HAWKE'S BAY
REGIONAL COUNCIL

Addendum to fish habitat modelling

for the Ngaruroro and Tutaekuri rivers

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Environmental Science - Hydrology

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Executive summary

The Greater Heretaunga plan change will address how much water is allocated, and when restrictions on water use are applied. The effect of water use on fish is an important consideration when setting these limits for water resource management. For the Ngaruroro and Tutaekuri rivers, the effects of water use were evaluated using hydraulic models to predict the change in fish habitat with flow (RHYHABSIM and SEFA).

This report outlines changes to the habitat-flow predictions made subsequent to the original reports that were completed by Kolt Johnson for the Ngaruroro River (2011) and the Tutaekuri River (2012). These changes were made as more information became available, including the development of more advanced water use modelling and groundwater-surface water flow models.

Changes to the estimated MALF (mean annual low flow) will change the flows required for a given habitat protection level, because MALF is used in the calculation of habitat protection levels. Therefore, the increase in the naturalised MALF (e.g. from 4,500 L/s to 4,700 L/s for the Ngaruroro) increased the flow required to protect habitat. The revised flow requirements for the Ngaruroro and Tutaekuri are summarised in the table below.

Table 1: Flow recommendation summary table. Flow requirements for the Tutaekuri River at Puketapu and the Ngaruroro River at Fernhill. The habitat protection level afforded by the existing trigger flow (as prescribed in the outgoing regional plan) is provided in the last column. This summary is based on the type of fish with the highest flow requirements (i.e. adult trout for the Tutaekuri; torrentfish for the Ngaruroro).

	MALF naturalised (100% habitat)	Flow for 90% habitat	Flow for 80% habitat	Flow for 70% habitat	Protection level at existing trigger flow
Tutaekuri (Puketapu)	3900 L/s *(was 3800 L/s)*	3300 L/s	2800 L/s	2300 L/s	65% at 2000 L/s
Ngaruroro	4700 L/s *(was 4500 L/s)*	4400 L/s	4000 L/s	3600 L/s	44% at 2400 L/s

For the Tutaekuri River, the increase in predicted flow requirements is a consequence of the updated habitat criteria for trout. The existing trigger flow of 2,000 L/s was expected to provide a high level of habitat protection, based on the habitat criteria used for the 1996 habitat survey (Wood, Draft 2002). The trout habitat criteria developed since that time, both from the Hawke's Bay and from the Rocky Mountains (Colorado), predict that more than 2,000 L/s is required to achieve habitat protection levels of 70%-90% in the Tutaekuri River (see Table above).

Other variations to the modelling were of less consequence for the flow recommendations. For example, the incorporation of the Rocky Mountain habitat criteria for trout did not translate to significant changes in flow required to achieve a given habitat protection level, compared to the Hawke's Bay criteria. Likewise, the importance of invertebrate production at median flows did not translate to higher flow requirements. Modelling of the Ngaruroro and Tutaekuri revealed little or no reduction in invertebrate habitat at median flows as a consequence of existing water use. In addition to water use representing a smaller proportion of median flow (compared to low flows), there is currently less water demand for irrigation and other uses at times when moisture levels are sufficient to sustain median river flows.

Other issues considered in this report include flow requirements for the fish passage, water temperature and dissolved oxygen. Water temperature, in particular, presents a likely constraint on the types of fish and invertebrates that can survive in the Ngaruroro and Tutaekuri rivers. However, the small change in temperature with flow for the Ngaruroro supports the establishment of trigger flows on the basis of hydraulic habitat protection.

A remaining issue is where to monitor trigger flows on the lower Ngaruroro River. The representativeness of the existing monitoring site for the lower river is compromised by the loss of flow to groundwater both upstream and downstream of the Fernhill monitoring site. Of the two alternatives (Hawke's Bay Expressway or Chesterhope), Chesterhope Bridge has better access and a longer flow record (monitored by NIWA since 1976). For the Tutaekuri River, the existing trigger-flow site at Puketapu provides an adequate representation of the timing of low flows for the habitat survey reach (Ngaroto), and the broader catchment.

1 Background

Hawke’s Bay Regional Council convened a group of community members to make recommendations on a plan change for the Greater Heretaunga area. ‘TANK’ is an acronym for the Tutaekuri, Ahuriri, Ngaruroro and Karamu river catchments, which make up the Greater Heretaunga area. The TANK Stakeholder Group is made up of approximately 30 individuals from agricultural and horticultural sectors, environmental and community interest groups, the health sector, territorial authorities and tangata whenua.

Issues being addressed in the plan change (in addition to broader management of land and water resources) include the establishment of water allocation limits and trigger flows for managing restrictions on water use during periods of low flow. The TANK stakeholder group have considered the effects of water use on fish and other life in rivers, to inform their recommendations for the plan change. For the Ngaruroro and Tutaekuri rivers, the effects of water use on fish habitat were evaluated.

Hydraulic habitat models, such as RHYHABSIM (River Hydraulic Habitat Simulation), predict the change in velocity and depth with flow, based on intensive surveys of channel shape and flow characteristics (Jowett, 2001). By comparing RHYHABSIM predictions of depths and velocities to the depths and velocities used by fish (termed ‘habitat criteria’), these methods can generate habitat-flow curves that describe the change in weighted usable area with flow. These habitat-flow curves provide an understanding of how the hydraulic habitat of fish changes in response to flow. The models do not provide a prediction of fish biomass, which can be further constrained by other physical constraints that are not related to diffuse water takes, such as disturbance and predation (Milhous & Bartholow, 2006).

RHYHABSIM can inform the setting of flow thresholds at which water takes are restricted. In the past, these flow thresholds were referred to as ‘minimum flows’. A problem with this term is that it implies the river flow will always remain above this minimum flow, which is not the case for the Ngaruroro and Tutaekuri. A more appropriate term for the Greater Heretaunga streams is ‘trigger flow’, given it triggers a management response that is intended to reduce the rate of flow recession, but not necessarily halt it.

For the Ngaruroro and Tutaekuri rivers, RHYHABSIM surveys were conducted to predict the response of hydraulic habitat to flow alteration. These investigations were reported by Kolt Johnson, including:

- Johnson, K. (2011) "Lower Ngaruroro River instream flow assessment". HBRC Plan Number 4249, EMT 10/37, Hawke's Bay Regional Council: Napier. Web link for document.
- Johnson, K. (2012) "Tutaekuri River instream flow assessment". HBRC Plan Number 4262, EMT 11/03, Hawke’s Bay Regional Council. Web link for document.

These reports are the primary references for the RHYHABSIM studies and include the methods used, which are not repeated here. This report provides an addendum to Johnson’s (2011; 2012) reports, outlining any changes to the instream flow predictions and statistics that have been made subsequent to the original reports. These changes were made as more information became available, including revised estimates of MALF (mean annual 7-day low flow). Some key learning points from the TANK Stakeholder Group process are captured in this report.

The location of the habitat survey for the Ngaruroro River is mapped in Figure 1-1. Johnson (2011) describes the rationale for reach selection, including its location downstream of flow losses to groundwater. For the Tutaekuri River, the study reach was located upstream of the Mangaone River confluence (Figure 1-2). This was selected in consultation with the Department of Conservation, Fish and Game New Zealand, and local Iwi representatives (Johnson, 2012).

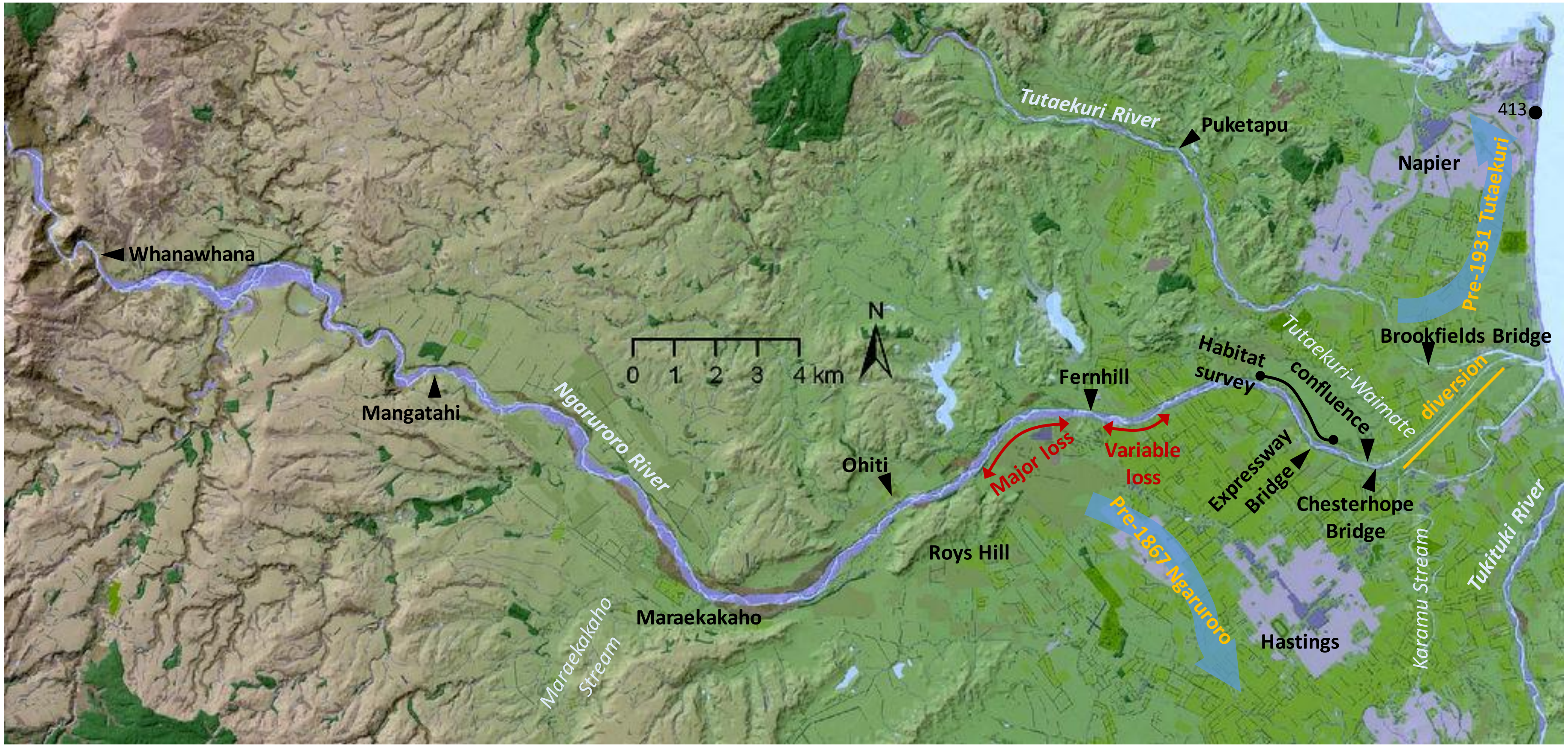


Figure 1-1: Ngaruroro River. Map of the lower Ngaruroro River showing the location of RHYHABSIM habitat survey downstream of Fernhill. Also shown are flow monitoring sites (e.g. Whanawhana, Fernhill and Chesterhope Bridge) and reaches that lose flow to groundwater (Minor loss, Major loss and Variable loss). This map is adapted from another report that describes the flow losses in more detail (Wilding, 2018).

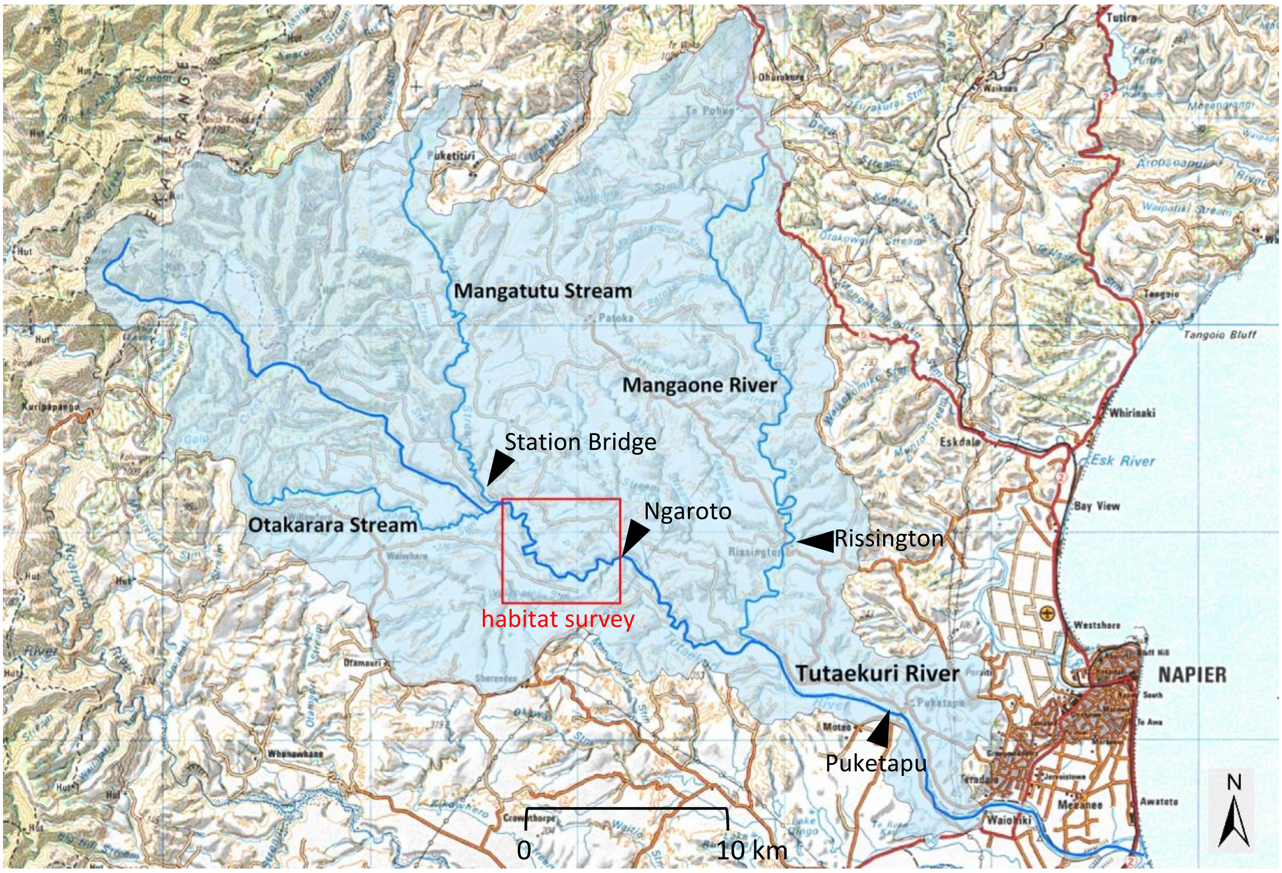


Figure 1-2: Tutaekuri study reach. The Tutaekuri River catchment, with the location of the 2009 instream habitat modelling study reach framed in red. Selected flow monitoring sites are arrowed, at which flow monitoring is continuous at Puketapu and Rissington. This map is adapted from Johnson (2012).

Earlier RHYHABSIM surveys were completed on the Ngaruroro River (Wood, 1997) and the Tutaekuri River (Wood, Draft 2002). The revised RHYHABSIM investigations, as reported by Johnson (2011, 2012), were completed in response to criticism of the original investigations by scientists from Cawthron Institute, on behalf of Eastern/Hawke's Bay Fish and Game Councils (Hayes, 1999). Issues raised included how well the selected reaches and cross-sections represented important habitat for trout. Additionally, the potential for the habitat criteria used for rainbow trout to under-estimate their flow requirements.

2 Methods

RHYHABSIM is referred to in this report both as the survey method and as the computer software that runs the hydraulic habitat model. The original habitat models developed by Johnson (2011; 2012) used RHYHABSIM software. However, development of the RHYHABSIM software ceased some years ago, and the modelling platform was replaced by SEFA (System for Environmental Flow Assessment), (Jowett *et al.*, 2014). Hence, all hydraulic habitat modelling presented in this report was completed using SEFA. The SEFA modelling successfully reproduced the original habitat-flow predictions that were generated using RHYHABSIM from the Ngaruroro survey. Therefore, I am confident that the different predictions presented here are primarily a consequence of the change in input information, rather than software changes.

