NZ Freshwater Miscellaneous Report No. 46

MINIMUM FLOW REQUIREMENTS FOR INSTREAM HABITAT IN THE WAIAU RIVER, SOUTHLAND, FROM THE MARAROA WEIR TO THE BORLAND BURN

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MAY
1993

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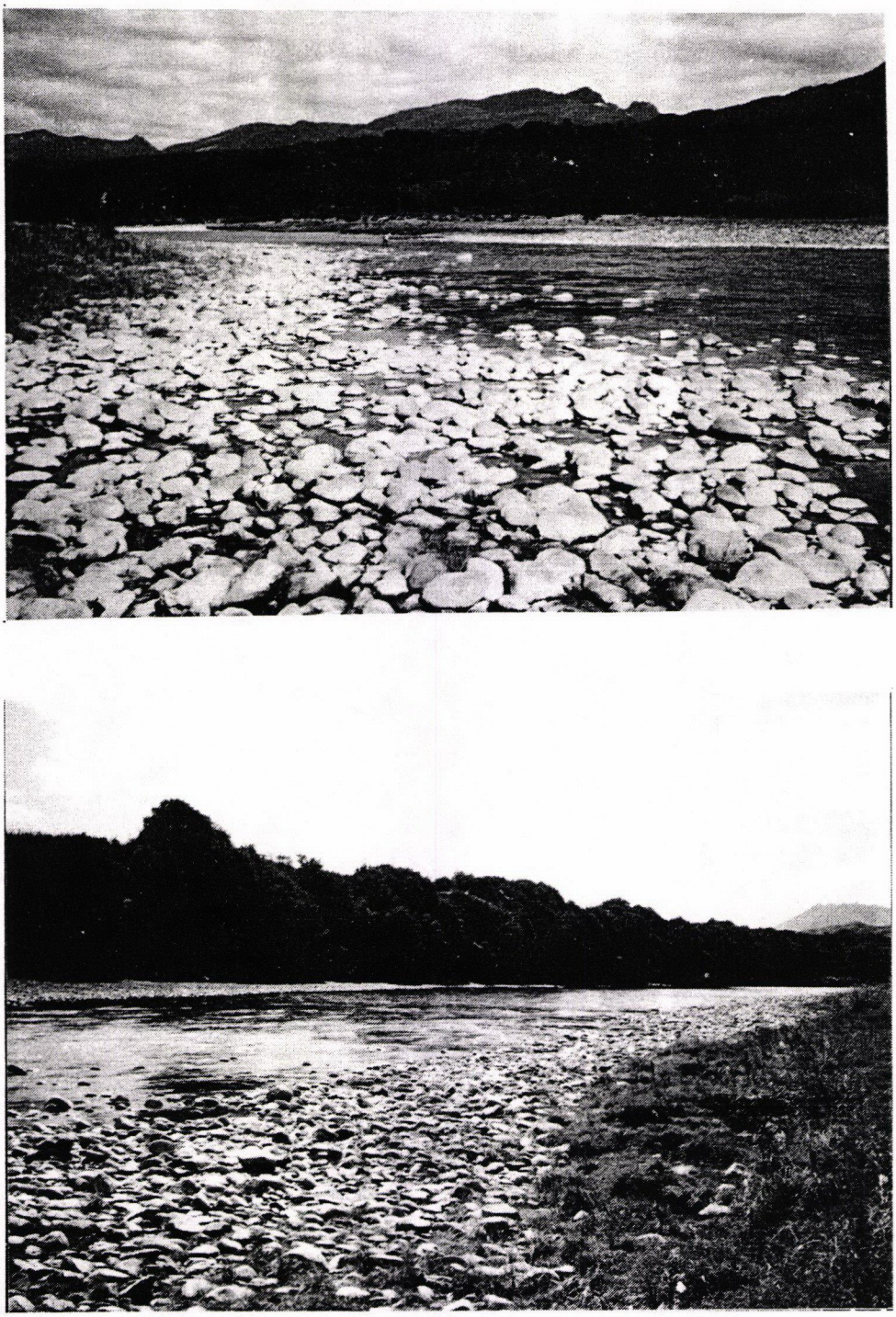


The Excelsior reach, just below Excelsior Creek confluence - flow 0.5 m^3/s.





The Redcliff reach, just above Redcliff Creek confluence - flow 2.1 m^3/s.



The Blackmount reach, in the Blackmount forest - flow 3.9 m^3/s.

Executive summary

The purpose of this study was to assess the flow required in the Waiau River between the Borland Burn and the Manapouri Lake Control Structure (Mararoa Weir) to:

- provide an adequate depth of water for passage of migrating trout
- maintain suitable instream habitat for adult brown trout and benthic invertebrates between the Borland Burn and Excelsior Creek
- maintain suitable instream habitat for benthic invertebrates between the Mararoa Weir and Excelsior Creek
- give an assessment of the relative "quality" of the habitat which would be maintained by an increased residual flow.

Three reaches were surveyed, each of quite different character, and each considered to be characteristic of a larger section of river. The most upstream reach, just below Excelsior Creek, had a flow of 0.52 m^3/s during the survey (with the control gates shut). It was well confined with large substrate elements and is typical of the river between the weir and Whare Creek. In the middle reach, just upstream of Redcliff Creek, tributaries had increased the flow to 2.1 m^3/s. This part of the river was steeper and less confined with more varied habitat, ranging from a deep pool to a steep narrow riffle and broad runs. At the lower reach, at Blackmount, where the flow had further increased to 3.9 m^3/s. This reach sampled the type of habitat in the river below Redcliff, where the slope lessens and there are long uniform sections of wide slow flowing water, broken by the occasional riffle.

The Blackmount reach was shallowest, with an average water depth of 0.24m. The minimum passage depth occurred in the Excelsior reach, where the maximum depth in the shallowest cross-section was 0.17m. Although this is generally considered to be sufficient for trout passage, it is probable that there are sections of the river where the passage depth is less than 0.15m. However, water depth in the shallowest cross-section was predicted to increase at a rate of 0.04m for every 1 m^3/s increase in flow so that a small increase in flow would probably provide adequate passage depths in the section of river below the Mararoa Weir.

