NIWA
Taihoro Nukurangi

Instream habitat, and minimum flow requirements in the Manuherikia River

Prepared for Otago Regional Council

June 2016

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NIWA CLIENT REPORT No: CHC2016-034
Report date: June 2016
NIWA Project: ORC16502

Quality Assurance Statement		
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	Approved for release by:	Charles Pearson

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Executive summary

The Otago Regional Council (ORC) is currently engaging with the community to set a minimum flow for the Manuherikia River taking into account the ecological, social, cultural and economic values of the catchment. The purpose of this study is to assess options for minimum flows for the Manuherikia River, upstream of Ophir, from an ecological view point, based on physical habitat for aquatic biota calculated using a 1-dimensional hydraulic model. There is currently no minimum flow, but there is a total allocation of ~28 m^3s^{-1} for abstractions from the river. The Otago Regional Council (ORC) wishes to put a defensible minimum flow in place.

To provide advice regarding minimum flow options we used the RHYHABSIM physical habitat model to assess the effects of changes in flows on instream physical habitat and aquatic biota. This model predicts how physical habitat availability will vary in response to flow changes for a particular species by calculating the change in weighted useable area (WUA). WUA is the wetted area of a stream weighted by its suitability for use by an aquatic species as described by habitat suitability criteria. The habitat suitability criteria applied in this study represented habitat for: diatoms, short filamentous algae, long filamentous algae, cyanobacteria, didymo, food producing habitat, *Deleatidium* mayfly nymphs, net-spinning caddis fly, midge larvae, cased caddis fly, upland bully, Koaro, Central Otago roundhead galaxias, flathead galaxias, large (>300 mm long) longfin eel, brown trout spawning, brown trout yearlings, adult brown trout (using two different suitability curves) and rainbow trout adult lies as set out in communications with ORC.

Hydraulic conditions were surveyed and instream habitat was modelled for different discharges in a study reach on the Manuherikia River upstream of the Dunstan Creek confluence. Fifteen cross-sections were chosen over a 2.4 km study reach. The instream hydraulic model was calibrated using measurements in the study reach taken at three different flows (observed on three separate occasions). These data were used to determine how wetted width, depth and velocity varied with flow. Habitat suitability criteria from existing general habitat suitability curves developed from studies across numerous rivers were used to calculate the relationships between flow and WUA for most of selected target species. Habitat suitability curves for didymo were supplied by ORC and curves for cyanobacteria were developed from data in Heath et al. (2013). Application of these habitat suitability criteria is standard procedure when applying physical habitat studies.

For the study reach, hydraulic modelling indicated that as flow discharge increases, river width increases rapidly at low flows and then increases steadily within the modelled flow range. Steady increases in both water depth and velocity were also calculated as flow increases. This meant that weighted useable area (WUA) increased for most biota until a flow of 2-3 m^3s^{-1} above which WUA started to decline. The WUA for *Deleatidium* (mayfly nymphs), food producing habitat and adult brown trout increased across the modelled flow range (0 to 6 m^3/s). Very little useable habitat was available for rainbow trout lies, because the water was too shallow and too slow. Modelled fish passage peaked between 3 m^3s^{-1} and 5 m^3s^{-1} and modelled trout passage was zero at flows less than 1.5 m^3s^{-1}.

An appropriate minimum flow for the Manuherikia River will depend on what level of protection is chosen for instream species versus the amount of water set aside for allocation. This report provides information on a range of potential minimum flows.

During the course of this study, it was observed that the study reach was upstream of a weir for abstracting irrigation water. It is likely that this weir is a significant impediment for fish migrating upstream. There may be other such structures elsewhere in the river that also affect fish movement and recruitment. Lack of flushing flows during the summer has allowed the accumulation of a mat of silt and periphyton that might be inhibiting invertebrate diversity and abundance and hence the value of the study reach for fish.

1 Introduction

1.1 Study brief and background

Otago Regional Council (ORC) contracted NIWA to carry out an instream habitat survey and analysis to provide advice on a minimum flow for the Manuherikia River having regard to the potential effects of different minimum flows on instream ecology. There is currently a strong demand for irrigation water from the river. ORC wish to put in place a defensible minimum flow so that they are in a position to confidently grant allocations knowing that the river's instream values will be protected.

The scope and nature of the services was to conduct surveys of physical habitat and then model the response of physical habitat for a range of target species to changes in flow in the Manuherikia River approximately 3.5 km upstream of its confluence with Dunstan Creek. The target species were specified by ORC. The specific aims of this study were:

- To assess the effects of variations in discharge on the amount of in-stream physical habitat available for a range of periphyton, macroinvertebrate and fish species present in the upper Manuherikia River (see Table 3-4).
- To examine how changes in flow affect physical habitat for these species and life stages at the specified field site.

This project focused on physical habitat as defined by the combination of depths, velocities and substrates found in the Manuherikia River compared to those deemed suitable as specified by existing habitat suitability criteria. The instream habitat modelling that was undertaken is a time-intensive method for providing information for the environmental management of flow regimes and the results produced are site-specific. Additional factors influencing habitat conditions such as geomorphological changes, water quality and temperature were not investigated as part of this project.

2 Approach

2.1 General procedure

We followed procedures recommended by the *Instream Flow Guidelines* developed by the Ministry for Environment (MfE 1998, 2008). ORC specified the main instream values that could be affected by abstraction and set these as the values to be investigated by the study. Ecological values are not the only values that are important because aesthetic values, landscape values, Māori cultural and traditional values can also be influenced by flow changes (MfE 1998), but only instream values are examined in this report.

We used physical habitat modelling and related techniques to assess the effects of changes in flows on the availability of suitable physical habitat for aquatic taxa. The analysis contained in this report quantifies the relationship between river flow and availability of suitable physical habitat for aquatic taxa. This report outlines how different minimum flows will negatively or positively influence physical habitat for particular species and the relative changes in availability of suitable physical habitat over a range of minimum flows.

2.2 Methods for determining instream flow requirements

Many factors influence the health of river ecosystems including temperature, oxygen, light, geomorphology and flow (Hynes 1970; Giller & Malmqvist 1998; Norris & Thoms 1999). All elements of a flow regime are important, including floods, average and low flows (Junk et al., 1989; Poff et al., 1997; Richter et al., 1997). A holistic approach must therefore be taken for the long-term management of river systems. Such an approach considers how human activities impact upon interactions between factors such as geology, sediment transport, channel structure, riparian conditions, water quality and biological habitat. However, apart from through dilution effects, flow rate (m^3s^{-1}) is only a surrogate variable; it is the water depth and velocity in a river, created by the interaction between flow rate and channel morphology, that provides physical habitat for plants, invertebrates and fish (Booker & Acreman 2006). Jowett (1992) found the single most important factor determining trout abundance was habitat for food; Gore et al., (1998) found relationships between physical habitat (i.e., wetted area) and actual benthic community diversity; and Gallagher & Gard (1999) found a positive correlation between physical habitat and spawning density of salmon.

The direct relationship between physical habitat and flow provides a means for assessing the ecological impact of changing the flow regime of a river (Cavendish & Duncan 1986; Jowett 1990; Beecher et al., 1993). However, assessment of river flow management options often involves assessing scenarios that fall outside the range of observed conditions, and thus predictive models are required. The Physical Habitat Simulation (PHABSIM) system (Bovee 1982; Bovee et al., 1998) was the first systematic modelling framework to be developed and many models based on a similar concept have been produced including CASiMIR in Germany (Jorde 1996; Eisner et al., 2005), EVHA in France (Ginot 1995), RHYHABSIM in New Zealand (Jowett 1989) and RSS in Norway (Killingtviet & Harby 1994). Essentially these models quantify the relationship between physical habitat, defined in terms of the combination of depth, velocity and substrate/cover, and various flows (e.g., Johnson et al., 1993; Elliott et al., 1996). Criticisms of this approach include lack of biological realism (Orth 1986) and mechanisms (Mathur et al., 1985; Booker et al., 2004). Nevertheless, the models have been applied throughout the world (Dunbar & Acreman 2001), primarily to assess impacts of abstraction or river impoundment. However, the method has also been used to assess the effects of channel restoration and modification (Acreman & Elliott 1996; Booker & Dunbar 2004). PHABSIM in particular has become a legal requirement for many impact studies in the USA (Reiser et al., 1989) and a standard tool employed by the Environment Agency of England and Wales to define the sensitivity of rivers to abstraction (Booker & Acreman 2006). RHYHABSIM has been applied to many rivers in New Zealand (Lamouroux & Jowett 2005) for a variety of reasons. Jowett and Biggs (2006) reviewed the results from six rivers in which habitat-based methods had been applied to flow setting. They found that in five of these cases the biological response and the retention of desired instream values was achieved.

The instream flow incremental methodology (IFIM; Bovee 1982; Bovee et al., 1998) is an example of an interdisciplinary framework that can be used in a holistic way to determine an appropriate flow regime by considering the effects of flow changes on instream values, river morphology, physical habitat, water temperature, water quality, and sediment (Figure 2-1). This report uses the IFIM approach to examine the effect of flow on instream physical habitat only. The approach used did not investigate potential changes in water temperature, water quality or sediment transport arising from changes in flow management.

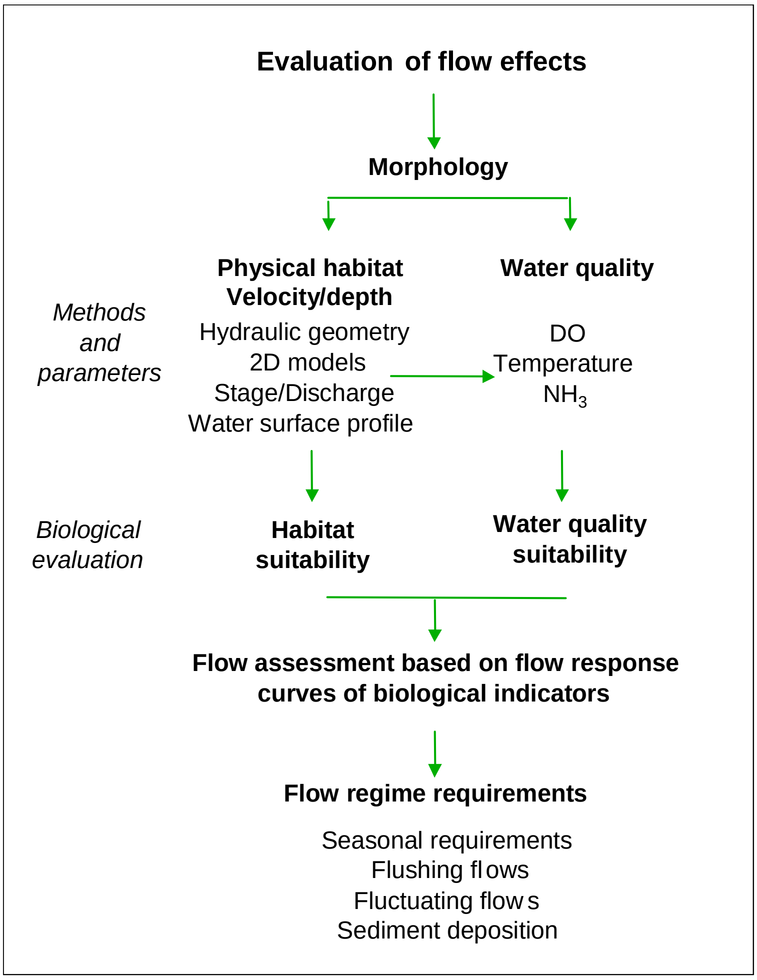

Figure 2-1: A framework for the consideration of flow requirements (Jowett & Biggs 2006).

A variety of approaches and frameworks to instream flow methods exist (Jowett 1997). In contrast with IFIM, other flow assessment frameworks are more closely aligned with the "natural flow paradigm" (Poff et al., 1997). The range of variability approach (RVA) and the associated indicators of hydrologic alteration (IHA) allow an appropriate range of variation, usually one standard deviation, in a set of 32 hydrologic parameters derived from the 'natural' flow record (Richter et al., 1997). The implicit assumption in this method is that the natural flow regime has intrinsic values or important ecological functions that will be maintained by retaining the key elements of the natural flow regime. Arthington et al., (1992) described a holistic method that considers not only the magnitude of low flows, but also the timing, duration and frequency of high flows. This concept was extended to the building block methodology (BBM), which "is essentially a prescriptive approach, designed to construct a flow regime for maintaining a river in a predetermined condition" (King et al., 2000). It is based on the concept that some flows within the complete hydrological regime are more important than others for the maintenance of the river ecosystem, and that these flows can be identified and described in terms of their magnitude, duration, timing, and frequency. More recently, Poff et al., (2010) proposed the ecological limits of hydrologic alteration (ELOHA) framework in which stakeholders and decision-makers explicitly evaluate acceptable risk as a balance between the perceived value of the ecological goals, the economic costs involved and the scientific uncertainties in functional relationships between ecological responses and flow alteration. Whilst there are many methods available for setting flows, all of which have pros and cons, physical habitat modelling and IFIM is the technique most commonly used throughout New Zealand at present. Therefore, this technique has been used to determine a minimum flow range for the Manuherikia River and below we explain how physical habitat modelling and IFIM are conducted.

2.3 Physical habitat modelling

The approach adopted in many physical habitat studies is described by Johnson et al., (1995), Jowett (1997) and Clausen et al., (2004). This approach includes four main steps: identification of river sections and species of interest; identification of habitats that exist within the sections of interest; selection of cross-sections which represent replicates of each habitat type; and collection of model calibration data (water surface elevation, depth and velocity). These calibration data are used to determine the spatial distribution of depths and velocities across each cross-section (e.g., Figure 2-2) and the relationship between water levels at each cross-section and the quantity of water flowing in the river (e.g., Figure 2-3).

The calibration data are collected in order to simulate hydraulic conditions in the river for a range of flows which can then be combined with appropriate habitat suitability criteria (HSC). This allows prediction of useable physical habitat for the species / life stage of interest. Useable physical habitat is commonly expressed as Weighted Useable Area (WUA) in m^2 per m of river channel. WUA is an aggregate measure of physical habitat quality and quantity and will be specific to a particular discharge and species / life stage. Assessment of the changes in WUA which might occur as a result of any proposed changes in flow regime can then be made. In New Zealand habitat modelling has typically followed either one of two methods.

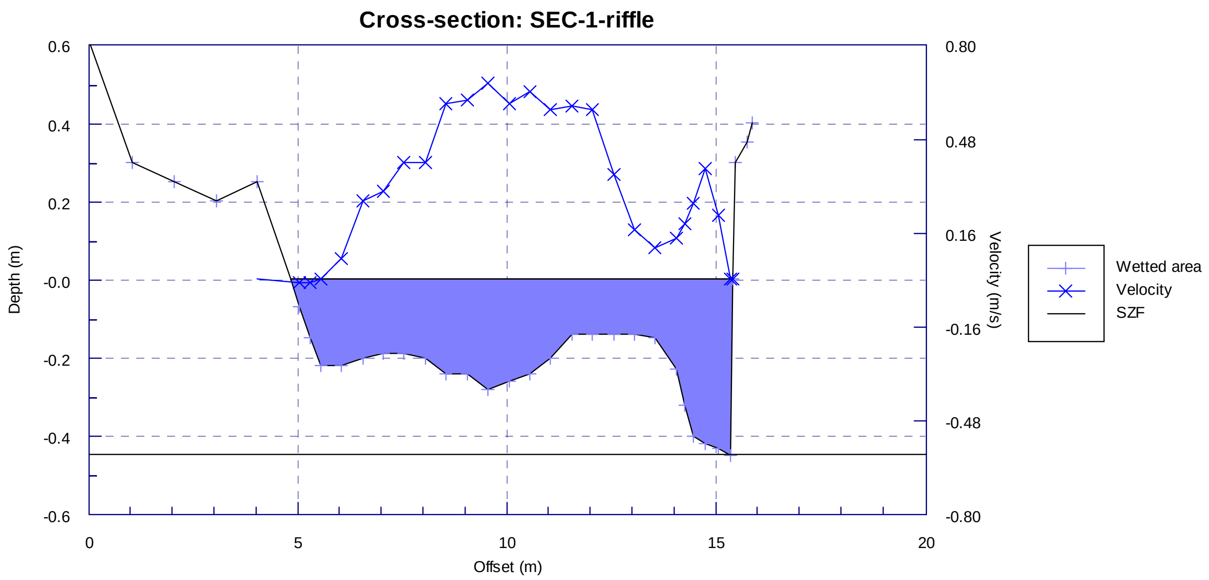

Figure 2-2: Example of velocities and depths measured for a cross-section. SZF = stage at zero flow.

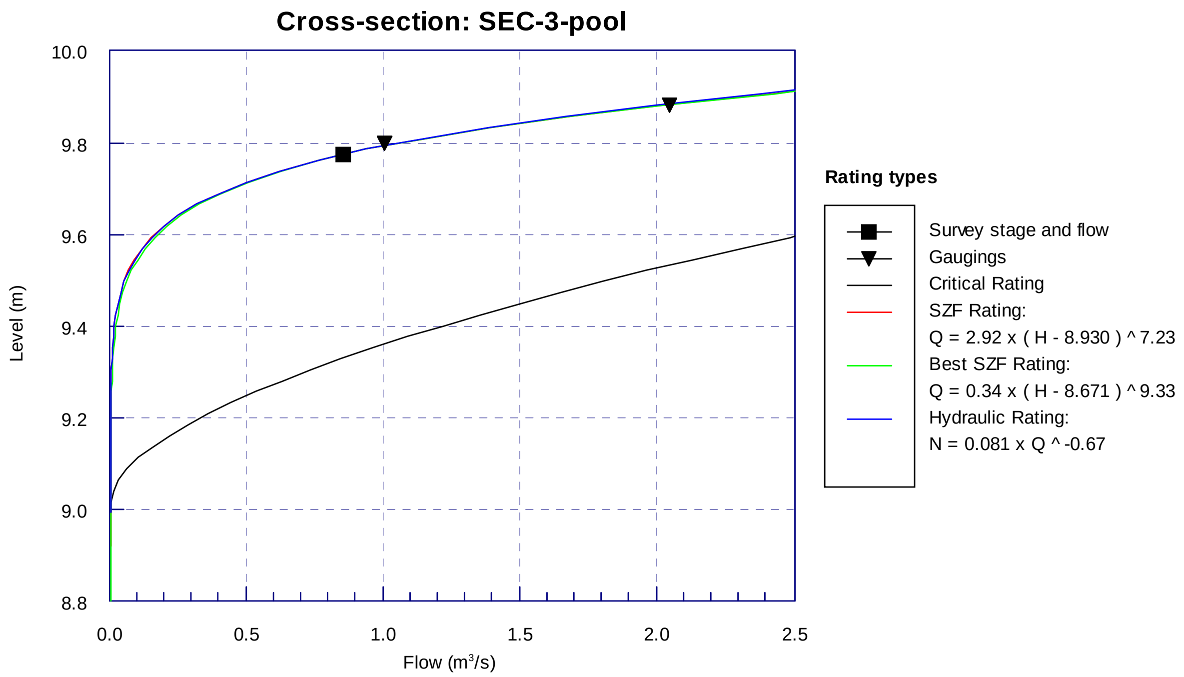

Figure 2-3: Example of a water level–discharge relationship at a cross-section.

