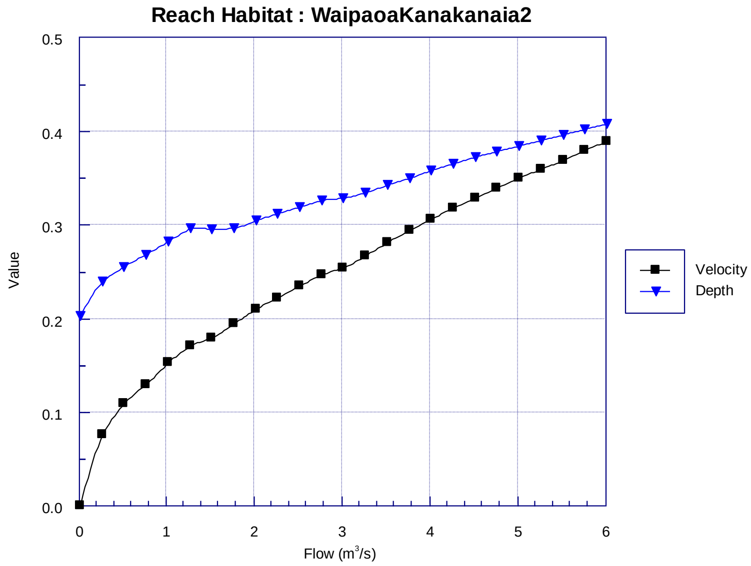


Figure 3-5: **Relationships between velocity (m/s) and depth (m) and flow of the Waipaoa River at Kanakanaia.**

Fish

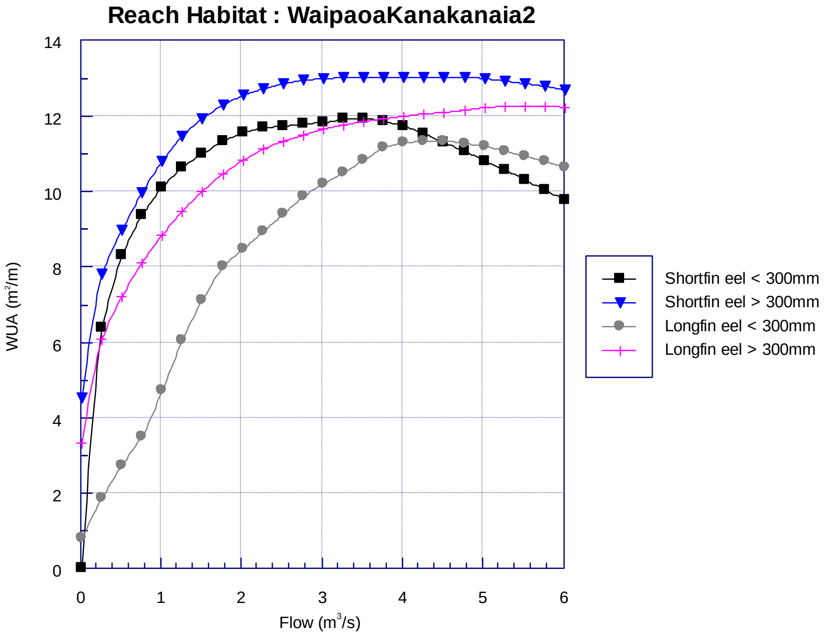


Figure 3-6: **Modelled weighted usable area (WUA) for eels in the Waipaoa River at Kanakanaia.**

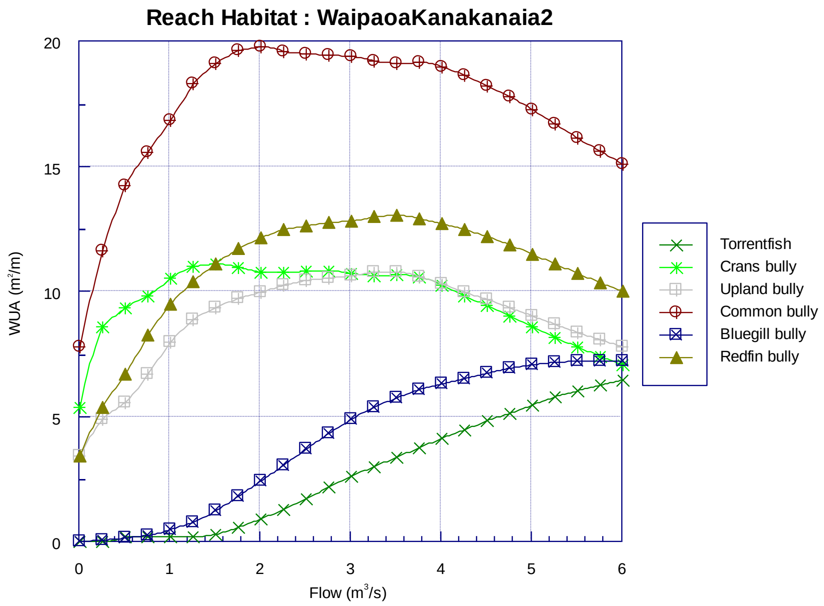


Figure 3-7: Modelled weighted usable area (WUA) for small-bodied native fishes in the Waipaoa River at Kanakanaia.

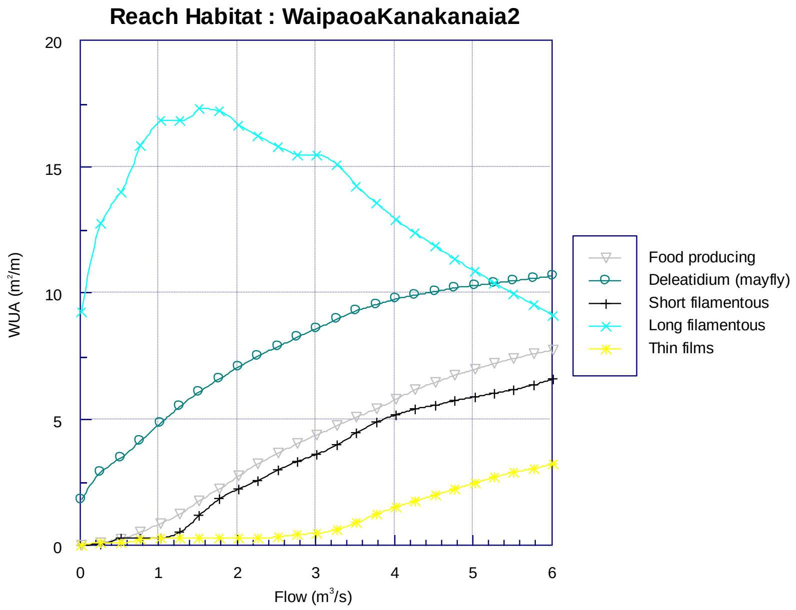


Figure 3-8: Modelled weighted usable area (WUA) for invertebrates and periphyton in the Waipaoa River at Kanakanaia.

Water temperature

Daily mean and daily maximum water temperature showed a strong seasonal pattern (Figure 3-9), with higher values in the summer and lower in the winter. Generally, the maximum daily water temperature was one degree higher than the mean water temperature; however, in the hot summer of 2016, the difference was up to 5 degrees. The training set had a higher maximum water temperature than the test set (Figure 3-9). Except for missing flow data between 26 March 2016 and

7 April 2016, the dataset had no gaps and few apparent outliers. Some additional results from the exploratory analyses are presented in Appendix A.

With respect to mean daily water temperature, the model with the best predictive accuracy, lowest test RMSE and PBIAS was a weighted linear regression (Table 3-3). The predictive performance of the models was similar to those reported by Feigl et al. (2021). Inspection of the residuals showed high levels of autocorrelation. The presence of autocorrelation cast doubt on the reliability of using the testing RMSE to estimate the model's predictive accuracy. Therefore, a heuristic, two times the test RMSE (Table 3-3; Table 3-4), should be used as an indicator of the prediction error.

With respect to maximum daily water temperature, only one model parameterisation was fitted to the data—the weighted multiple linear regression parameterisation shown to be the best model for mean water temperature. The decision to fit and test the performance of this single model was made due to the very high correlation between mean and maximum daily water temperature (Appendix 1). The fit and prediction statistics are presented in Table 3-4.