The SEFA model produces plots of the change in hydraulic habitat with flow for each type of fish. Rather than presenting TANK stakeholders with a complex set of habitat-flow plots, the information was reduced to a discrete set of options using habitat protection levels (Jowett & Hayes, 2004; Wilding, 2003).

The conversion of habitat-flow response curves to habitat protection levels is demonstrated in Figure 2-1. For example, an 80% protection level is a flow that equates to 80% of the habitat available to that type of fish in that particular river. Averaging the lowest flows across a number of years gives a MALF (mean annual low flow). The MALF is used to define how much habitat is typically available in each river (unless the maximum habitat occurs at lower flows), because the lowest flow that a river drops to each year can also be a bottleneck for fish populations (Jowett, 1992). That bottleneck can constrain the number of fish surviving through to the next spawning season.

Among the many types of fish modelled, trigger-flow recommendations are typically based on the species with the highest flow requirements. This provides community-level protection by meeting or exceeding the flow requirements for all species modelled. In its simplified form, options for trigger flows can then be presented as a 90% protection level, 80% protection level, and so on, for only the species with the highest flow requirements. As well as reducing the complexity of the SEFA output, this protection-level approach enables consistency in the level of protection applied to different rivers. Note that while this is an enabling approach, it is not compulsory to apply consistent levels of protection between rivers.

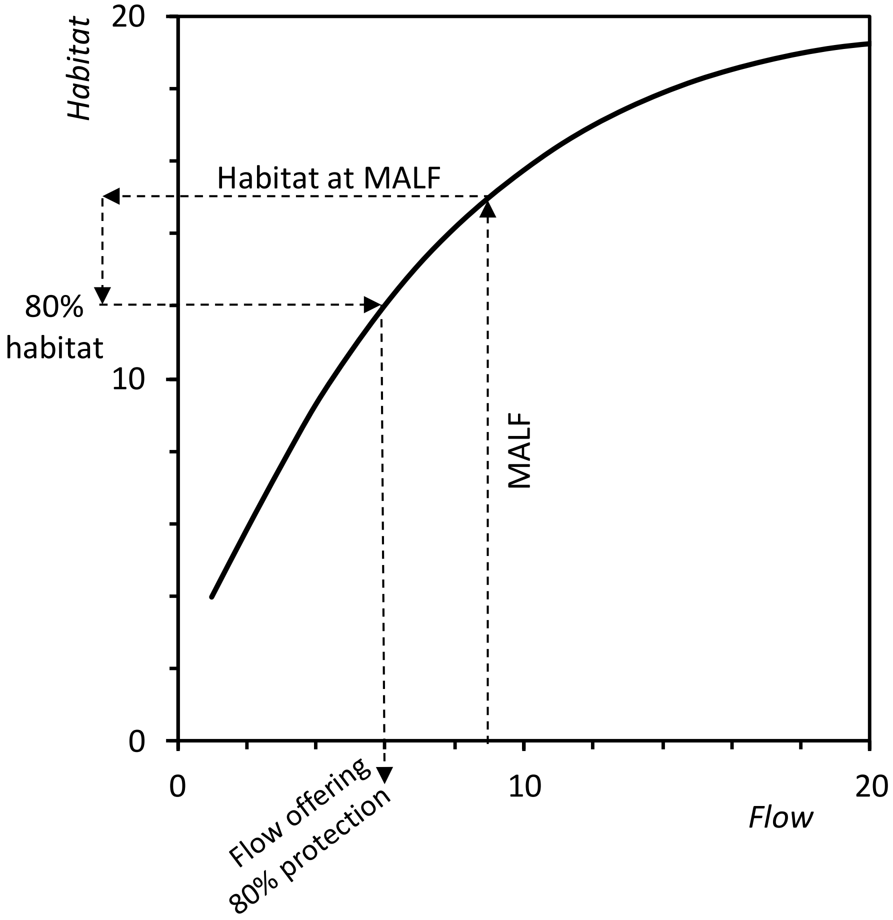


Figure 2-1: Method for calculating habitat protection levels. Follow the dashed arrows to see how MALF (Mean Annual Low Flow) is used to calculate the flow required for fish habitat protection levels from the RHYHABSIM habitat-flow curve (black line).

Given that MALF is used in the calculation of habitat protection levels, changes to the estimated MALF will change the flows that achieve a given habitat protection level. In particular, in a river where water use increases over time, the lowest actual flow that a river drops to each year will decrease over time and MALF would consequently reduce. In this case, calculating MALF using observed flows would generate a gradual decline in the habitat protection level over time.

To avoid an unintended decline in habitat protection levels as a consequence of increased water use, the method uses the 'naturalised MALF', which is the MALF estimated to occur in the absence of water abstraction. Better models were developed subsequent to the RHYHABSIM reports (Johnson, 2011; Johnson, 2012), for estimating water use and the degree of stream depletion from groundwater takes throughout the Heretaunga Plains (Rakowski & Knowling, 2018). These model results were used to revise the naturalised MALF, as described by Smith *et al.* (2017).

Smith *et al.* (2017) estimated a naturalised MALF of **4,700 L/s** for the **Ngaruroro** at Fernhill, compared to 4,500 L/s used by Johnson (2011), (Table 2-1). The increase from 4,500 to 4,700 L/s was largely because:

(a) the revised MALF excluded uncertain flow and abstraction data prior to 1998

(b) the stream depleting effects of consented groundwater abstractions were included in the revised calculations

For the **Tutaekuri** River at Ngaroto, there was only a minor change in MALF, despite the more intensive naturalisation process (Table 2-1). The revised Tutaekuri River naturalisation was calculated using surface water takes plus the stream depletion effects of groundwater abstraction in the Moteo Valley (Waldron, in prep 2018). The Tutaekuri habitat protection levels were then recalculated based on revised estimates of MALF.

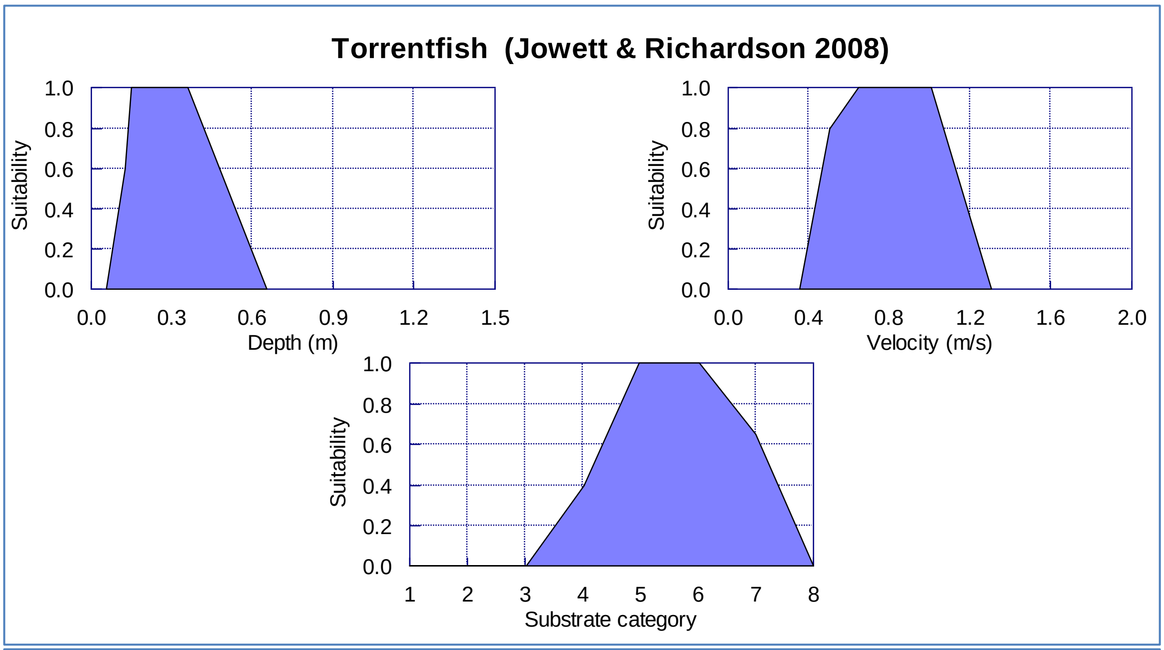
Table 2-1: Revised MALF estimates. Revised MALF (Mean Annual Low Flow) estimates for the Ngaruroro and Tutaekuri rivers used in this report, compared to the value used in earlier RHYHABSIM reports (Johnson, 2011; Johnson, 2012). The measured MALF (i.e. not corrected for water use) and the data period are also tabulated. The values used for habitat protection calculations are given in parentheses, in addition to the reporting values that were rounded to two significant digits.

River and location	MALF L/s Naturalised (revised)	MALF L/s Measured (revised)	Median L/s Naturalised	Data period	2011/12 report MALF L/s Naturalised
Ngaruroro at Fernhill	4700 (4698)	3800 (3819)	20000 (20162)	1998-2015	4500
Tutaekuri at Ngaroto	2700 (2680)	2400 (2440)	4600 (4620)	1980-2015	2800
Tutaekuri at Puketapu	3900 (3894)	3500 (3508)	8000 (7988)	1980-2015	3800

The RHYHABSIM study-reach for the Tutaekuri River was located at Ngaroto, which is upstream of the flow monitoring site at Puketapu (see Johnson (2012) for site-selection process). It was therefore necessary to translate flows from the study reach to the monitoring site. This was calculated as the equivalent flow at Puketapu, based on a linear regression model developed from a series of same-day gaugings at Ngaroto and Puketapu (NgarotoFlow = 0.6147 x PuketapuFlow + 289.6; Units L/s; N = 33; R^2 = 0.90).

Calculations were completed using at least three significant-digits, to reduce rounding errors. Sometimes the number of digits is interpreted as an indicator of precision, hence the final recommendations were restricted to two significant digits. The use of two significant digits also follows the convention used in previous regional plans.

Another change to the flow recommendations here arises from the use of additional habitat criteria. SEFA uses habitat criteria as the biological model to predict the velocities and depths used by each type of fish. The relative suitability of water depth, velocity and substrate type are described on a scale of 0 (unsuitable) to 1 (suitable). For example, the use of higher velocity areas by torrentfish are described by a suitability that peaks at a velocity of approximately 1 m/s (Figure 2-2). In addition to developing different habitat criteria for each species, size-class criteria have been developed for some species (e.g. small eels and large eels).



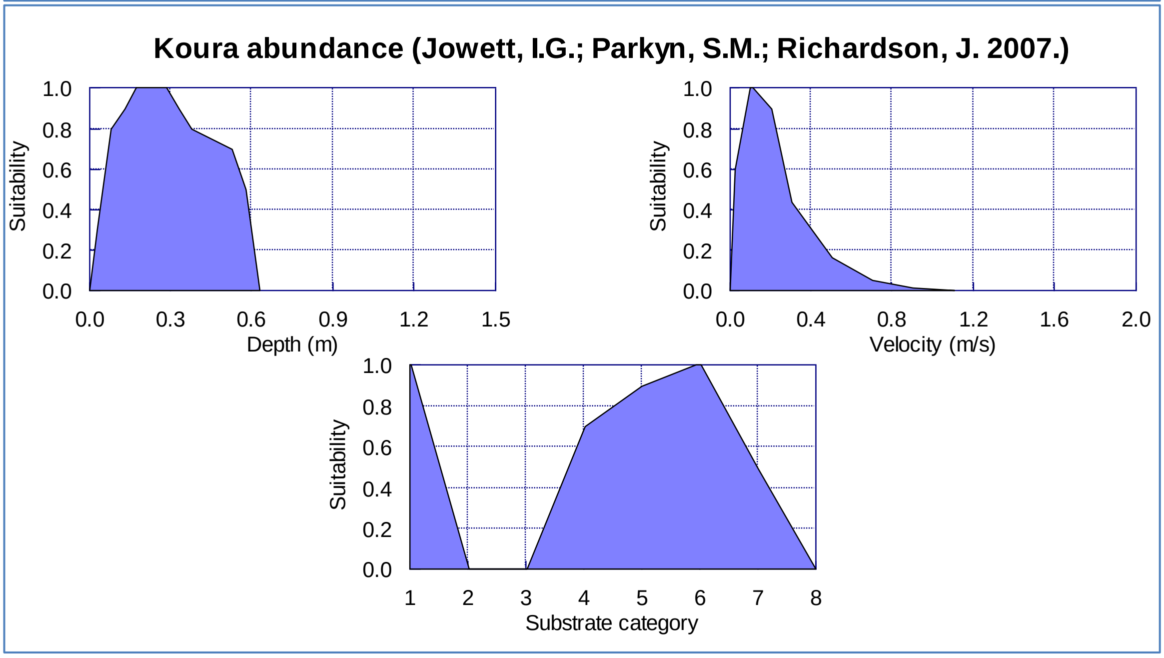


Figure 2-2: Habitat criteria for torrentfish and koura. Examples of how the different habitats used by different species are represented in the SEFA model. For example, a velocity of 1 m/s is suitable for torrentfish (score of 1), but unsuitable for koura (score of 0.005). Substrate indices from 1 to 8 represent: vegetation (1), silt (2), sand (3), fine gravel (4), gravel (5), cobble (6), boulder (7) and bedrock (8).

A long list of species and size classes was used for the previous Ngaruroro and Tutaekuri habitat modelling (Johnson, 2011; Johnson, 2012), including:

- longfin eel <300mm
- longfin eel >300mm
- shortfin eel <300mm

- shortfin eel >300mm
- common bully
- torrentfish
- redfin bully
- inanga (feeding)
- Cran's bully
- common smelt
- koaro
- dwarf galaxias
- bluegill bully
- rainbow trout <100mm
- rainbow trout >200mm (provisional Hawke's Bay criteria)
- mayfly (*Deleatidium*)
- general macroinvertebrate habitat
- (lamprey - used for Ngaruroro only)
- (brown trout <100mm – used for Ngaruroro only)
- (brown trout adult (Hayes & Jowett, 1994) – used for Ngaruroro only)

Habitat criteria have not been developed for all species. Hence, species like yellow-eyed mullet and black flounder were not modelled, despite occurring in these rivers. From what we know of these omitted species, they are not expected to have higher flow requirements than torrentfish. For example, yellow-eyed mullet were observed feeding in pools and slow runs, rather than amongst fast water riffles. The body-form of the black flounder is adept in fast-water. However, black flounder do not appear to depend on swift water, because they were encountered in both slow and fast water (*pers. obs.*).

The only habitat criteria added for this addendum (subsequent to the 2011/2012 reports) were for koura and adult trout. The habitat criteria for koura (freshwater crayfish) were developed in response to requests by stakeholders concerned for this mahinga kai (traditional food) species. The use of water depth, velocity and cover by koura were investigated by Jowett *et al.* (2008). Ian Jowett was asked to adapt these Generalised Additive Models into habitat criteria that are compatible with SEFA. The original article contained several models that were appropriate at different spatial scales. The large-scale model was not appropriate for SEFA as it was intended for predicting where koura occur across the New Zealand stream network (a presence-absence model). Instead, the abundance model was chosen, which operated at a more appropriate scale for SEFA habitat criteria (point grain, reach extent) and the scale at which water abstraction may affect an existing population of koura within a river reach (Wilding, 2012).

The original koura abundance model did not include substrate because it was not a statistically significant predictor of koura abundance. The original abundance model did include habitat cover as a predictor of abundance (e.g. overhanging trees). Cover could not be used here because the Ngaruroro and Tutaekuri surveys did not include these cover classes. In response to concern from stakeholders that changes in substrate could impact on koura, Ian Jowett was asked to add an expert-based substrate category. The resulting criteria are plotted in Figure 2-2, with the tabulated criteria provided in Appendix A.

The second addition was habitat criteria for adult trout. Johnson (2011) had included trout in the original reports, including provisional rainbow trout criteria that had been developed specifically for Hawke's Bay rivers by Cawthron Institute. However, the Cawthron report on the Hawke's Bay rainbow trout criteria is incomplete (Hayes & Addley, 2013) so is still 'provisional'. Habitat criteria developed in Colorado for Rocky Mountain streams were added to the modelling (Wilding *et al.*, 2014), in response to recent concerns by Cawthron scientists that some trout criteria may under-estimate the flow requirements of adult trout (Hayes *et al.*, 2016).

Addressing the concerns from Cawthron also necessitated the use of two criteria for brown trout in this report. Both criteria were sourced from the same journal article (Hayes & Jowett, 1994). One is the 'habitat use' criteria, as used by Cawthron scientists for comparison with their bioenergetics research (Hayes *et al.*, 2016). The second are the 'habitat preference' criteria for adult brown trout, as used by Johnson (2011) for the Ngaruroro River. Implications of the Cawthron bioenergetics research are discussed in Section 4.