The first method is known as the "habitat mapping" method. The number and distribution of habitat types within the reach of interest are identified using habitat mapping techniques. Stage-discharge relationships are applied to simulate hydraulic conditions at isolated cross-sections placed throughout the reach of interest. Identification of the habitat type and several observations of water surface level and discharge are required at each cross-section. Modelled conditions at these cross-sections are then used in conjunction with results from the habitat mapping to weight each cross-section and therefore represent conditions in the reach of interest. The advantage of the habitat mapping method is that it does not require the selection of a representative reach from within the length of river that is of interest.

The second method is known as the "representative reach" method. One-dimensional hydraulic modelling approaches are applied to a series of cross-sections located contiguously along the river to form a study site within the length of river that is of interest. The habitat types of each cross-section may be identified and can be used to assess the representativeness of the modelled reach. The advantage of the representative reach approach is that it allows more physically-based methods to be used in hydraulic simulation. This can be advantageous in rivers with particularly complex hydraulic characteristics caused by low width-to-depth ratios, the presence of in-channel vegetation or frequent groundwater-surface water interactions.

Both the "habitat mapping" and the "representative reach" methods may involve identification of habitat types (e.g., Table 2-1). Methods for identification of physical habitat types have been developed and applied over many years on different river types for research and river management purposes internationally (Jowett 1993; Maddock 1999; Maddock et al., 2004). These methods aim to identify the types and spatial configuration of geomorphic and hydraulic units. Habitat identification and mapping is often used in conjunction with physical habitat studies when 'upscaling' results from discrete sections to provide catchment wide assessments, or make river management recommendations. Information on the application and testing of habitat mapping approaches is described in the literature (e.g., Bisson et al., 1982; Hawkins et al., 1993; Jowett 1993; Roper & Scarnecchia 1995; Poole et al., 1997; Vadas Jr. & Orth 1998; Bjorkland et al., 2001; Parasiewicz 2001; Parasiewicz & Dunbar 2001; Roper et al., 2002; Dauwalter et al., 2006). Physical habitat units have been defined and classified by many authors, leading to an array of terms in use to describe the physical environment utilised by the instream biota. The terms used to describe these units differ between authors and include 'channel geomorphic units' (CGU's) (e.g., Hawkins et al., 1993), 'mesohabitats' (e.g., Tickner et al., 2000), 'physical biotopes' (e.g., Padmore 1997) and 'hydraulic biotopes' (e.g., Wadeson 1994). Newson & Newson (2000) provided a review of the use of some of these terms and the differences between them.

2.4 Flow setting

The National Policy Statement for Freshwater Management (NPS-FM) states that, for flowing water, water quantity limits (i.e., environment flows as defined in MfE 2013) must comprise at least a minimum flow and an allocation rate. In situations where a regional council has not set minimum flows for a catchment, proposed interim limits for ecological flows for rivers with mean flows greater than or equal to 5 m^3s^{-1} were proposed by the Ministry of the Environment (MfE 2008). These proposed limits are for a minimum flow of 80% of the mean annual low flow as calculated by the regional council and a total allocation of 50% of MALF. For rivers and streams with mean flows less than or equal to 5 m^3s^{-1} a minimum flow of 90% of the mean annual low flow as calculated by the regional council and a total allocation of 30% of MALF was proposed. MfE (2013) suggests that this default minimum flow would be superseded following any more detailed study, such as a physical habitat modelling study. (NB. Beca (2008) defines the MALF in these cases as the 7-day MALF).

Table 2-1: Habitat type definitions used in this study (after Hawkins et al., 1993 and Maddock 1999).

Channel Geomorphic Unit (CGU)	Hydraulic character	Brief Description
Fall (Fa)	Turbulent and very fast	Vertical drops of water over the full span of the channel, commonly found in bedrock and step-pool stream reaches
Cascade (Ca)	Turbulent and very fast	Highly turbulent series of short falls and small scour basins, frequently characterised by very large substrate and a stepped profile
Chute (Ch)	Turbulent and very fast	Narrow steep slots or slides in bedrock
Rapid (Ra)	Turbulent and fast	Moderately steep channel units with coarse substrate, unlike cascades possess planar profile
Riffle (Ri)	Turbulent and moderately fast	Most common type of turbulent fast water mesohabitat in low gradient alluvial channels. Substrate is finer than other fast turbulent mesohabitats. Less white water, with some substrate breaking the surface
Run (Ru)	Non-turbulent and moderately fast	Moderately fast and shallow gradient with ripples on the water surface. Deeper than riffles with little, if any, substrate breaking the surface
Glide (Gl)	Non-turbulent and moderately slow	Smooth 'glass-like' surface, with visible flow movement along the surface. Relatively shallow compared to pools
Pool (Pl)	Non-turbulent and slow	Relatively deep and slow flowing (compared to glides), with fine substrate. Usually little surface water movement visible. Consists of transition from pool-head, mid-pool and pool-tail.
Ponded (Pd)	Non-turbulent and slow	Water ponded behind an obstruction – weir, sluice or other obstruction
Other (O)		To be used in unusual circumstances where feature does not fit any recognised type

Regardless of the method of data collection, simulated hydraulic conditions are then compared with the habitat suitability criteria in order to assess how the combined quality and quantity of physical habitat varies as flow changes. The habitat value at each point is calculated as a joint function of depth, velocity and substrate type using the method shown in Figure 2-4. The area of useable physical habitat, or weighted useable area (WUA), is calculated by multiplying the area represented by each point by its joint habitat value. For example in Figure 2-4, at a given point in the river (representing an area of reasonably uniform depth and velocity) where the depth is 0.1 m, depth suitability is only 65% optimal, according to knowledge of the depth requirements of the fish. Similarly, the velocity recorded at the point is 0.25 m/s, which is optimal (suitability weighting of 1), and the substrate is 50% fine gravel (sub-optimal, with a weighting of 0.4) and 50% cobbles (optimal with a weighting of 1) which together give an overall suitability weighting of 0.7). Multiplying these weighting factors together we get a joint habitat suitability weighting of 0.455 for that point in the river for the selected fish species. If the depth had been 0.2 m and there had been no fine gravel, then that point in the river would have been optimal (i.e., 1 for depth × 1 for velocity × 1 for substrate = 1). This exercise is repeated within the habitat assessment model for the depth/velocity/substrate characteristics in every grid square across the river, and the area covered by each square is multiplied by the point suitability. These areas, which have been weighted by their respective point suitability values, are then summed to give a measure of total area of suitable physical habitat for the given species at the given flow. This process is then repeated for a series of other flows with the depths, velocities, and habitat values being modelled for the new flows as described above. The total area of suitable physical habitat is then plotted as a function of flow to show how the area of suitable physical habitat for a given species changes with flow. Variations in the amount of suitable habitat with flow are then used to assess the effect of different flows for target organisms.

Where habitat modelling has been conducted, various approaches to setting levels of protection provided by a minimum flow can be used. For example, for maintaining a maximum amount of habitat, a percentage of habitat at median flow, or using a breakpoint on the habitat/flow relationship (Jowett 1997). The latter has possibly been the most common procedure used where minimum flow requirements have been assessed using habitat methods. While there is no percentage or absolute value associated with a breakpoint, it is a point of diminishing return, where proportionately more habitat is lost with decreasing the flow than is gained by increasing the flow.

Habitat methods can also incorporate flow regime requirements, in terms of both seasonal variation and flow fluctuations. Flow fluctuations are an important component of the habitat of most naturally flowing streams. Such fluctuations remove excess accumulations of silt and accumulated organic matter (e.g., from algal slimes) and rejuvenate stream habitats. Extended periods without a flow disturbance can result in a shift in benthic community composition such as a reduction in diversity and an increase in density and biomass of snails and other species (Suren et al., 2003).

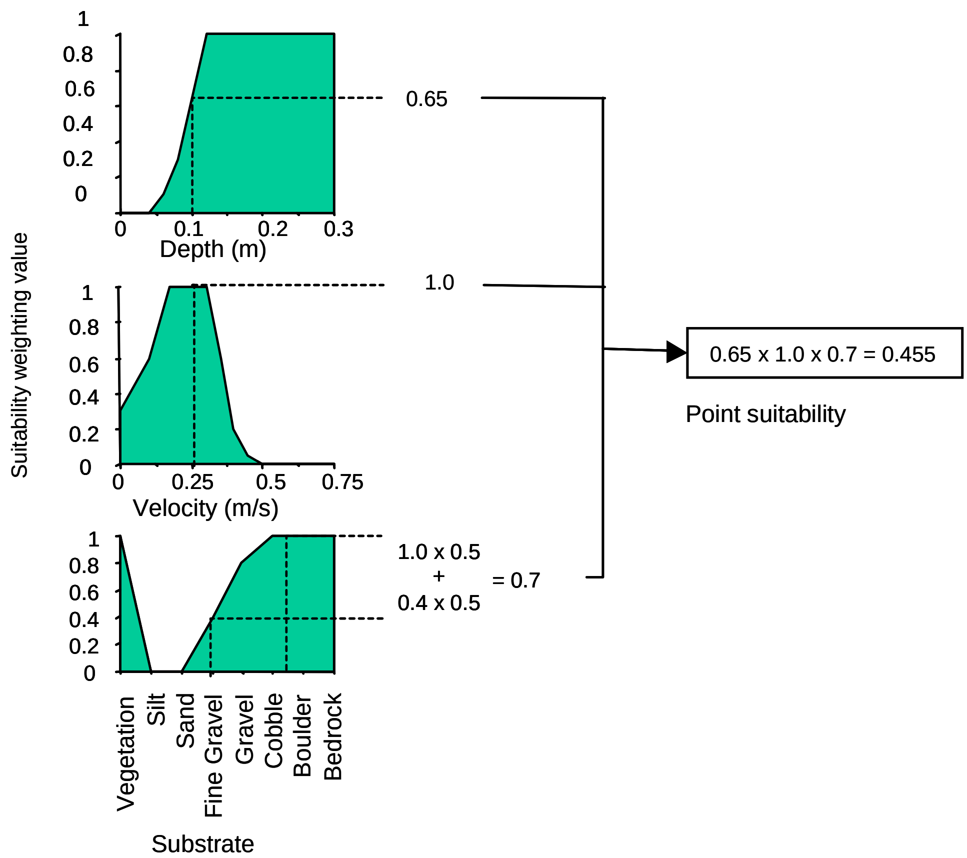

Figure 2-4: Calculation of habitat suitability for a fish species. This example is for a fish species at a point with a depth of 0.1 m, velocity of 0.25 ms^{-1}, and substrate comprising 50% fine gravel and 50% cobble. The individual suitability weighting values for depth (0.65), velocity (1.0), and substrate (0.7) are multiplied together to give a combined point suitability of 0.455.

2.5 Fish passage

The depths and velocities obtained from the modelling can be used to model fish passage. Commonly used criteria for brown trout passage are a minimum depth of 0.25 m and velocities less than 1.25 ms^{-1}. Some small native fish are benthic crawlers and can find passage where depths and velocities are not suitable for water column swimming fish. The Rhyhabsim model used for this study provides data on contiguous and total passage. Contiguous width is the maximum width in a cross-section with the required minimum depth and velocities less than the maximum. Total width is the sum of all the elements of the cross-section that meet the specified criteria.

3 Data collection

3.1 Site location

The Manuherikia River is located in Central Otago and drains the Dunstan Mountains, St Bathans and Hawkdun Ranges and Rough Ridge (Figure 3-1). It joins the Clutha River at Alexandra. At this junction the Manuherikia River is a 7th order stream with a catchment area of ~3041 km^2 at its confluence with the Clutha River. At the study site the river is a 6th order stream with a catchment area of ~483 km^2.

This study concentrated on a 2.4 km reach ~3.5 km upstream from the Dunstan Creek confluence, approximately 21 km upstream of Ophir and upstream of the irrigation intake at ~1347170E 5014440N. There is another irrigation scheme intake ~4 km upstream of the study reach. This reach was judged to be the most critical by ORC, should future irrigation flows from the Falls Dam (Figures 3.1, 3.2), currently being distributed via this reach, be diverted in either pipes or races. Below this reach there are tributary inflows from Dunstan Creek, the Ida Burn and other tributaries. The upstream end of the study reach was located at ~1348670E, 5015540N (NZTM) and the reach extended for 2370 m to the downstream end of the study reach at ~1347250E, 5014510N (NZTM). The Manuherikia River study reach is predominately a single thread, cobble and gravel bed stream and is characterised by runs and shallow pool habitats (see Section 4*).*

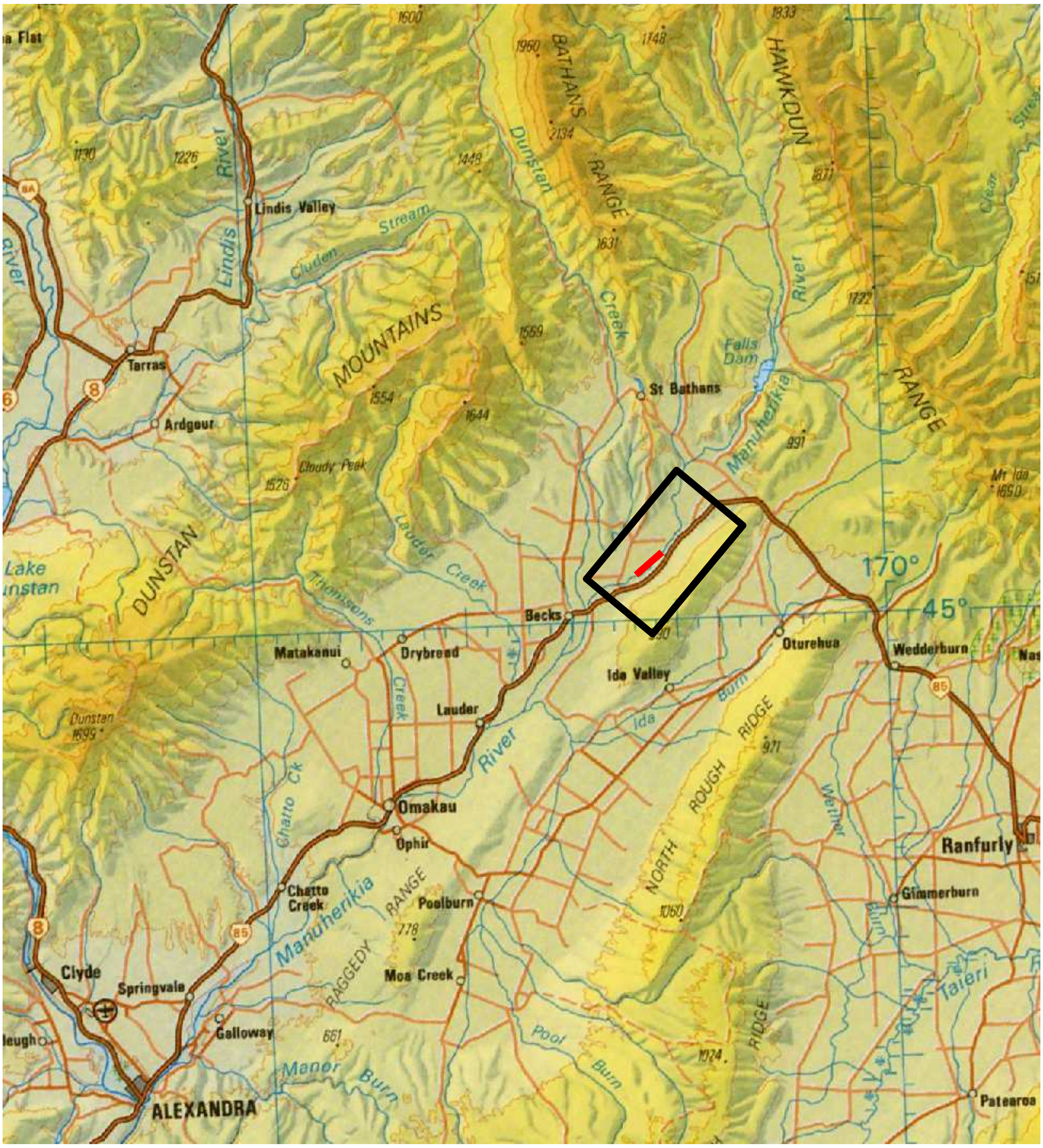

Figure 3-1: The location of the study area (block rectangle) relative to the length of Manuherikia River. The reach that was habitat mapped is shown by the red line.

The specific location of the study reach is shown in Figure 3-2.