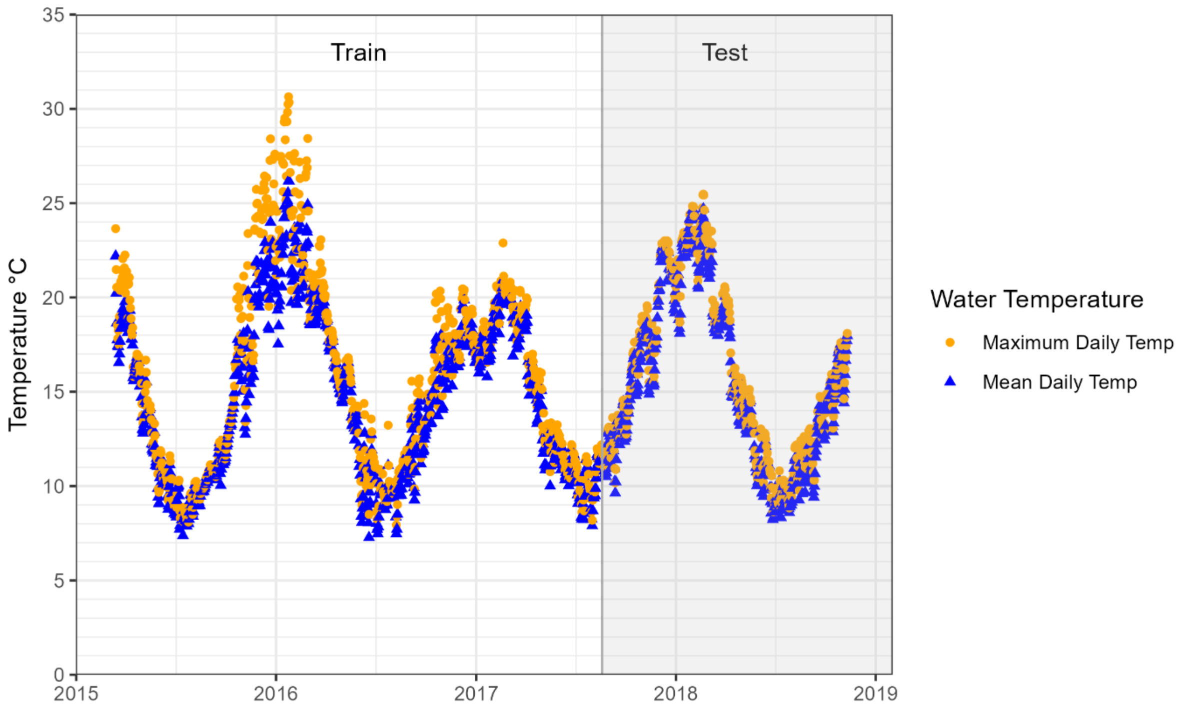


Figure 3-9: Time series of mean and maximum daily water temperatures within the Waipaoa River at Kanakanaia.

Table 3-3: Performance statistics of five different models of mean daily water temperature as a function of air temperature and river discharge.

Model	r^2	RMSE (°C)	PBIAS
Random Forest	0.922	1.51	5.04
Multiple Linear Regression	0.939	1.47	5.32
Logistic Regression	0.942	1.47	5.42
GAM	0.944	1.37	5.15
Weighted Multiple Linear Regression	0.942	1.20	3.18

Table 3-4: Performance statistics of the single model of maximum daily water temperature as a function of air temperature and river discharge.

Model	r^2	RMSE	PBIAS
Weighted Multiple Linear Regression	0.937	1.42	-1.31

Predicted water temperatures (means and maxima) were often higher than air temperatures (Figure 3-10; Figure 3-11). This paradoxical result may be due to the air temperature data being sourced from a station < 10 km from the coast, hence experiencing a cooler microclimate not reflective of the air temperatures driving water temperature in the mid- to upper-catchment of the Waipaoa River at Kanakanaia.

Mean daily water temperature increases as discharge drops below 3000 L/s (Figure 3-10). Mean water temperature increases particularly strongly as discharge declines below 2000 L/s. The shape of the relationship water temperature has with discharge is constant across different air temperature scenarios, but the curve is strongly elevated as air temperature increases.

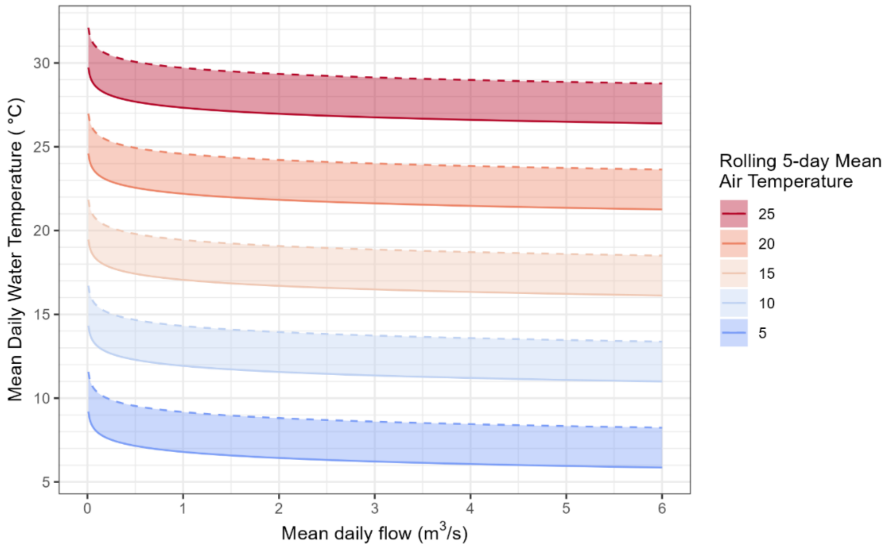


Figure 3-10: Mean daily water temperature of the Waipaoa River as a function of river discharge and air temperature. Solid lines are the predictions of the fitted model, with the dashed lines indicating the upper 95% confidence interval of model predictions.

Maximum daily water temperature generally exhibits the same responses to air temperature and river discharge as mean daily water temperature, with two exceptions: Relative to mean water temperature, maximum water temperature increases more rapidly, first, as a function of air temperature and, second, as river discharge declines below 3000 L/s (Figure 3-11).

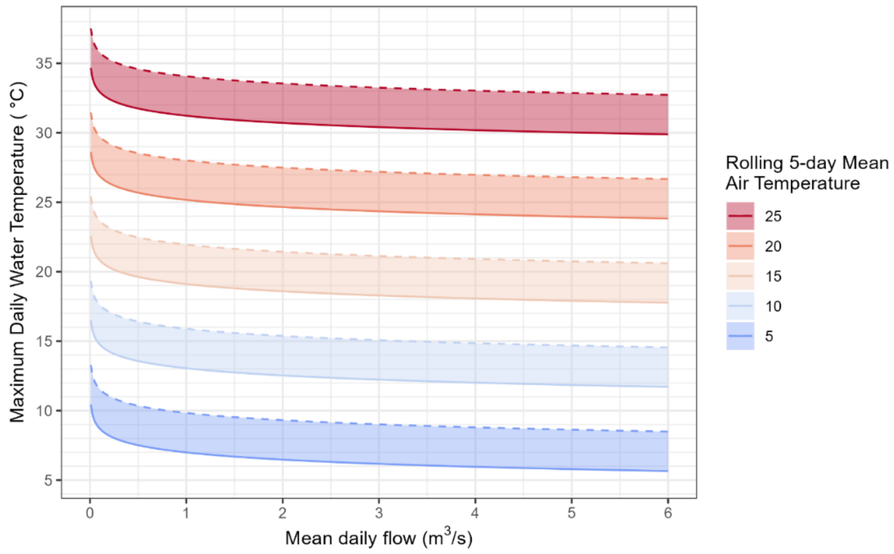


Figure 3-11: Maximum daily water temperature of the Waipaoa River as a function of river discharge and air temperature. Solid lines are the predictions of the fitted model, with the dashed lines indicating the upper 95% confidence interval of model predictions.