The change of invertebrate habitat at flows greater than MALF were investigated, given the potential for invertebrate production at higher flows to sustain fish abundance (Hayes *et al.*, 2016; Jowett, 1992). For this analysis, the estimated change in flow (from surface water and groundwater use) was used to predict the alteration of invertebrate habitat up to median flows. This analysis used habitat criteria developed for general invertebrate production (Waters, 1976), which exceeded the flow requirements predicted using mayfly habitat criteria (*Deleatidium*, Jowett *et al.*, 1991).

The potential for reduced flows to obstruct the movement of fish through shallow riffles was also modelled in response to concerns raised by stakeholders. SEFA can be used to determine the width of river that is deep enough for the passage of fish. This represents the contiguous width that exceeds the required minimum depth, in the shallowest cross-section of those surveyed. Three different depth requirements were modelled: 0.18 m, 0.2 m and 0.25 m. The depth of 0.25 m is the default value in SEFA. The 0.2 m depth was used by Otago Fish and Game Council for adult trout in the Lindis River (Gabrielsson, 2016). The 0.18 m depth was used by Cawthron Institute for the Waimea River (Young & Allen, 2013). The SEFA model also requires a maximum water velocity to be specified for this width of river, for which we used the SEFA default value of 1.25 m/s so that depth was the main determinant of passage-width.

We investigated the relative sensitivity of the SEFA model predictions to depth, velocity and substrate for torrentfish in the Ngaruroro River and for trout in the Tutaekuri River. Each parameter was omitted in turn by setting it as optimal across all values. The parameter that produced the largest change in the habitat-flow response, when omitted, was considered to be the most sensitive parameter. This parameter has the greatest leverage on the trigger-flow predictions.

The frequency and duration of low flows was also investigated at the request of Hawke's Bay Regional Council planning staff. This provides broader understanding of the effect of water use on the flow regime. This analysis identified the number of years when flow dropped below nominated thresholds (i.e. frequency of low flows), plus the number of days per year when flow was below a given threshold. The comparison was then drawn between the measured and naturalised flow.

3 Results

3.1 Habitat Criteria

New habitat criteria were developed for koura (freshwater crayfish) from Generalised Additive Models (Jowett *et al.*, 2008). These criteria predicted that koura habitat would peak at flows less than 2,000 L/s in the Ngaruroro River (Figure 3-1). Less than 1,000 L/s is estimated to maintain 90% of peak habitat for koura, compared to torrentfish, which require 4,400 L/s for a 90% protection level. Koura are more likely to get washed away if exposed to fast water, compared to torrentfish whose fins and body shape help them adhere to the bed under high velocities. Predictions for the Tutaekuri River provided a similar contrast between koura and torrentfish (Figure 3-1).

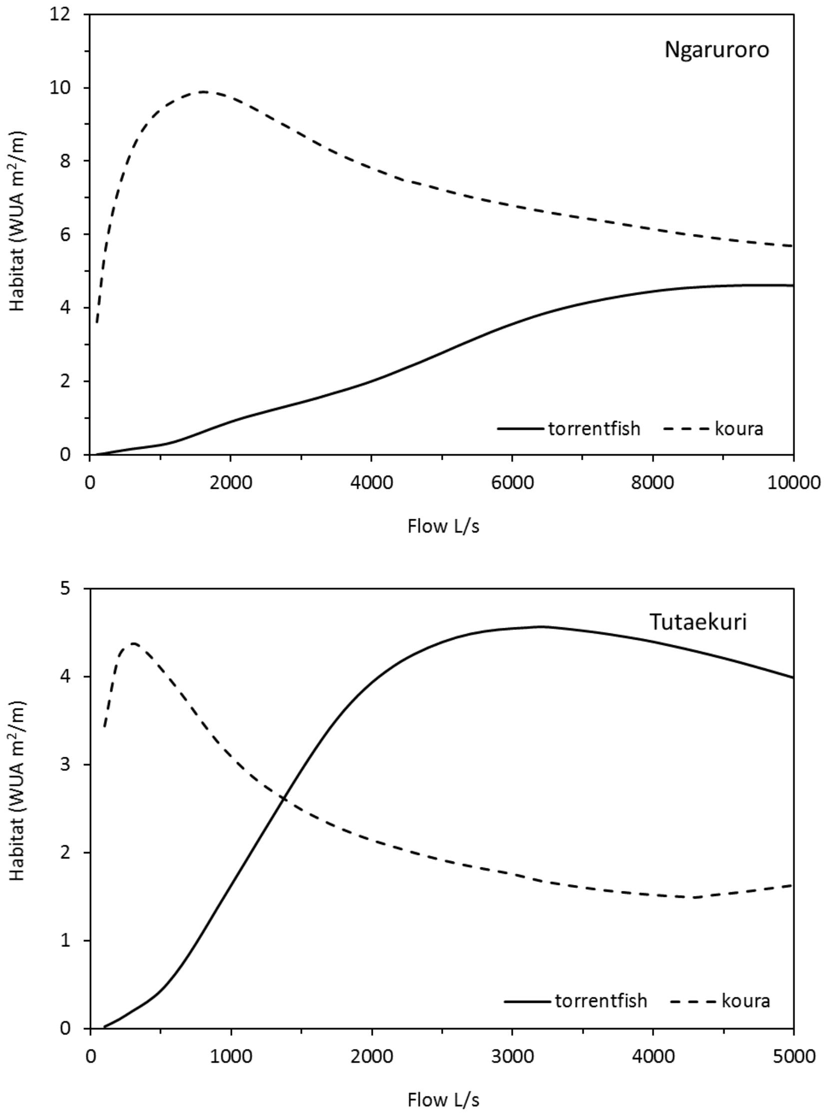


Figure 3-1: Habitat-flow response for koura. Habitat flow response for koura (freshwater crayfish), with the response for torrentfish overlaid for comparison. The upper plot is for the Ngaruroro River downstream of Fernhill. The lower plot is for the Tutaekuri River at Ngaroto.

Following concerns from scientists at Cawthron Institute that flow requirements for trout were being under-predicted by RHYHABSIM (Hayes *et al.*, 2016), new habitat criteria were applied to the Ngaruroro and Tutaekuri. The additional criteria for adult trout (both rainbow and brown) were developed for Rocky Mountain streams (Wilding *et al.*, 2014), and describe a preference for deeper and faster water compared to the habitat use criteria for brown trout used by Cawthron (Figure 3-2).

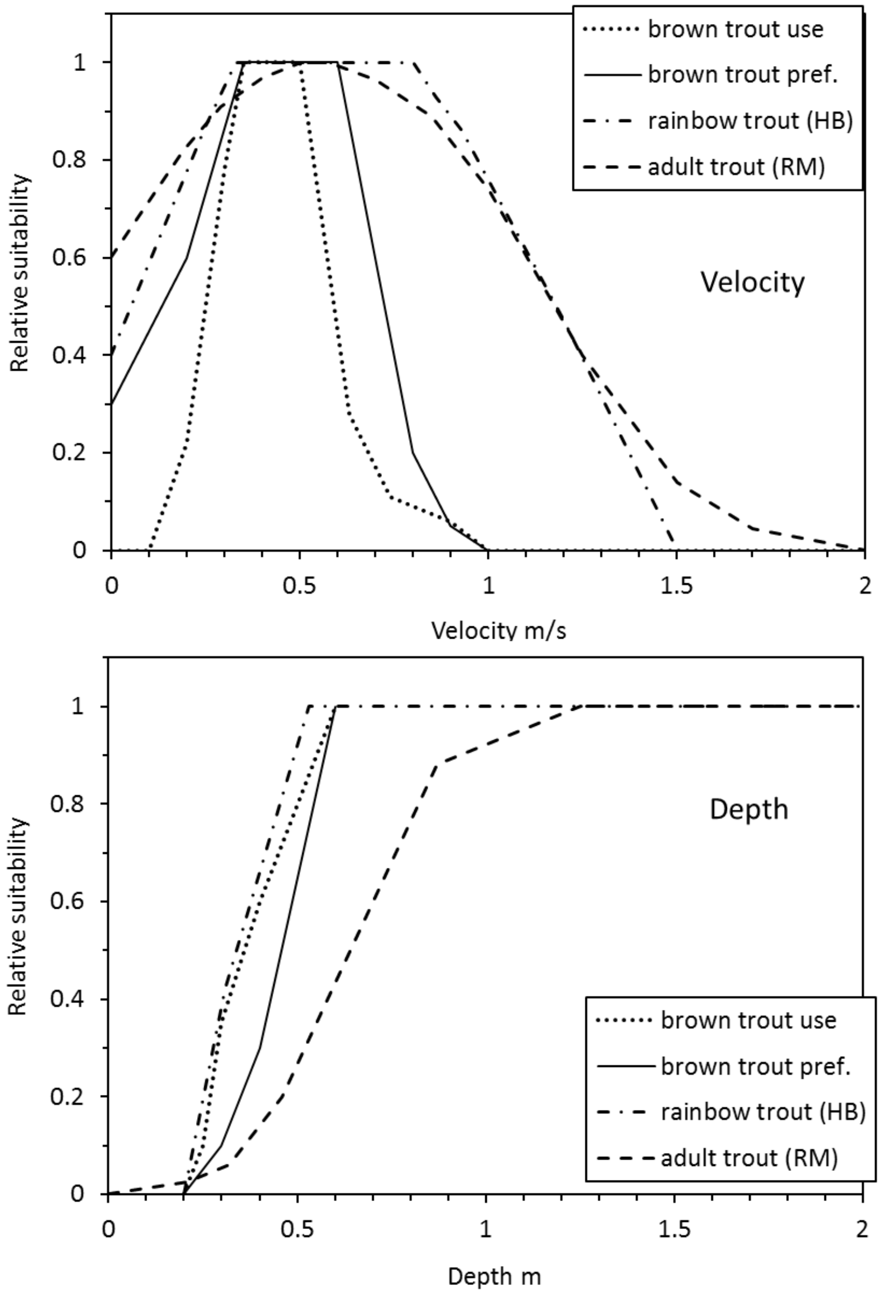


Figure 3-2: Trout habitat criteria. The suitability of different depths (lower plot) and velocities (upper plot) for trout are displayed here on a relative scale, with 1 being most suitable and 0 the least suitable. The habitat use criteria that Cawthron scientists compared to their bioenergetics research ('brown trout use') predict that trout will use lower velocities than the criteria developed from rainbow trout in Hawke's Bay ('rainbow trout HB'). Also displayed are the adult trout criteria developed for Rocky Mountain streams ('adult trout RM'), which were added to the habitat modelling for this report.

When applied to the Ngaruroro, the Rocky Mountain criteria predicted that habitat maxima for adult trout occurred at flows higher than all other criteria, including brown trout (preference), Hawke's Bay rainbow trout and torrentfish (>30,000; 11,700; 23,400 and 9,600 L/s respectively). However, torrentfish still have higher flow requirements for the Ngaruroro River (Table 3-1), because the rate of decline of habitat at low flows was steeper than for adult trout (Figure 3-3). Basing the trigger flows on torrentfish is justified because, for a given flow reduction (e.g. 1,000 L/s during low flows), torrentfish habitat would lose a greater proportion of habitat than trout.

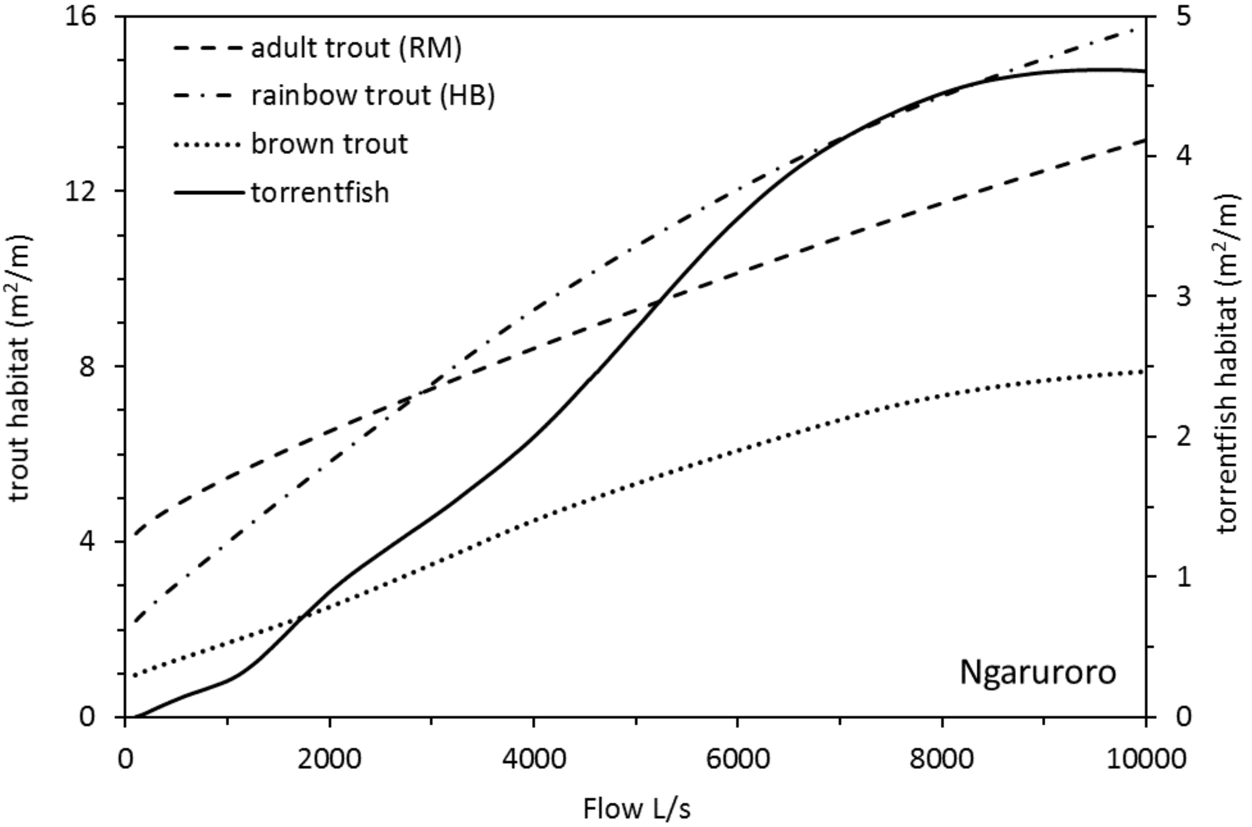


Figure 3-3: Ngaruroro habitat-flow response for trout. The habitat-flow response using the Rocky Mountain criteria for adult trout (RM) (Wilding *et al.*, 2014), compared to habitat criteria used by Johnson (2011) for rainbow trout (Hawke's Bay) and brown trout (preference). These are plotted along with the species with the highest flow requirements (torrentfish).

The reverse was true for the Tutaekuri River, where trout were more sensitive to reduced flow than torrentfish (Figure 3-4; Table 3-2). Of the trout criteria used, the Rocky Mountain criteria again predicted habitat to peak at flows greater than the other trout criteria (>20,000 L/s for Rocky Mountain criteria; 5,400 L/s for Hawke's Bay rainbow trout; 2,600 L/s for brown trout preference). This translated to higher trigger-flows using Rocky Mountain criteria for adult trout, compared to the Hawke's Bay criteria for rainbow trout. However, the increase was small (2%-7% higher, depending on the protection level selected, Table 3-2). This increase was small because the calculation of habitat protection levels was more sensitive to the rate of decline of habitat with flow, rather than the flow magnitude required to reach maximum habitat.