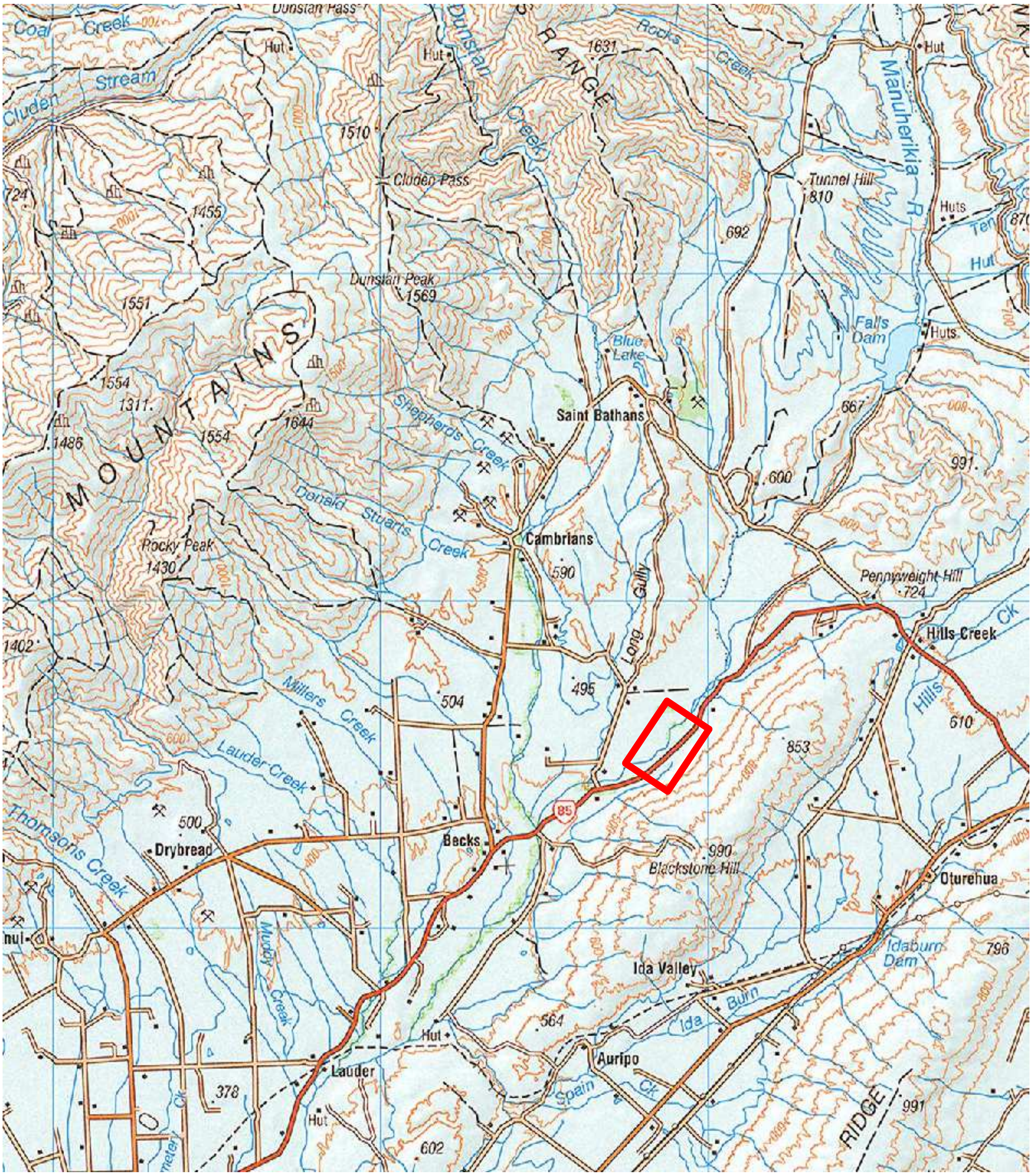

Figure 3-2: Specific location of the study reach (red rectangle)

3.2 Hydrology

Continuous flow data have been collected at the Manuherikia at Ophir water-level recorder since 1971. The flow recorder site has a catchment area of 2036 km^2 and is ~21 km downstream of the study reach. Flow summary statistics (for period 1971-2015) for the site are shown in Table 3-1. Water is released from the Falls Dam (Figure 3-2) and is taken from the river for irrigation. The irrigation water not taken could enhance low flows. On the other hand, if more was taken than released then low flows could be reduced. Throughout the catchment there are many Deemed permits (mining rights) so that the allocated take is ~28 m^{3}s^{-1}, but this is approximately twice the mean flow so all of these rights cannot be exercised at once. However, use of those permits upstream of Ophir could affect low flows recorded there.

Table 3-1: Flow summary statistics (m^3/s) for Manuherikia River at Ophir (1971-2015).

Site	Mean	Median	7D MALF	Upper Quartile	Lower Quartile
Manuherikia River at Ophir	13.9	9.1	2.06	17.6	4.00

3.3 Instream habitat survey and analysis

To determine the proportions of different habitat types in the survey reach, meso-habitat types (Table 2-1) were 'mapped' for 2375 m of Manuherikia River (Figure 3-2). The 15 cross-sections surveyed were contained within this length and comprised five riffles, five runs and five pools. Each cross-section was therefore placed to represent the conditions typical to a particular meso-habitat type. Appendix A contains photographs of the cross-sections. One survey peg on each bank was used to mark, relocate and resurvey each cross-section. Water velocities, depths, and substrate composition were recorded at an average spacing of 1.1 m, or less, at each cross-section. The flow averaged across all 15 sections is given in Table 3-3. Water levels at all cross-sections and discharge at cross-section 11 (see Appendix B) were then measured at further discharges (Table 3-3). Cross-section 11 was deemed to provide the best conditions for an accurate flow measurement. The flow at cross-section 11 was assumed for all cross-sections. No tributaries were present within the surveyed reach.

Table 3-2: Cross-sectional characteristics. Habitat type definitions given in Table 2-1. Distances are from the upstream end of the study reach.

Section	Morphology	Distance (m)	Weight (%)	No points instream	No. points All	Ave. point spacing (m)	Ave spacing all points (m)
1	Pool	122	3.44	12	27	0.8	0.7
2	Pool	271	3.12	13	34	0.8	0.9
3	Run	562	5.25	14	35	1.1	1.1
4	Riffle	720	7.07	17	32	0.8	0.7
5	Run	829	3.79	20	39	0.5	0.5
6	Riffle	850	3.8	15	36	0.8	0.9
7	Pool	908	2.38	20	33	0.6	0.6
8	Riffle	977	12.4	17	36	0.6	0.7
9	Run	1068	10.93	24	45	0.5	0.6
10	Riffle	1092	4.47	23	47	0.6	0.8
11	Run	1273	21.77	20	37	1.0	1.0
12	Run	1354	4.69	21	37	0.9	0.8
13	Riffle	1392	6.98	21	35	0.9	0.9
14	Pool	1450	2.45	20	36	0.5	0.7
15	Pool	1665	7.46	25	32	0.7	0.7

[1] 'Instream' spacing refers to the average distance between survey points in the stream channel.

[2] 'All' spacing refers to the average distance between survey points across the entire cross-section.

The weight given to each cross-section within RHYHABSIM was calculated from the proportion of the mapped habitat type occupied by each cross-section.

Table 3-3: Calibration flows (m^3s^{-1}) (measured in the study reach – see Section 3.3).

Date	Discharge (m^3s^{-1})	The cross-section(s) where flows were measured
3/02/16	2.2	Average for 15 sections
14/04/16	2.049	11
2/05/16	1.39	11

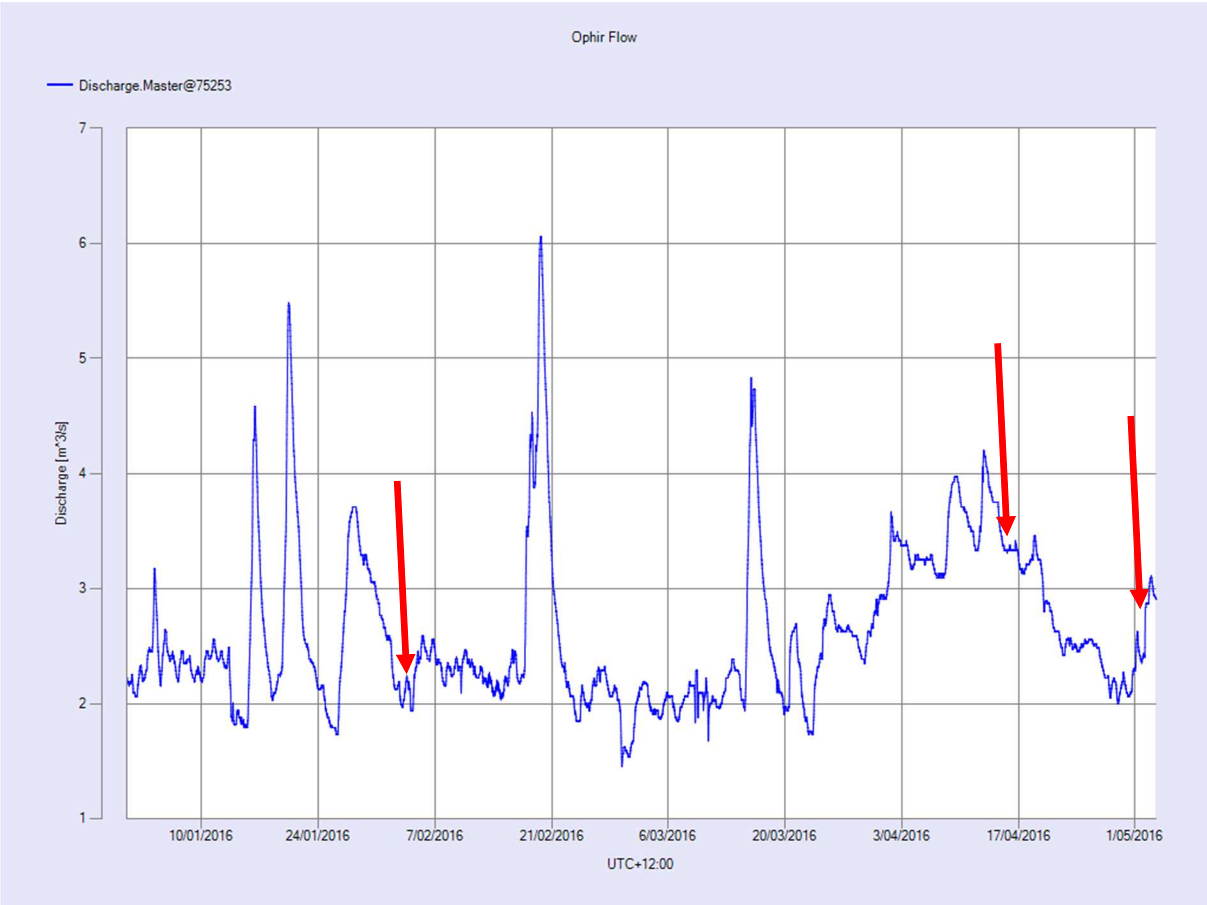

Figure 3-3: Timing of the survey and calibration flow (red arrows) relative to the flow at the Manuherikia at Ophir ~21 km downstream from the study reach.

Cross-sectional topography, water surface levels and the locations of survey pegs was measured using a Trimble R10 GNSS differential GPS on 3 February 2016. Water levels were measured relative to the tops of pegs on 03/02/2016, 12/04/2016 and 2/5/2016.

Mean water column velocities were measured using a Sontek Flowtracker acoustic Doppler velocimeter placed at 0.4 of the depth for at least 40 seconds. Depths were measured using a wading rod. On 3/02/16 velocities, depths and substrate compositions were measured across all cross-sections. Substrate composition was recorded using an eight class substrate classification as determined by the habitat suitability criteria (Appendix A) of: vegetation, silt (<0.06 mm), sand (0.06−2 mm), fine gravel (2−8 mm), gravel (8−64 mm), cobble (64−256 mm), boulder (>256 mm) and bedrock. On 12/04/2016 and 2/5/2016 velocities and depths were measured across a chosen cross-section (11) with relatively uniform depths to allow best calculation of discharge and those flows were attributed to all the other cross-sections.

The habitat analysis proceeded as follows:

1. Discharges were computed from depth and velocity measurements for each cross-section.
2. A stage-discharge relationship was developed for each cross-section using a least squares fit to the logarithms of the measured flows and stages (water-levels) including an estimated stage at zero flow.
3. Water depths were computed at each measurement point across each cross-section for a range of simulated flows using measured bed topography data and calculated stage-discharge relationships. Velocities were computed for each cell at each flow using the flow conveyance method to disaggregate velocity across each cross-section based on the measured pattern of velocity distribution (Jowett et al., 2008).
4. Habitat suitability was evaluated at each measurement point from habitat suitability criteria for each target species.
5. The weighted useable area (WUA) for each simulated flow was calculated as the sum of the habitat suitability indices across each cross-section, weighted by the proportion of the habitat type which each cross-section represented in the river.
6. WUA was plotted against flow and the resulting relationships were examined to assess the appropriateness of various minimum flow options.

Pool cross-sections 1 and 7 were too deep to use the Flowtracker velocimeter across the entire section, but some of the water depths of the deeper portions were measured during the cross-section survey. Where water velocities were unable to be measured they were estimated so that the cross-section flow was similar to the average of the remaining cross-sections.

3.4 Habitat suitability criteria

The habitat suitability criteria (HSC) chosen for a study must be appropriate for the species known to occur, or likely to occur, in the study river. The HSC to be used in this study were nominated by ORC and are listed in Table 3-4 and are shown in Appendix B. Figure 3-4 shows the fish species found in the Manuherikia River and recorded in New Zealand’s Freshwater Fish Database (https://nzffdms.niwa.co.nz).

Table 3-4: Aquatic species and habitat suitability indices.

Taxa group/Species	HSC name	HSC source
Periphyton	diatoms	unpublished NIWA data
	short filamentous	unpublished NIWA data
	long filamentous	unpublished NIWA data
	cyanobacteria	Ex Heath et al. (2013)
	didymo	Jowett
Stream invertebrates	food producing	Waters (1976)
	mayfly nymphs *(Deleatidium*)	Jowett et al., (1991)
	net-spinning caddis fly *(Aoteapsyche)*	Jowett et al., (1991)
	midge larvae (Chironomidae)	Jowett et al., (1991)
	cased caddis fly (*Pycnocentrodes*)	Jowett et al., (1991)
Fish	koaro	Jowett & Richardson (2008)
	Central Otago roundhead galaxias	Jowett & Richardson (2008)
	flathead galaxias	Jowett & Richardson (2008)
	longfin eel > 300 mm	Jowett & Richardson (2008)
	upland bully	Jowett & Richardson (2008)
	rainbow trout feeding	Thomas & Bovee (1993)
	brown Trout adult	Hayes and Jowett (1994)
	brown Trout adult	Bovee (1995)
	brown trout yearling	Raleigh *et al*. (1986)
	brown Trout spawning	Shirvell & Dungey (1983)
	rainbow trout adult lies	Jowett *et al*. (1991)

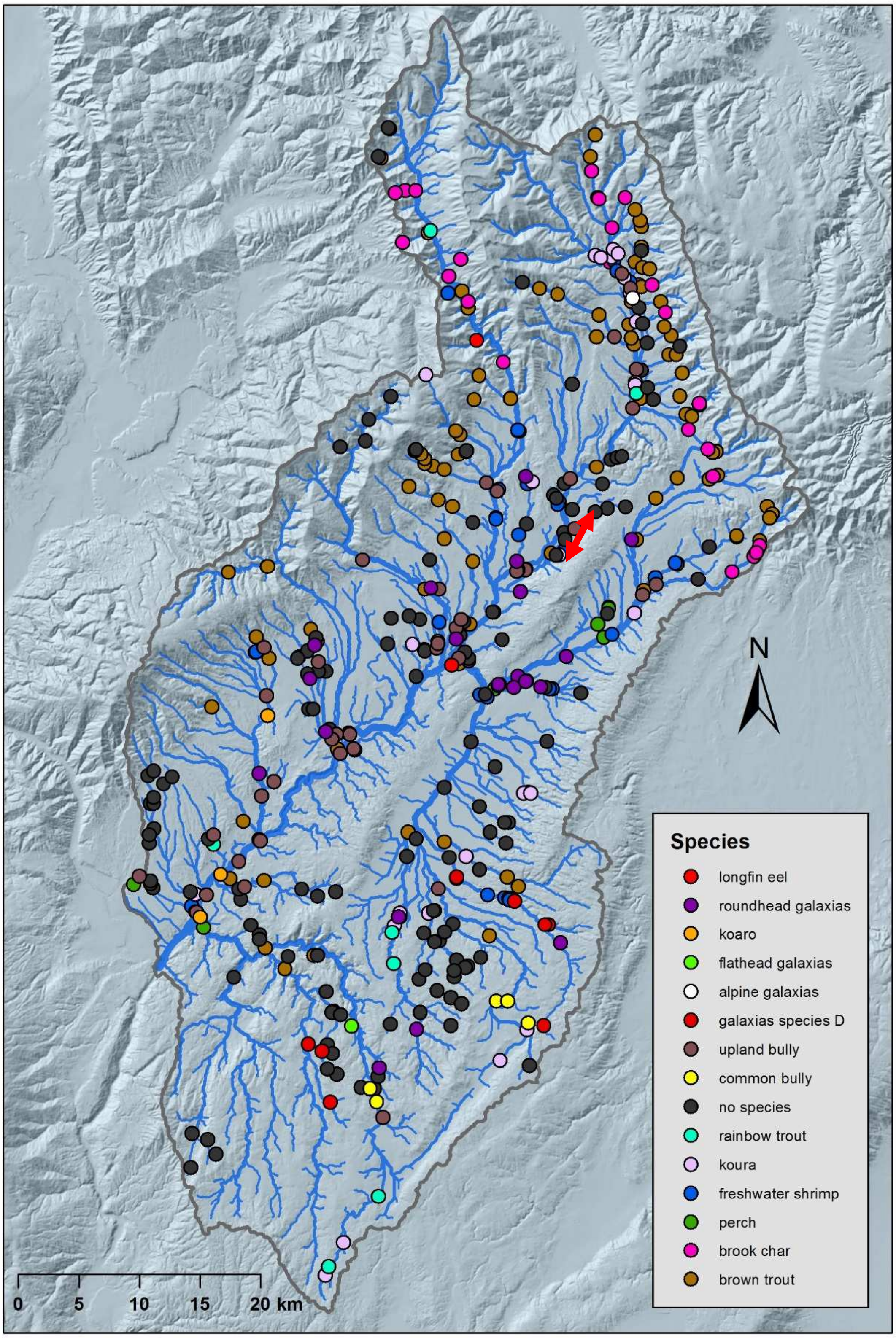

Figure 3-4: The Manuherikia River and its tributaries showing the species and location of fish recorded in the Freshwater Fish Database. At locations where more than one species was found only one species will be shown because of over-plotting. The red line shows the approximate extent of the study reach.