3.3.2 Te Arai River at Reays Bridge / Pykes Weir

Hydraulics

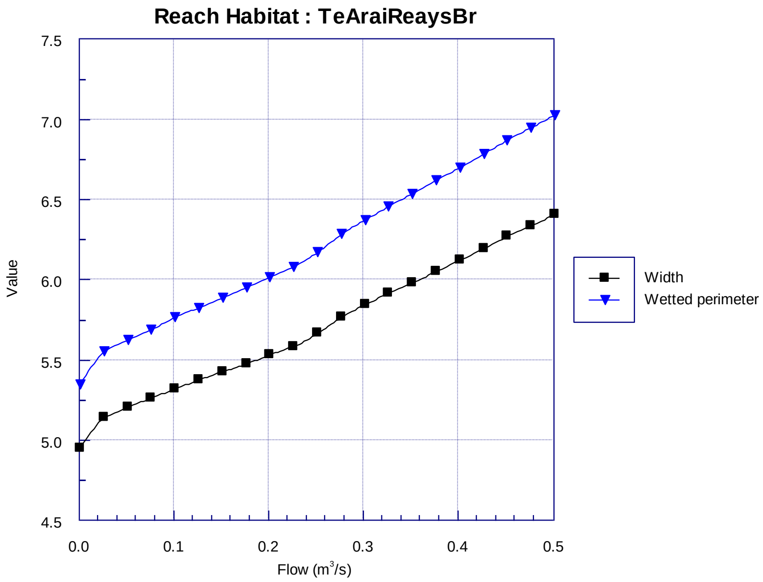


Figure 3-12: Wetted width (m) and perimeter (m) of Te Arai River at Reays Bridge as a function of flow.

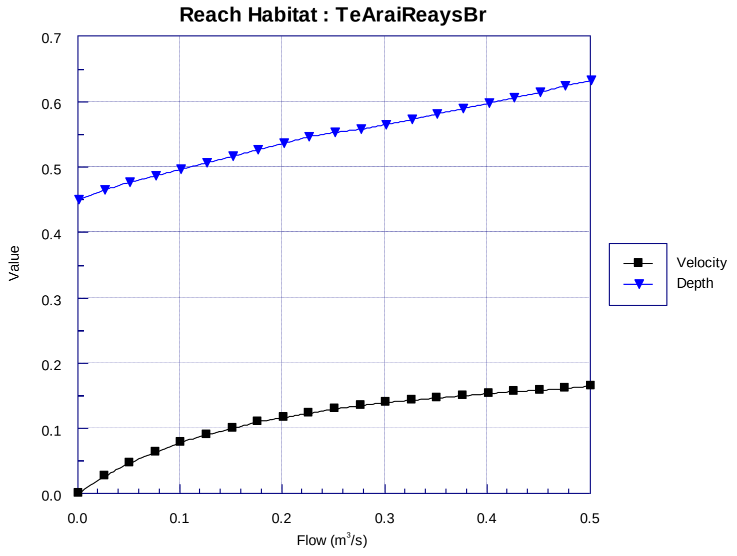


Figure 3-13: Velocity (m/s) and depth (m) of Te Arai River at Reays Bridge as a function of flow.

Fish

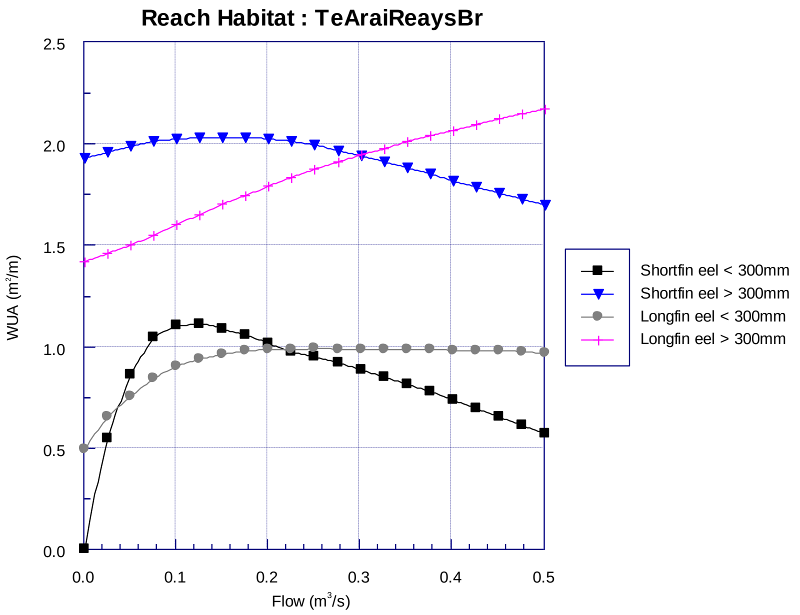


Figure 3-14: Modelled weighted usable area (WUA) of eels as a function of flow in Te Arai River at Reays Bridge.

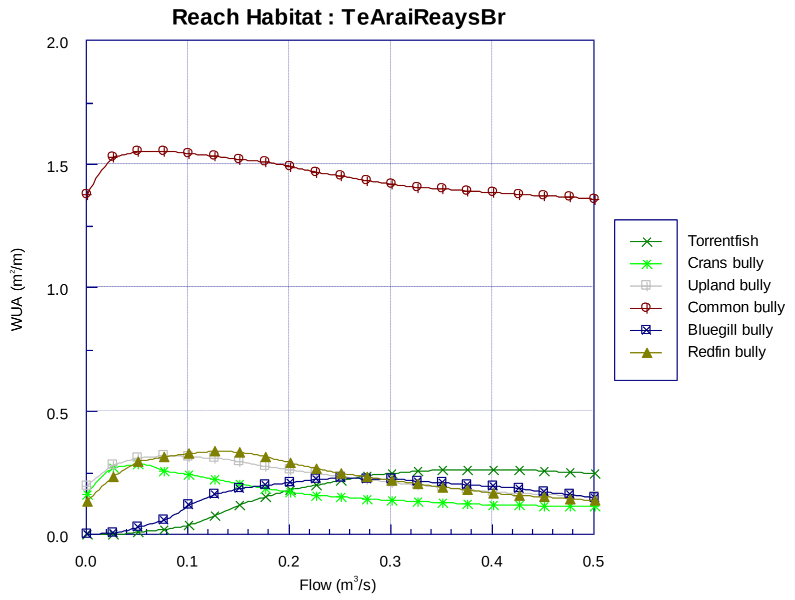


Figure 3-15: Modelled weighted usable area (WUA) of small-bodied fishes as a function of flow in Te Arai River at Reays Bridge.

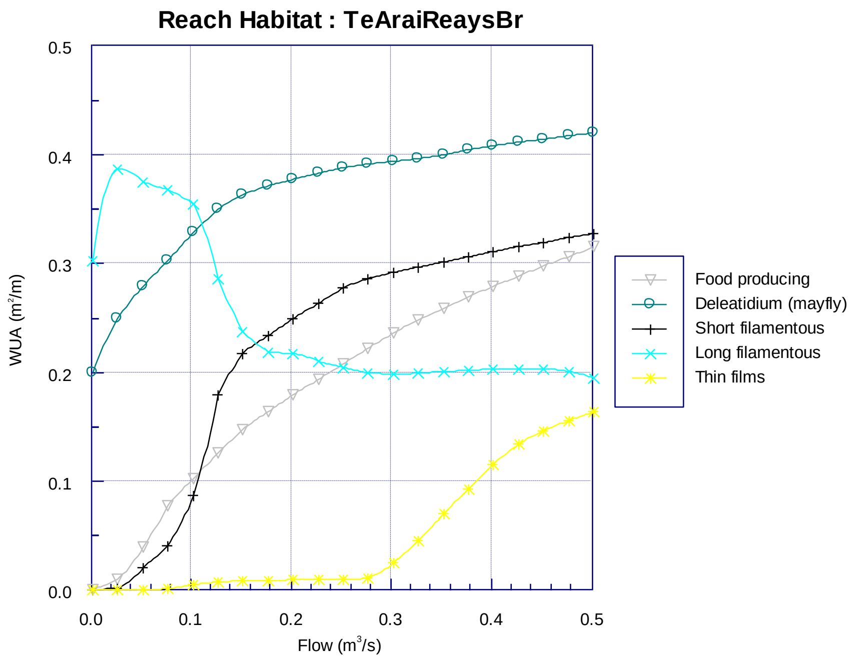


Figure 3-16: Modelled weighted usable area (WUA) of invertebrates and periphyton as a function of flow in Te Arai River at Reays Bridge.