In the upper and lower reaches (Excelsior and Blackmount) the variation of adult brown trout habitat and food producing (benthic invertebrate) habitat with flow was remarkably similar, with a rapid increase in both types of usable habitat as the flow increased up to about 10 m^3/s and a slower rate of increase above that. Less variation was apparent in the Redcliff reach, because of its steepness and higher water velocities at low flows. Flow assessments for all three reaches were based on both trout and food producing criteria.

The amount of potential habitat in the river with flows of 15-30 m^3/s was comparable with the best rivers in the "100 rivers" survey, some of which were renowned trout rivers. Even flows in the range of 7.5-12.5 m^3/s would create habitat equivalent to that of the top ten rivers in the "100 rivers" survey.

When the potential habitat in the three reaches was averaged to give a clearer appreciation of the overall variation with flow, it showed that a residual flow in excess of 10 m^3/s would enhance adult brown trout and food producing habitat considerably. For flows in excess of 15 m^3/s, the sum of the trout and food producing habitat exceeded any of the rivers surveyed previously, indicating that the Waiau River between the Mararoa Weir and the Borland Burn is a potentially excellent trout river.

Introduction

Prior to 1970 the full flow of the Waiau River, over 450 m^3/s, flowed from Lake Manapouri to the sea near Tuatapere. In 1970 a temporary rock weir was constructed across the Waiau River and a large proportion of the river's flow was diverted through the Manapouri Power Station and discharged into Doubtful Sound. In November 1976, the Manapouri Control Structure (commonly known as the Mararoa Weir) was completed and the majority of the water of the Mararoa and Waiau Rivers diverted, with only a small flow (0.29 m^3/s) released through the fishpass for much of the time. The minimum flow from the Mararoa Weir provides very little instream habitat for fish and benthic invertebrate communities in the section of the river immediately below the Mararoa Weir.

Further downstream, this flow is augmented by tributary flows, notably Excelsior, Whare, and Redcliff Creeks which join the Waiau 1, 2, and 11 kilometres below the weir respectively (Figure 1). The Borland Burn and Monowai River flow into the Waiau

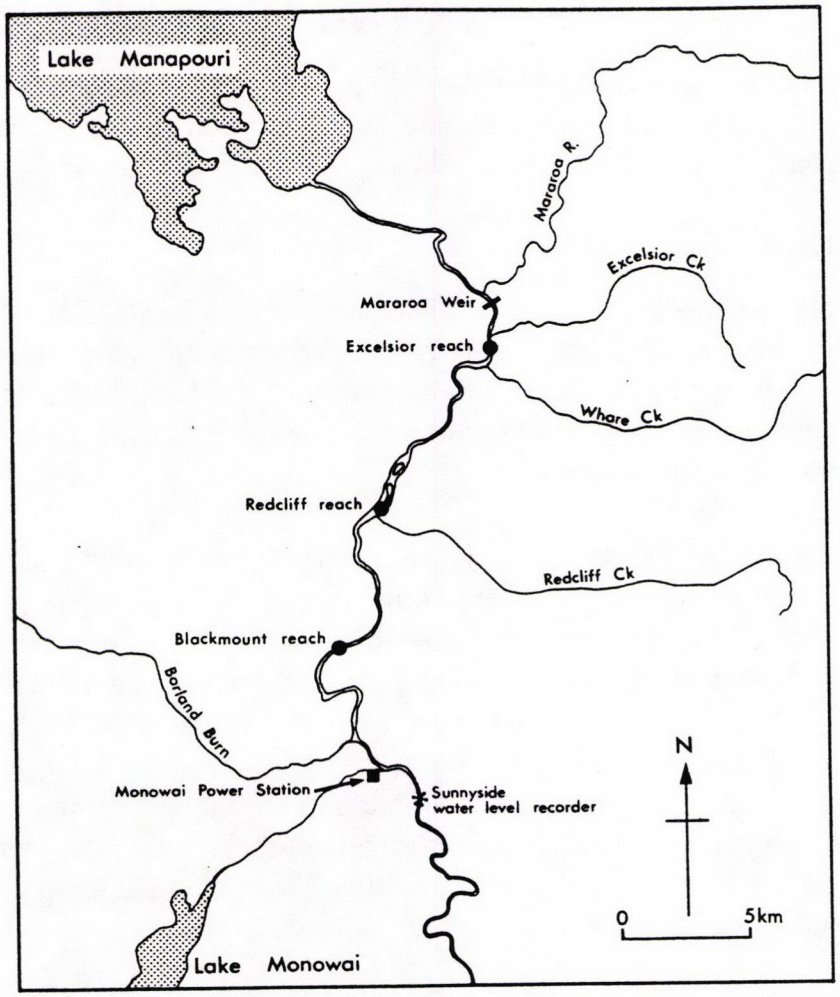


FIGURE 1. Location of the instream habitat survey reaches in the Waiau River.

River about 25 kilometres below the weir. By Sunnyside, just below Monowai Power Station, tributary flows have increased the Waiau discharge to a mean flow of about 37.5 m^3/s.

The purpose of this study is to assess the flow required to improve the instream environment between Mararoa Weir and Borland Burn by creating suitable conditions for benthic invertebrates and adult brown trout. The study involved:

- surveying three representative reaches of the Waiau River between the Mararoa Weir and the Borland Burn
- developing hydraulic models of these reaches to predict how instream habitat for drift-feeding brown trout and benthic invertebrates varies with flow
- comparing the relative "quality" of the predicted instream habitat for trout and benthic invertebrate communities with similar data from a range of rivers around New Zealand
- determining flows necessary for adequate trout passage
- determining "minimum" and "optimum" flow requirements for the maintenance of instream habitat for adult brown trout and benthic invertebrates.

For readers unfamiliar with the subject the concepts of habitat suitability and the background to the methods used for assessing flow requirements based on habitat suitability are described in the appendix.

Selection of reaches

Three reaches were selected at approximately equal intervals between the Mararoa Weir and the Borland Burn (Figure 1). In terms of river morphology (Brierly undated), the first reach was just below Excelsior Creek in the confined Duncraigen reach, the second just upstream of the Redcliff Creek in the unconfined Redcliff reach, and the third in the confined Blackmount reach.