3.5 Data analysis

3.5.1 Recreation

No formal analysis on recreational values was undertaken. Instead observations were made at the time of the survey, when the flow was about the 7d-MALF of the Ophir site, of the suitability of depths and velocities for fishing and bathing. At this flow the river at the study reach is too shallow and too narrow for rafting, kayaking, and jet-boating. Jet boating requires a depth of 0.25->0.6 m and a width >5 m, while some rafting kayak passage is available between 0.2 and 0.5 m depth the preference is for depths >0.8 m and widths >20 m (Ministry for the Environment, 1998).

3.5.2 Flow variability

Flow variability is important for providing flushing flows for river health, i.e., flushing periphyton from the river bed, removing any drapes of fine sediment from larger bed material, transporting bed load, maintaining river morphology and nourishing beaches.

One way of estimating the flushing flow capacity of a river is to count the number of flows greater than a threshold. In New Zealand it is common to use the frequency of events (floods per year) exceeding three times the long-term median flow (FRE3) (Clausen and Biggs 1997) for this purpose in gravel-bed rivers.

There is no water level record near the study site to enable a representative FRE3 value to be calculated. However, FRE3 was calculated from the flow record from the Manuherikia River at Ophir for the entire record 1 February 1971 to 15 November 2015, using the average daily flow time series, a threshold of three times the median flow of 9.09 m^3s^{-1} and a window of 5 days where events over the threshold occurring within this window are counted as one.

4 Results

4.1 Physical characteristics

The site where habitat measurements were conducted in the Manuherikia River was located upstream of the Omakau Irrigation Scheme intake. In this study reach of the Manuherikia River the substrate consisted mainly of cobble, gravel and fine gravel in varying proportions with interstitial spaces filled with sand and silt. Most substrates were covered with a drape of algae and silt. The site contained no instream macrophytes and 7 of the 15 cross-sections had overhead vegetation in the form of overhanging willow in places (e.g., Figure 4-1). No areas of long green filamentous algae were observed within the site. During the survey there were a lot of algal fragments floating in the water column, including clumps of didymo. Photographs of all cross-sections are given in Appendix B.

Figure 4-1: Run near section 11 showing overhanging willows of the true left bank in the foreground and near section 12 on the true left in the distance.

For this study reach, hydraulic modelling predicted that as discharge increases, width increases rapidly to 2.5 m^3s^{-1} flows and then increases at a relatively constant rate (Figure 4-2) due to the vertical bank profiles present at this site (Figures 4-1, Appendix B). Steady increases in both depth and velocity are also predicted as flow increases above 0.5 m^3s^{-1} (Figure 4-3).

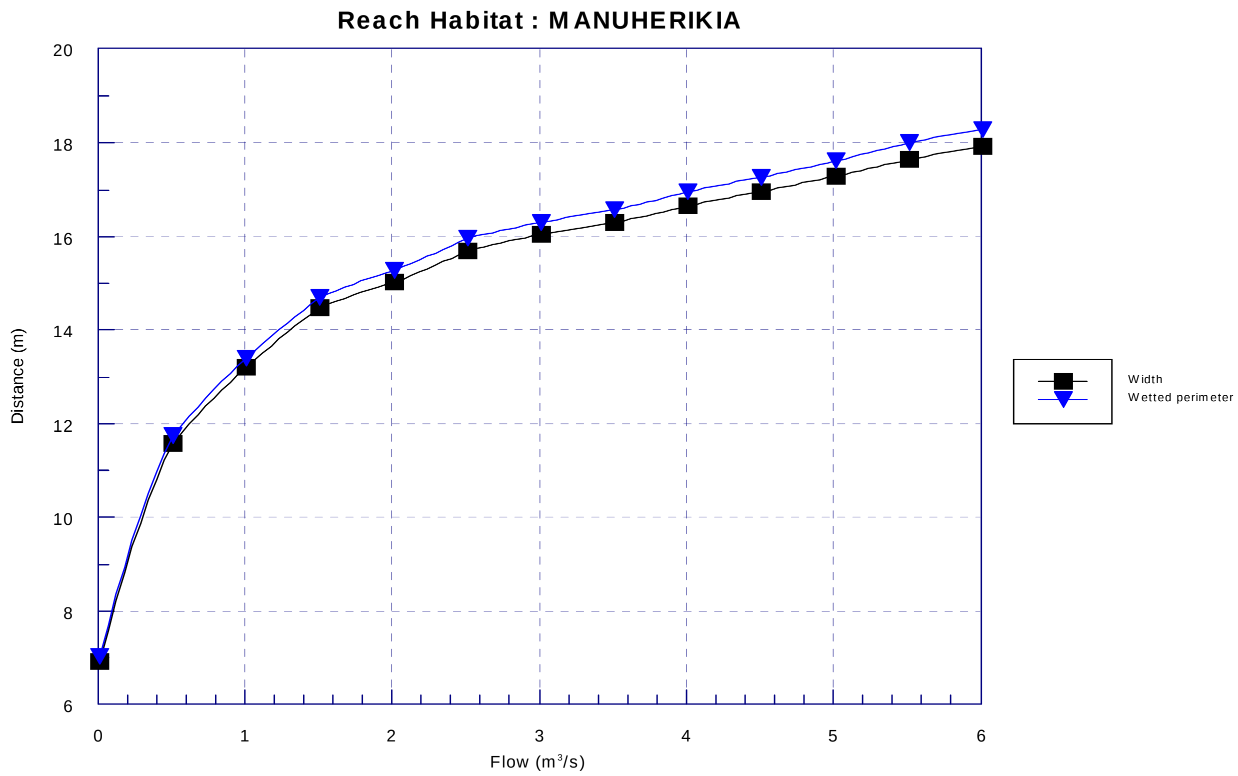

Figure 4-2: Mean width and wetted perimeter against discharge for the Manuherikia River survey reach.

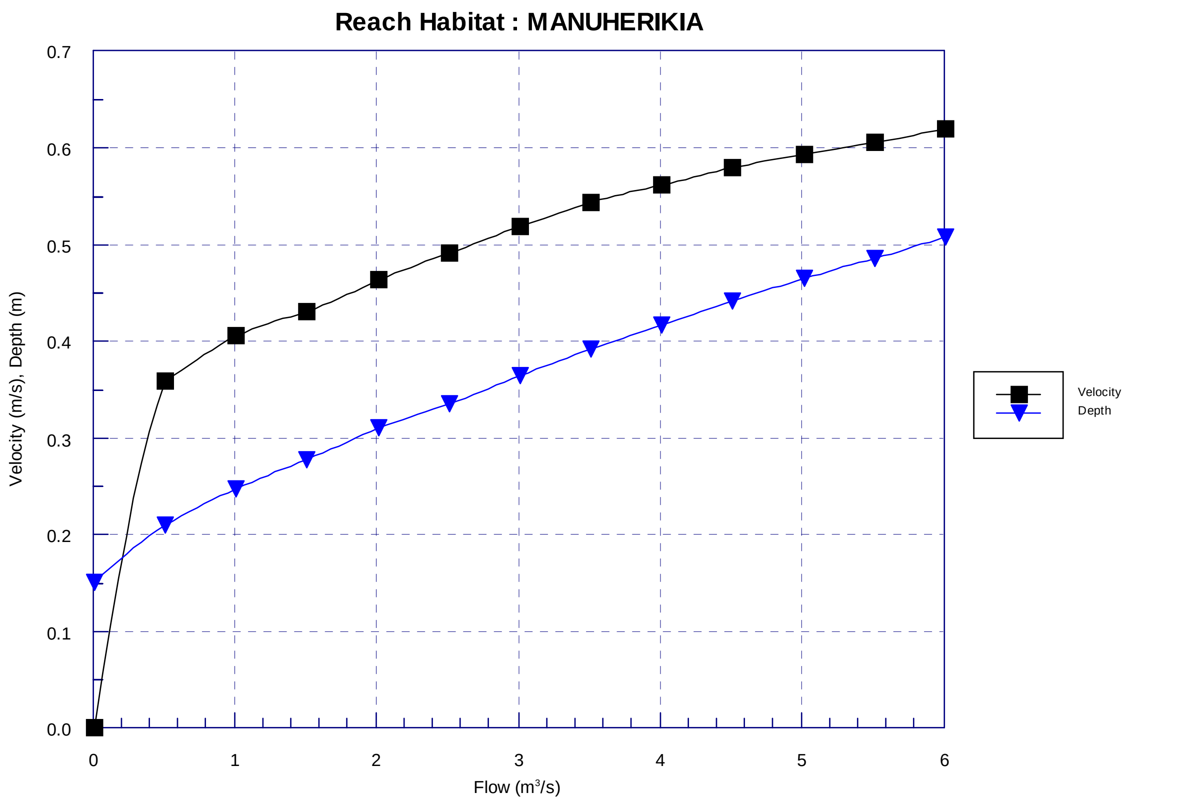

Figure 4-3: Mean velocity and depth against discharge for the Manuherikia River survey reach.

4.2 Instream habitat

WUA (m^2/m) can be used to assess flow requirements in relation to physical habitat. WUA is an aggregate measure of physical habitat quality and quantity. WUA was calculated using the habitat suitability criteria listed in Table 3-4. In this study, WUA was modelled for flows between 0 and 6 m^3/s since this was the flow range of most interest. While the study site flows are not monitored, this flow range is likely to include flows up to the median flow.

4.2.1 Periphyton

The habitat suitability criteria (HSC) for diatoms indicate a preference for fast velocities regardless of water depth (given clear water) (Appendix A). These conditions generally occur at flows greater than the modelled flows in the survey reach as indicated by the steady increase in WUA for diatoms as discharge increases (Figure 4-4). WUA for didymo and *Phormidium* increases rapidly as flow increases to 3 $\mathbf{m^3s^{-1}}$ and reduces slowly at flows increase above 4.5 $\mathbf{m^3s^{-1}}$. For long filamentous algae, generally considered nuisance algae, HSC indicate a preference shallow and slow flowing water. WUA for this group peaks at 0.5 $m^3s^{-1}$and reduces substantially as flow increases, but remains at a low level, probably in slow water at the edge of channels (Figure 4-4). Short filamentous algae HSC favour moderately deep depths and moderately fast velocities (Appendix A). This combination of conditions increases with flow so WUA for short filamentous algae peaks at 2.5 m^3s^{-1} (Figure 4-4).

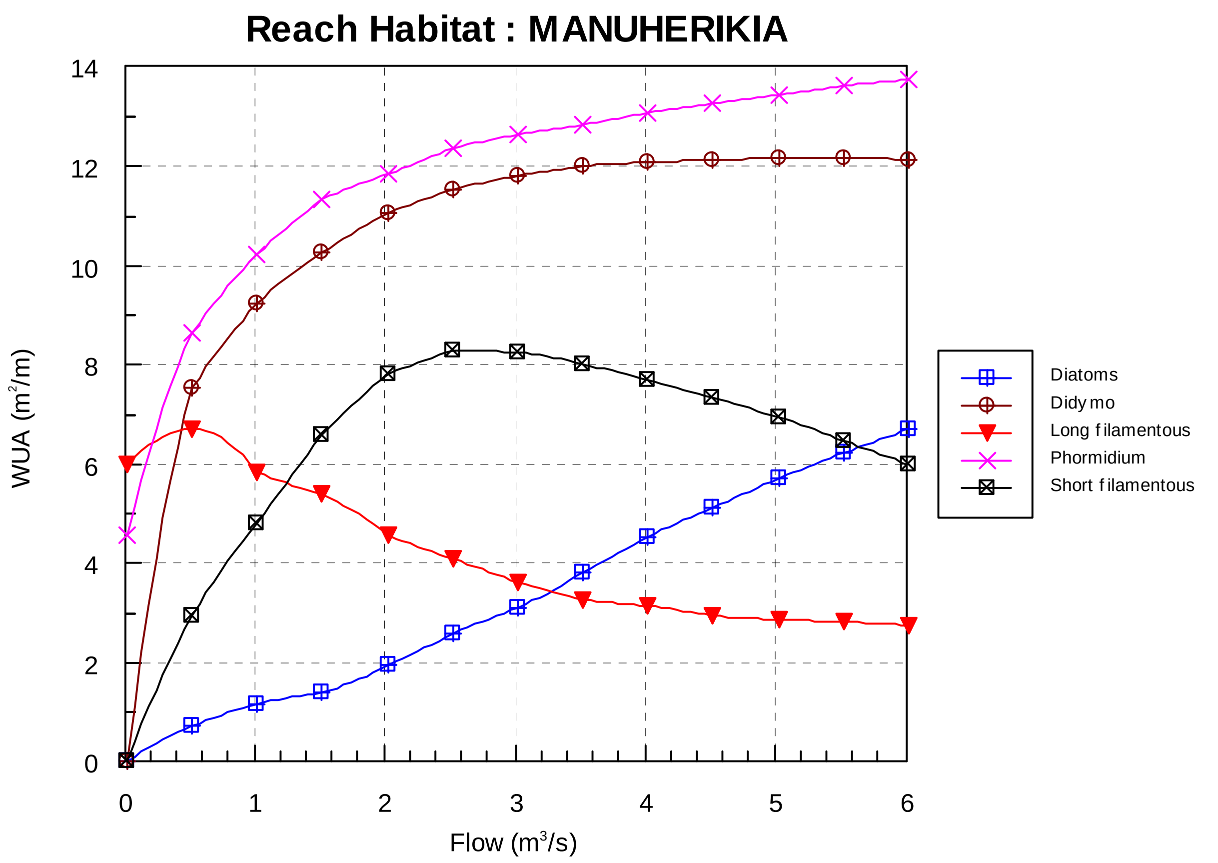

Figure 4-4: Variation of weighted useable area (WUA m^2/m) with flow for periphyton HSCs.

Figure 4-5 shows the habitat suitability index for the various periphyton communities and may be interpreted as indicating the proportion of the wetted bed that is physically suitable for each periphyton community. HSI derived from HCSs representing periphyton communities is of interest because it indicates the proportion of the wetted bed that is suitable. HSI may be more relevant for periphyton than for fish because fish can more to utilise available habitat whereas periphyton cannot move. Figure 4-5 indicates that a large proportion of the wetted river bed is high suitable for long filamentous algae at very low flows and for Phormidium across the range of modelled flows. This indicates the potential for nuisance algae blooms at lower flows.

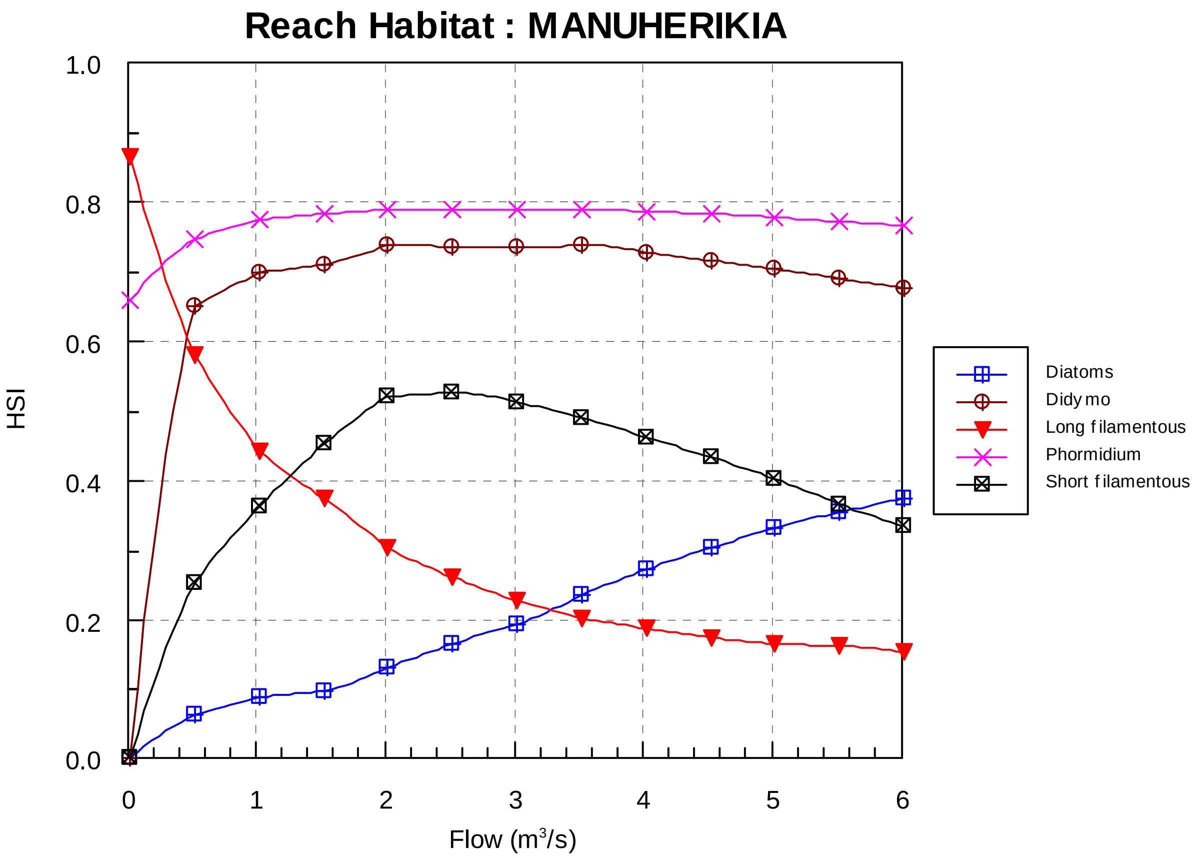

Figure 4-5: Variation in habitat suitability with flow for periphyton communities.