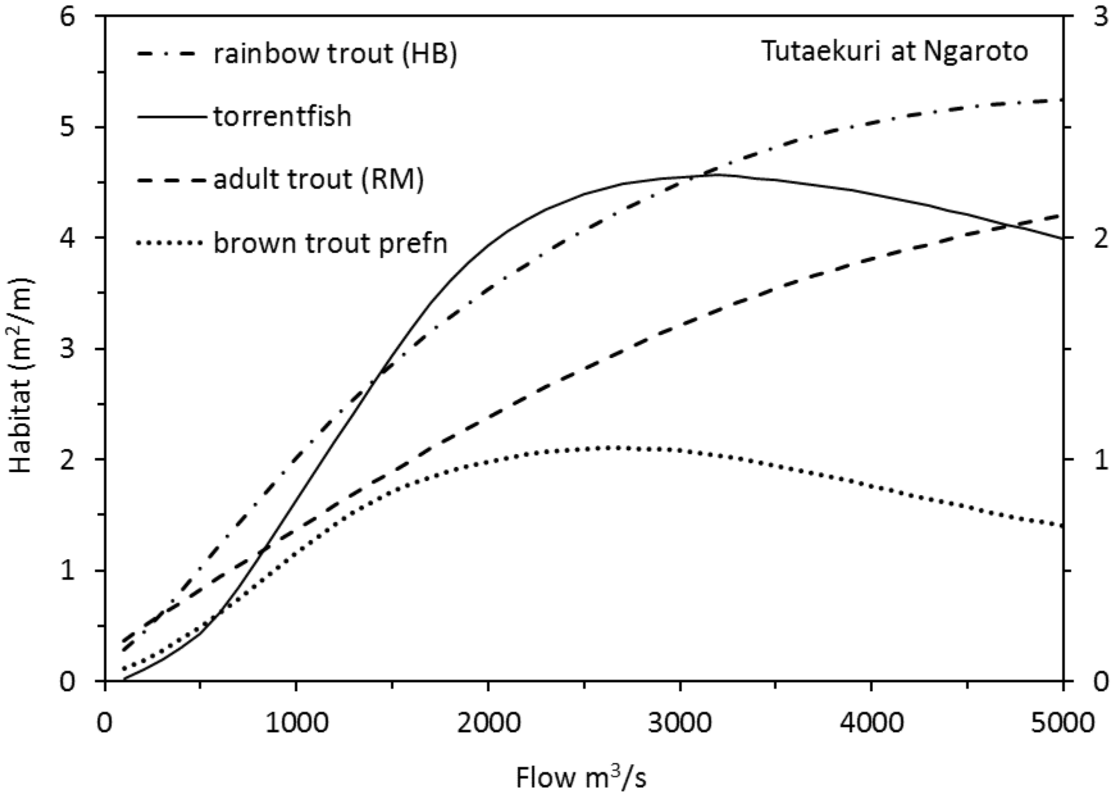


Figure 3-4: Tutaekuri habitat-flow response for trout. The habitat-flow response using the Rocky Mountain criteria for adult trout (RM) (Wilding *et al.*, 2014), compared to habitat criteria used by Johnson (2011) for rainbow trout (Hawke's Bay) and brown trout (preference). The 'adult trout (RM)' and 'brown trout prefn' criteria are plotted against the right y-axis (same units).

The detailed flow requirements (by species and by protection level) are tabulated for the Ngaruroro at Fernhill (Table 3-1) and the Tutaekuri at Ngaroto (Table 3-2). From this detailed breakdown, the summary table focuses on the species with the highest flow requirements (Table 3-3). The latter also provides corresponding flow requirements for the Tutaekuri River at Puketapu, using the flow relationship with Ngaroto where habitat was modelled. The habitat protection levels afforded by the existing trigger flows (as prescribed by the current Regional Resource Management Plan) are 44% for the Ngaruroro at Fernhill and 65% for the Tutaekuri at Puketapu (Table 3-3).

Table 3-1: Ngaruroro flows for each species. Flows providing a range of habitat protection levels (90%, 80% and 70%) for each criteria modelled in the Ngaruroro River at downstream of Fernhill. This is based on the revised estimate of MALF (revised from 4,500 to 4,700 L/s), with any habitat criteria denoted by * being additional to those modelled by Johnson (2011). The highest flow requirements are in bold font.

Ngaruroro downstream of Fernhill	Flow (L/s) for 3 habitat protection levels		
Habitat Criteria	**90%**	**80%**	**70%**
shortfin eel < 300 mm (Jowett & Richardson, 2008)	1120	620	410
shortfin eel > 300 mm (Jowett & Richardson, 2008)	1920	1190	690
longfin eel < 300 mm (Jowett & Richardson, 2008)	2720	1950	1370
longfin eel > 300 mm (Jowett & Richardson, 2008)	2860	1880	1190
longfin eel > 300 mm (Jellyman et al., 2003)	2990	1500	380
longfin eel < 300 mm (Jellyman et al., 2003)	1950	690	150
torrentfish (Jowett & Richardson, 2008)	**4370**	**4030**	**3630**
koaro (Jowett & Richardson, 2008)	2960	2230	1700
bluegill bully (Jowett & Richardson, 2008)	3970	3450	2890
common bully (Jowett & Richardson, 2008)	1120	700	430
Cran's bully (Jowett & Richardson, 2008)	450	200	100
redfin bully (Jowett & Richardson, 2008)	1160	810	520
inanga feeding	280	210	160
dwarf galaxias (Jowett & Richardson, 2008)	480	210	100
common smelt (Jowett & Richardson, 2008)	2210	1220	630
adult trout RM (Wilding, 2012) *	3680	2710	1800
juvenile trout RM (Wilding, 2012) *	3290	2220	1370
rainbow trout > 200 mm (Hawkes Bay, provisional)	4000	3370	2790
rainbow trout < 100 mm (Jowett & Richardson, 2008)	740	540	400
brown trout (Jowett & Hayes, 1994)	4100	3570	3080
brown trout <100 mm (Jowett & Richardson, 2008)	2290	1630	1200
koura abundance (Jowett et al., 2008) *	770	520	360
invertebrates (Waters, 1976)	4170	3670	3230
Deleatidium mayfly (Jowett et al., 2007)	3280	2120	1270

Table 3-2: Tutaekuri flows for each species. Flows providing a range of habitat protection levels (90%, 80% and 70%) for each criteria modelled in the Tutaekuri River at Ngaroto. This is based on a revised estimate of the mean annual low flow (revised from 2,800 to 2,700 L/s), with any habitat criteria denoted by * being additional to those modelled by Johnson (2012). The highest flow requirement is in bold font.

Tutaekuri at Ngaroto	Flow (L/s) for 3 habitat protection levels		
Habitat Criteria	**90%**	**80%**	**70%**
shortfin eel < 300 mm (Jowett & Richardson, 2008)	380	200	120
shortfin eel > 300 mm (Jowett & Richardson, 2008)	510	390	300
longfin eel < 300 mm (Jowett & Richardson, 2008)	610	430	320
longfin eel > 300 mm (Jowett & Richardson, 2008)	760	590	470
longfin eel > 300 mm (Jellyman *et al.*, 2003)	480	210	110
longfin eel < 300 mm (Jellyman et al., 2003)	2160	1740	1310
torrentfish (Jowett & Richardson, 2008)	2080	1790	1580
koaro (Jowett & Richardson, 2008)	1260	950	740
bluegill bully (Jowett & Richardson, 2008)	1320	1140	240
common bully (Jowett & Richardson, 2008)	260	180	130
Cran's bully (Jowett & Richardson, 2008)	130	100	100
redfin bully (Jowett & Richardson, 2008)	360	240	160
inanga feeding	100	100	100
common smelt (Jowett & Richardson, 2008)	540	410	330
adult trout RM (Wilding, 2012) *	**2330**	**1990**	**1680**
juvenile trout RM (Wilding, 2012) *	1830	1360	1000
rainbow trout (> 200 mm) (Hawkes Bay, provisional)	2250	1890	1570
rainbow trout (< 100 mm) (Jowett & Richardson, 2008)	270	160	100
brown trout (Jowett & Hayes, 1994) *	1800	1500	1250
koura abundance (Jowett et al., 2008) *	150	110	100
invertebrates (Waters, 1976)	1980	1560	1260
Deleatidium mayfly (Jowett & Davey, 2007)	1680	1170	820

Table 3-3: Flow recommendation summary. Summary of flow requirements for three locations, based on the species with the highest flow requirements (see Table 3-1 and Table 3-2). In addition to the Tutaekuri River at Ngaroto, this table provides the corresponding flow at the Puketapu flow monitoring site. The habitat protection level afforded by the existing trigger flow (as prescribed in the current regional plan) is provided in the last column.

	MALF naturalised (100% habitat)	Flow for 90% habitat	Flow for 80% habitat	Flow for 70% habitat	Protection at existing trigger
Tutaekuri (Puketapu) *adult trout*	3900 L/s *(was 3800)*	3300 L/s	2800 L/s	2300 L/s	65% at 2000 L/s
Tutaekuri (Ngaroto) *adult trout*	2700 L/s (*was 2800*)	2330 L/s	1990 L/s	1680 L/s	N/A
Ngaruroro (Fernhill) *torrentfish*	4700 L/s *(was 4500)*	4400 L/s	4000 L/s	3600 L/s	44% at 2400 L/s

3.2 Flow for Invertebrate Habitat

The change in habitat for invertebrate production was investigated at flows greater than MALF. This was in response to criticism from Cawthron scientists that trigger flows recommended by regional councils failed to recognise the importance of invertebrate production at higher flows in providing food for trout (Stuff, 18 June 2016, URL). The estimated flow reduction from the use of surface water and groundwater was used to predict the alteration of invertebrate habitat up to median flows.

The predicted change in invertebrate habitat from estimated actual water use was minor at median flows. For the Ngaruroro, invertebrate habitat was predicted to be equivalent (9.86 m^2/m under naturalised median flow, versus 9.86 m^2/m at measured flow). Flow alteration is less pronounced at higher flows in the Ngaruroro River (Figure 3-5). In addition to water use representing a smaller proportion of higher river flows, there is less water demand for irrigation and other uses at times when moisture levels are sufficient to sustain median river flows. The decline in habitat during low-flow periods was greater, with invertebrate habitat reduced from 5.2 to 4.3 m^2/m (habitat at naturalized versus measured MALF, respectively). This indicates that the low-flow period is more critical, both in terms of fish habitat and invertebrate habitat.

A similar result was obtained for the Tutaekuri River (Figure 8), with a minor decline in invertebrate habitat from 2.13 to 2.12 m^2/m, going from the naturalised median flow to the measured median (data period 1980 to 2015). The decline in invertebrate habitat at MALF (from 3.81 to 3.71 m^2/m) was greater than the decline at median flow. Compared to the Ngaruroro, the Tutaekuri experienced a smaller reduction in habitat from estimated water use at MALF (Tutaekuri 3%; Ngaruroro 17%), reflecting less water use in the Tutaekuri catchment.

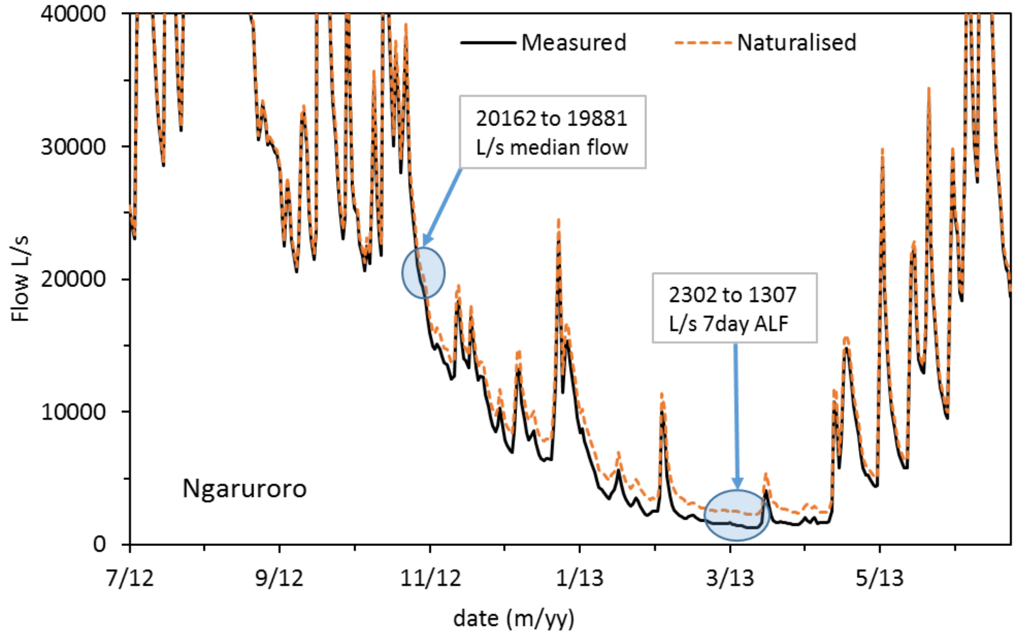


Figure 3-5: Flow alteration for the Ngaruroro in 2013. Measured flow for the Ngaruroro River (Fernhill) through 2013 is plotted (black line) together with estimated flow in the absence of water use (orange dashed line). The median flow was calculated from the full time-series (1976-2015). One occurrence of the median flow is indicated on the above plot, together with the annual low flow (ALF) for the 2012/2013 water year. The 2012/2013 water year represented severe drought, with flow alteration less pronounced in wetter years.

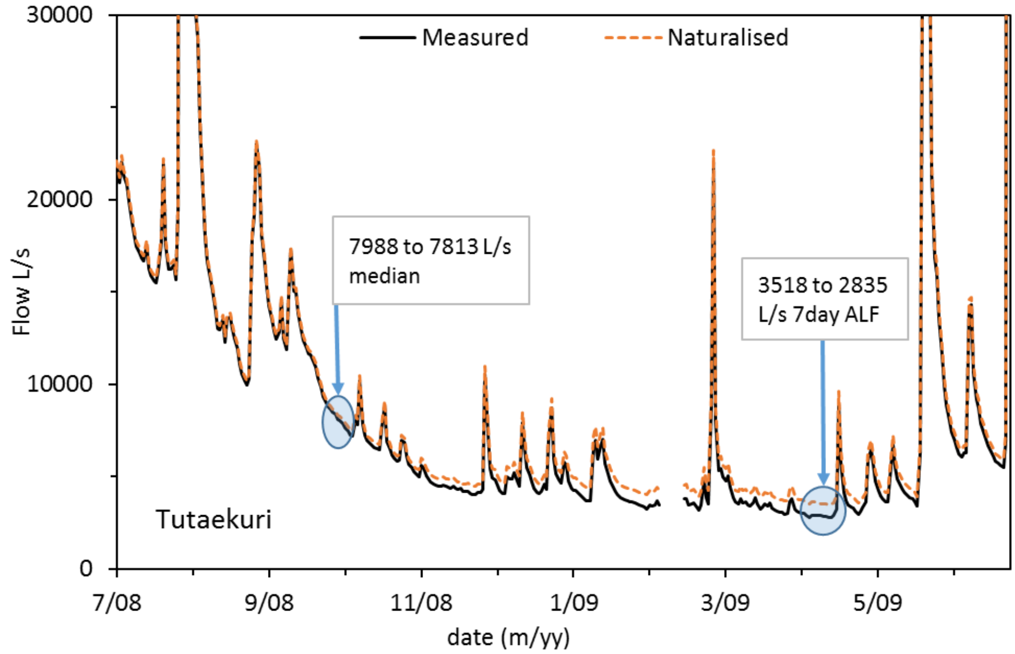


Figure 3-6: Flow alteration for the Tutaekuri in 2009. Measured flow for the Tutaekuri River (Puketapu) through 2009 is plotted (black line) together with estimated flow in the absence of water use (orange dashed line). One occurrence of the median flow is indicated on the above plot, together with the annual low flow (ALF) for the 2008/09 water year. The 2008/09 water year represented severe drought, with flow alteration less pronounced in wetter years.

3.3 Sensitivity Analysis

Sensitivity analysis revealed that the SEFA predictions for torrentfish in the Ngaruroro River are more sensitive to velocity, rather than to depth or substrate. This is demonstrated in Figure 3-7, where the habitat-flow curve with velocity switched off (dot-dash line) is most different from the full model predictions (solid black line). Therefore, it is the requirement for fast water that primarily drives the flow requirements for torrentfish. Of the three variables, model predictions were least sensitive to substrate.