4 Assessment of alternative critical low flows

4.1 Approach

4.1.1 Critical low flow scenarios considered

Here we offer an assessment of the relative environmental outcomes of three alternative CLFs. Cease-to-take flows, which are the limits GDC ultimately require, are set in light of CLFs (see Section 1.2). Later, in Section 5, we discuss some factors that must be considered when using CLFs to set CTTFs. This CLF assessment was undertaken to illustrate how the information presented in the preceding section may be used for river flow management purposes. We do not 'recommend' any particular CLF and understand that the choice made by GDC will represent a balance among the competing objectives of maintaining/improving freshwater values and maintaining agricultural outcomes whilst recognising the requirements of the NPSFM and giving effect to Te Mana o Te Wai three tiers.

We assessed potential outcomes of CLFs within three water quantity zones (WQZs) of two freshwater management units (FMUs):

1. The Waipaoa surface WQZ within the Poverty Bay Flats FMU.
2. The Upper Te Arai WQZ within Te Arai FMU.
3. The Lower Te Arai WQZ within Te Arai FMU.

Data used for our assessments come from the Waipaoa River at Kanakanaia, Te Arai at the water supply intake (water works) and Te Arai at Reays Bridge, which respectively correspond to the above three WQZs. Reays Bridge is ca. 3 km downstream of Pykes Weir flow recorder.

Three CLFs were considered for the Waipaoa River at Kanakanaia and the Lower Te Arai River. By contrast we offer assessment of a single CLF scenario for Te Arai at the water works. The Upper Te Arai at the water works was treated differently to the Waipaoa River at Kanakanaia because (a) a natural flow record was available, enabling what is arguably a more defensible approach to CLF setting; (b) there are no substantial water takes above the water works; and (c) the major take below the water works is for domestic water supply and so there is currently no Block A CTTF or allocation cap at the water works. Further details concerning the somewhat unique nature of Te Arai at the water works are provided in sections below.

Methods used to derive CLFs for the Waipaoa River at Kanakanaia and the Lower Te Arai River were similar to Booker et al. (2010) and included assessment of the following options:

1. *Instream values*.
2. Observed mean annual low flow *(Observed MALF)*.
3. *Status quo*.

For the *status quo* option the CLFs and allocation caps for Block A and Block B bands are presented in Table 1-2.

Ideally, Option 2 (Observed MALF) would have been consistent with the recommendations of Hayes et al. (2021), who recommended the CTTF and allocation rates presented in Table 4-1, which are based on percentages of *naturalised* MALF. Naturalised flow data were not, however, available for any rivers in the FMUs considered here and so naturalised MALF is unknown. In the absence of naturalised MALF we used observed MALF under the assumption that it is a close approximation of naturalised MALF[20].

Note that Hayes et al. (2021) did not distinguish between CLF and CTTF. They presented 'minimum flows' which were essentially operational take limits equivalent to our CTTFs. However, we hereafter equate the 'minimum flows' of Hayes et al. (2021) with our CLFs. Equating the minimum flows of Hayes et al. (2021) with our CLFs (cf. CTTF) is more consistent with the logic presented below concerning the Natural Flow Paradigm as a heuristic for CLF setting.

Table 4-1: Proposed default cease-to-take flow (CTTF) and primary allocation limits, expressed as % of naturalised 7-d mean annual low flow (MALF).

Limit	River with mean daily flow ≤ 5 m^3/s	River with mean daily flow > 5 m^3/s
CTTF	90% of naturalised 7-day MALF	80% of naturalised 7-day MALF
Allocation rate	20% of naturalised 7-day MALF	30% of naturalised 7-day MALF

Observed (100% of) MALF is used for Option 2. Arguably, setting CLFs as a reasonably high percentage of *naturalised* MALF is scientifically defensible. Traits of aquatic populations have evolved to the natural flow regime (following the 'Natural Flow Paradigm'; Lytle and Poff 2004), and so populations should have evolved some degree of resistance and resilience to naturalised flow-driven stress associated with low flow events with the same magnitude, frequency, and duration as naturalised MALF. It follows that the same populations are likely resistant and resilient to flow-driven stress associated with flow conditions that are associated with a flow that is very close to—a high percentage of—naturalised MALF[21]. The same argument cannot, however, be made for observed MALF, which may already be well below a percentage of naturalised MALF as a consequence of historical water takes.

The observed MALFs for Waipaoa River at Kanakanaia, Te Arai at the water supply intake (water works) and Te Arai at Reays Bridge are presented in Table 2-5.

Option 1—instream values—presents take limits that, given the limited data and models available, correspond with high levels of protection to instream values as would be consistent with the requirements of the NPSFM, including all aspects of ecosystem health, threatened species and mahinga kai (see Appendix 1A of the NPSFM 2020). Option 1 is used as the point of reference for Options 2 and 3. The potential outcomes from Options 2 and 3 are summarised using a five-point categorical scale relative to Option 1 and under the assumption that Option 1 supports a '*high*' level of protection of values. Relative to '*high'* the other four levels of value maintenance were '*moderate-high*', '*moderate*', '*moderate-low*' and '*low*'.

4.1.2 Relative influence of flow-response curves on assessment

The flow-response curves presented in Section 3.3 had unequal influences on our assessment. Flow-response curves had either a 'primary' or a 'secondary' influence on our assessment (we may refer to

[20] We comment on the validity of this assumption in the next section of this report.
[21] Under specific assumptions such as: contemporary, within-year frequency of MALF is not significantly greater than naturalised within-year frequency of MALF.

each class of curve as ‘primary’ and ‘secondary flow-response curves’, respectively). Curves that had a primary influence

- reflected the potential responses of particularly highly valued assets (i.e., eels);
- were based on sampling methods of relatively low bias; or
- explicitly captured potential mechanisms outlined in Section 3.1.

Longfin and shortfin eels are high-value species within the Waipaoa and Te Arai catchments (following Booker et al. 2010). Maintenance and/or rehabilitation of eel populations may, therefore, be ‘fundamental objectives[22]’ of the GDC regional plan. Consequently, **eel flow-response curves had a primary influence on our assessment**.

Flow-response curves for *Deleatidium* mayflies, water temperature and mean wetted width also had a primary influence on our assessment. Although these flow-response curves may not represent variables of high, direct value, they were selected for two reasons:

- they can be estimated with relatively little bias, when compared with the flow-response curves of other variables/species presented in Section 3; and
- they capture relationships between variables in conceptual models of the mechanisms linking low river flows to ecological outcomes. Specifically
  - *Deleatidium* mayflies are an important part of food chains and represent a source of food for fish;
  - water temperature can represent a stressor to various ecosystem functions during low flow periods; and
  - wetted width represent the total area of aquatic habitat available in river ecosystems.

Because these curves can be estimated with relatively little bias, we can be more confident that they accurately represent true response-environment patterns, rather than response-environment relationships that may be an artefact of biased sampling methods (as is the case for observations of fish to create habitat suitability criteria). Consider, for example, *Deleatidium*: Sampling benthic invertebrates like *Deleatidium* typically involves use of a Hess or Surber sampler, which is placed on the bottom of a river at a point to remove the invertebrates from a fixed area. These sampling devices can be deployed with near equal efficiency across the range of velocities, depths and substrate compositions relevant to low-flow assessment.

Further, with a careful approach, the act of macroinvertebrate sampling *in situ* is unlikely to significantly displace macroinvertebrates. If the act of sampling significantly displaced organisms, then the resultant abundance-environment relationships may be an artefact of the sampling process itself, and not reflect potential underlying mechanisms.

[22] Decision scientists and natural resource management experts distinguish between ‘fundamental’ and ‘means’ objectives. Fundamental objectives are what matter most to stakeholders and represent the things that we really must achieve. Means objectives are useful in that they help us achieve fundamental objectives, but are not endpoints in and of themselves. See: Conroy, M.J., Peterson, J.T., 2013. Decision Making in Natural Resource Management: A Structured, Adaptive Approach. John Wiley & Sons, Ltd.