The first reach, just below Excelsior Creek, was a single well-confined channel with pool, run, and riffle habitats and a bed formed predominantly of boulders (Table 1). This section of the river was relatively uniform with long sections of boulder run and slow flowing pool habitat which appeared to be potentially excellent habitat for trout.

The second reach just above Redcliff Creek was much more diverse, probably as a result of its less confined nature, predominantly cobble bed, and more frequent channel movement. The survey reach included two riffles, one of them quite steep, a run, and a 2 metre deep pool, which was fed by a broad riffle. The pool had a steep vegetated left bank that would provide some cover for the trout in the pool.

The third reach in the Blackmount forest was more uniform than either of the upstream reaches. Very long, slow runs or shallow pools were quite characteristic of the river in this area. The survey reach contained a small section of riffle/run and a longer section of uniform, slow run. Trout were observed in this slow run.

These three reaches were considered to be representative of the general character of the river. It is often difficult to decide what is representative. Experience has shown me that unless differences between reaches are considerable and very obvious, the amount of instream habitat tends to vary with flow in the same way, although there can be differences in the amount. In this case, it will be shown later that patterns of habitat variation with flow were similar in all three reaches and that there was relatively little variation in instream habitat – confirming the experience gained from other similar studies.

Survey method and habitat prediction

The number of cross-sections surveyed in each reach varied with river characteristics. The more uniform Blackmount reach required fewer cross-sections to characterise the habitat than the other two reaches. Cross-sections were located so that they represented the average hydraulic properties of the river as well as the available habitat, with closer spacing through riffles where river gradients changed more rapidly than in pools and runs. Each cross-section profile was surveyed, water velocities measured, and visual estimates of substrate composition made. Substrates were classified as bedrock, boulder (264 mm), cobble (264-64 mm), gravel (64-8 mm), fine gravel (8-2 mm), sand (<2 mm), and vegetation (terrestrial or aquatic vegetable matter). River banks were surveyed up to 0.5 metres above existing water level by levelling to avoid any inaccuracy in cross-section definition when extrapolating to higher flows.

Tributary flows in Whare and Excelsior Creeks were gauged so that their flows could be compared with flows in the main river.

Hydraulic models of each reach were developed by fitting roughness coefficients (Manning's N) between adjacent cross-sections for the flow and elevation differences recorded during the survey. Two profiles were surveyed downstream of the first cross-section in each reach. These were used to develop the relationship between flow and stage for the downstream section of the habitat reach. This avoided returning to the sites at a later date to measure water levels at different flows. Values of Manning's N for the upper reach (Excelsior Creek) were estimated for higher flows, because it was considered that increased flow would submerge the larger substrate elements with a consequent reduction in hydraulic losses. The sensitivity of the habitat calculation to Manning's N was tested by comparing estimates of weighted usable area derived from the measured values of N with those derived using estimated values of N. Water surface profiles were predicted for flows up to 20-30 m^3/s depending on the reach. The hydraulic methods are described in more detail in the appendix and in Jowett (1989). Water depths and velocities at all measurement points were predicted over a range of flows from 2-4 m^3/s to 20-30 m^3/s. The suitability of each point as food producing, *Deleatidium*

spp. (mayfly), and brown trout habitat was assessed and summed over the reach. The analysis of *Deleatidium* habitat was included because its habitat preferences have been described (Jowett *et al.* 1991) and it provides a useful comparison with the more general food producing habitat.

Habitat units are units of area (e.g. square metres), therefore larger rivers usually contain more habitat. Thus, weighted usable area is expressed as a percentage of the river width or area for comparisons between rivers of different size. Five metres of usable width in a 20 metre wide river (i.e. 5 m) is equivalent to 5 square metres per metre length of river (i.e. 5 m^2/m) and both can be expressed as 25% WUA. These are the units used in this report.

Table 1. Characteristics of habitat survey reaches

	Excelsior	Redcliff	Blackmount
Distance from weir (km)	1.2	10.8	18.3
No. of cross-sections	14	16	10
Reach length (m)	324.30	167.15	236.80
Gradient	0.0009	0.0064	0.0026
Survey discharge (m^3/s)	0.52	2.11	3.91
Mean depth (m)	0.39	0.50	0.24
Mean velocity (m/s)	0.06	0.26	0.24
Mean width (m)	28.4	24.1	58.0
Substrate composition (%)			
Boulder	42.5	9.0	19.4
Cobble	29.5	41.4	39.5
Gravel	23.8	47.6	34.9
Fine gravel	0.0	0.0	0.6
Sand	4.0	1.8	5.6
Silt & vegetation	0.1	0.2	0.1
Weighted usable area (%)			
Adult brown trout	11.0	18.1	6.4
Food producing	1.5	23.1	22.4
Deleatidium (mayfly)	8.0	32.1	29.9

Note: Whare Creek flow = 0.64 m^3/s
Excelsior Creek flow = 0.22 m^3/s

Tributary flows

The flow of the Waiau River below Excelsior Creek was measured during the survey at 0.52 m^3/s. Excelsior Creek contributed almost half of this indicating that the discharge from the weir was in the order of 0.3 m^3/s – close to the nominal minimum flow. The