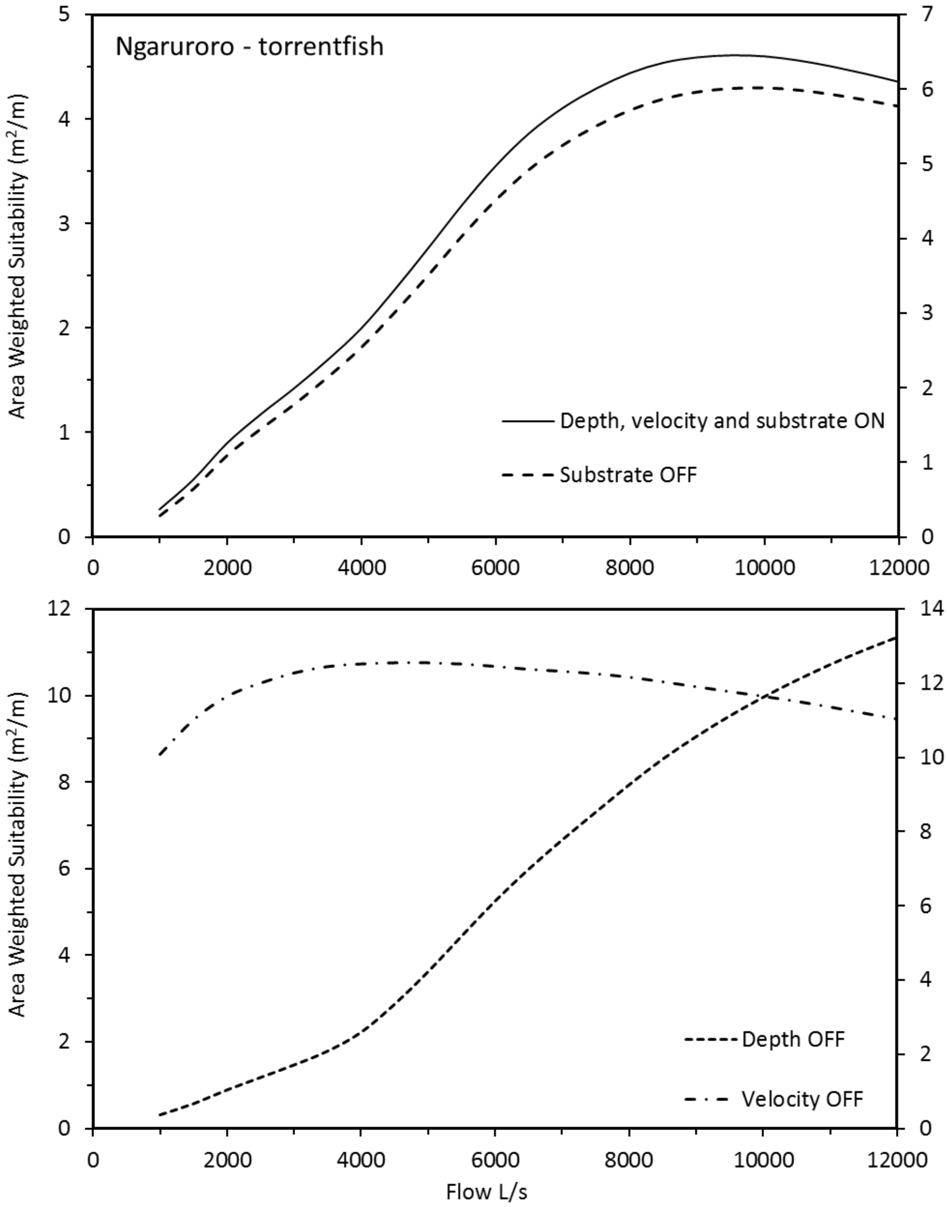


Figure 3-7: Ngaruroro model sensitivity to depth, velocity and substrate. The sensitivity of SEFA habitat-flow predictions to substrate, depth and velocity. Predictions for torrentfish in the Ngaruroro were re-run with each parameter switched off (i.e. set to optimal). To understand model sensitivity, compare each plotted line to the solid line ('Depth, velocity, substrate ON'), which represents the complete model used for deriving trigger flows. The y-axis values are less important because the habitat protection method standardises by habitat maxima in deriving trigger flows (each line has a separate y-axis).

Analysis for the Tutaekuri River shows that predictions for adult trout habitat were sensitive to depth and velocity (Figure 3-8). There is a marked reduction in the flow that provides 80% habitat protection when depth is set as optimal, which demonstrates that suitable velocities are present in the Tutaekuri River at lower flows. However, those velocities need to occur in deeper water in order for trout to use them. The flows required to achieve suitable velocities in deeper water are greater than the flows required to achieve those same velocities in shallow riffles. This velocity-depth interaction was diagnosed by pairwise comparison of habitat-flow curves for different trout criteria. A pair that have equivalent depth criteria, and differing velocity criteria are the brown trout (use) criteria and the Hawke's Bay rainbow trout criteria (Figure 3-2). The higher velocity requirements of the Hawke's Bay criteria resulted in a 66% increase in the flow required for 90% habitat protection. The other pair with similar velocity criteria, but different depth criteria, are the Hawke's Bay criteria and Rocky Mountain criteria (Figure 3-2). The requirement for deeper water predicted using the Rocky Mountain criteria resulted in only a 4% increase in the flow required for 90% habitat protection. The benefit of deeper water predicted by the Rocky Mountain criteria, resulted in habitat maxima occurring at flows much greater than MALF (>20,000 L/s for Rocky Mountain criteria; 5,400 L/s for Hawke's Bay rainbow trout).

Note that the Rocky Mountain criteria for adult trout treat all substrate types as suitable, which explains why there was no change when substrate was switched off (note separate y-axis scale for each line).

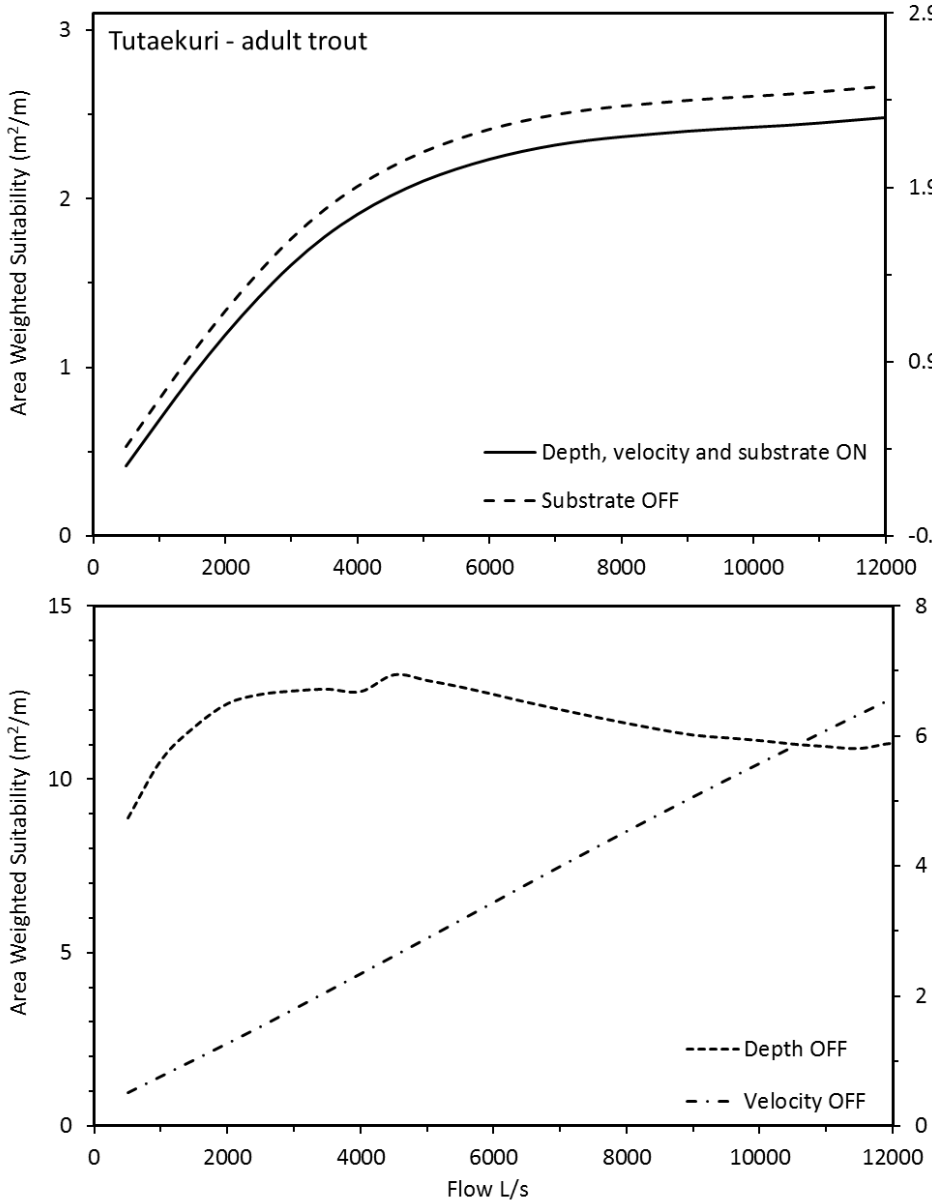


Figure 3-8: Tutaekuri model sensitivity to depth, velocity and substrate. The sensitivity of SEFA habitat-flow predictions to substrate, depth and velocity. Predictions for adult trout (RM) in the Tutaekuri at Ngaroto were re-run with each parameter switched off (i.e. set to optimal). To understand model sensitivity, compare each plotted line to the solid line ('Depth, velocity, substrate ON'), which represents the complete model used for deriving trigger flows. Each line has a separate y-axis. The y-axis values are less important because the habitat protection method standardises by habitat at MALF in deriving trigger flows.

3.4 Frequency and Duration of Low Flows

Flows will vary naturally from year to year in response to climate variability, dropping to lower flows during drier years. If trigger flows are raised, the river flows would be less than this threshold more frequently (Table 3-4). This holds true under existing water use and in the absence of water use. However, more water use will increase the frequency that the flow is less than a given trigger. For example, flow in the Ngaruroro River dropped to less than 2,400 L/s (the existing trigger flow at Fernhill) in 7 years during the 1998 to 2015 period.

Flow would also have dropped below this level in the absence of water use, but only in 2 years instead of 7 (using naturalised flow series 1998-2015).

The duration of low flows also increases with water use (Figure 3-9). For example, the Ngaruroro River flow was estimated to have been less than 2,400 L/s for an average of 7 more days per year (1998 to 2015) as a consequence of water use. During most years, flow did not fall below 2,400 L/s (11 out of 18 measured years; 16 out of 18 naturalised years). The biggest increase in the duration of low flows as a consequence of water use was during dry years: there were 64 days with observed flow less than 2,400 L/s during 2013, compared to 8 days when using the naturalised daily mean flows.

Table 3-4: Frequency of low flows for the Ngaruroro and Tutaekuri. The number of years in which the annual low-flow dropped below each flow threshold (7-day mean minimum flow for the July to June water-year). Both measured and naturalised flows are presented for the Ngaruroro at Fernhill (period 1998-2015) and the Tutaekuri at Puketapu (1981-2015). Numbers with bold font indicate the number of years when flow was less than existing trigger flows. Naturalised flows are the flows estimated to have occurred if there was no water use (based on estimated actual use, rather than total allocation).

	Ngaruroro	/18 years		**Tutaekuri**	/33 years
Flow threshold (L/s)	measured	naturalised		measured	naturalised
1000	0	0		0	0
2000	2	0		**0**	**0**
2400	**7**	**2**		2	2
3000	7	4		10	4
3500	10	7		17	14
4000	12	7		23	18
4500	13	9		28	25
5000	16	13		30	28

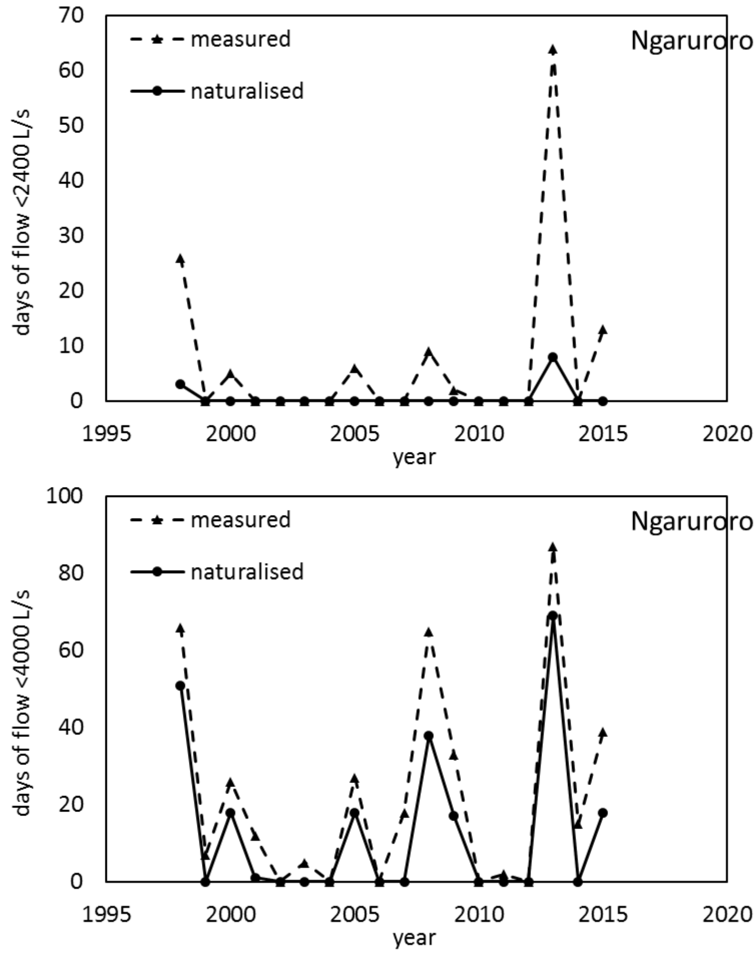


Figure 3-9: Days of low flows for the Ngaruroro River. Water use increases the number of days per year when flow is below a given threshold. The upper plot shows the number of days when the measured flow was less than the existing trigger flow (2,400 L/s) for the Ngaruroro River at Fernhill. The lower plot uses a different threshold of 4,000 L/s (80% protection level for torrentfish).

3.5 Flow for Fish Passage

Flows required for fish passage were also investigated. Fish move about the river in search of food, habitat and to seek refuge from stressful conditions. If the river gets too shallow, then fish may be prevented from moving upstream or downstream. As described in the Methods (Section 2), SEFA was used to determine the contiguous width of river over which the water is deep enough for the passage of fish through the shallowest riffle surveyed. A decline in passage width was predicted at flows less than 3,600 L/s for a minimum fish-passage depth of 0.25 m (Figure 3-10). This decline started at lower flows for the shallower passage depths (2,200 L/s for 0.18 m passage depth).

Flows greater than 1,800 L/s are predicted to provide a passable depth at least 1 m wide for 0.25 m minimum depth. This flow is less than the existing and alternative trigger flows, which are based on hydraulic habitat. Therefore, adequate fish passage is expected to be provided at all trigger flows considered in these assessments of hydraulic habitat.

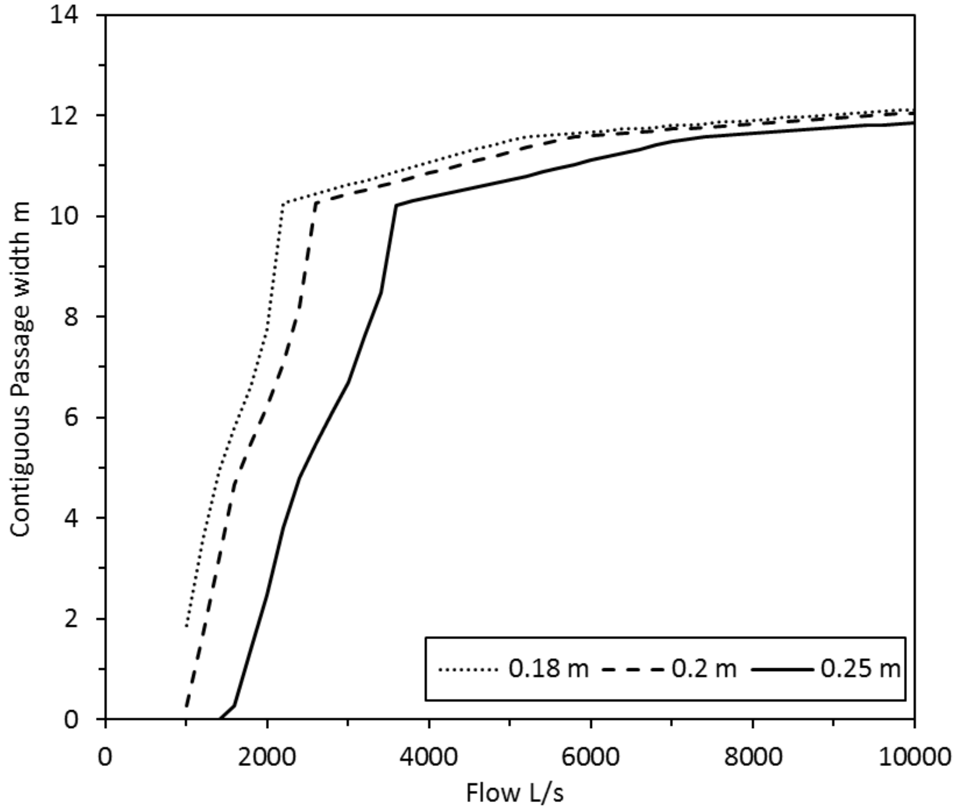


Figure 3-10: Ngaruroro fish passage. Fish passage for large fish (e.g. adult trout) through the shallowest cross-section surveyed. Passage is represented as the contiguous width of river that exceeds the depth threshold. Three depth thresholds were modelled using SEFA (0.18, 0.2 and 0.25 m).