4.2.2 Stream invertebrates

Food producing habitat (Waters 1976) is optimised at depths between 20–80 cm, water velocities around 0.75 m/s and on cobble substrate (Appendix A). Given this combination of physical factors, WUA for food producing habitat increases with flow rapidly up to 2.5 m^3s^{-1} and then increases slowly to peak at 4.5 m^3/s (Figure 4-5).

Compared to food producing WUA, there is predicted to be greater WUA for *Deleatidium* at all discharges (Figure 4-6). Whilst their HSCs indicated that depth and substrate suitability is similar for both *Deleatidium* and food producing habitat, this particular mayfly HSC has a broader range of optimal water velocities (0.41–1.25 m/s) which results in higher predicted higher WUA across all flows. The WUA for the net spinning caddis fly (*Aoteapsyche*) increases steadily as flow increases. WUA for the stony cased caddis fly (*Pycnocentrodes*) increases rapidly with flow until 2 m^3s^{-1}, peaks at 3.5 m^3s^{-1} and then declines. WUA for midges (Orthocladinae) increases rapidly with flow until 2 m^3s^{-1} and then continues to increase slowly.

The thick drape of silt and algae on the bed material that was observed in the field indicated that it had been some time since the last flushing event. The drape is likely to reduce invertebrate abundance and there may be less effective WUA than indicated in Figure 4-5. This is because *Deleatidium* in particular prefer to graze on thin periphyton films covering the gravel and these thin films are less abundant when the bed material is covered in a drape of thicker algae and silt. While formal invertebrate sampling was not done, a few large gravel and cobble particles at most cross-sections were inspected for invertebrates and only very few cased caddis and small *Deleatidium* were found.

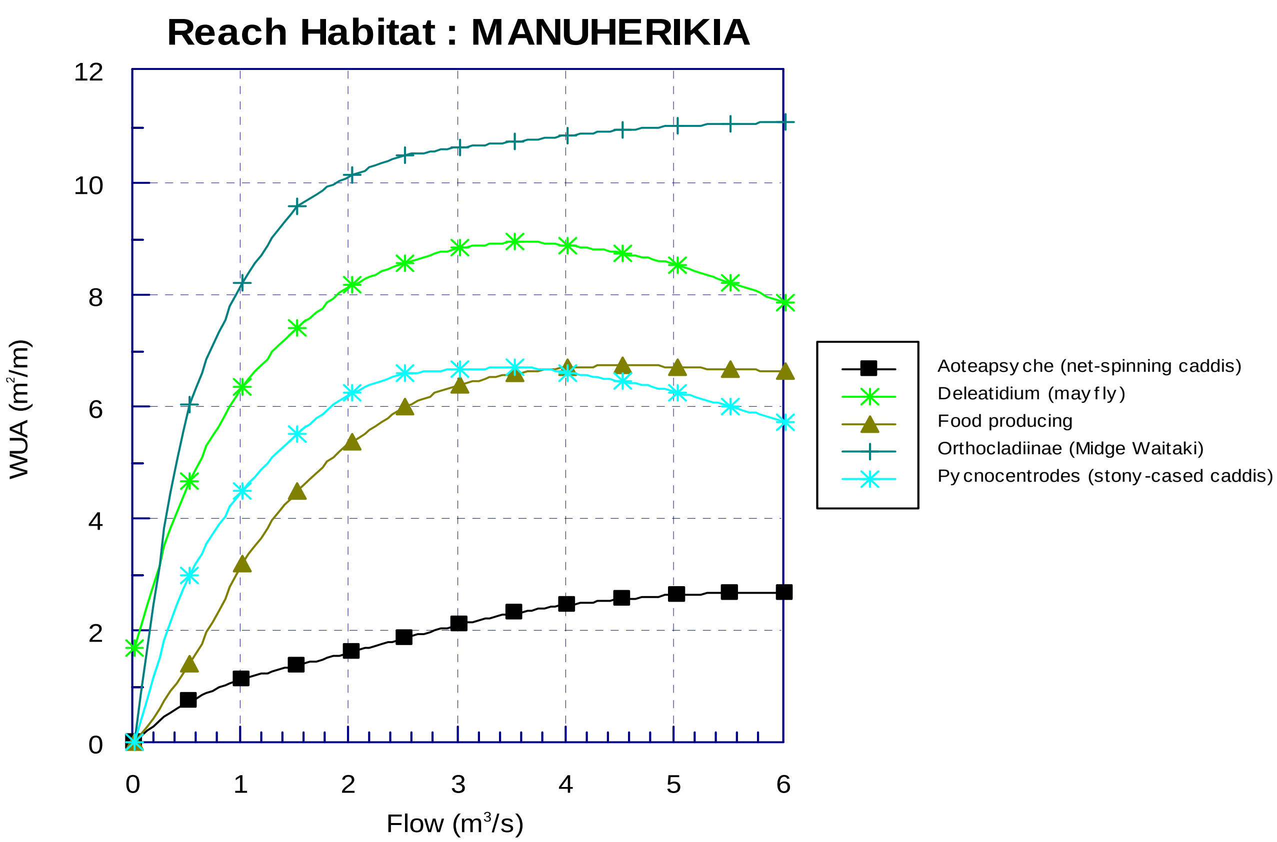

Figure 4-6: Variation of weighted useable area (WUA m^2/m) with flow for common benthic invertebrates and food producing habitat.

4.2.3 Fish

WUA for flathead galaxias adults increases rapidly to peak at 1.5 m^3s^{-1} and then shows a substantial decline with increasing flows. WUA for upland bully shows a similar trajectory, but it peaks at 1 m^3s^{-1} (Figure 4-6). For large longfin eels WUA increases to 2 m^3s^{-1} and then remains steady as flow increases. WUA for koaro has a similar relationship with flow to 2 m^3s^{-1} and then declines relatively rapidly as flow increases. Roundhead galaxias adult WUA increases rapidly to a low peak at 0.5 m^3s^{-1} and then declines as flow increases.

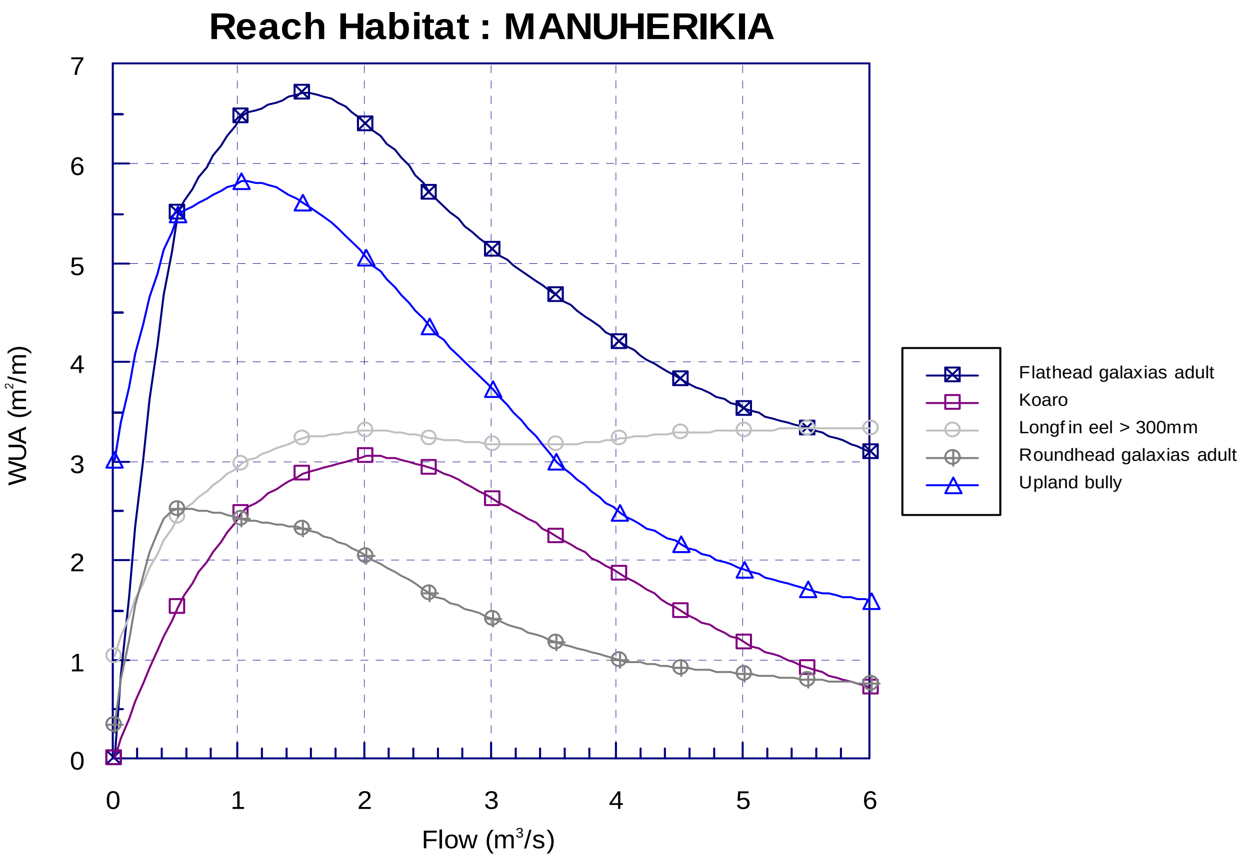

Figure 4-7: Variation of weighted useable area (WUA m^2/m) with flow for five species of native fish.

Brown trout yearling WUA increases rapidly to 2 m^3s^{-1} and then continues to increase but is more or less constant at flows greater than 4 m^3s^{-1} (Figure 4-7). Adult brown trout WUA, as predicted by both habitat suitability curves, increases consistently as flow increases. Spawning habitat peaks at 2 m^3s^{-1} (Figure 4-7).

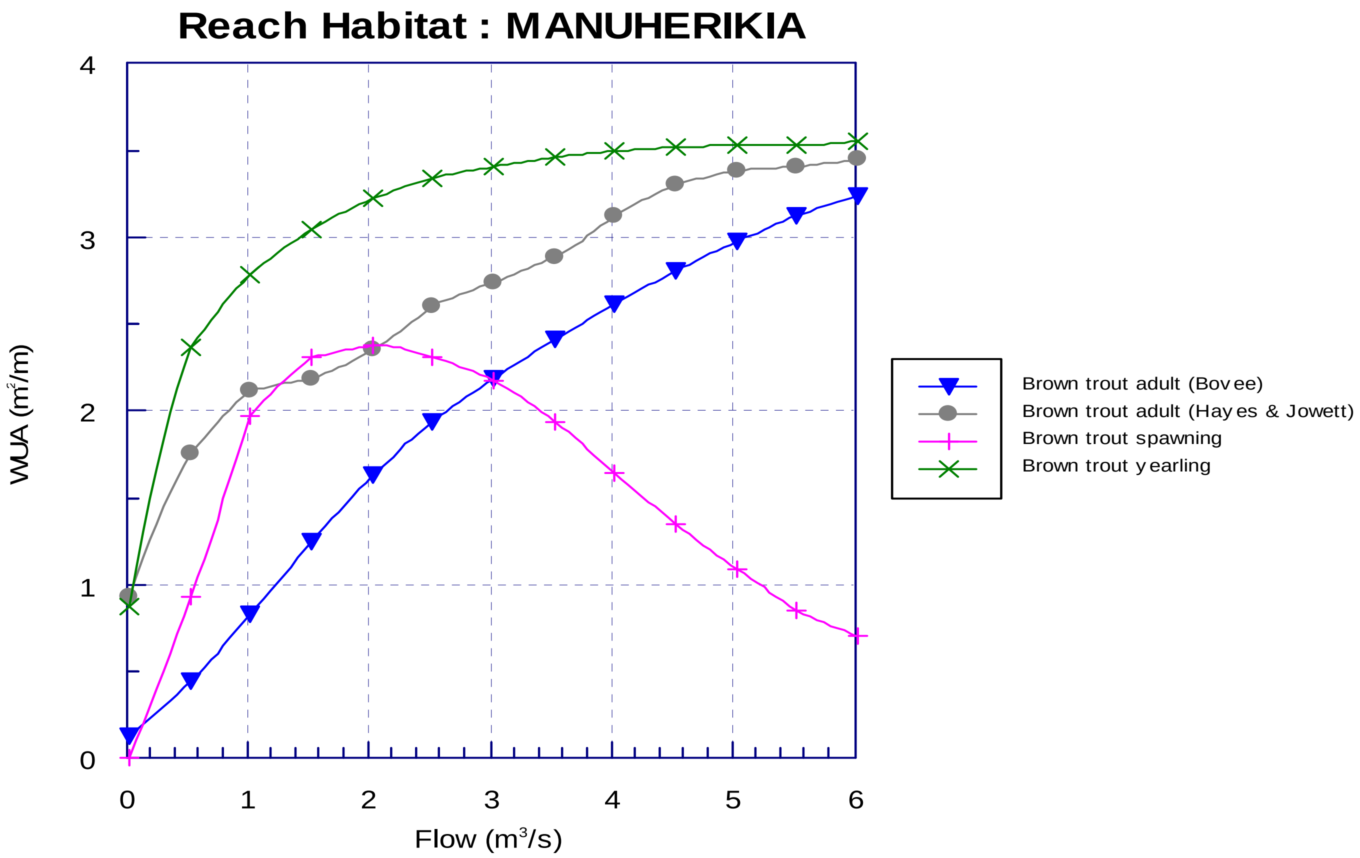

Figure 4-8: Variation of weighted useable area (WUA m^2/m) with flow for using two different habitat suitability curves for adult brown trout life stages and for brown trout spawning and yearlings.

There is relatively little WUA suitable for rainbow trout lies, but what there is increases rapidly from low discharges (Figure 4-8). Their HSC indicates that rainbow trout adults prefer to feed in deep water of moderate velocity (Appendix A), so as water depths increase so does suitable WUA that increases over the range of modelled flows, but the overall amount of WUA is low due to the lack of deep pools in the surveyed reach.

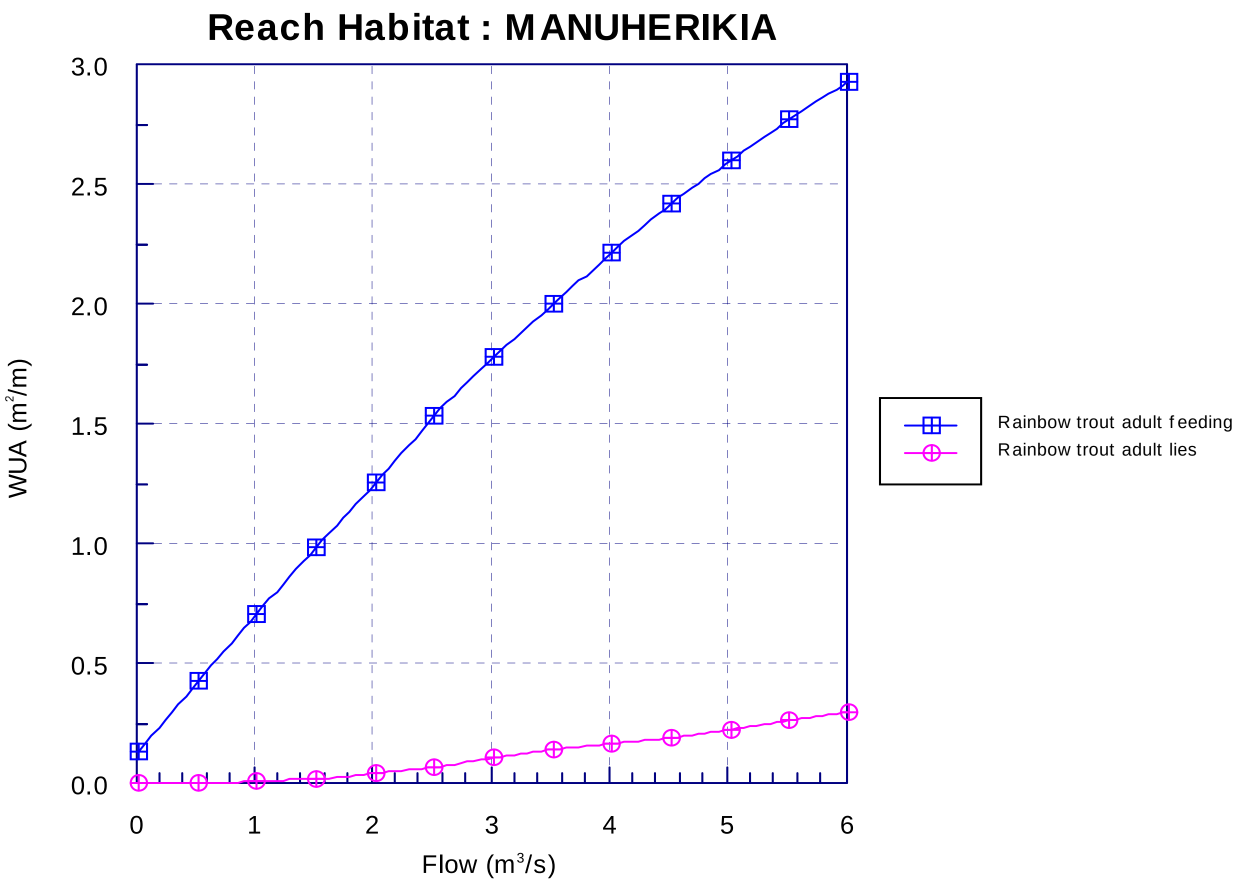

Figure 4-9: Variation of weighted useable area (WUA m2/m) with flow for rainbow trout lies.

4.2.4 Fish passage

Figure 4-10 shows fish passage using a minimum depth of 0.25 m and velocities less than 1.25 ms^{-1}. These are criteria for trout. The smaller native fish could find passage at shallower depths. The passage width increases rapidly as flows increase to 2 m^3s^{-1} and peaks in the range from 3.5 to 4.5 m^3s^{-1}.

Observations during the field survey noted that the weir and irrigation off-take near the downstream end of the study reach provide a substantial impediment to upstream fish passage for water column swimming fish and will limit their passage and recruitment much more than any limitations inherent in the natural waterway. Some native fish are benthic climbers and may be able to overcome such obstacles. Eels, koaro, shortjawed kokopu, and redfinned bullies have been found above vertical falls of 10 meters high (McDowall, 1993).