The above advantages do not apply to, for example, electrofishing. The efficiency of electrofishing varies enormously across species, life-stages within species, and across microhabitats within rivers (e.g., Peterson et al., 2004; Price and Peterson, 2010; Reyjol et al., 2005). Fish are relatively mobile organisms with well-developed senses. Their distribution across microhabitats—the resolution at which HSCs are estimated—is likely affected by electrofishers walking through a river reach as well as the disturbance caused by electric-shocking the water. These features of electrofishing lowers confidence in their accuracy, in that abundance-environment relationships may reflect sampling biases. This is important because data derived via electrofishing is often used to construct habitat suitability criteria that are input to physical habitat models.

In addition to having relatively little bias, flow-response curves for *Deleatidium* mayflies, water temperature and wetted width capture mechanisms in the conceptual models presented in Section 3.1 (refer to that section for details). By contrast, low flows are not hypothesised to influence fishes directly through their affects on the availability of microhabitat. When microhabitat preferences of fishes are estimated accurately, they have been shown to vary:

- across life-stages within species (e.g., adults are associated with different microhabitats than juveniles); and
- across processes of individuals (e.g., adult fish may feed in one microhabitat but rest and/or digest food in another; microhabitats used for spawning may differ strongly from those used for feeding and refuge).

As a result of the poor fit with the conceptual models in Section 3.1, potential biases, and lower direct value relative to eels, **flow-response curves of small-bodied native fishes (non-eel fishes) had a secondary influence on our assessment**. Small-bodied native fishes are nevertheless critical species supporting ecosystem health and mahinga kai, and so may represent 'means objectives'[22] in plans. Reduction of nuisance periphyton (long filamentous periphyton) may also be a planning objective, so flow-response curves of periphyton also had a secondary influence on our assessment.

4.1.3 Use of flow-response curves

The primary and secondary flow-response curves presented in Section 3 represent the response to flow by *variables* that contribute to NPSFM compulsory values. They do not, in the strict sense, represent the response of NPSFM *attributes* to flow. Consequently, the flow-response curves presented herein cannot be used to identify CLFs that correspond with quantitative, NPSFM attribute targets.

Flow-response curves of the form presented in Section 3 of this report usually exhibit a positive relationship between an ecological value (e.g., WUA of a fish) and flow at low-to-medium flows. The typical observation is—over the range of flows that we may consider as potential CLFs—the higher the discharge, the higher the ecological values supported. In the absence of specific targets, therefore, interpretation of flow-response curves to identify potential CLFs is influenced by a subjective decision, and the CLF selected represents a somewhat arbitrarily selected level of protection for the ecological value in question.

In the present study flow-response curves were subjectively examined by eye to identify potential discontinuities in the gradient of the relationship between response and flow. Specifically, we identified discharge levels below which ecological values decline particularly rapidly. Not all flow-response curves exhibited such discontinuities. Those curves had a lower influence on assessments.

4.1.4 The influence of downstream losses and gains in discharge

As shown in Section 2.2 there may be losses in surface flow below flow recording sites, where flow allocation rules may be designed and monitored, but that there was little to no evidence for significant losses below flow monitoring sites when flow at those sites was close to the current CTTF. Accordingly, we assume that CTTFs set and monitored at the three focal sites of this study are transmitted well downstream, with negligible losses after the CTTF has been reached. To be clear, this is an assumption we have made given very limited data, to advance our assessments. This assumption would have to be tested with improved flow monitoring in the future.

4.2 Waipaoa River at Kanakanaia

4.2.1 Option 1 - 'Instream values' critical low flow

There is little change to wetted width of the Waipaoa River at Kanakanaia as flow declines from 6000 L/s to 3000 L/s. Once flow drops below 3000 L/s, wetted width declines rapidly. Weighted usable areas of small and large longfin eel change relatively little between 6000 – 3000 L/s, but decline sharply once flow drops below 3000 L/s. Weighted usable areas of small and large shortfin eel decline steeply once flow drops below 2000 L/s. Unlike eels and wetted width, the slope of the relationship between *Deleatidium* WUA and flow is more constant. The more we decrease flow the more we reduce WUA of *Deleatidium*—there is no obvious flow at which the slope changes abruptly.

The partial[23] warming effect of discharge on water temperature was noticeable as discharge dropped below 3000 L/s, but became stronger as discharge dropped below 2000 L/s. As discharge drops below 2000 L/s, mean water temperature may increase by as much as ca. 3-4 °C (Figure 3-10). As discharge drops below 2000 L/s maximum water temperature may increase by as much as ca. 4–5 °C, and—given the model and (limited) data—is predicted to exceed 35 °C under the 25 °C air temperature scenario (Figure 3-11). Temperatures of that magnitude can be lethal for native aquatic animals in New Zealand (Olsen et al., 2012).

Based on the primary flow-response curves, instream values of the Waipaoa River at Kanakanaia decline relatively quickly once flow drops below 3000-2000 L/s. Te Mana o te Wai directs councils to set water take limits that prioritise river health over non-environmental uses of water, hence limits that are 'environmentally conservative.' It follows that **an environmentally conservative CLF for the Waipaoa River at Kanakanaia that maintains *high* levels of instream values is 3000 L/s**.

A CLF of 3000 L/s at Kanakanaia is above the observed MALF of 2300 L/s (Table 2-5) considered under Option 2. A CLF of 3000 L/s should also support high small-bodied native fish values, as the WUA of such species declines relatively quickly as flow drops below 4000–2000 L/s (depending on the species). At 3000 L/s WUA of nuisance, long-filamentous periphyton is ca. 86% of the maximum WUA of long-filamentous periphyton, which occurs at ca. 1600 L/s.

A CLF of 3000 L/s for the Waipaoa River at Kanakanaia is 1000 L/s greater than the CLF supporting *instream values* suggested in the 2010 report (Booker et al., 2010, who suggested 2000 L/s). The reasons for this difference are as follows:

- For the present assessment we did not give all flow-response curves equal weight. What we called primary flow-response curves had a stronger influence on our assessment, and these curves happen to exhibit relatively clear and rapid declines in

[23] The 'partial' effect of discharge is the modelled/isolated effect of discharge after controlling for the effect of air temperature.

value once flow dropped below 3000 L/s. The 2010 report did not use the same relative weighting system that we have used here. Section 4.2 presents the rationale for the unequal weighting of flow-response curves used herein.

- The hydrology data and MALF estimates for the Waipaoa River have been revised as part of this study (Section 2). The revised estimate of observed MALF for the Waipaoa River at Kanakanaia is 2550 L/s; 550 L/s greater than the *instream values* CLF suggested in the 2010 report. Best available general information[24] indicates that a CLF that is 22% below the observed MALF (not the naturalised MALF) will not support *high* levels of instream values (Hayes et al., 2021; Lytle and Poff, 2004; Poff et al., 2010). Use of best available information is consistent with Clause 1.6 of the NPSFM.

- The overarching NPSFM concept of Te Mana o te Wai directs councils to set environmentally conservative limits. Our assessment has been carried out with this requirement in mind.

- The information presented in Section 3.3 comprises output of quantitative models whose parameters have been estimated as a result of data collected within the Waipaoa River at Kanakanaia. As such, the information presented in Section 3.3 is relatively objective. However, use of that information in CLF assessment involves numerous subjective elements, including relative weighting of flow-response curves and—in this assessment and that of the 2010 report—choice of flow values at which slopes of WUA curves change abruptly. Subjective elements of assessments such as these are common in resource management (Conroy and Peterson, 2013), but they may result in variation in assessments across assessors.

4.2.2 Options 2 and 3

If we were to select the observed MALF of the Waipaoa River at Kanakanaia as our CLF (2550 L/s; Option 2), then we may observe the following changes to the values supported, relative to the *instream values* option (Option 1):

- Reductions in WUA of ca. 5% and 8% for small and large longfin eel respectively.
- A ca. 5% reduction in wetted width and a 12% reduction in *Deleatidium* WUA.
- A negligible increase in mean and maximum water temperature (by ca. 0.5 °C).