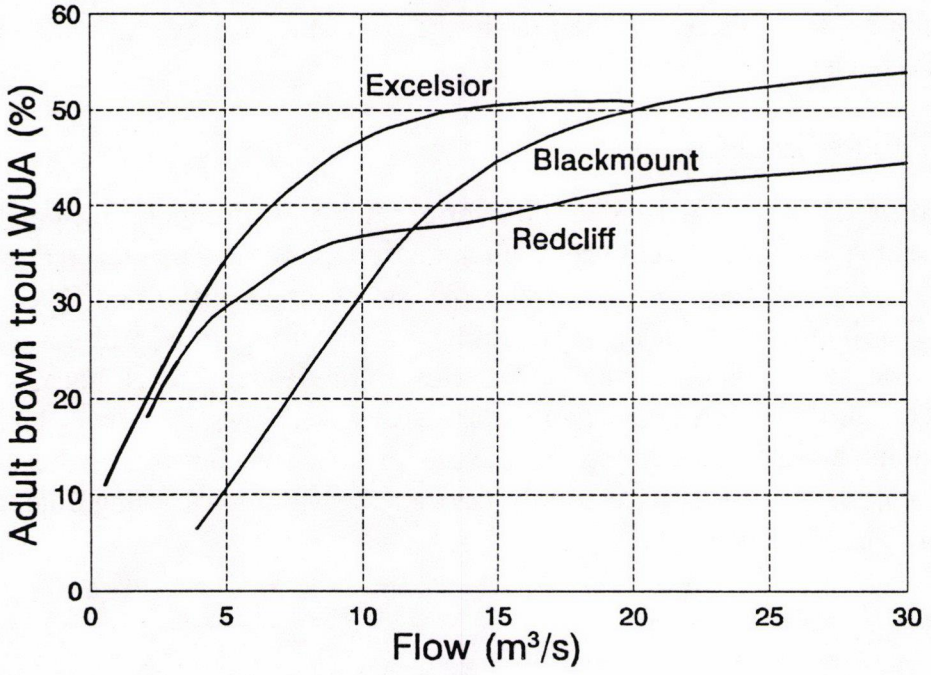


FIGURE 2. Variation in the weighted usable area of adult brown trout habitat with flow.

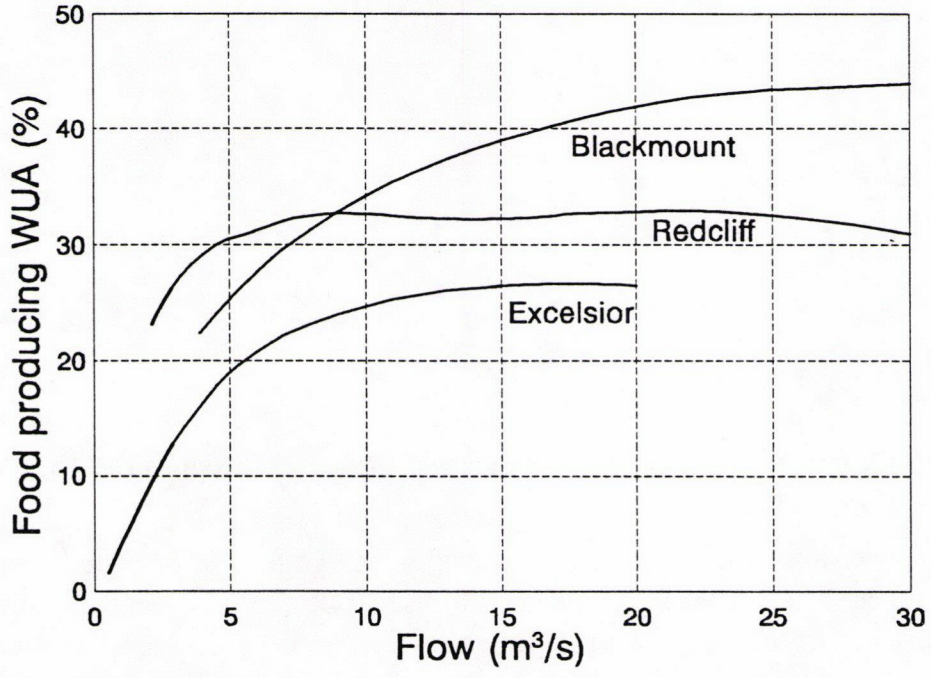


FIGURE 3. Variation in the weighted usable area of food-producing habitat with flow.

flow just upstream of Redcliff Creek was 2.11 m^3/s, about a third of which was contributed by Whare Creek. At Blackmount the flow had increased to 3.9 m^3/s. Overall, tributary flows increased the flow in the river at an average rate of about 0.2 m^3/s per kilometre.

Habitat changes with flow

As expected, predicted habitat for benthic invertebrates (food producing), *Deleatidium*, and drift-feeding habitat for adult brown all increased as the flow increased above the normal residual flow in the river. Generally, the curves for Excelsior and Blackmount were of similar shape with initial rapid increases with flow rising to an optimum (Figures 2-4). There was less variation of habitat with flow in the Redcliff reach because of its steeper nature and relatively high water velocities at lower flows. The flow which gave optimum habitat at the confined upstream (Excelsior) reach was less than at the broader Redcliff reach, which in turn was generally less than the wide slow flowing Blackmount reach (Table 2).

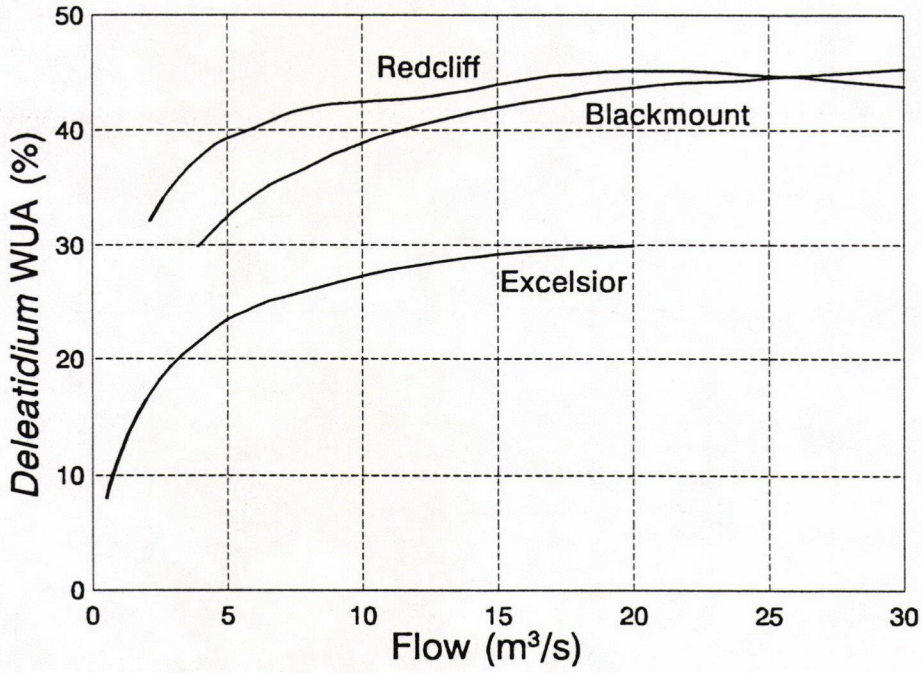


FIGURE 4. Variation in the weighted usable area of *Deleatidium* habitat with flow.