For the Tutaekuri River, fish passage is not likely to be a critical issue. The existing trigger flow of 2,000 L/s corresponds to a contiguous width of 0.75 m that provides depths of at least 0.25 m through the shallowest riffle surveyed (flow measured at Puketapu corresponding to depths in the Ngaroto survey reach). Achieving a 1 m wide contiguous width for passage would require flows of 2,150 L/s for 0.25 m deep, 1,200 L/s for 0.2 m deep and 800 L/s for 0.18 m deep.

4 Discussion

This report provides an update on fish habitat modelling results for the Ngaruroro and Tutaekuri rivers. It is additional, and complementary, to previous studies reported by Johnson (2011, 2012). Subsequent to those studies, modelling of groundwater and surface water interaction (Rakowski & Knowling, 2018) has provided better estimates of MALF (mean annual low flow) for the Tutaekuri and Ngaruroro rivers. This report updates Johnson's (2011, 2012) flow recommendations by incorporating the revised MALF estimates. For example, an increase in the naturalised MALF estimate for the Ngaruroro River (from 4,500 to 4,700 L/s) consequently increased the flow predicted to provide 90% of habitat for torrentfish (from 4,200 to 4,400 L/s). The revised flows for both rivers are summarised in Table 3-3. Additional modelling was also undertaken to address concerns raised by stakeholders and HBRC planners.

Habitat Criteria

New habitat criteria were developed for koura (freshwater crayfish) in response to stakeholders' concerns for this mahinga kai (traditional food) species. Although adequate flow is important for koura, the modelling confirmed that torrentfish have higher flow requirements than koura. Therefore, the addition of koura did not change the flow recommendations.

New habitat criteria were modelled for adult trout. Since the completion of the RHYHABSIM investigations on the Ngaruroro and Tutaekuri rivers (under the guidance of Cawthron scientists and other stakeholders), new research was published by Cawthron scientists that criticised RHYHABSIM for producing habitat maxima at flows less than those estimated from a bioenergetics model for the Mataura River (South Island) (Hayes *et al.*, 2016).

Those criticisms were based on a comparison of habitat-flow predictions using the brown trout criteria developed by Hayes and Jowett (1994). The conclusions of that research are therefore specific to the brown trout criteria used, rather than the RHYHABSIM model as a whole. Higher flow requirements are predicted by the habitat criteria used here, compared to the brown trout criteria used in the comparison with the bioenergetics research (Hayes *et al.*, 2016). The brown trout criteria evaluated by Hayes *et al.* (2016), describe habitat optima at lower velocities, compared to the brown trout criteria used by Johnson (2011). It appears that Hayes *et al.* (2016) employed the 'habitat use' model, instead of the 'habitat preference' model which predicts higher flow requirements (both models were developed by Hayes & Jowett, 1994). The 'habitat preference' models, as used by Johnson (2011), better accounted for bias in the habitat available in the rivers. Hence, the latter are expected to produce more robust models for application to a wider range of rivers and flows (Bovee, 1986). The flow requirements for brown trout presented in this report are based on habitat preference criteria, as used by Johnson (2011).

In addition to the habitat criteria for brown trout, Johnson (2011, 2012) also used criteria for rainbow trout. These provisional criteria were developed for Hawke's Bay rivers (Hayes & Addley, 2013), and predicted habitat peaking at higher flows than the brown trout criteria (both the 'use' and 'preference' criteria), because of the predicted preference for higher velocities in deep water (Figure 3-2). This translated to higher flows to achieve a given protection level.

Subsequent research by Rasmus Gabrielsson (Cawthron), found the habitat criteria developed by Wilding *et al.* (2014) for Rocky Mountain streams gave better predictions of brown trout abundance in the Lindis River (South Island) than other habitat criteria that were tested (the Hawke's Bay rainbow trout criteria were not tested). For the Ngaruroro River at least, the Rocky Mountain criteria predict that habitat for adult trout would peak at higher flows than the Hawke's Bay provisional criteria for adult rainbow trout. The Hawke's Bay criteria retain a provisional status because the Cawthron report on the development of these criteria was not completed (Hayes & Addley, 2013). Therefore, these more recent criteria were added to the SEFA model predictions for the Ngaruroro and Tutaekuri rivers.

The Rocky Mountain trout criteria predict higher flow requirements than other trout criteria, which reflects the different methods used to analyse the habitat use data (Wilding *et al.*, 2014). These habitat criteria incorporate generalities across the region of interest (e.g. species, location, time of day). The criteria divide trout into size guilds (i.e. juvenile, adult >170 mm), rather than dividing by species because rainbow trout and brown trout displayed similar habitat preference within each size class. Substrate was omitted because it had little effect on habitat-flow predictions for trout in Rocky Mountain streams (in contrast to spawning habitat, invertebrate habitat, etc.). Interaction between depth and velocity (e.g. if shallow areas tend to be slower flowing) was accounted for during the model construction stage. The criteria also better accounted for what habitat were available to trout at the time of the survey (e.g. few deep pools), compared to earlier criteria developed from the same trout observations (Thomas & Bovee, 1993). For this reason, the newer criteria predicted a preference for deeper water by adult trout, rather than avoidance.

The bioenergetics modelling also predicted that optimal flows for trout would vary with temperature and food supply (Hayes & Addley, 2013). Temperature and food cannot be controlled in these rivers and it is not practical to vary trigger flows with water temperature, which can increase by 10°C between morning and afternoon. Trout have evolved strategies for dealing with varying temperature. For example, trout may restrict their feeding to the morning, when cooler temperatures support energetically-profitable feeding. The higher velocities preferred at higher temperatures, as predicted by bioenergetics research (Hayes & Addley, 2013), are captured within the range of preferred velocities predicted by the Rocky Mountain adult trout criteria.

For the Ngaruroro and Tutaekuri, the Rocky Mountain criteria for adult trout identified a benefit from higher flows than those predicted using the other habitat criteria, including the brown trout criteria used by Cawthron. But this benefit did not translate to increased flow recommendations for the Ngaruroro, which were based on the resident species with the highest flow requirements (torrentfish).

The Rocky Mountain criteria produced marginally higher flow requirements for the Tutaekuri River at Ngaroto (e.g. 2,330 L/s, compared to 2,250 L/s to achieve a 90% habitat protection level using the provisional rainbow trout criteria). This increase was small because the calculation of habitat protection levels for adult trout was more sensitive to the rate of decline of habitat with flow. Whether the criteria peak at median flow or 10 times median flow is inconsequential when using the habitat protection method, which only considers habitat up to MALF (Jowett & Hayes, 2004) or up to median flow (Wilding, 2003). However, the flow providing maximum habitat may be important in rivers elsewhere if maximum habitat for all species occurs at low flows.

The sensitivity of the SEFA habitat-flow predictions to changes in depth, velocity and substrate were also investigated, in response to questions from stakeholders. For torrentfish in the Ngaruroro River, the rate of decline in habitat with flow was most sensitive to declining water velocity and least sensitive to substrate. Although substrate size is important to torrentfish, which reside amongst the cobbles and pick invertebrates off the rocks, reduced low-flows would not prevent torrentfish from accessing suitable substrates in the Ngaruroro River.

For the Tutaekuri River, the habitat-flow response for adult trout was sensitive to reduced depth and velocity. The flow required to achieve suitable velocities in deep water are greater than the flows required to achieve those same velocities in shallow riffles. The benefit of higher velocities in deep water was predicted by both the Rocky Mountain trout criteria and the provisional Hawke's Bay criteria.

The existing trigger flow of 2,000 L/s for the Tutaekuri River at Puketapu was based on RHYHABSIM surveys completed in 1996 between the Mangaone confluence and Puketapu (Wood, Draft 2002). Revisiting the 1996 survey data is helpful in understanding the difference between the earlier recommendation of 2,000 L/s and the flows presented here (2,300 L/s to 3,300 L/s, Table 3-3). Despite the changes in the location of the survey reach and changes to cross-section selection, the higher flow-requirements were primarily due to the change in habitat criteria for trout. The trout criteria used in the original analysis all indicated a flow of 2,000 L/s would meet or exceed a 90% habitat protection level. Applying the new habitat criteria for adult trout to the 1996 survey data produced higher flow requirements that were equivalent to the 2009 survey. The 1996 and 2009 flow requirements were equivalent at a 90% habitat protection level (3,280 L/s and 3,320 L/s), at an 80% protection level (2,730 L/s and 2,770 L/s), and at a 70% protection level (2,240 L/s and 2,260 L/s) for adult trout (Rocky Mountain criteria). The provisional criteria for Hawke's Bay rainbow trout also produced equivalent flow requirements, when applied to the 1996 and 2009 models. This re-analysis also indicates that the flow requirements based on the 2009 survey upstream of Mangaone will meet the flow requirements for habitat protection further downstream in the Puketapu reach (as represented by the 1996 data).

Flow for Invertebrate habitat

Food supply is important for trout, in addition to water depth and velocity. This has been established by previous research (Jowett, 1992), in addition to the bioenergetics research by Cawthron Institute (Hayes *et al.*, 2016). Cawthron scientists proposed that trigger flows adopted by regional councils may need revision, because these flows failed to recognise the importance of invertebrate production at higher flows in providing food for trout (Stuff, 18 June 2016, URL). Median flows (in addition to MALF) were incorporated in the original method for calculating habitat protection levels, as developed by regional council scientists (Wilding, 2003). Median flows were included because of their potential importance to fish and invertebrates (Jowett, 1992). But, median flows were removed by NIWA and Cawthron scientists in a revision of the method (Jowett & Hayes, 2004). The revised version, excluding median flows, was adopted by Johnson (2011) for the Ngaruroro and Tutaekuri rivers. To reintroduce the higher flows, we investigated the change in invertebrate habitat at higher flows.

Modelling of the Ngaruroro and Tutaekuri rivers revealed little or no reduction of invertebrate habitat at median flows as a consequence of existing water use. One reason for this is that water use represents a smaller proportion of median flow, compared to low flows. Furthermore, there is currently less water demand for irrigation and other uses at times when moisture levels are sufficient to sustain median river flows. The decline in habitat as a consequence of water use was greater during low-flow periods. This demonstrates that the low-flow period is more critical, both in terms of fish habitat and invertebrate habitat. Therefore, basing trigger flows on low-flow statistics is appropriate for the Ngaruroro and Tutaekuri rivers.

Flow for Fish Passage

The movement of fish through the Ngaruroro River is not expected to be a critical factor for trigger flows. The model predicted that flows greater than 1,800 L/s would provide a passable depth at least 1 m wide through the shallowest cross-section surveyed. This is for water exceeding 0.25 m depth. Other studies have used shallower depths for fish-passage depths (e.g. 0.2 m from (Gabrielsson, 2016); 0.18 m from (Young & Allen, 2013), which also require less flow than the existing trigger flow of 2,400 L/s at Fernhill.

Likewise, fish passage depths are not expected to be a critical issue for the Tutaekuri River, with the existing trigger flow of 2,000 L/s providing water 0.25 m deep through the shallowest riffle surveyed.

Flow and Water Temperature

High water temperatures can be stressful for fish and invertebrates. The potential for reduced flow to increase temperature was investigated by Rutherford (2001) for the Ngaruroro River. This modelling predicted water temperature could exceed 28°C at flows less than 3,000 L/s. The severity of these temperatures is of concern in itself for the life-supporting capacity of the river. It also has implications for setting limits on water use, both in terms of the magnitude of trigger flows and the species of fish and invertebrates that would naturally persist in the lower Ngaruroro to benefit from restrictions on water use.

A second investigation in 2016 examined whether the high temperatures predicted by Rutherford (2001) were realized in the Ngaruroro River during the extreme low-flows of 2013. The investigation was reported in a memo that is appended to this report (Appendix B). Water temperatures in the Ngaruroro at Fernhill did not reach the predicted extremes during 2013. The highest observed water temperature was 24.9°C when air temperature was 34.6°C (10 January 2013). The flow on that day was low for January (4,830 L/s). But it was 6 weeks later when flows dropped to their annual low (1,449 L/s on 27 Feb 2013).

This lag between the hottest day and the lowest flow is typical because long periods of flow recession are required to reach extreme low flows. This indicates that the worst-case scenario that was modelled by Rutherford (2001) is an unlikely scenario. Using data from the 2013 monitoring did not reveal an increase in water temperature in response to flows less than 15,000 L/s. In the validation memo (Appendix B), I recommended that trigger flows are considered on the basis of flow requirements for hydraulic habitat, rather than temperature, given the lack of change of temperature with flow, and given that water temperatures were not as bad as expected.

The interaction between flow and temperature was not investigated for the Tutaekuri River. Continuous temperature data from the Tutaekuri River at Puketapu indicate that it reaches temperatures as high as those observed in the Ngaruroro River at Fernhill (99%ile of 24.9°C and 24.9°C respectively). Given these rivers can reach high temperatures, the survival of cold-water species through summer may depend on access to thermal refuges (e.g. cool tributaries; outflow of cool groundwater from the river bed).

High temperatures potentially affect fish by denaturing protein, or by oxygen demand exceeding supply (Verberk *et al.*, 2016b). The amount of oxygen required by fish increases with temperature (Clarke & Fraser, 2004), and fish will become stressed when their oxygen demand exceeds the supply of oxygen from the water (Verberk *et al.*, 2011). Therefore, the management of temperature stress also requires consideration of oxygen stress (Verberk *et al.*, 2016a). High water temperature in the afternoon can coincide with super-saturated oxygen levels generated by benthic algae. The benefit from photosynthesis in the afternoon is lost at night when algae become net consumers of oxygen. However, inadequate oxygen supply during cooler mornings is not expected to be a critical issue for setting flows in the Ngaruroro River. These shallow gravel-bed rivers produce turbulent mixing through cobble riffles under low-flow conditions, which reaerates the water to compensate for oxygen consumed by algae and organic matter. Backwaters, isolated braids and the low-gradient tidal sections are expected to be at higher risk of low-oxygen conditions, compared to the turbulent mainstem (Wilding *et al.*, 2012).

Monitoring Trigger Flows

Another issue to consider is where Hawke's Bay Regional Council monitor trigger flows. For the lower Ngaruroro River, this issue was discussed in Wilding (2018). To summarise, flow losses from the Ngaruroro River to groundwater make flows measured at the existing monitoring site at Fernhill unrepresentative of what is happening upstream and downstream of that site (mapped in Figure 1-1). In addition, there are also technical challenges with maintaining stage-flow ratings for the mobile braided channel at Fernhill. As a consequence, the period of precise flow record for Fernhill is considerably shorter than the water level record, which began in 1952 (Arnold & Horrell, 2013).

Alternatives to monitoring at the Fernhill site include monitoring at Chesterhope Bridge or the Hawke's Bay Expressway (SH50a) bridge (Figure 1-1). Relocating flow monitoring from Fernhill to Chesterhope may be a better option than the Expressway bridge, which does not offer pedestrian access and lacks an established flow record. NIWA has monitored flow at Chesterhope since 1976, providing a long-term, continuous flow record. Such a relocation would require an adequate correction for inflows from the Tutaekuri-Waimate Stream immediately upstream of Chesterhope Bridge to relate measured flow to the critical reach (for further explanation, see Wilding, 2017).