With respect to the secondary flow-response curves, Option 2 may result in the following changes to the small-bodied fish community and periphyton:

- Reductions in WUA of torrentfish and bluegill bully of 20% and 30% respectively.
- Generally small (< 10%) reductions in WUA of Crans bully, upland bully, common bully and redfin bully.
- Small (< 10%) increases in WUA of nuisance periphyton.

[24] By 'general information' we mean information about setting minimum flows in New Zealand (and international) rivers in general, not just within Gisborne.

Therefore, **relative to the *high* levels of values supported by the *instream values* option, the *observed MALF* option may support *moderate-high* values**.

Relative to the *instream values* option, the *status quo* CLF may support:

- Reductions in WUA of ca. 48% and 25% for small and large longfin eel respectively.
- Reductions in WUA of ca. 13% and 15% for small and large shortfin eel respectively.
- A ca. 30% reduction in wetted width and a 29% reduction *Deleatidium* WUA.
- A small increase in mean and maximum water temperature (by ca. 1 °C).

With respect to the secondary flow-response curves, Option 3 may result in the following changes to the small-bodied fish community and periphyton, relative to the *instream values* CLF:

- Reductions in WUA of torrentfish and bluegill bully of 96% and 80% respectively.
- Generally moderate (< 25%) reductions in WUA of Crans bully, upland bully, common bully and redfin bully.
- Small (13%) increases in WUA of nuisance periphyton.

Therefore, **relative to the *high* levels of values supported by the *instream values* option, the *status quo* option may support *moderate* values**.

4.3 Te Arai River at Reays Bridge / Pykes Weir

4.3.1 Option 1 - 'Instream values' critical low flow

Wetted width of Te Arai at Reays Bridge declines with flow at an approximately constant rate at flows from 40 L/s to 500 L/s (Figure 3-12). Below 40 L/s there is a rapid decline in wetted width (Figure 3-12). Weighted usable areas of small eels (both species) decline relatively quickly once flow drops below 100 L/s (Figure 3-14). According to the models, WUA of large longfin eels increases ca. constantly with flow, while WUA of large shortfin eels appears less affected by flow (Figure 3-14). The slope of the relationship between *Deleatidium* WUA and flow is constant over flows from 140 – 500 L/s, with a more rapid decline evident when flow drops below 140 L/s (Figure 3-16).

With respect to the secondary flow-response curves, there is some evidence for rapid declines in WUA of the more flow-sensitive small-bodied fishes[25] as flow drops below ca. 150 L/s (Figure 3-15). Weighted usable area of nuisance periphyton increases rapidly as flow decreases below ca. 150 L/s (Figure 3-16).

Based on the flow-response curves summarised above, instream values of Te Arai River at Reays Bridge may decline relatively quickly once flow drops below ca. 150 L/s. One could suggest that **an environmentally conservative CLF for Te Arai River at Reays Bridge / Pykes Weir that maintains *high* levels of instream values is 150 L/s**.

A CLF of 150 L/s at Reays Bridge is above the observed MALF of 60 L/s (Table 2-5) considered under Option 2 and is the same '*high* instream values' flow identified in the 2010 report. The current CLF for this site is 60 L/s—equal to the revised estimate of observed MALF.

[25] E.g., torrentfish and bluegill bully

4.3.2 Options 2 and 3

If we were to select the observed MALF of Te Arai at Reays Bridge / Pykes Weir as our CLF (60 L/s; Option 2), then we may observe the following changes to the values supported, relative to the *instream values* option (Option 1):

- Reductions in WUA of ca. 9% and 11% for small and large longfin eel respectively.
- Reductions in WUA of ca. 18% and 0% for small and large shortfin eel respectively.
- A ca. 3% reduction in wetted width and a 22% reduction *Deleatidium* WUA.

With respect to the secondary flow-response curves, Option 2 may result in the following changes to the small-bodied fish community and periphyton, relative to the *instream values* CLF:

- Reductions in WUA of torrentfish, bluegill bully and redfin of 100%, 50% and 21% respectively. The models indicate torrentifish may be extirpated under Option 2.
- No change in WUA of upland bully.
- Generally small (< 10%) increases in WUA of Crans bully and common bully.
- A large, 70% increase in WUA of nuisance periphyton.

Therefore, **relative to the *high* levels of values supported by the *instream values* option, the *observed MALF* option may support *low-moderate* values**.

We predict the same outcomes from the *status quo* CLF, given the current CLF for Te Arai at Reays Bridge / Pykes Weir is the same the revised observed MALF.

Therefore, **relative to the *high* levels of values supported by the *instream values* option, the *status quo* option may support *low-moderate* values**.

4.4 Te Arai River at the water works

4.4.1 Estimated naturalised MALF

As noted in Section 2 the municipal water take from Te Arai River may be 100% of surface flow at the water works—leaving the river with zero flow—10% of the time. Without the water take, flow of Te Arai at the water works is below MALF (40 L/s; Table 2-5) approximately 5% of the time, but after the water take that flow is less than MALF approximately 35% of the time (Figure 2-6).

The current magnitude of water take from Te Arai at the water works is not consistent with the requirements of the NPSFM. We note, however, that this water take is important as it is for domestic use and there is currently no Block A CTTF or allocation cap for Te Arai at the water works. If there are alternative water sources for municipal supply that can be utilised in a cost-effective fashion and GDC would like to better maintain/rehabilitate instream values of Te Arai between the water works and Pykes Weir, a Block A CTTF may be set at the water works.

Unlike the Waipaoa River at Kanakanaia and Te Arai River at Pykes Weir, the default CLF recommendation of Hayes et al. (2021), presented in Table 4-1, is a scientifically-defensible option for Te Arai River at the water works. The flow recorder for Te Arai at the water works is just above the municipal water supply intake. There are no notable abstractions above the water works. As such, one may assume that the flow record of Te Arai River at the water works is approximately naturalised[26]. In turn, we assume that the MALF of 40 L/s presented in Table 2-5 is a reasonable approximation of naturalised MALF, and can be used to implement the default CLF of Hayes et al. (2021). **A CLF for Te Arai (water works) of 90% of naturalised MALF (ie. 36 L/s) may maintain relatively high instream values.**

In Section 4.1.1 we briefly discussed why naturalised MALF—or a high percentage of naturalised MALF—may be a scientifically-defensible CLF. Internationally, there is a growing body of evidence supporting the general applicability of the Natural Flow Paradigm. The Natural Flow Paradigm generally states that the physiological, behavioural and life-history traits of riverine species have evolved within the context of natural flow regimes and, consequently, those traits are—to varying degrees—adapted to the natural flow regime (Lytle and Poff, 2004). The Natural Flow Paradigm does not suggest that riverine species have no resistance or resilience to departures from the natural flow regime, nor does it suggest that all species have equal levels of adaptation to the natural flow regime. In the context of minimum flow management, the Natural Flow Paradigm implies that species have evolved some degree of resistance and resilience to the natural frequency distribution of annual low flows, of which naturalised MALF is a summary statistic.

Arguably, basing CLFs on naturalised MALF is more scientifically-defensible than use of WUA models—like the ones presented in this report and the 2010 report. Application of WUA models to flow management have been criticised on several bases (see Section 4.1.2, and as examples, Hayes et al. (2016) and Lancaster and Downes (2010a, b)). By contrast, the large literature in support of the Natural Flow Paradigm comprises strong evidence in support of basing default flow rules of naturalised regimes when a strong, mechanistic understanding of flow-ecology relationships is deficient (Poff et al., 2010).

[26] We note the flow record for Te Arai at the water works is not a long one. As such, even though the flow record is natural, its statistical properties—including MALF—are uncertain.

5 Translating critical low flows into cease-to-take flows

Our assessments above present potential CLFs for the Waipaoa and Te Arai Rivers. These CLFs are summarised in Table 5-1.

Table 5-1: Example CLFs for the Waipaoa and Te Arai Rivers. CLFs are presented in units of litres per second (L/s). Relative maintenance of instream values provided in brackets after each CLF.