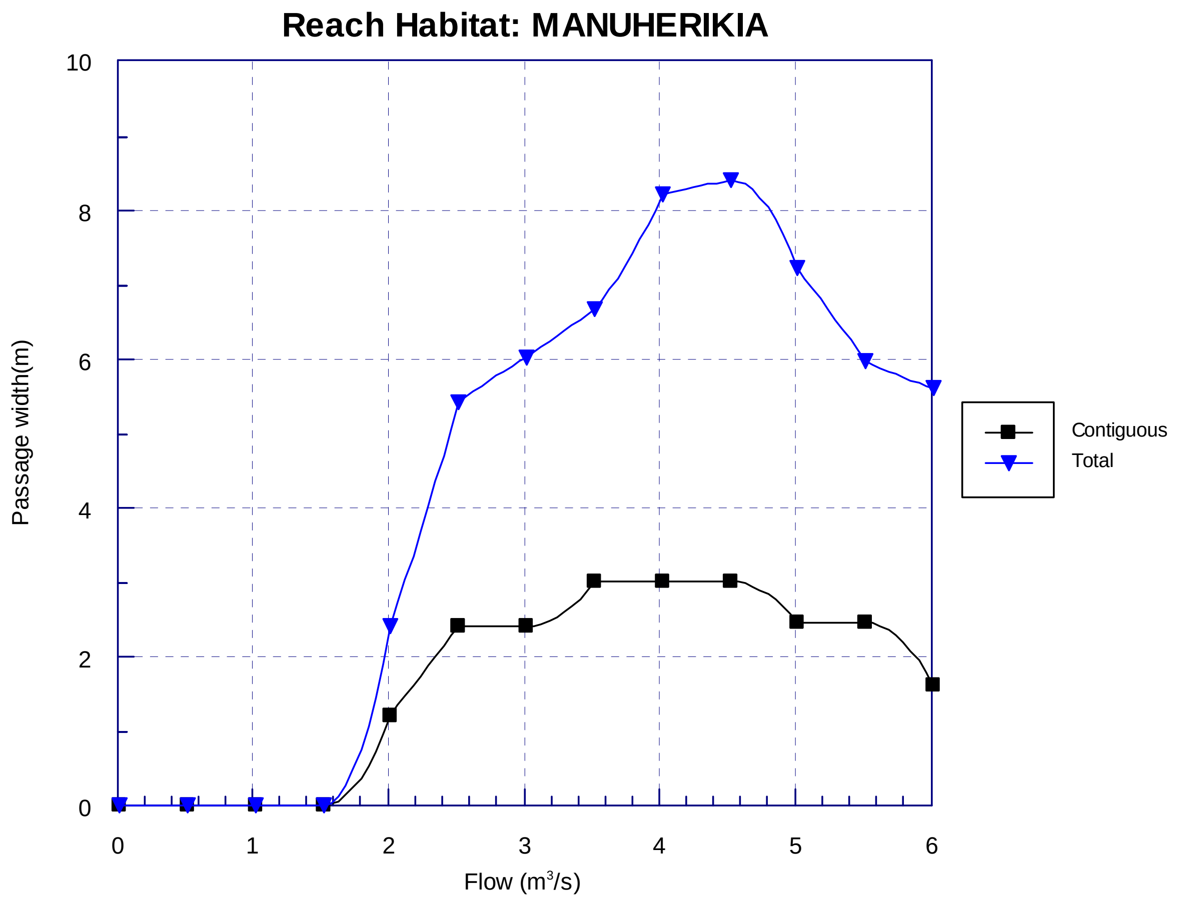

Figure 4-10: Contiguous and total fish passage width for the modelled flows.

Table 4-2 shows the contiguous and total passage width for each cross-section at the time of the survey. For the cross-sections the minimum passage width was 2.5 m and the maximum width was 17 m.

Table 4-1: The contiguous and total passage width for each cross-section at the time of the survey.

Minimum passage depth : 0.25m
Maximum passage velocity: 1.25m/s

Section	Flow (m^3s^{-1})	Continuous passage width (m)	Total (m)
SEC-1 Pool	2.45	9	9
SEC-2 Pool	2.429	9.3	9.3
SEC-3 run	1.937	11	11
SEC-4 riffle	2.091	2.5	3.3
SEC-5 run	2.142	5.9	5.9
SEC-6 riffle	2.445	4.8	4.8
SEC-7 pool	2.222	8.1	8.1
SEC-8 riffle	2.53	2.4	4.8
SEC-9 run	2.2	11.3	11.3
SEC-10 riffle	2.535	3.6	6.6
SEC-11 run	2.277	8	8
SEC-12 run	2.51	10.8	10.8
SEC-13 riffle	2.406	3.6	6.5
SEC-14 pool	2.156	9.3	9.3
SEC-15 pool	2.21	17.1	17.1
Reach minimum		**2.4**	**3.3**

4.2.5 Recreation

The pools in the river would be suitable for bathing from a depth and velocity point of view at the flows measured during the survey. Recreational benefits of kayaking or tubing the river at the survey flows would be marginal from a depth point of view and the weir downstream of the study reach would require portage of the kayaks or tubes past the weir. This is because, at the flows observed such recreation would provide little challenge and given the other opportunities in the region the study reach is unlikely to be used for kayaking or tubing. The presence in the water column of numerous particles of didymo and long filamentous algae would detract from any bathing pleasure. The thick coating of silt and algae on the bed material was also a deterrent because it was very slippery.

The river would be suitable for trout fishing, although only one trout was observed during the survey. It is very likely that the barrier associated with the irrigation off-take inhibits trout recruitment to the study reach.

4.2.6 Flow variability – flushing flows

There were on average 5.9 events/year that exceeded three times the median flow on the archived record at Ophir. However, it is not clear how representative this is of the study site where flood flows can be captured by the Falls Dam and lows flows are supplemented by irrigation flows which would affect the median flows at the site. The Ophir site flows are also affected by irrigation abstractions.

A large amount of algae (including didymo) was observed floating in the water column in the field. This may have been due to an upstream flushing effect as the amount of water being made available from the Falls Dam was increased by 50% (from 50% of the maximum abstraction rate to 75% of the maximum abstraction rate) just before the survey. This increase in flow was not observed to be having a material effect on the obvious algal and silt drape on the study reach substrate. The depth and extent of drape was so well established that it would appear that it was some time since the bed had been sufficiently disturbed to flush algae and sediment. Field observations indicated that the material on the substrate appeared to be affecting invertebrate abundance and diversity as there were only low numbers of cased caddis and small mayfly nymphs on the underside of larger substrate particles.

5 Flow regime requirements

5.1 Introduction

The selection of minimum flows is a matter of judgement, where the habitat requirements and perceived values of different freshwater attributes must be considered. Decisions need to be made about what level of habitat protection is required, either on average across the species or for specific key target species. For example, one option is to maintain 70% - 80% of maximum habitat averaged across several species. Another option is to maintain 90% maximum habitat for flow sensitive fish species. Minimum flow recommendations may be a compromise between various freshwater values, and are usually made to prevent a sharp decline in habitat for most species or to retain a percentage of the maximum habitat, thus aiming to retain some habitat for all species that make up the aquatic community present in the study area. Prevention of nuisance algae may also be considered in relation to flow requirements. Higher levels of habitat protection may also be set for rarer species or for criteria viewed to be critical to the ecological functioning of the river such as production of food for fish or removal of nuisance algae. Table 5-1 lists the optimum flow (the flow that provides maximum WUA), the breakpoint flow (for flow where WUA changes most rapidly with increasing flow) and the flow required to maintain 75 % of the optimum habitat for each species/life stage. Optimum flows (point of maximum physical habitat) range from 0.5 to >6 m^3s^{-1}. Breakpoint flows (point where physical habitat starts to decrease rapidly as flow decreases) range from 0.5 to 4 m^3s^{-1} with most in the range 1 to 2.5 m^3s^{-1}. Flows where physical habitat is 75% of the maximum flow range from 0.8 to 4 m^3s^{-1}.

Table 5-1: The optimum flow, breakpoint flow and flow required to maintain 75% of the physical habitat for each species and life stage.

Group	Species or life stage	Optimum flow (m^3s^{-1})	Break point flow (m^3s^{-1})	75% max. habitat flow (m^3s^{-1})
Periphyton	cyanobacteria	>6	1.5	1
	diatoms	>6	none	4
	didymo	5	1	0.8
	long filamentous algae	0.5	1	1.75
	short filamentous algae	2.5	2	1.4
Stream invertebrates	cased caddis fly (*Pycnocentrodes*)	3	2	1.2
	food producing	4	2	1.8
	mayfly nymphs *(Deleatidium)*	3.5	2	1.2
	midge larvae (Chironomidae)	>6	1.5	1
	net-spinning caddis fly *(Aoteapsyche)*	>6	4	2.8
Fish: trout	brown trout adult (Bovee)	>6	2.5	4
	brown trout adult (Hayes & Jowett)	>6	1	2.5

	brown trout spawning	2	1.5	0.9
	brown trout yearling	>6	1	0.8
	rainbow trout adult lies	>6	none	4.5
	rainbow trout feeding	>6	none	3.75
Fish: native				
	Central Otago roundhead galaxias	0.5	0.5	0.5
	flathead galaxias	1.5	1	0.4
	koaro	2	1	0.9
	longfin eel > 300 mm	2	0.5	0.5
	upland bully	1	0.5	0.25

5.2 Minimum flows

Low flows can limit the amount of available suitable physical habitat and it is often assumed that frequently occurring low flows will limit fish populations. The mean annual low flow has been used as a measure of frequently occurring low flows affecting population levels for long-lived fish species (e.g., Jowett 1992). Alternatively, minimum flows are often selected so that they prevent a serious decline in habitat or the flow below which habitat declines sharply. However, effects on ecosystem health depend to some extent on the amount of time that the flow is likely to be at that minimum because when low flows persist periphyton tends build up and trap silt... Because of the arid climate and high irrigation demand in the Manuherikia catchment, flows are likely to be at the minimum flow for much of the irrigation season (September to April) and this should be kept in mind when setting the minimum flow.

The length of river of most relevance for minimum flow setting in this case is the 13 km of the Manuherikia River between its confluence with Dunstan Creek and Loop Road. There are no large tributaries contributing flow to this reach. The minimum flow downstream of the Dunstan Creek Confluence may well need to be greater than for the study reach. Options for transferring a minimum flow from the study reach to downstream of the Dunstan Creek Confluence might include adjusting by catchment area or estimated 7day-MALF at the two locations.

Figure 5-2 gives the WUA for each species over the range of modelled flows for the 2370 m study reach and may be useful for determining minimum flows.

Table 5-2: **WUA (m²) at different flows over the 2370 m study reach.**

Flow (m^3s^{-1})	0	1	2	3	4	5	6
Diatoms	0	2,370	4,740	7,110	10,191	13,746	15,405
Didymo	0	21,804	26,070	27,966	28,677	28,677	28,677
Long filamentous	14,220	13,746	10,665	9,006	7,584	7,110	6,636
Phormidium	10,428	24,411	28,203	29,862	30,810	31,758	32,706
Short filamentous	0	11,376	18,486	19,197	18,486	16,590	14,220
Flathead galaxias	0	15,405	14,931	12,324	9,954	8,295	7,584
Koaro	0	5,688	7,347	6,162	4,266	2,844	1,896
Longfin eel >300 mm	711	6,992	7,821	7,466	7,584	7,821	7,940
Roundhead galaxias	0	5,807	4,740	3,318	2,370	1,896	1,659
Upland bully	0	13,746	12,087	9,006	5,688	4,503	4,029
Brown trout adult	474	1,896	3,911	5,214	6,044	6,873	7,584
Brown trout adult	2,133	5,096	5,570	6,399	7,466	8,058	8,224
Brown trout yearling	2,015	6,636	7,584	7,940	8,177	8,295	8,295
Brown trout spawning	0	4,503	5,570	5,096	3,911	2,489	1,659
Rainbow trout lies	0	24	83	261	379	545	687
Aoteapsyche	0	2,370	3,674	4,859	5,214	5,451	5,451
Deleatidium	4,266	14,694	19,197	20,619	20,619	19,908	18,723
Food Producing	0	7,347	12,561	14,813	15,405	15,405	15,168
Orthocladinae	0	19,671	23,937	24,885	25,359	25,833	25,975
Pycnocentrodes	0	10,665	14,576	15,287	14,813	14,457	13,746
Bed area (m²)		31,047	34,365	37,720	39,105	40,290	42,660

5.3 Minimum flow options

This section considers the implications of different minimum flows on ecological values over the range of modelled flows.

5.3.1 Minimum flow 0.5 m^3s^{-1}

- Periphyton: optimum physical habitat (WUA) for nuisance long filamentous algae, relatively low levels of didymo and cyanobacteria and low levels of the preferred diatoms and short filamentous algae, although the wetted bed area would be relatively low (~27,000 m²).
- Invertebrates: low amounts of WUA for all groups.
- Native fish: less than optimum WUA for most species. Optimum flow for adult Central Otago round head galaxias.
- Brown and rainbow trout: far from optimum WUA for all species and life-stages.

- Fish passage: no passage for trout, but passage possible for most benthic native species.

5.3.2 Minimum flow 1.0 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae, break point flow for didymo, and retention of ~ 50% of short filamentous algae WUA.
- Invertebrates: increased WUA compared to lower flows, but still low amounts of WUA for all groups.
- Native fish: more than 75% of maximum WUA for all species retained at this flow. Optimum WUA for upland bully.
- Brown and rainbow trout: retention of >75% of maximum WUA for brown trout spawning and yearlings. Breakpoint for brown trout adult (Bovee) and yearlings.
- Fish passage: no passage for trout, but passage available for most benthic native species.

5.3.3 Minimum flow 1.5 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae, break point flow for cyanobacteria, and retention of ~ 75% of maximum WUA for short filamentous algae.
- Invertebrates: more than 75% retention of maximum WUA except for total food production and net-spinning caddis.
- Native fish: more than 75% of maximum WUA retained for all species at this flow. Optimum WUA for adult flat head galaxias.
- Brown and rainbow trout: retention of >75% of maximum WUA for brown trout spawning and yearlings. Near optimum WUA for brown trout spawning. Considerably less than optimum for adult brown trout and rainbow trout life-stages.
- Fish passage: no passage for trout, but passage available for most benthic native species.

5.3.4 Minimum flow 2.0 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae (<75%), break point flow for short filamentous algae, retention of ~75% of maximum WUA for all groups except diatoms.
- Invertebrates: more than 75% retention of maximum WUA except for net-spinning caddis. Breakpoint flow for cased caddis, food production and mayfly nymphs.
- Native fish: more than 75% of maximum WUA retained for all species at this flow. Optimum WUA for koaro and large longfin eels. WUA starting to decline for other native fish.
- Brown and rainbow trout: retention of >75% of maximum WUA yearlings. Optimum WUA for brown trout spawning. Way less than optimum for adult brown trout and rainbow trout life-stages.
- Fish passage: one third (1 m) of maximum contiguous passage for trout, and passage available for native species.

5.3.5 Minimum flow 2.5 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae (<60%), optimum flow for short filamentous algae, retention of ~75% of maximum WUA for all other groups except diatoms.
- Invertebrates: more than 75% retention of maximum WUA for all species except for net-spinning caddis.
- Native fish: more than 75% of maximum WUA retained for all species at this flow. WUA starting to decline for all but large longfin eels.
- Brown and rainbow trout: retention of >75% of maximum WUA for brown yearlings except adult brown trout (Hayes and Jowett). Less than optimum for adult brown trout and rainbow trout life-stages.
- Fish passage: 77% of maximum (~2.4 m) contiguous passage for trout, and passage available for native species.

5.3.6 Minimum flow 3.0 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae (~50%), optimum flow for short filamentous algae, and retention of ~ 75% of maximum WUA for all other groups except diatoms.
- Invertebrates: more than 75% retention of maximum WUA.
- Native fish: less than 75% of maximum WUA retained for all species at this flow except for koaro and large longfin eels. WUA declining except for large longfin eels.
- Brown and rainbow trout: retention of >75% of maximum WUA for brown trout spawning, yearlings and adults (Bovee). Less than optimum for adult brown trout and rainbow trout life-stages.
- Fish passage: 77% of maximum (~2.4 m) contiguous passage for trout, and passage available for native species.

5.3.7 Minimum flow 4.0 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae (<50%), retention of >75% of WUA for all other groups. WUA for short filamentous algae declining.
- Invertebrates: more than 75% retention of maximum WUA for all species.
- Native fish: less than 75% of maximum WUA retained for all species at this flow except large longfin eels. WUA declining except for large longfin eels.
- Brown and rainbow trout: retention of >75% of maximum WUA for all trout life-stages except for brown trout spawning.
- Fish passage: maximum (~3.0 m) contiguous passage for trout, and passage available for native species.

5.3.8 Minimum flow 5.0 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae (<50%), retention of >75% of WUA for all other groups. WUA for short filamentous algae declining.
- Invertebrates: more than 75% retention of maximum WUA for all species.
- Native fish: less than 75% of maximum WUA retained for all species at this flow except for large longfin eels. WUA continuing to decline except that for large longfin eels.
- Brown and rainbow trout: retention of >75% of maximum WUA for all trout life-stages except for that for brown trout spawning which continues to decline.
- Fish passage: starting to decline with ~2.4 m of contiguous passage for trout, and passage available for native species.

5.3.9 Minimum flow 6.0 m^3s^{-1}

- Periphyton: reducing WUA for nuisance long filamentous algae (<40%), retention of >75% of WUA for all other groups. WUA for short filamentous algae declining.
- Invertebrates: more than 75% retention of maximum WUA for all species with WUA for some species starting to decline.
- Native fish: much less than 75% of maximum WUA retained for all species at this flow except for large longfin eels. WUA continuing to decline except that for large longfin eels.
- Brown and rainbow trout: retention of >75% of maximum WUA for all trout life-stages except for that for brown trout spawning which continues to decline.
- Fish passage: declining with ~1.6 m) contiguous passage for trout, and passage available for native species.