For the Tutaekuri River, water takes are more widespread throughout the catchment compared to the Ngaruroro River, where the effects of flow loss are most significant downstream of Fernhill. The more widely distributed water use in the Tutaekuri catchment was one of the reasons for selecting a habitat survey reach upstream of Ngaroto (Johnson, 2012). However, the monitoring site at Puketapu (mapped in Figure 1-2) provides an adequate representation of the timing of low flows for the habitat survey reach, and the broader catchment. The good correlation of concurrent gaugings between the sites enabled the estimation of trigger flows for the monitoring site (Tutaekuri River at Puketapu) that provide the corresponding level of habitat protection for the study reach (Tutaekuri River at Ngaroto; R^2 = 0.97, N=33). Concurrent flow gaugings also revealed the good correlation between the Puketapu monitoring site and major tributaries (Mangaone at Rissington R^2 = 0.99, N=125; Mangatutu at Station Bridge R^2 = 0.99, N=13). This supports ongoing monitoring of trigger flows at the Puketapu site.

5 Conclusions

This report updates Johnson's (2011, 2012) flow recommendations for the Ngaruroro and Tutaekuri rivers by incorporating the revised MALF estimates and additional habitat criteria for trout and koura. The revisions increased the MALF estimate for the Ngaruroro River from 4,500 to 4,700 L/s and, consequently, increased the flow predicted to provide 90% habitat protection for torrentfish from 4,200 to 4,400 L/s. The revised flows for the Ngaruroro and Tutaekuri rivers are summarised in Table 3-3 for a range of habitat protection levels.

Changes were also made to the habitat criteria that were used to predict flow requirements. New criteria for koura were adapted for this study. This addition did not change the potential trigger flows for the Ngaruroro River, because torrentfish are predicted to have higher flow requirements.

For the Tutaekuri River, trout are predicted to have the highest flow requirements. Bioenergetics modelling by Cawthron Institute indicated that some trout criteria could underestimate the benefits of high flows for trout. New habitat criteria for adult trout were therefore incorporated from the Rocky Mountains that predict habitat peaking at flows much greater than other trout criteria. For example, habitat is predicted to peak at flows well beyond the calibrated flow range (>20,000 L/s) in the Tutaekuri River at Ngaroto, compared to a peak at 5,400 L/s using the Hawke's Bay criteria for rainbow trout. Despite this difference in optimal flows, both the Rocky Mountain criteria and the Hawke's Bay criteria predicted equivalent flows to achieve a given protection level. The similar flow predictions from two different habitat criteria (from Hawke's Bay and Rocky Mountains) lend support to the revised flow predictions. These flows exceed the existing trigger flow of 2,000 L/s because of the different habitat criteria used for the 1996 survey.

The bioenergetics research by Cawthron also reinforced the importance of invertebrate production for trout populations, and the potential for invertebrate populations to benefit from habitat available at flows greater than MALF. Modelling of the Ngaruroro and Tutaekuri rivers revealed little or no reduction of invertebrate habitat at median flows as a consequence of existing water use. The decline of invertebrate habitat as a consequence of water use was greater at annual low-flows, demonstrating that the low-flow period is more critical, in terms of hydraulic habitat for both fish and invertebrates.

Water temperature presents a likely constraint on the types of fish and invertebrates that can survive in the Ngaruroro and Tutaekuri rivers. However, the small change in temperature with flow for the Ngaruroro supports the establishment of trigger flows on the basis of hydraulic habitat protection.

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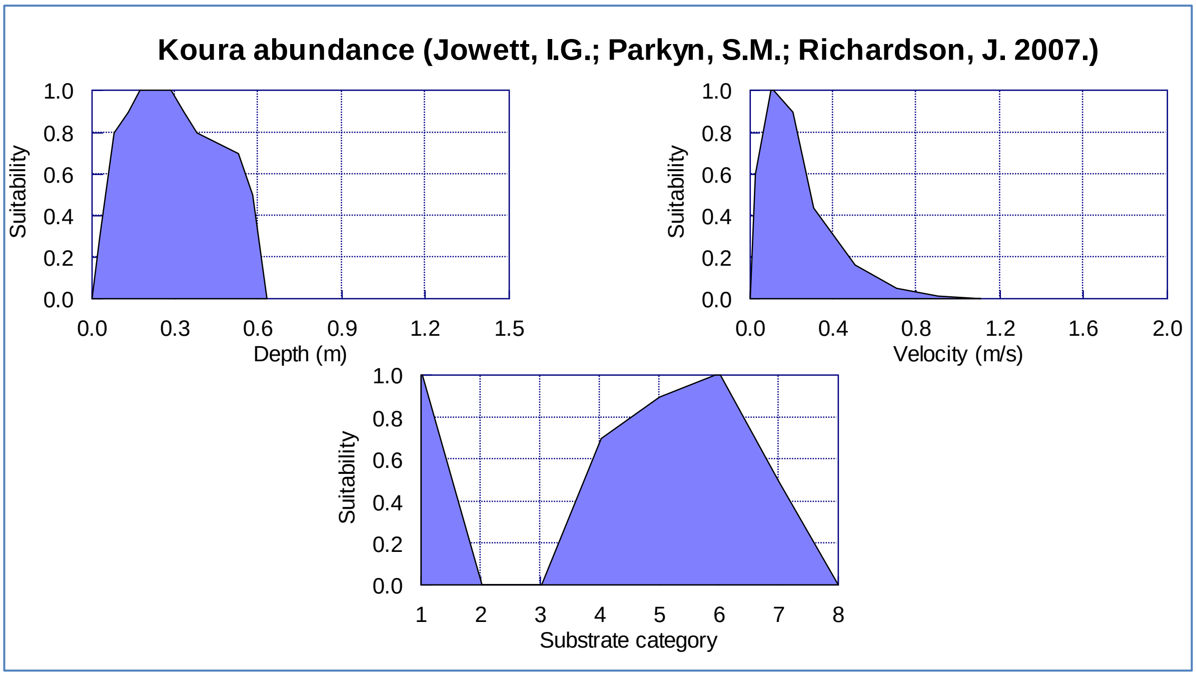
Appendix A Habitat Criteria

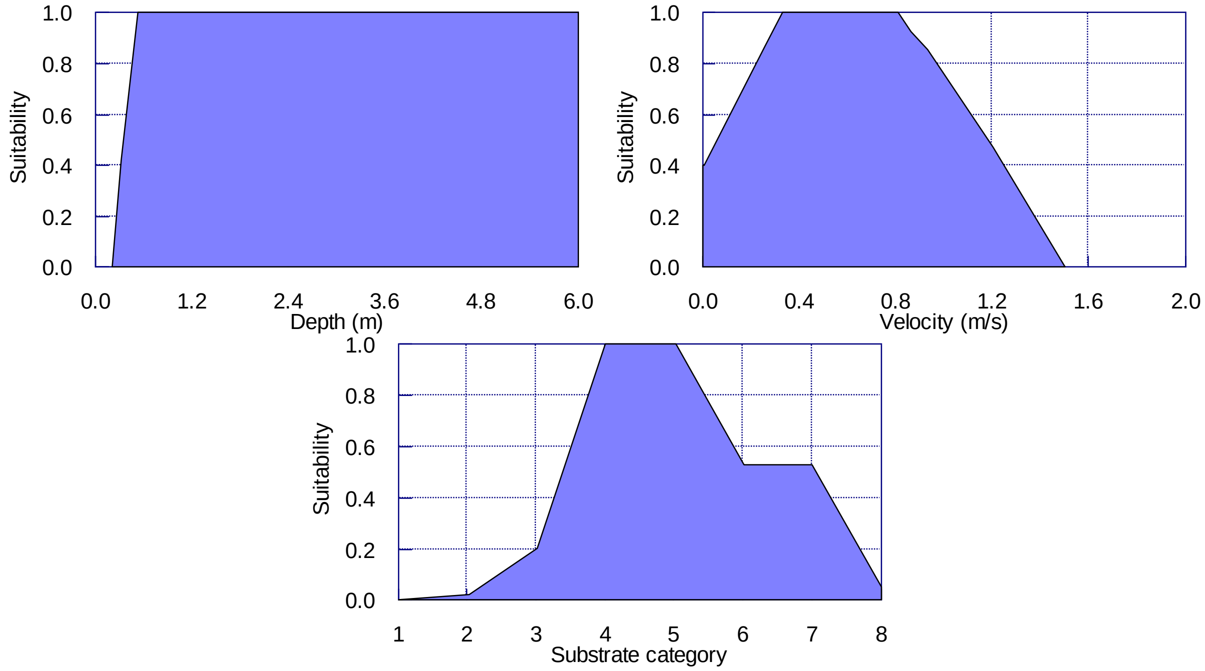
Numerical description of selected habitat criteria. The weights from 0 to 1 represents the relative suitability of each increment in velocity, depth and substrate class. Substrate indices from 1 to 8 represent: vegetation (1), silt (2), sand (3), fine gravel (4), gravel (5), cobble (6), boulder (7) and bedrock (8).

Koura abundance//Jowett, I.G.; Parkyn, S.M.; Richardson, J. 2007.												
Velocity m/s	0	0.02	0.1	0.2	0.3	0.5	0.7	0.9	1.1			
Weight	0	0.6	1	0.9	0.44	0.16	0.05	0.01	0			
Depth m	0	0.025	0.075	0.125	0.175	0.225	0.275	0.325	0.375	0.525	0.575	0.625
Weight	0	0.3	0.8	0.9	1	1	1	0.9	0.8	0.7	0.5	0
Substrate	1	2	3	4	5	6	7	8				
Weight	1	0	0	0.7	0.9	1	0.5	0				
end												



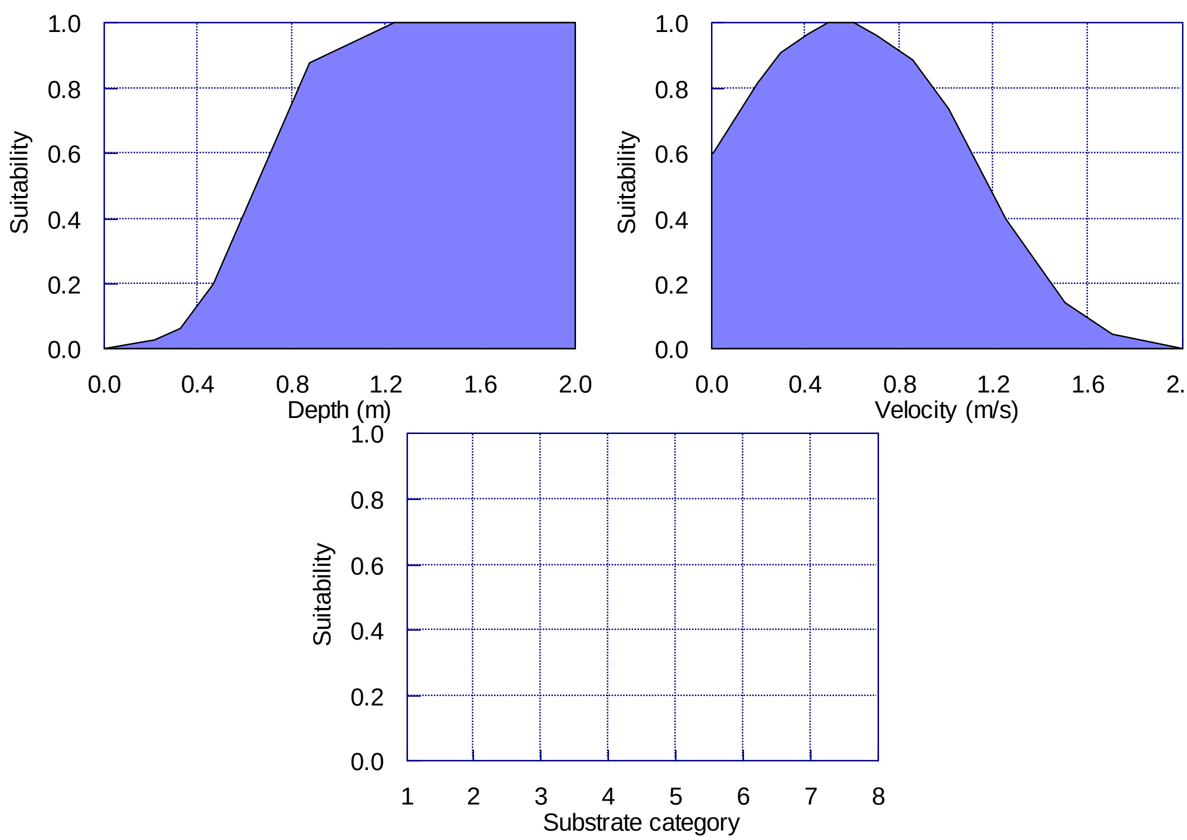
Rainbow Trout//Provisional Hawke's Bay Rivers												
Velocity m/s	0	0.25	0.33	0.8	0.86	0.93	1.2	1.5				
Weight	0.4	0.87	1	1	0.93	0.86	0.47	0				
Depth m	0.2	0.31	0.53	6								
Weight	0	0.42	1	1								
Substrate	1	2	3	4	5	6	7	8				
Weight	0	0.02	0.2	1	1	0.53	0.53	0.05				
end												

Provisional Hawke's Bay Rivers (Rainbow Trout)



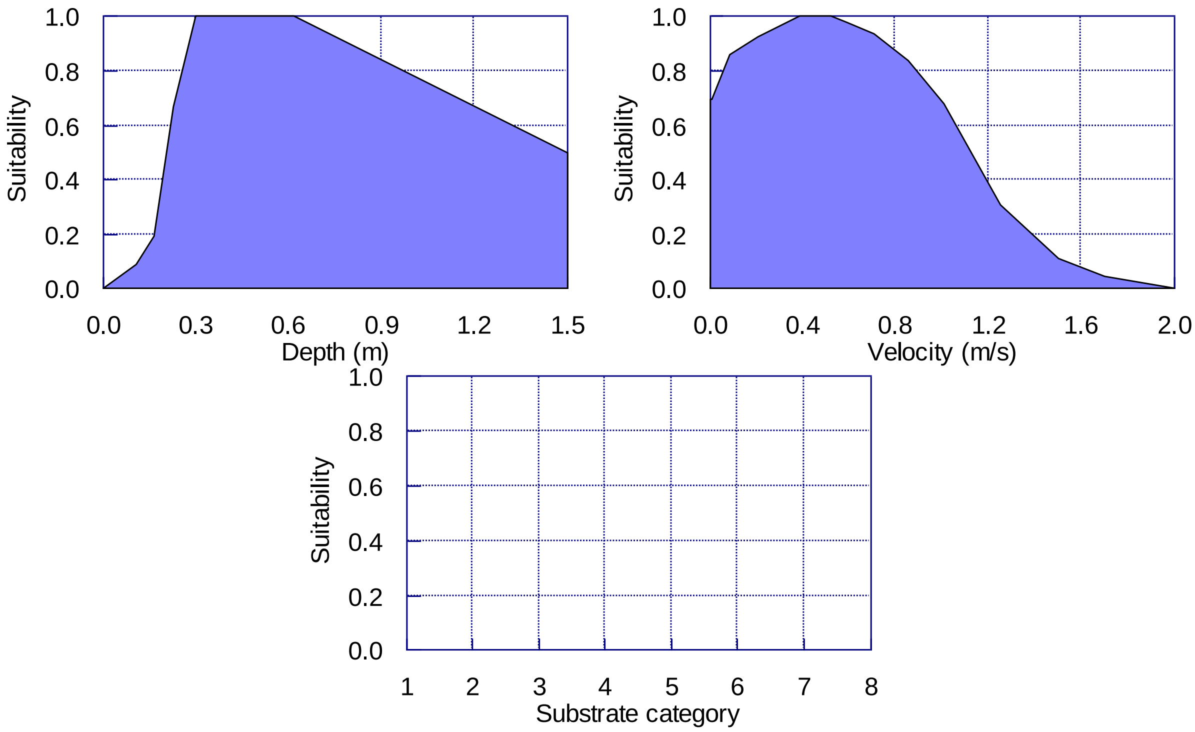
Adult Trout (T2)//from Appendix 2 in Wilding, T. K. 2012. Regional methods for evaluating the effects of flow alteration on stream ecosystems. PhD, Colorado State University.													
Velocity m/s	0	0.19	0.29	0.402	0.5	0.578	0.7	0.85	1	1.25	1.5	1.7	2
Weight	0.6	0.82	0.91	0.97	1	1	0.965	0.89	0.74	0.4	0.14	0.045	0
Depth m	0	0.21	0.32	0.46	0.87	1.25	2						
Weight	0	0.025	0.06	0.2	0.88	1	1						
end													

Adult Trout (T2) (from Appendix 2 in Wilding, T. K. 2012. Regional methods for evaluating the effects of flow alteration on stream ecosystems. PhD, Colorado State University.)