	Option 3 (status quo)	Option 2 (Observed MALF)	Option 1 (instream values)
Waipaoa @ Kanakanaia	1,300 (moderate)	2,550 (moderate-high)	3,000 (high)
Te Arai @ Reays Bridge	60 (low-moderate)	60 (low-moderate)	150 (high)
			Option 1 (instream values; naturalised MALF default)
Te Arai @ water works			36 (high)

As explained in Section 1.2, Block A CTTFs must be greater than CLFs to reduce the risk of undesirable environmental outcomes and to ensure take rules are consistent with the NPSFM 2020. Cease-to-take flows must be based on the CLF as well as the maximum take rate ('allocation cap' in GDC plans) under Block A. Consider, for example, the following hypothetical case (also see Figure 1-1):

- River A has a CLF of 2000 ML/day.
- The council chooses to equate CTTF with the CLF with an allocation cap of 2000 ML/day—the allocation cap equals the CTTF.
- During a low flow event, River A drops to 2000 ML/day and irrigators are notified that CTTF has been reached and takes must cease. At this point in time irrigators are abstracting at the maximum rate, hence at the allocation cap.
- Irrigators take 24 hours to respond to the CTTF notification, during which time they continue to take at the allocation cap.
- Given the allocation cap is the same as the CTTF, the 24-hour response time, and the abstraction at the maximum rate, the flow in River A is reduced to zero before taking ceases.

To reduce the risk of dropping below the CLF, CTTFs may be set using a simple rule:

CTTF = CLF + Block A allocation cap (Eqn. 1)

This very simple equation highlights a planning trade-off: a larger Block A allocation cap increases Block A water availability up until the CTTF is reached, but it also increases the CTTF, so results in cessation of supply at higher flows.

Essentially, Equation 1 applies two assumptions. The first assumption is a worst-case scenario for streamflow depletion akin to "all allowable water is taken all the time (and all abstractions instantaneously deplete flows)". Application of that assumption is consistent with the precautionary approach required by the NPSFM. The second assumption is that all abstractions are subject to the CTTF. Given these two assumptions, application of Equation 1 would eliminate flow dropping below

CLF because of abstraction. However, neither assumption is likely to be 100% correct. If all allowable water is not taken all the time, then Equation 1 will produce a CTTF that is too high (overly environmentally-conservative). If some abstractions are not controlled by the CTTF because they are not assigned to Block A, then Equation 1 will produce a CTTF that is too low (insufficiently environmentally-conservative). Planners should consider these assumptions when applying Equation 1.

A lag in irrigator responses to CTTF notifications[27] will likely result in some fluctuations in flow about the CTTF. For any fixed period of lag, the magnitude of these fluctuations will be a positive function of the ratio *(Block A allocation cap) / CTTF*. That is, the larger the allocation cap relative to the CTTF the larger the potential magnitude of fluctuations of flow around CTTF. These fluctuations may have a detrimental effect on instream values (Blinn et al., 1995; Kjærstad et al., 2018). One way to keep the magnitude of potential fluctuations low is by using a Block A allocation cap that is a relatively low percentage of the CLF (say, 33% of CLF). This is consistent with the recommendations of Hayes et al. (2021). For illustrative purposes only, in Table 5-2 we have translated the CLFs of Table 5-1 into allocation caps and CTTFs.

Table 5-2: Translation of the example CLFs for the Waipaoa and Te Arai Rivers (in Table 5-1) into allocation caps and CTTFs. Allocation caps and CTTFs are presented in units of litres per second (L/s). Here, allocation caps are set at 33% of the CLFs in Table 5-1. CTTFs are then determined using Eqn. 1.

	Option 3 (status quo)		**Option 2 (Observed MALF)**		**Option 1 (instream values)**	
	CTTF	Cap	CTTF	Cap	CTTF	Cap
Waipaoa @ Kanakanaia	1,733	433	3,400	850	4,000	1,000
Te Arai @ Reays Bridge	80	20	80	20	200	50
					Option 1 (instream values; naturalised MALF default)	
Te Arai @ water works					48	12

We appreciate that these CTTFs and allocation caps represent a substantial change to those currently implemented in Gisborne. A potential way to increase water security for irrigators while still protecting riverine values from over-abstraction is to implement a multi-band allocation system, such as the one explored by Booker and Rajanayaka (2023).

[27] Both when flow drops below the CTTF, as well as when it rises above the CTTF

6 Improving evidence-based take limits in the Gisborne District

To improve evidence-based take limits we recommend the following, in addition to the recommendations offered in Section 2 of this report:

6.1 Explore alternative approaches to minimum-flow setting 2024–2025

NIWA is currently investing in the development of mechanistic flow-ecology models to support design of water take rules. These models will be ready for trial application during the summer-autumn of 2024-2025. **We recommend GDC collaborate with NIWA to apply these models to the Waipaoa and Te Arai Rivers to cross-check CLFs for these rivers.**

We contend that these models will produce forecasts of response to flow that are more accurate and scientifically-defensible than those arising from traditional WUA models (similar to the arguments of Hayes et al. 2016). The mechanistic models NIWA is developing are ecosystem models designed for forecasting the carrying capacity of a river reach as a function of how low flows affect benthic[28] food webs.

Development of the models has been funded by NIWA, but applying these models to the GDC district would require some collection of local habitat and ecological data, such that we may calibrate the model for use in the Waipaoa and Te Arai Rivers. Accordingly, this workstream would require additional funding. The Envirolink Fund is a possible source of the additional funds required for this workstream.

6.2 Naturalise flow series for the Waipaoa and Te Arai Rivers

It is difficult to complete a robust assessment of the impacts of water takes without estimates of naturalised flow series. Naturalised flow series serve as a benchmark against which to compare modified flow regimes and proposed flow targets (like CLFs). Furthermore, water accounting is a requirement of the NPSFM. **We recommend investing in the development of naturalised flow series for the Waipaoa and Te Arai Rivers**. Using naturalised flow series GDC would be estimate naturalised MALF for sites of interest, operationalising the default minimum values of Hayes et al. (2021) within the Waipaoa and Te Arai catchments. These default CLFs would serve as a very useful corroboration of any model-derived CLFs (like the ones presented in this report), thereby increasing the credibility of water take rules in the district.

6.3 Begin monitoring for adaptive management of river flows

The CLF assessment carried out herein was constrained by lack of data. **We recommend implementing some monitoring consistent with the plan of Stoffels et al. (2022), which GDC helped develop**. Monitoring activities need to be developed in light of the conceptual models of Section 3.1. NIWA would be glad to work with GDC to help prioritise monitoring activities from Stoffels et al. (2022) to suit local needs and budget. This could be done through a one day in-person or online workshop.

6.4 Consider a banded water allocation system

A banded water allocation system, similar to the one explored by Booker and Rajanayaka (2023), may help balance the need to ensure water security for irrigators as well as the need to meet the requirements of the NPSFM. Recommendation 6.2, above, is a prerequisite for this workstream. **We**

[28] River bottom

recommend undertaking an analysis of how alternative banded systems affect the naturalised flow duration curves of Te Arai and Waipaoa Rivers. Analysis of how banded water take limits affect hydrology should be extended to analyses of those hydrological impacts go on to affect riverine values, including instream ecology.

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Appendix A Exploratory analysis of water temperature

The water temperature showed a bimodal distribution as temperature switched from summer to winter (Figure A-1).