Habitat flow decisions can be based on either percentage habitat or actual area. For instance, if the area of habitat available is maximised, one could expect trout numbers to be maximised. Conversely, if percentage habitat is maximised, one could expect trout density to be a maximum. I prefer to use percentage habitat for the following reasons:

- it is a valid measure of the "quality" of the habitat because it can be likened to a measure of "efficiency" i.e. the proportion of water area which is useful habitat

- it allows for comparison between rivers and thus provides information on the relative quality of the river
- optima are often more clearly defined, whereas area tends to remain relatively constant over a wide range of flow.

Flow recommendations are sometimes based on flows which provide optimum amounts of habitat, but can also based on the flow below which habitat begins to decline sharply, a so-called point of inflection. A point of inflection can often be difficult to define. In this case, I have taken it to be the flow where lines tangential to the optimum and minimum habitat values meet (see Figures 2-4). Table 2 lists flows for optima and points of inflection based on percentage habitat. Curves for habitat area have similar shapes – showing rapid increases in usable habitat at first then reaching a stage where there is little increase with flow.

Table 2. Flows (m^3/s) required to provide optimum habitat (WUA %) and flows below which habitat begins to decline sharply in the three surveyed reaches.

Optimum WUA and flow at	**Excelsior**		**Redcliff**		**Blackmount**	
	WUA	flow	WUA	flow	WUA	flow
Adult brown trout	51	18	>42	<30	58	30
Food producing	27	16	33	20	44	30
Deleatidium	30	20	45	20	44	>30
WUA at point of inflection and flow at	**Excelsior**		**Redcliff**		**Blackmount**	
	WUA	flow	WUA	flow	WUA	flow
Adult brown trout	43	8	38	14	45	15
Food producing	22	7	32	8	34	10
Deleatidium	26	7	43	11	39	11

Ranking Waiau river habitat in terms of habitat quality

Sixty-five larger New Zealand rivers were surveyed as part of the national "100 rivers" survey (Jowett 1990). Each of the reaches in these rivers was modelled hydraulically using similar techniques to those described in this report and the available habitat at minimum flows predicted. As described in the appendix, instream habitat at minimum flow has been shown to be related to brown trout abundance, and the amount of food producing habitat at median flow is related to the weight of benthic invertebrates in the rivers. Thus, comparing the amount of instream habitat in the Waiau River with other

New Zealand rivers gives a measure of the relative quality of habitat. This can be expressed as the percentage of the rivers in the national database that contain "better" habitat (i.e. the weighted usable area (WUA) is greater).

Table 3 lists the flows and the sum of the food producing and adult brown trout habitat (WUA as a percentage of water surface area) of the Waiau River reaches and for the "top ten" rivers in the existing national database. On this basis the Waiau River reaches could be outstanding, – among the "top ten" in terms of food producing and brown trout habitat – if flows exceed the point of inflection on the WUA/flow curves and could equal the best in the country if flows are maintained at optimum habitat. However, the Waiau River reaches differ from others in the country in that they have more trout habitat than food producing habitat, whereas other rivers tend to have more food producing habitat than trout habitat. This is a result of the relatively low proportion of riffle habitat in the Waiau River reaches and, to a degree, is consistent with other lake outlets, such as the Clutha, Hurunui, and Gowan Rivers. Lake outlet rivers tend to contain relatively large amounts of adult trout habitat because of their morphology – the result of the channel shape created by relatively steady flows. Of the four lake outlet rivers surveyed, three contain more trout habitat (in terms of percentage of the water surface area) than any others in the national survey.

Table 3. Total weighted usable area (adult trout habitat at mean annual low flow (MALF) plus food producing habitat at median flow) for the Waiau River* reaches, the Clutha River, and the "top ten" in New Zealand.

Habitat ranking	River	Flow (m^3/s)		Total WUA (%)	Ratio of trout to food-producing habitat
		MALF	Median		
1	Hurunui	8.2	19.4	79.6	0.69
2	Gowan	8.7	22.0	72.9	0.92
3	Inangahua	2.0	7.6	70.0	0.47
4	Motueka	7.7	32.8	67.1	0.68
5	Patea	0.8	3.1	63.7	0.25
6	Rangitikei	4.6	13.1	63.2	0.32
7	Buller	3.9	10.0	63.2	0.32
8	Stony	2.3	3.6	62.7	0.59
9	Wanganui	5.0	15.8	62.3	0.30
10	Ahuriri	8.0	18.0	59.8	0.43
13	Clutha	75.5	174.8	57.7	3.61
	Waiau River at existing minimum flows				
	Excelsior	0.5	0.5	12.5	7.33
	Redcliff	2.1	2.1	41.2	0.78
	Blackmount	3.9	3.9	28.8	0.29
	Waiau River with WUA at point of inflection				
	Excelsior	7.5	7.5	59	2.69
	Redcliff	11	11	69	1.19
	Blackmount	12.5	12.5	76	1.11
	Waiau River with optimum WUA				
	Excelsior	15	15	73	2.48
	Redcliff	20	20	75	1.27
	Blackmount	30	30	102	1.32

* the median flow is assumed to equal the mean annual minimum flow for the Waiau reaches.

Minimum flow assessments

Fish passage

Requirements for fish passage are that there be sufficient depth of water for the largest fish species that moves through the section of the river and that there be no sections where the water velocity exceeds the burst swimming speed of the "slowest" fish that moves through the section. In most natural channels, the velocity is unlikely to restrict the passage of most native fish species because the margins of the channel contain shallow areas with low velocities. Trout require slightly deeper water for passage but have the ability to swim for short distances at velocities which are rarely exceeded across whole sections of a river channel. Thus, the primary requirement for passage in the Waiau River is that there be sufficient depth of water for adult trout in the shallowest section of the river.