Juvenile Trout (T1)//from Appendix 2 in Wilding, T. K. 2012. Regional methods for evaluating the effects of flow alteration on stream ecosystems. PhD, Colorado State University														
Velocity m/s	0	0.08	0.2	0.29	0.4	0.49	0.58	0.7	0.85	1	1.25	1.5	1.7	2
Weight	0.7	0.86	0.93	0.965	1	1	0.982	0.94	0.84	0.68	0.31	0.11	0.045	0
Depth m	0	0.1	0.16	0.22	0.3	0.6	1.5							
Weight	0	0.09	0.195	0.67	1	1	0.5							
end														

Juvenile Trout (T1) (from Appendix 2 in Wilding, T. K. 2012. Regional methods for evaluating the effects of flow alteration on stream ecosystems. PhD, Colorado State University.)



Appendix B Validation of the Ngaruroro Temperature Model

MEMO

To:	Iain Maxwell
From:	Thomas Wilding
Date:	30/03/2016
Subject:	**TEMPERATURE-FLOW RELATIONSHIPS FOR NGARURORO RIVER - COMPARING MODEL PREDICTIONS TO 2013 OBSERVATIONS**
File Ref:	311-601
Cc:	Jeff Smith; Stephen Swabey; Kit Rutherford

Background

Rutherford (2001) modelled the change in temperature with flow for the Ngaruroro River downstream of between Whanawhana to Chesterhope. The STREAMLINE model predicted that water temperature could exceed 28 °C at flows less than 3 m^3/s. This is a very high temperature. For example, Rutherford (2001) predicted the biological consequences of such high temperatures could include 80% mortality of mayflies (*Deleatidium*). Additionally, unsuitable temperatures are expected to affect reproductive performance, before it affects growth and survival (Begon et al., 1990).

The severity of these temperatures is of concern in itself for the life-supporting capacity of the river. It also has implications for setting limits on water use, both in terms of the magnitude of minimum flows and the species of fish and invertebrates that would naturally persist in the lower Ngaruroro to benefit from restrictions on water use.

This memo therefore revisits predictions from the STREAMLINE model, comparing predicted temperatures to observed temperatures during the 2013 drought. Recommendations are then provided on how temperature effects can be incorporated into the TANK limit setting process.

Temperature and Flow

Cool water from high in the mountains can remain cool if it flows quickly enough to reach the sea before it has had time to warm to lowland temperatures. As river flow decreases, velocities decrease, so the travel time to the sea increases. The increase in travel time can allow the river to warm to its maximum, which is termed the dynamic equilibrium temperature. Other factors that affect the rate of warming include shading, water depth and inflows of cold water (Bartholow, 1989). Rutherford (2001) provides a more complete review of how flow affects water temperature.

Methods

Temperature loggers have been deployed in the Ngaruroro River at Fernhill subsequent to the 2001 study by Rutherford (2001). Continuous temperature data were collected during the 2013 drought (8 January 2013 to 8 January 2014). The 2013 drought was notable for producing extremely low flows - the lowest flows in the Ngaruroro since 1983 (using the Whanawhana site, which has a more complete record). The lowest gauged flow at Fernhill was 1,449 L/s (27 Feb 2013), which is less than the extreme lows modelled by Rutherford

(2001), and below the existing minimum flow of 2,400 L/s. These data are therefore ideal for examining temperatures during water short periods.

The temperature data were processed using the NEMS (National Environmental Monitoring Standards), (Schmidt et al., 2013). Periods when data quality did not meet the standard were excluded from the analysis (data <QC600). The 2013 logger data used in this study had a median absolute deviation from check data of 0.14 °C (8 January 2013 to 2 December 2013). The continuous monitoring data were checked against temperatures measured during gaugings using a Sontek FlowTracker. The Flowtracker records a temperature measurement, with timestamp, at each vertical across the river. So rather than use the cross-section average temperature, which has an ambiguous timestamp, an individual offset temperature was selected from the raw data file (.dis file) and pasted into the Hilltop data archive (Allsites.hts) as check data.

The weak gravel banks of the Ngaruroro River allow the river to move and braid, especially during high flow events. As flows recede, some braids can dry up, including the braid that was the main channel before the event. This makes it challenging to monitor the temperature of the river flow for more than a few weeks. Data loggers are more than capable of consistently reading to the highest NEMS standard (QC600 ± 0.8 °C). Hence data processing was more focussed on determining whether the sensor was still monitoring water temperature of the main river flow.

The Flowtracker temperature profiles allowed exclusion of higher temperatures from shallow margins and smaller braids (confirmed using velocity and depth). For example, data for the period 2 December 2013 till 8 January 2014 was not used because logger temperatures were more extreme than the Flowtracker measurements from the main channel (e.g. 19.3 °C logger versus 17.3 °C from main channel on 12 December 2013). That period was archived as lower quality data (QC400), and was not used in this study.

Gaugings only provide spot measurements at specific times, so the question remains of when the logger became disconnected from the main channel. This relied on other lines of evidence, including visual cues of a noisier trace and marked deviations from correlated measures (e.g. Bridge Pa ground temperature).

The 2013 data from Fernhill provided a check of predictions by Rutherford (2001) for that site. It does not provide a check for predicted temperature increases downstream of Fernhill. There was not a temperature logger deployed downstream of Fernhill during 2013. To get some appreciation of temperature increases downstream of Fernhill, two temperature loggers were deployed 10 to 15 March 2016 (Hobo U24-001). One was deployed at Fernhill (under bridge) and the other located 11 km downstream (Chesterhope, 70 m upstream of Tutaekuri-Waimate confluence; E1932084 N5609641). Prior to deployment, the two loggers read within 0.12 °C of each other, after 10 minutes deployed side by side in the Karamu River (where one of the loggers was deployed prior to use in Ngaruroro study). Check-data was collected at the time of deployment and retrieval using a Hach HQ40D conductivity probe, confirming the data achieved the NEMS standard (QC600). The loggers were deployed in the braid with the most flow (centre braid at both sites) and were zip-tied to wooden branches protruding out of the gravel in a flowing location.

Results and Discussion

Ngaruroro River temperature did not exceed 25 °C during the 2013 monitoring period. The maximum of 24.9 °C was recorded on 10 January 2013. On that day, air temperature reached 34.6 °C at Bridge Pa climate station (humidity 22%). From 18 years of record at Bridge Pa, there were only 5 days that recorded temperatures as high or greater (0.07% exceedance of daily maxima; 22 February 1997 to 15 February 2016). January is normally the hottest month for air temperature, with extreme temperatures also occurring December and February.

River flow was 4,830 L/s on that hottest day (10 January 2013). That is a low flow for January, but it was 6 weeks later when flows dropped to their annual low (1,449 L/s on 27 Feb 2013). This offset between the hottest day and the lowest flow is normal, with long periods of flow recession required to reach extreme low flows. Model predictions were about 2 °C hotter than observed, even for a flow of 5,000 L/s (27.7 °C at Chesterhope from Rutherford's Figure 24).

Water temperature did not exceed 25 °C during 2013 at Fernhill, but it could have increased further downstream. There was not a temperature logger deployed downstream of Fernhill during 2013 to quantify downstream increases. Temperature loggers were deployed in March 2016 to get some measure of temperature increases downstream of Fernhill. One was deployed at Fernhill and the other 11 km downstream (Chesterhope, upstream of Tutaekuri-Waimate confluence). This detected a 0.9 °C increase in daily maximum temperature over the 11 km reach on 10 March 2016 (23.2 °C at Fernhill to 24.1 °C at Chesterhope). This increase was observed on a day when air temperatures reached 32.4 °C at Bridge Pa and river flow was 3,370 L/s. The median gain in water temperature observed over subsequent cooler days was the same (median increase 0.9 °C for 11 to 15 March).

The temperature increase observed by Rutherford (2001) was of a similar magnitude, with an increase in the order of 0.5 to 1 °C between Fernhill and Carrick Road (values estimated from Rutherford's Figure 14 for 27 February to 3 March 2001). The temperature model predicted that water temperature would reach an equilibrium, under low-flow conditions, between Fernhill and Carrick Rd (6.5 km downstream of Fernhill), with negligible increases further downstream (Chesterhope is about 11 km downstream of Fernhill). The predicted temperature increase was about 0.6 °C. Applying this increase to the 2013 maximum observed at Fernhill, gives a maximum of 25.5 °C at Chesterhope (24.9 + 0.6). Conversely, the observed 24.9 °C maximum should be compared to a predicted maximum of 27.1 °C at Fernhill (27.7 – 0.6).

The next analysis looked at the observed relationship between water temperature and river flow. First it was necessary to account for climate, because most of the day to day and seasonal variability in water temperature is climate driven. Ground temperature at Bridge Pa (at 10 cm depth) provided an adequate linear predictor (**Figure 6-1**), and was better correlated with water temperature than air temperature at the same site (R^2 = 0.95 and 0.73 respectively, n = 321). The relationship with flow could then be investigated using the residuals from the ground temperature relationship (residual = water temp - 0.782*ground temp + 3.233). What is clear from the plot of temperature residuals versus flow is that the response is not linear (**Figure 6-2**). Focussing on the upper bound (i.e. the highest temperatures for a given flow in **Figure 6-2**), temperature increased as flow reduced at least until flow dropped to 15,000 L/s. But extreme temperatures levelled off at flows less than 15,000 L/s. This levelling off could result from water temperature reaching an equilibrium, at which point declining flows would not increase water temperature.

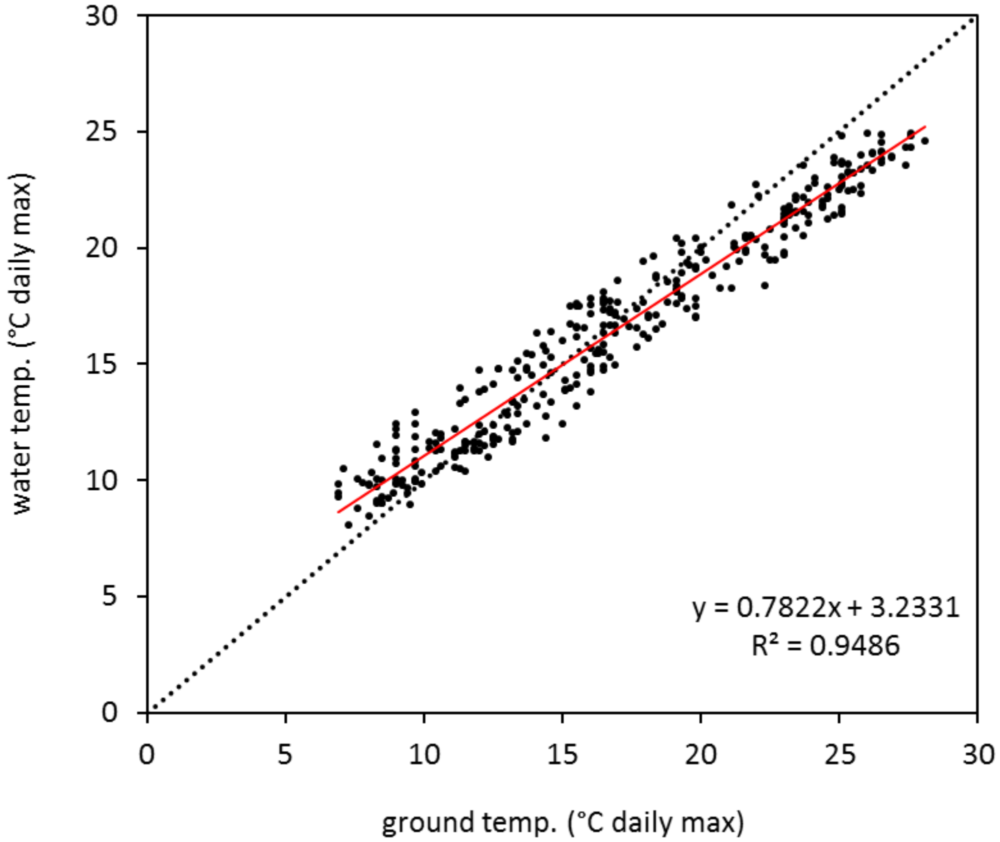


Figure 6-1 The daily maximum water temperature at Fernhill plotted against ground temperature at Bridge Pa (daily maximum at 0.1 m depth). The regression line (red) deviates slightly from the 1:1 line (dotted line). The equation shown was then used to isolate climatic effect on water temperature, before examining the effect of river flow.

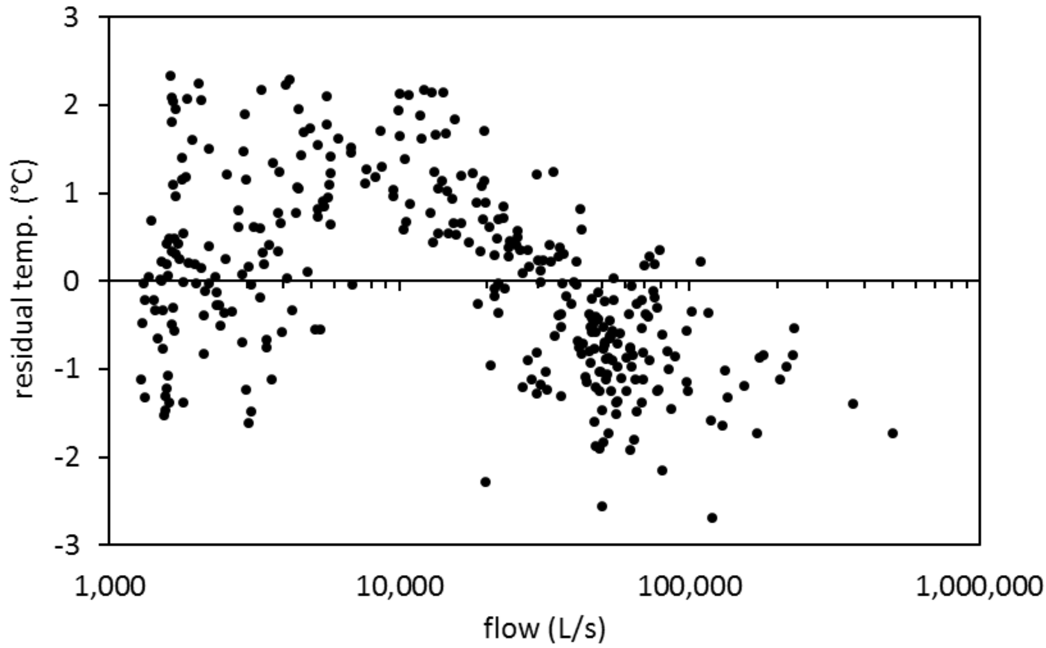


Figure 6-2 Temperature versus river flow. The effect of climate on water temperature (daily maximum) was first reduced using the equation in **Figure 6-1**. Residuals greater than zero are warmer than average, for a given soil temperature.

The predictions from the STREAMLINE model were for summer meteorology with a 15% exceedance (e.g. 25 °C air temperature), (Rutherford, 2001). This 15% exceedance for meteorology data did not translate to a 15% exceedance for water temperature (using combined 2013 data and the 1998-99 data). For example, no days exceeded 27 °C; 1% of daily maxima exceeded 26 °C and 3% of daily maxima exceeded 25 °C. Each parameter extreme needs to coincide in order to produce extreme water temperatures (e.g. hot air, low wind, low flow), which is less likely than each extreme on its own.

Conclusions and Recommendations

This memo is not intended to predict water temperatures for the Ngaruroro, nor replace the existing model that was completed by Rutherford (2001). The objective was to compare predicted extreme temperatures to observed temperatures during the 2013 drought. Water temperatures in the Ngaruroro at Fernhill did not reach the predicted extreme of 27.1 °C. The highest observed water temperature was 24.9 °C when air temperature was 34.6 °C (10 January 2013). This does not necessarily mean the model is wrong, instead confirming that the worst case scenario is an unlikely scenario.

The model predictions of high water temperatures are of consequence (e.g. for life supporting capacity). But, what is of more consequence for water allocation and setting minimum flows, is the relative change in temperature as a consequence of reduced flow. The model predicted little change in water temperature as a result of reduced flow because temperatures were approaching equilibrium downstream of Fernhill. The lack of change is supported by the 2013 monitoring, which did not detect an increase in water temperature at flows less than 15,000 L/s.

Given the lack of change of temperature with flow, and that water temperatures were not as bad as expected, I would recommend that minimum flows be set based on flow requirements for hydraulic habitat (Johnson, 2011) rather than temperature. Ongoing monitoring of water temperature in the Ngaruroro River (e.g. at Motorway Bridge) would be worthwhile to inform subsequent plan changes.

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