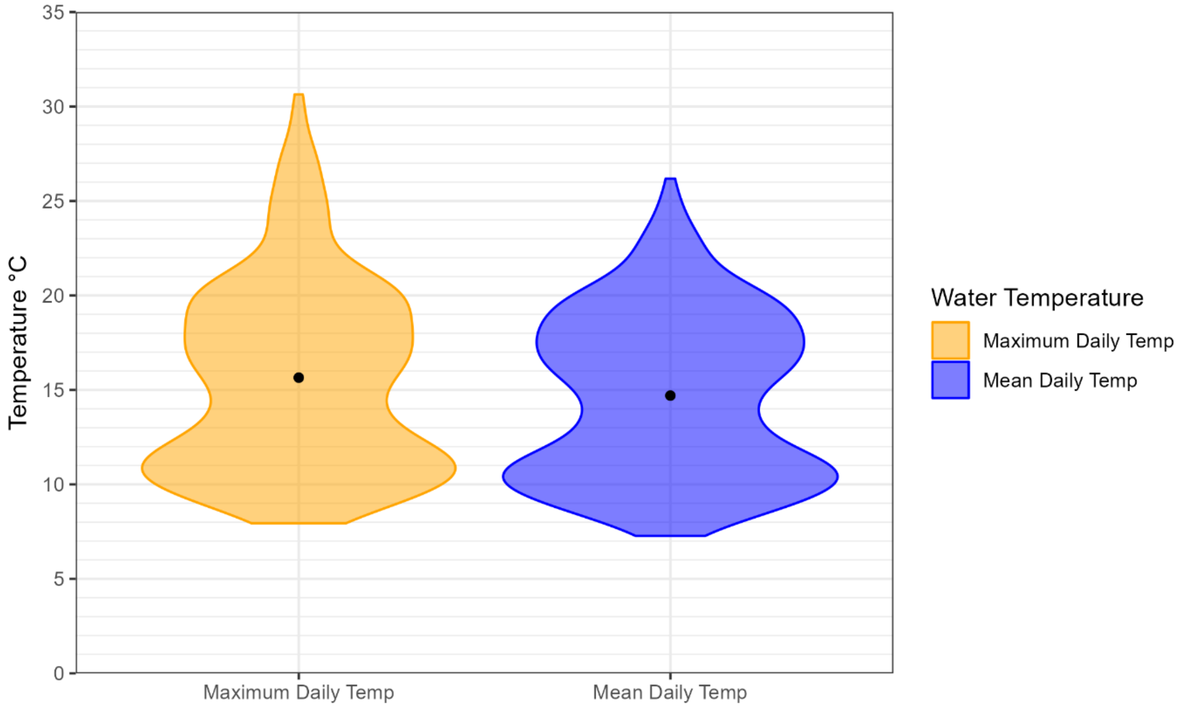

Figure A-1: The mean and maximum daily water temperature show a bimodal distribution related to summer and winter conditions. Data plotted are from the training data. The black dot is the mean of the distribution.

Principal component analysis revealed a strong association between mean and maximum water temperatures, loading negatively onto PC1 (principal component 1; Figure A-2). In addition, mean air temperature, maximum air temperature and solar radiation also loading negatively onto PC1, was mean air temperature having a close association with the water temperature parameters. This indicates that air and water temperature are associated with one another, plus higher levels of solar radiation are also associated with higher temperatures. The flow was positively associated with PC1 (Figure A-2). It was noted that higher flows are associated with lower temperatures. Conversely, rainfall loaded onto PC2, loading in the opposite sense to solar radiation but similar overall direction as flow (Figure A-2). So as rainfall goes up, the amount of solar radiation (and sunshine) would be expected to decrease.

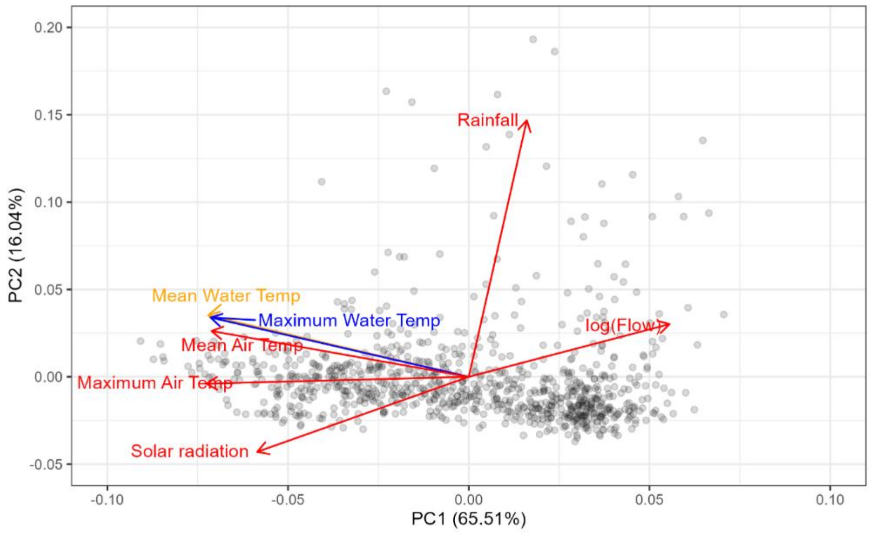

Figure A-2: Principal components plot showing the relationships between water temperature observations and potential driving variables.

We focused on the key variables: water temperature (mean and maximum), flow and air temperature. The general trend was that the flow tends to go down as air and water temperature rise, as the black line in Figure A-3 indicates. On top of the trend, there is quite a lot of variability from day to day. The flow figures have been log-transformed, which better represents the variation in flow relative to temperature.

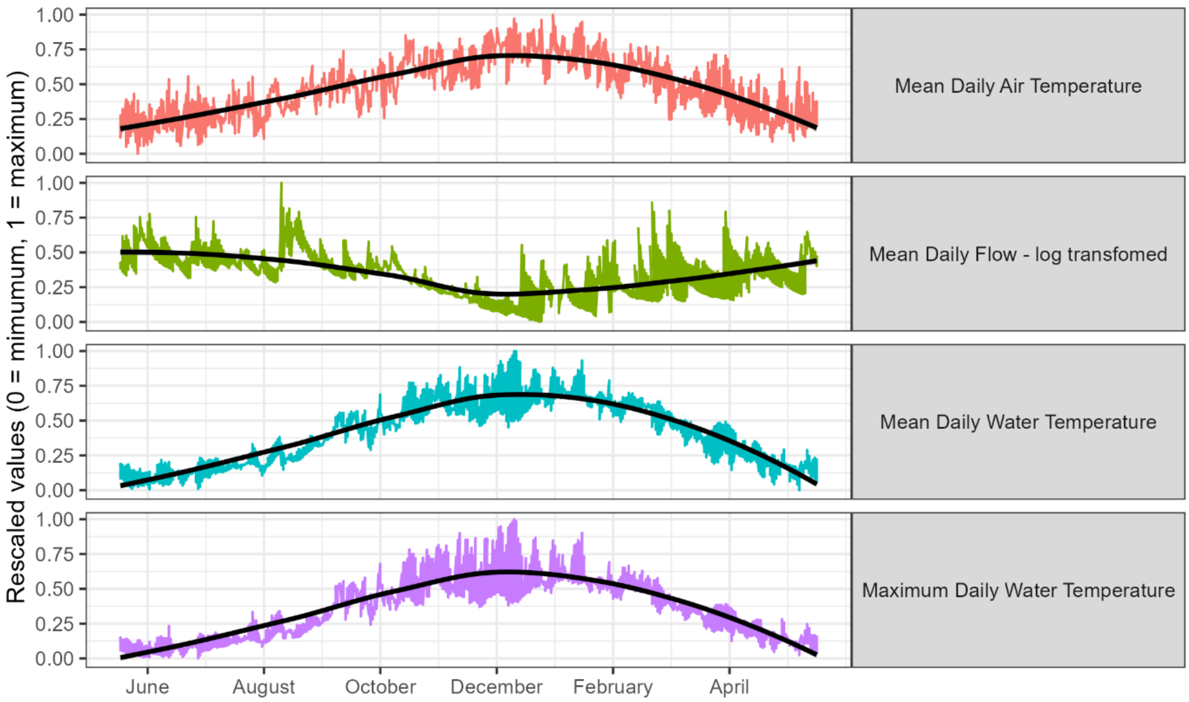

Figure A-3: Rescaled daily mean air and water temperature and log transformed flow from two years of training data. The black line is best fit of a GAM.

Various statistical models were trialled on the raw training data and with new variables created by introducing lagged and rolling averages of meteorological and hydrological parameters. The use of shrinking and dimensional reduction methods, such as elastic net and partial least squares (James et al., 2021) pointed towards air temperature as a critical variable, particularly the rolling average air temperature. However, these methods did not produce more accurate models, compared with simpler models such as multiple linear regression with only two predictors (air temperature and flow), so they were not pursued in detail. Various models with different degrees of flexibility were tested with the flow and rolling 5-day mean of air temperature as the predictor variables.