In the three reaches surveyed, the maximum depth in the shallowest cross-section was 0.17 m in the upstream reach (Excelsior), 0.29 m in the Redcliff reach, and 0.35 m in the Blackmount reach. Minimum passage depth for adult trout is generally thought to be about 0.15 m (Jowett 1987), so even at minimum flows there would appear to be sufficient water for passage through all reaches. However, the surveys were not intended, and did not necessarily identify, the shallowest sections of the river, either upstream or downstream of Excelsior Creek, and I would suspect that there are sections of the river where the maximum depth is less than 0.15 m at minimum flow.

Very small increases in flow would give sufficient water depth for fish passage. A flow increase of 1 m^3/s would increase the minimum depth in all sections by about 0.04 m.

Trout

The primary flow-related requirements of adult brown trout in New Zealand have been shown to be the suitability of the habitat for drift-feeding brown trout (brown trout which are actively feeding on drifting invertebrates) and for food production (the riffle habitat which contains the highest densities of benthic invertebrates). At minimum flow, the habitat in the upper reach (Excelsior) is particularly unsuitable as food producing habitat. However generally in the three reaches, the amount of trout and food producing habitat at minimum flow ranges from above to below average for the "100 rivers" dataset, with good food producing habitat in the two lower reaches and good trout habitat in the Redcliff reach. The analysis of habitat variation shows that there is a substantial increase in habitat with flow, both for trout and food production.

To assess the effects of various minimum flows on habitat, weighted usable areas (in terms of both area and percentage) for adult brown trout and food producing habitat were taken from Figures 2-4 for minimum flow discharges of 0 to 30 m^3/s in steps of 5 m^3/s – making an appropriate allowance for tributary flows. The tributary flows were

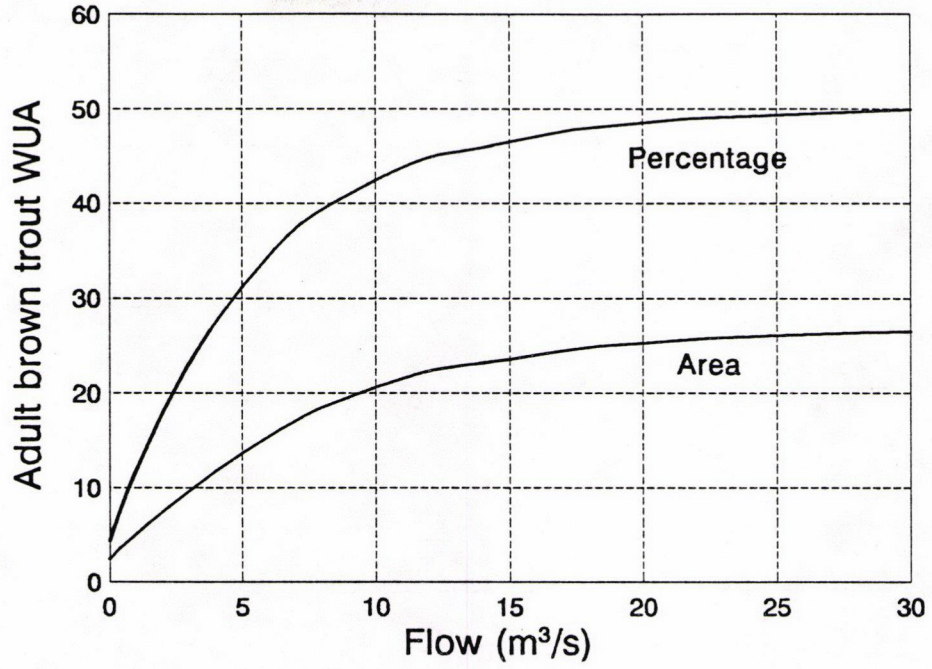


Fig. 5 Variation of adult brown trout drift-feeding habitat for flow. Average weighted usable area in m^2/m and percentage for the three reaches.

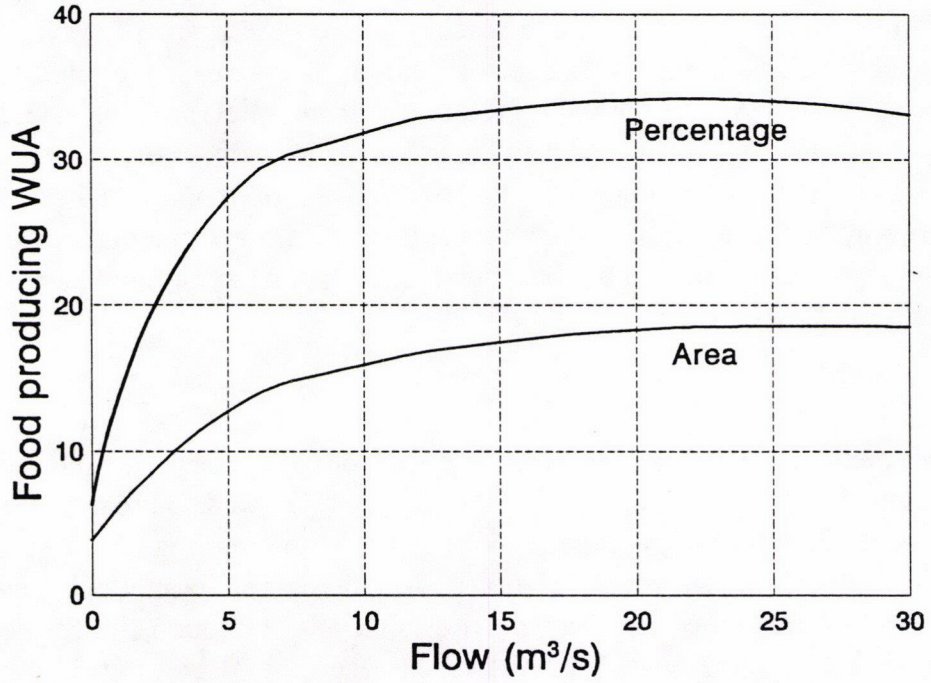


Fig. 6 Variation of food producing habitat for flow. Average weighted usable area in m^2/m and percentage for the three reaches.