The ability of various minimum flow options to maintain freshwater values can be informed by assessing the effect on WUA for various freshwater attributes. The community may deem that it is necessary to maintain life-supporting capacity by providing habitat for native fish and their prey. It should also be noted that because of the climate and irrigation demand the river is likely to be at the minimum flow for months at a time.

5.4 Methodological considerations

When determining an appropriate minimum flow it is also important to consider the species that currently occur in the reach, their abundance and protection level. For fish communities, upland bullies and brown trout have been observed in the Manuherikia River. Whatever minimum flow is proposed should be weighted in favour of these species.

Existing generic HSCs were applied in this study. It should be noted that results would change were the analysis to be repeated with different HSCs. See Kelly et al., (2015) for discussion of sensitivity of results to changes in HSCs and how results for invertebrates may alter when local rather than generic HSCs are applied.

6 Conclusions

- Physical habitat modelling was used to assess the effects of changes in flows on instream physical habitat and aquatic species in the Manuherikia River catchment.
- The habitat modelling results show how different minimum flows alter instream ecological values. The trade-off in habitat retention/loss for different ecological values is illustrated in Figures 4-4 to 4.10.
- The effects on ecological values of the range of modelled flows has been listed to enable an appreciation of how availability of suitable physical habitat for various species would be enhanced or reduced by the selection of a particular minimum flow.
- A minimum flow of 2 m^3s^{-1} would mean that 78% of fish habitat and 79% of maximum habitat for all modelled HSCs (including that of nuisance periphyton), on average, would be retained.
- A minimum flow of 2 m^3s^{-1} would mean that 92% of native fish maximum WUA would be retained as well as 86% of benthic macro-invertebrate WUA.
- The Manuherikia River at the study site has long periods of relatively low flows that results in a build-up of silt and periphyton on the river bed substrate, and this probably limits the availability of suitable physical habitat, so the WUA values modelled probably represent an upper value for the amount of habit that is able to be used.
- The weir and irrigation off-take near the downstream end of the study reach provide a substantial impediment to upstream fish passage to water column swimming fish and will limit fish passage and recruitment much more than any limitations inherent in the natural waterway.

7 Acknowledgements

We thank Martin Robertson and Ginny Sutton (NIWA) for the flow gaugings. Thanks also to Dr Doug Booker for his constructive review.

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Appendix A Photographs of the surveyed cross-sections of the Manuherikia River

Figure B-1. Section 1.

Figure B-2. Section 2

Figure B-3. Section 3.

Figure B-4. Section 4.

Figure B-5. Section 5.

Figure B-6. Section 6.

Figure B-7. Section 7.

Figure B-8. Section 8.

Figure B-9. Section 9.

Figure B-10. Section 10.

Figure B-11. Section 11.

Figure B-12. Section 12.

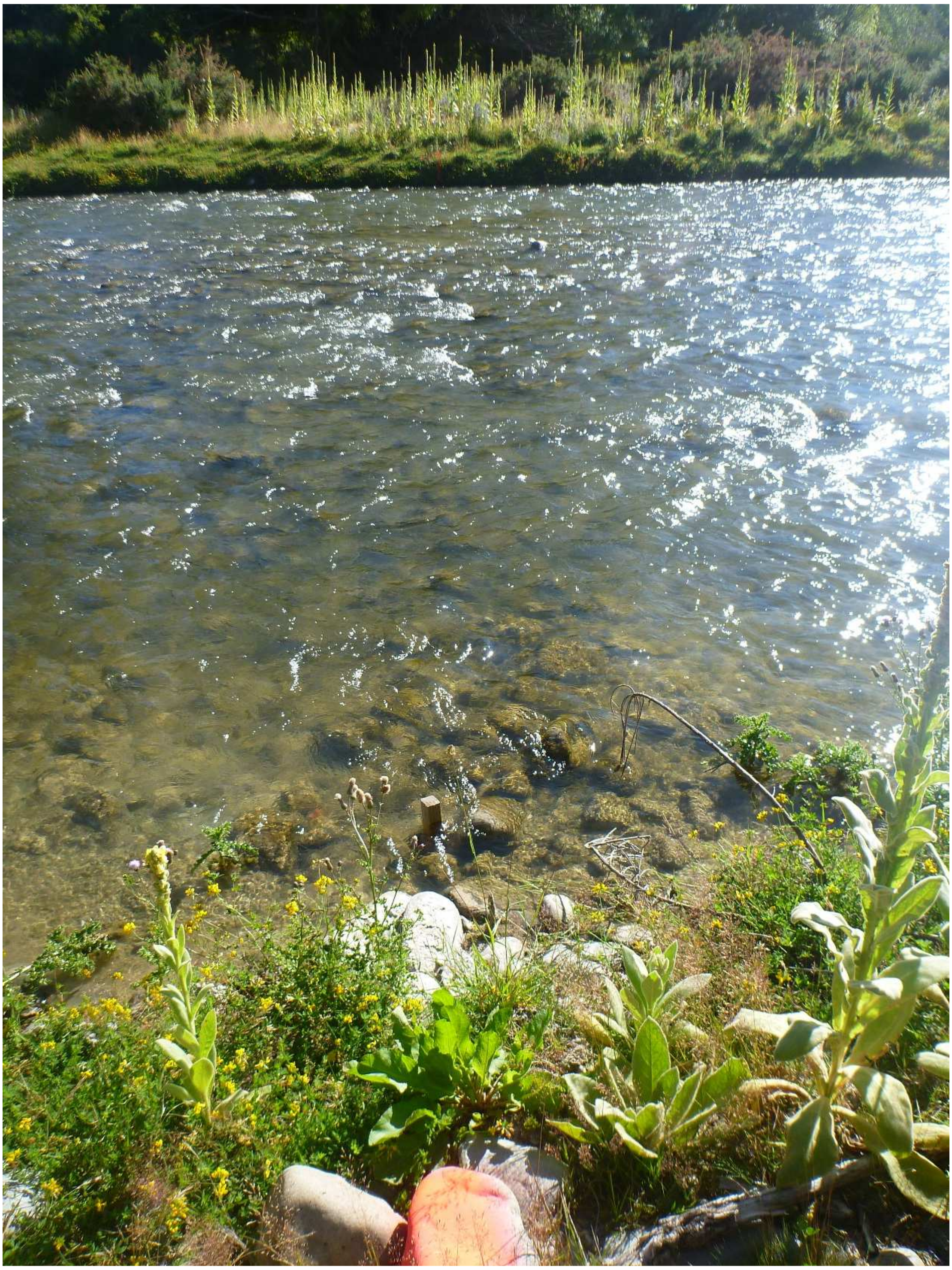


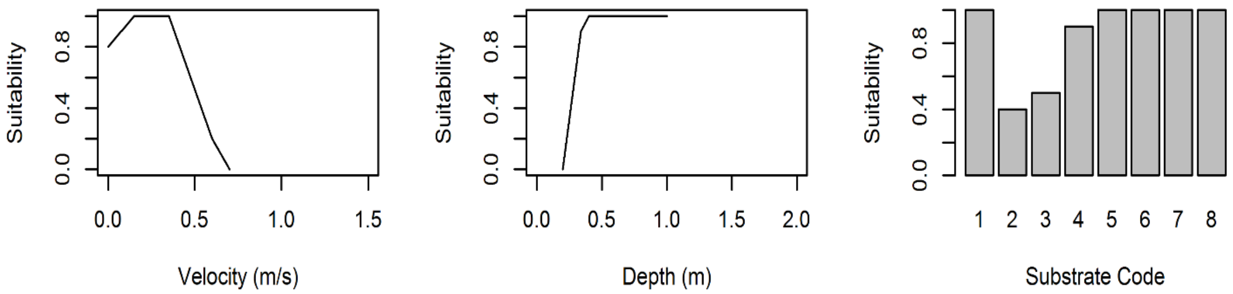
Figure B-13. Section 13.

Figure B-14. Section 14.

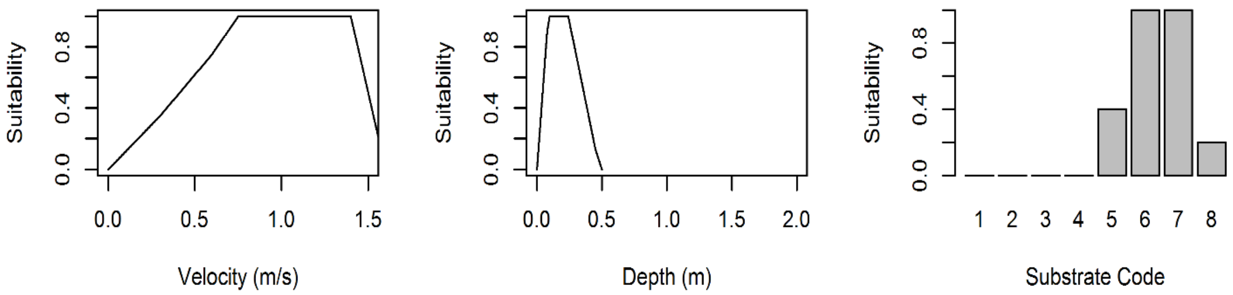
Figure B-15. Section 15.

Appendix B Habitat suitability criteria

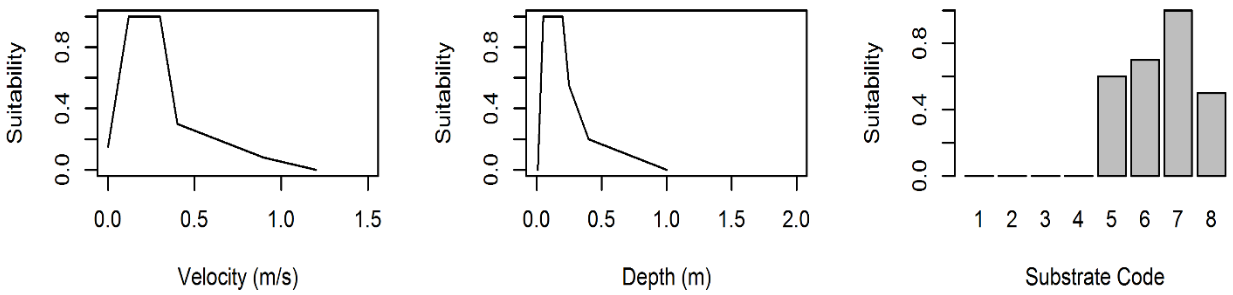
Longfin eel > 300mm
Jowett & Richardson 2008



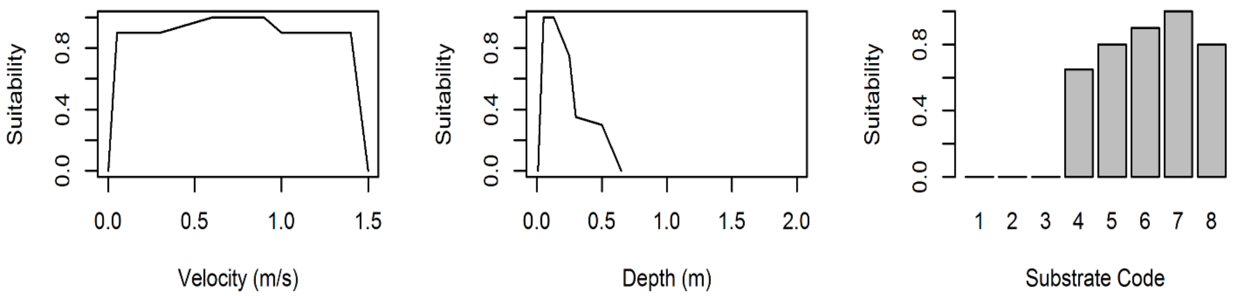
Koaro
Jowett & Richardson 2008

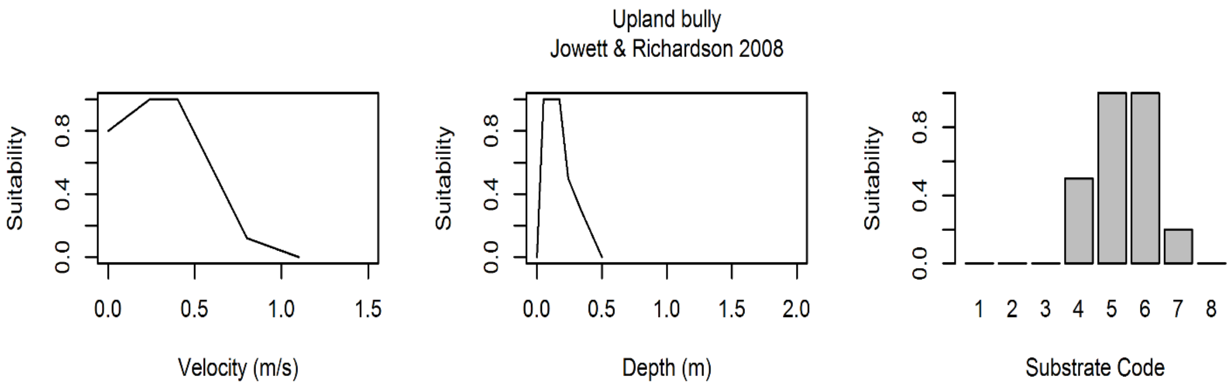


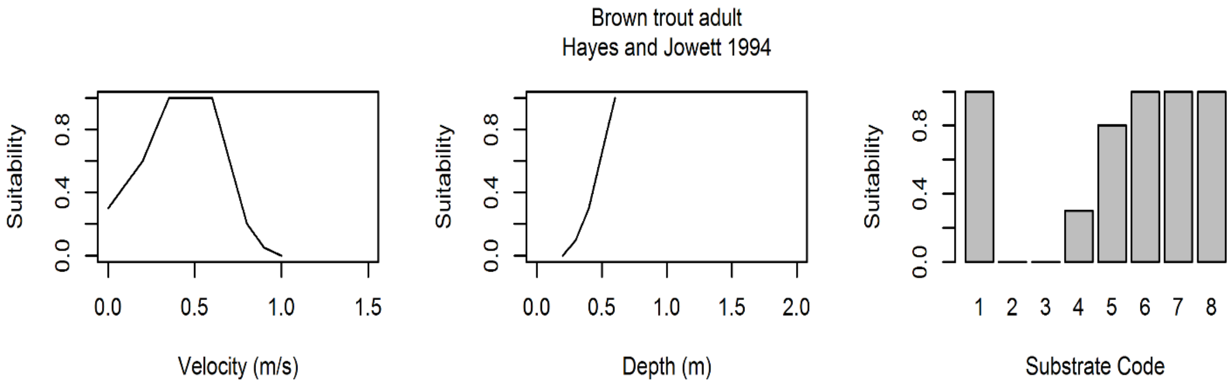
Roundhead galaxias adult
Jowett & Richardson 2008

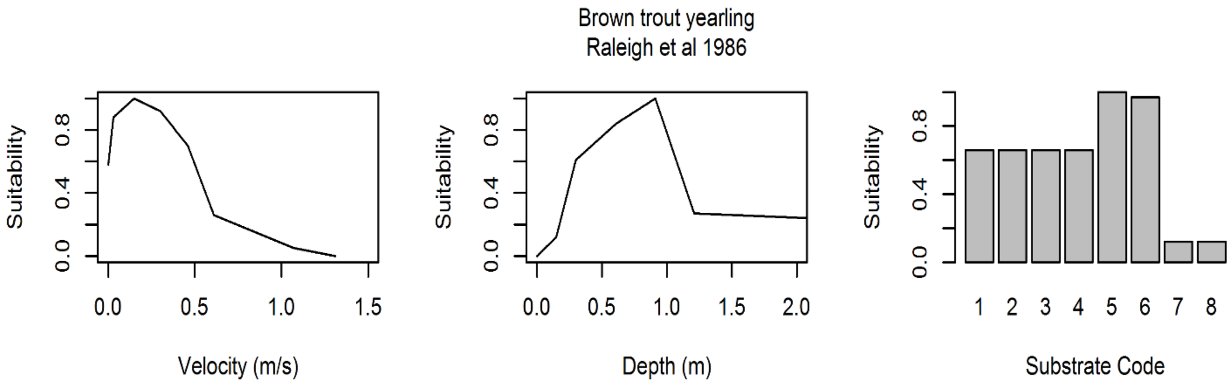


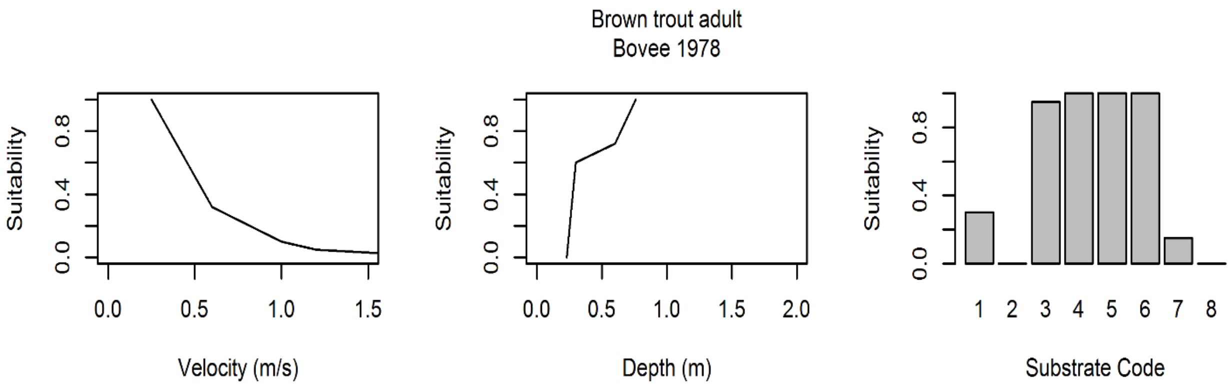
Flathead galaxias adult
Jowett & Richardson 2008