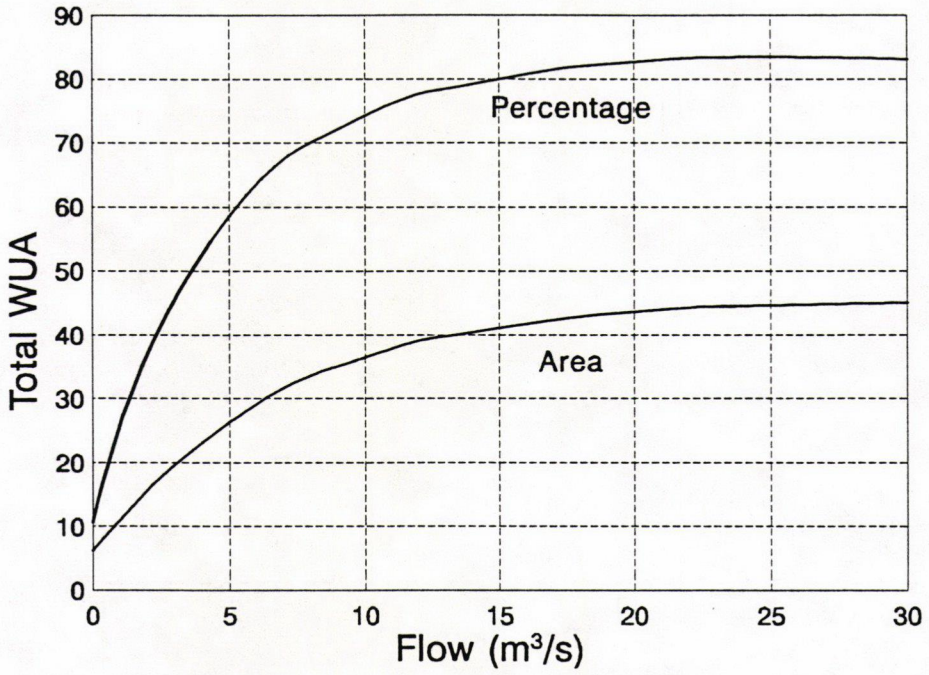


Fig. 7 Variation of food producing and adult brown trout drift-feeding habitat for flow. Average weighted usable area in m^2/m and percentage for the three reaches.

taken to be 0.25 m^3/s for the Excelsior reach, 1.5 m^3/s for the Redcliff reach, and 3.5 m^3/s for the Blackmount reach. For each minimum flow discharge, the average for the river was taken as the average of the three reaches and plotted against flow (Figures 5-7). There is some habitat in the river at zero minimum flow – this is provided by the tributary flows. The total WUA (trout plus food producing habitat) scale of Figure 7 is directly comparable with the WUA values in Table 3 and shows that there is more than 80% usable habitat for flows of between 20 and 30 m^3/s – more than the highest in the "100 rivers" survey. All three figures show that substantial improvements are gained for minimum flows of up to 10 m^3/s, but beyond 10-15 m^3/s the incremental benefits of increased minimum flows are less.

Native fish

Most native fish exhibit habitat preferences or at least occupy specific habitat niches. These have been described quantitatively for a few species (Glova & Duncan 1985) and derived by consultation with people experienced in native fish sampling for others – the so called Delphi technique. However, relationships between the habitat occupied by these fish and their abundance have not been established. Although the species of native fish present in the section of Waiau River between the Mararoa weir and the Borland Burn have not yet been determined, it is possible to make a good "guess" based on the sampling data presented in Hayes *et al.* (1992) and the unpublished results of the native fish surveys in the "100 rivers". The resident fish are likely to be long fin eels, common river galaxias, upland bullies, and common bullies. In addition lampreys,

koaro, and possibly smelt may pass through the river – the first two migrating from their preferred habitats and the latter probably from the land-locked lake population. Native fish surveys of upstream areas of larger South Island rivers in the "100 rivers" survey have shown that they commonly contain upland bullies and common river galaxias in relatively high numbers and common bullies and long fin eels in low to moderate numbers. Stratified sampling during these surveys have shown that all four species are most abundant in the margins, particularly the margins of riffles – where the river margins were defined as the edge where depths were less than 0.15 m. The galaxias and upland bullies were also reasonably abundant in riffle areas with depths of 0.15 m to 0.25 m, but noticeably lacking from deeper water or the central portions of the rivers surveyed. These observations suggest that suitable habitat for these native fish will be available at practically any flow.

Minimum flow

The selection of a "minimum" flow is rather arbitrary and ideally should relate to some overall water management policy. Issues such as the value of the water, the potential value of the fishery, and principles embodied in the Resource Management Act need to be considered.

This study has demonstrated that excellent trout habitat would be created by flows in excess of 10 m^3/s and that native fish habitat exists at all flows, although maximum amounts probably occur at lower flows. It should be noted that, although I have not predicted habitat change with flows in excess of 20-30 m^3/s (because of the hydraulic uncertainties in that degree of extrapolation), it is probable that for flows in excess of 30 m^3/s, the incremental gain in habitat is small and that there could even be a loss of trout and food producing habitat. If I were required to define "absolute minimum" flows I would say that under the existing flow, food producing habitat in the upper reach (Excelsior) is low compared with other rivers around the country and flows should be increased to about 6 m^3/s to give 18% WUA – a standard exceeded by over 85% of the rivers in the national "100 rivers" survey. The trout habitat in the Blackmount reach is marginally low and would only require a small increase to bring it up to the amount exceeded by 85% of the rivers in the national survey (see the appendix for further discussion of habitat "standards").

Given the outstanding potential habitat in the river, I suggest that consideration be given to maintaining a minimum flow in excess of 10 m^3/s in the Waiau River below the Mararoa Weir.