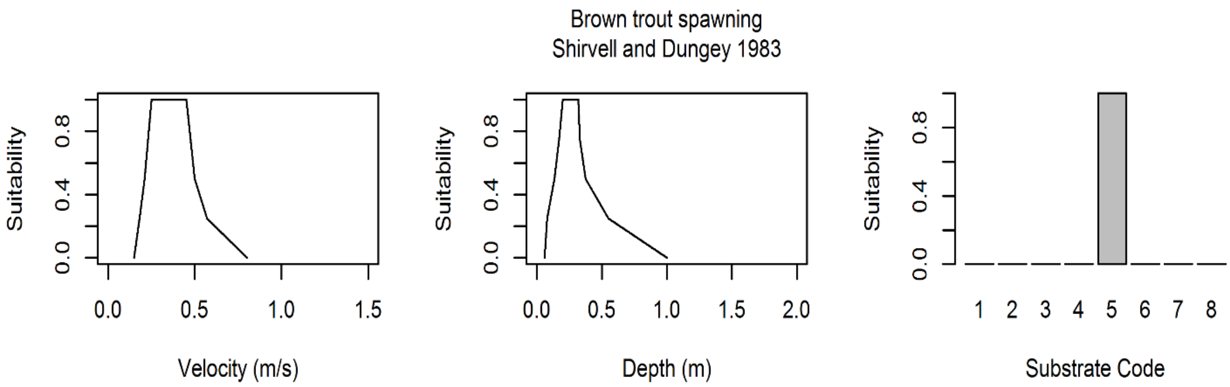


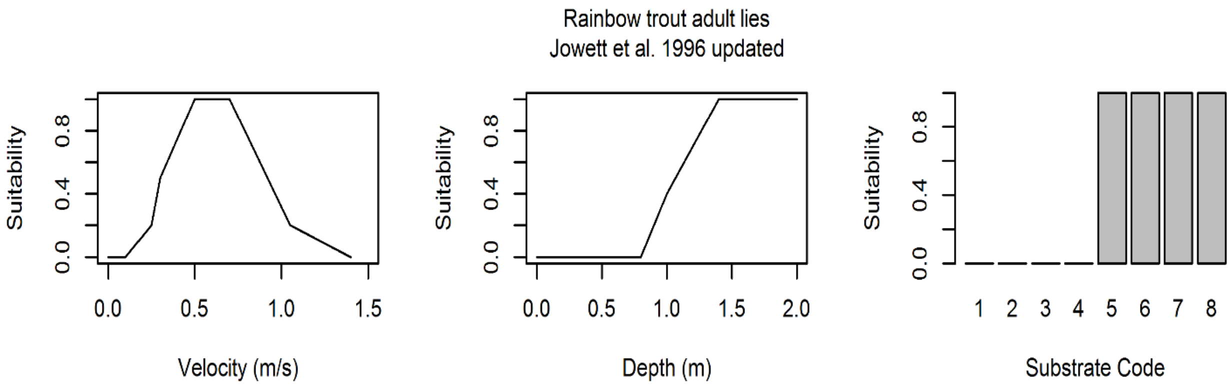

Upland bully
Jowett & Richardson 2008
Suitability
Velocity (m/s)
Depth (m)
Substrate Code

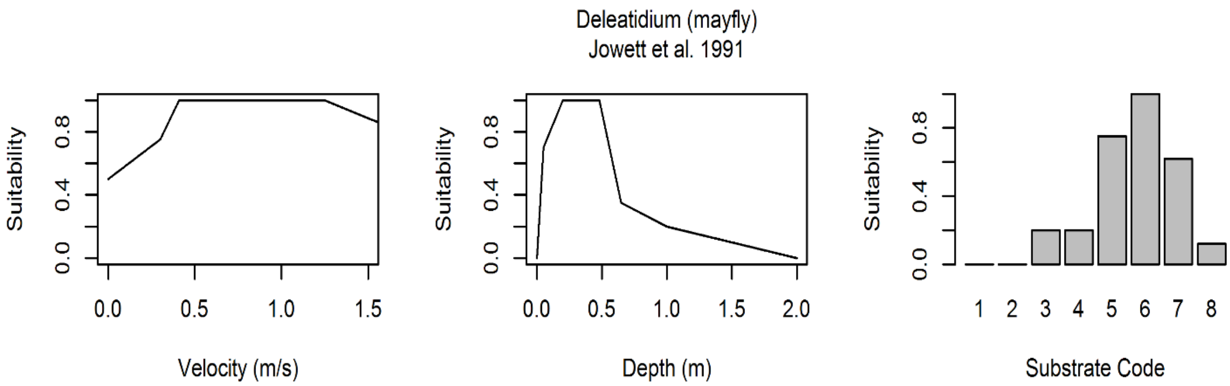

Brown trout adult
Hayes and Jowett 1994
Suitability
Velocity (m/s)
Depth (m)
Substrate Code

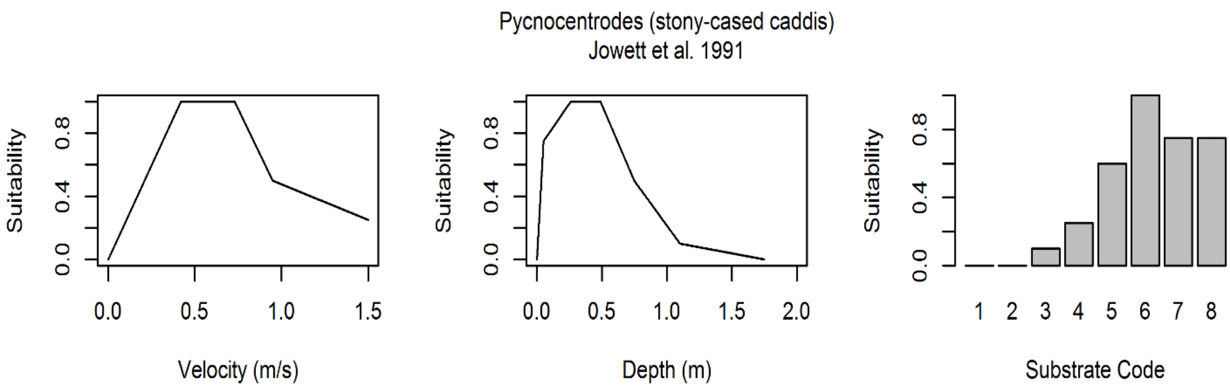

Brown trout yearling
Raleigh et al 1986
Suitability
Velocity (m/s)
Depth (m)
Substrate Code

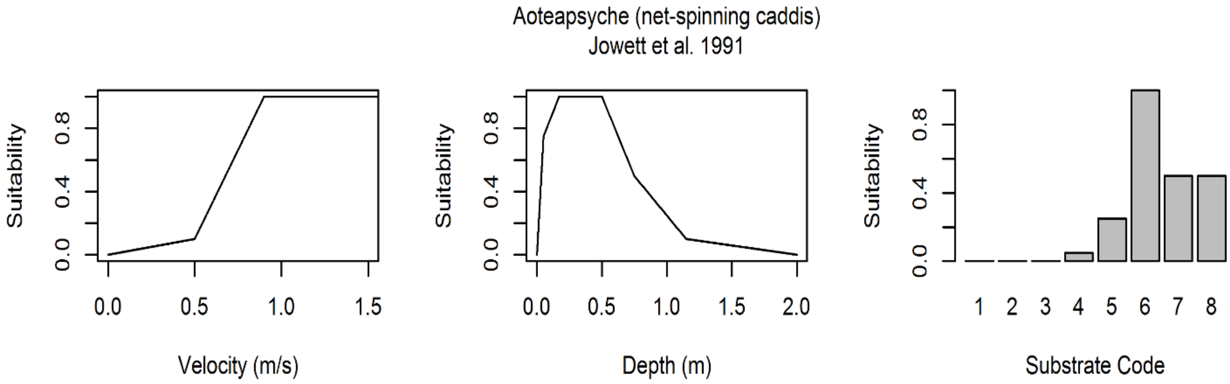

Brown trout adult
Bovee 1978
Suitability
Velocity (m/s)
Depth (m)
Substrate Code

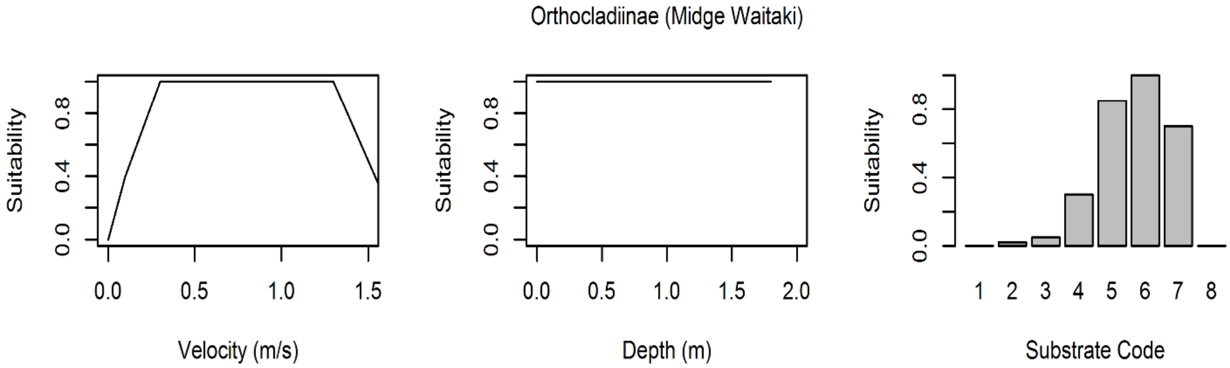

Brown trout spawning
Shirvell and Dungey 1983
Suitability
0.0 0.4 0.8
0.0 0.5 1.0 1.5
Velocity (m/s)
0.0 0.5 1.0 1.5 2.0
Depth (m)
1 2 3 4 5 6 7 8
Substrate Code

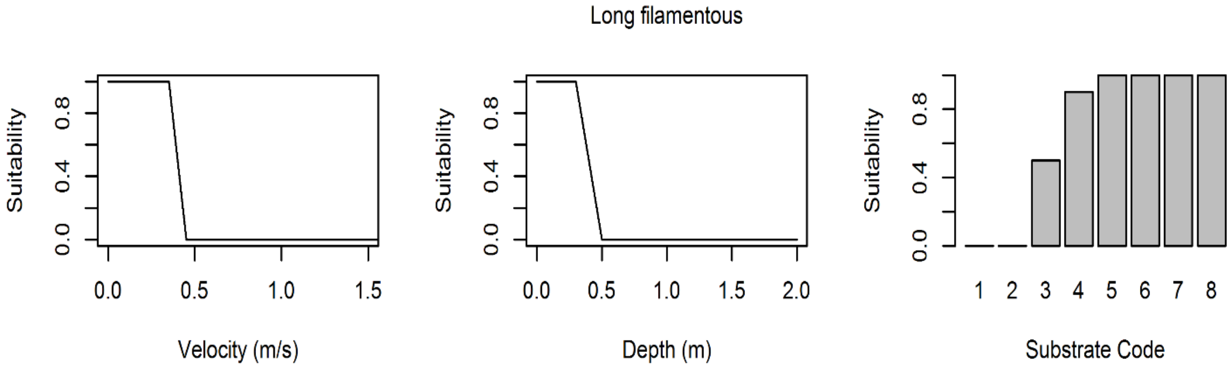

Rainbow trout adult lies
Jowett et al. 1996 updated
Suitability
0.0 0.4 0.8
0.0 0.5 1.0 1.5
Velocity (m/s)
0.0 0.5 1.0 1.5 2.0
Depth (m)
1 2 3 4 5 6 7 8
Substrate Code

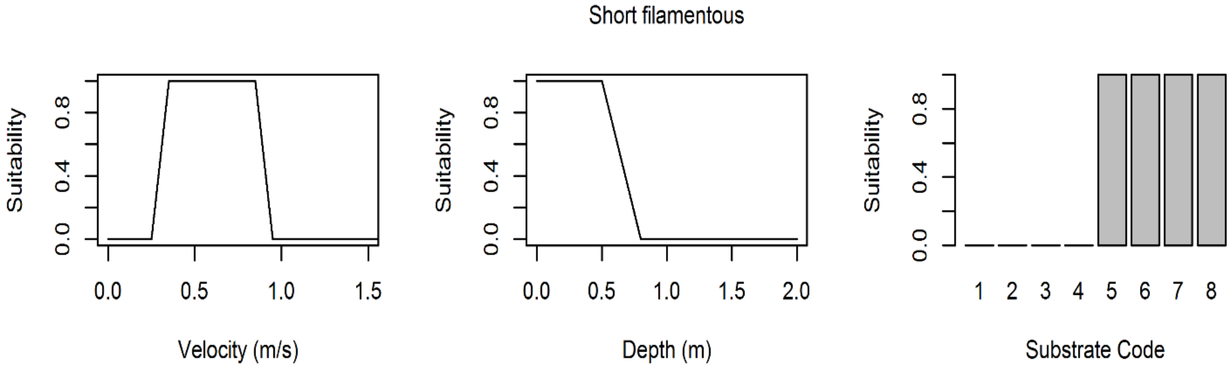

Deleatidium (mayfly)
Jowett et al. 1991
Suitability
0.0 0.4 0.8
0.0 0.5 1.0 1.5
Velocity (m/s)
0.0 0.5 1.0 1.5 2.0
Depth (m)
1 2 3 4 5 6 7 8
Substrate Code

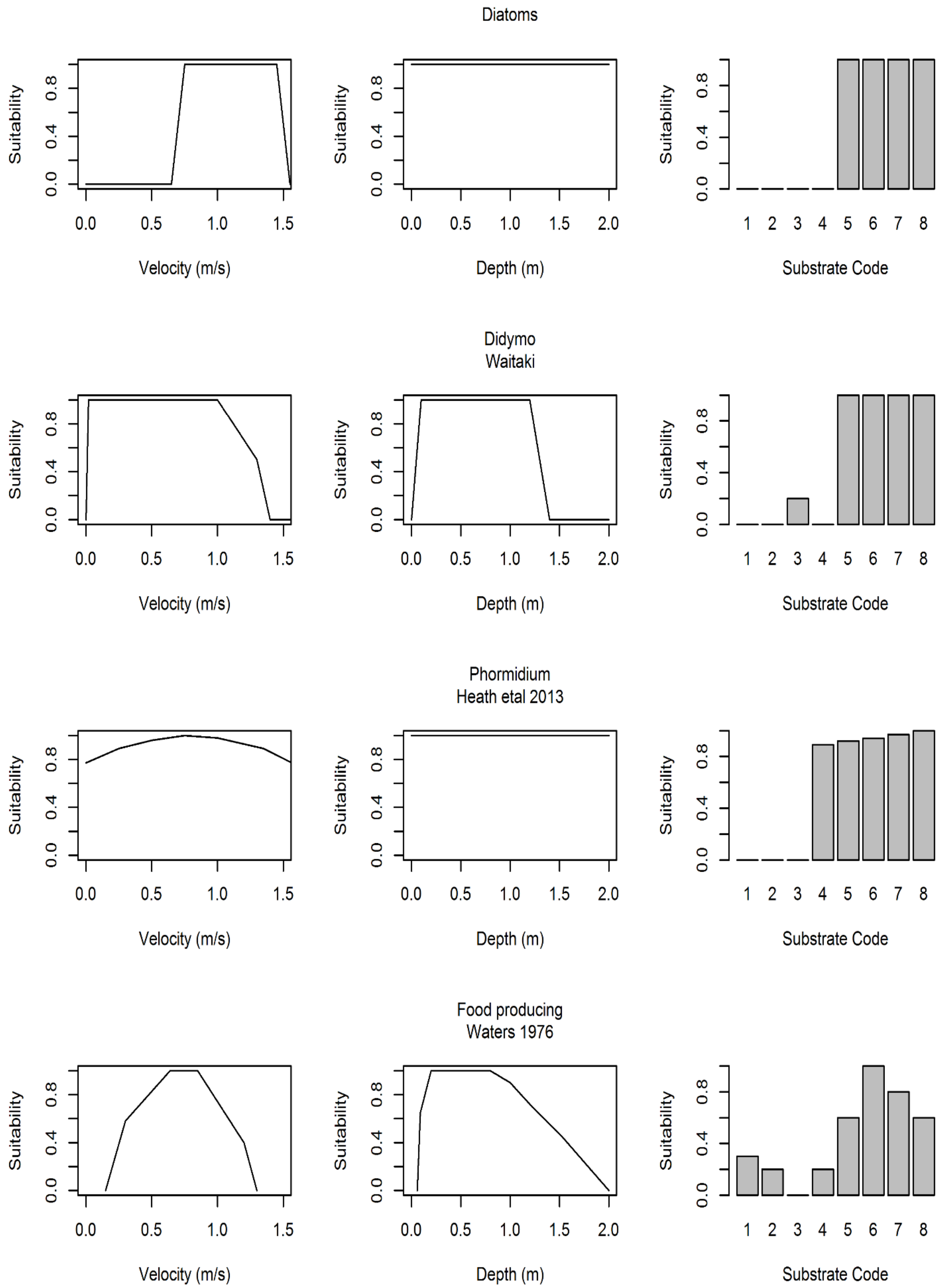

Pycnocentrodes (stony-cased caddis)
Jowett et al. 1991
Suitability
0.0 0.4 0.8
0.0 0.5 1.0 1.5
Velocity (m/s)
0.0 0.5 1.0 1.5 2.0
Depth (m)
1 2 3 4 5 6 7 8
Substrate Code


Aoteapsyche (net-spinning caddis)
Jowett et al. 1991
Suitability
Velocity (m/s)
Depth (m)
Substrate Code


Orthocladiinae (Midge Waitaki)
Suitability
Velocity (m/s)
Depth (m)
Substrate Code


Long filamentous
Suitability
Velocity (m/s)
Depth (m)
Substrate Code


Short filamentous
Suitability
Velocity (m/s)
Depth (m)
Substrate Code


Diatoms
Didymo
Waitaki
Phormidium
Heath etal 2013
Food producing
Waters 1976
Suitability
0.0
0.4
0.8
Velocity (m/s)
0.0
0.5
1.0
1.5
Depth (m)
0.0
0.5
1.0
1.5
2.0
Substrate Code
1
2
3
4
5
6
7
8