Appendix

Background to instream habitat methods

Habitat suitability and the instream flow incremental methodology

The concept of habitat suitability is all around us. All life, except perhaps the simplest, has adapted to a particular range of habitats. The concept of "good" habitat is familiar to most people. It is commonly used by anglers and hunters seeking their prey. In the aquatic environment, instream habitat usually refers to the physical habitat – water velocity, depth, substrate, and perhaps cover. Usually, animals are most abundant where the habitat quality is best, in lesser numbers where the habitat is poor, and absent from totally unsuitable habitat. If the characteristics of the habitats occupied by many animals are surveyed, it is possible to determine the relative quality of the different habitats from the abundance of animals in them. Habitat suitability curves provide a means of describing what is considered to be "good" habitat. If the range of suitable habitat for a species or life stage of a species can be determined, it is possible to quantify the area of suitable habitat available within a river. This area is termed the usable area. Habitat

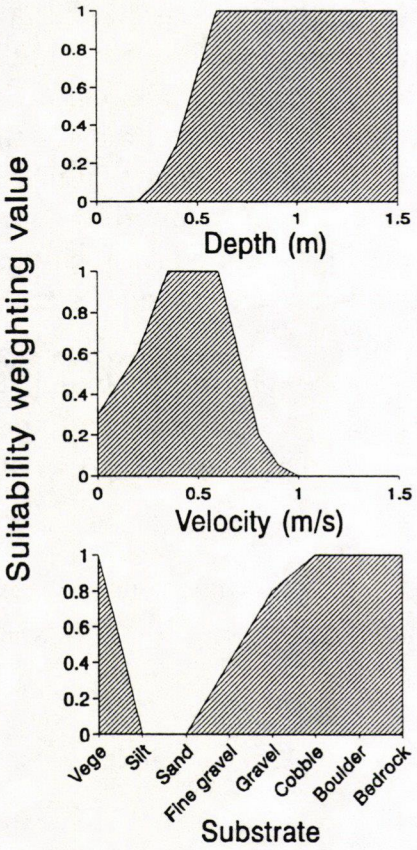


FIGURE A1. Example of drift-feeding habitat suitability curves for adult brown trout [from Jowett (1993)].

suitability can vary from zero (unsuitable) to one (optimum). Figure A1 shows an example of a set of suitability curves for adult brown trout drift feeding habitat derived from measurements at about 400 trout feeding locations.

Once habitat suitability curves or criteria are defined they can be applied to habitat survey data (Figure A2) and the amount of suitable habitat calculated. This is the basis of the instream flow incremental methodology (IFIM)(Bovee 1982). The method was recognised as the most "defensible" method of assessing instream flow needs in the U.S. although it has received some criticism (Mathur *et al.* 1985; Scott and Shirvell 1987). The fundamental criticism was that, although it seemed reasonable to assess instream flow needs on the basis of the amount of suitable habitat, there was no evidence that there was any correlation between species abundance and the amount of suitable habitat. This is not an unreasonable criticism – use of inappropriate habitat suitability curves could give misleading results. Some of the early habitat curves for brown trout appeared to describe resting habitat (e.g. Bovee 1978) rather than feeding habitat and even now there are significant differences between the brown trout preference curves derived in New Zealand (Jowett 1993) and the curves derived in the U.S. (Raleigh *et al.* 1984). It is also doubtful whether users of IFIM considered all the necessary requirements for a species. For example, the primary requirements for salmonids are both space and food (Chapman 1966). Assessing instream flow needs for a river based on salmonid space requirements and not considering the production of food is like designing a house with no kitchen.

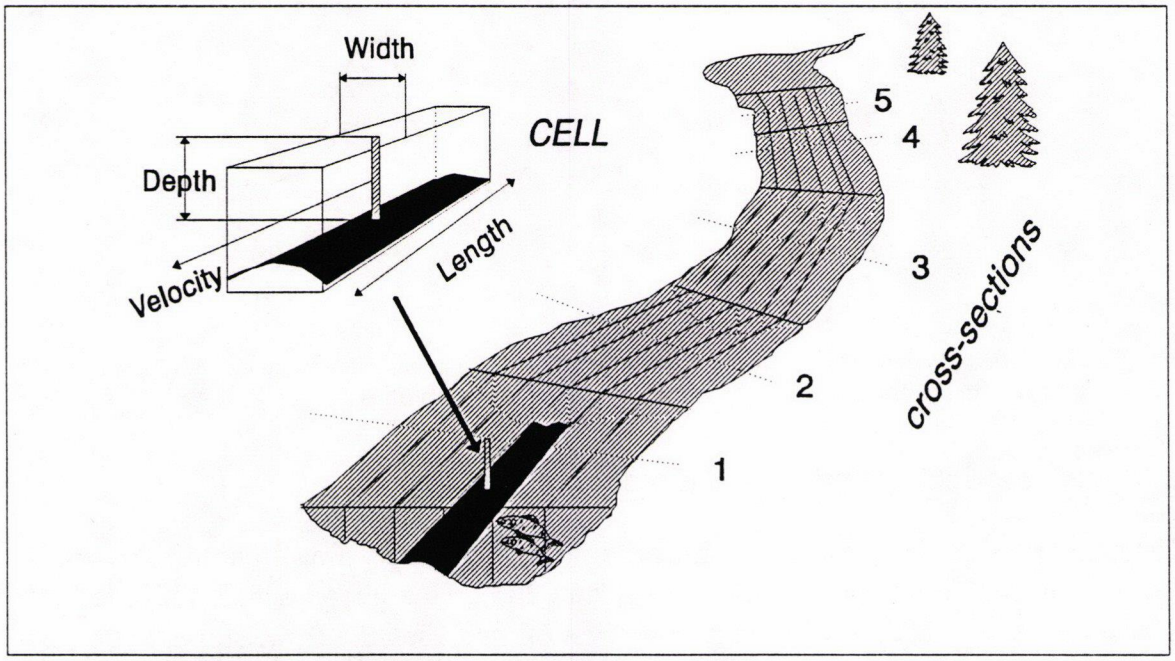


FIGURE A2. Instream habitat model of river reach showing cross-sections and cells.

Trout habitat preferences

Angling texts from the turn of the century describe likely trout streams and more recent books (e.g. Hill and Marshall 1985) accurately describe locations where trout are likely to be found. In New Zealand, the physical characteristics of drift-feeding locations used by large brown trout were measured in two rivers. Similar water velocities were utilised in both rivers although the availability of these was different in each river (Figure A3). These data can be formed into habitat preference curves (refer to Figure A1). A significant relationship ($r = 0.395$, $P < 0.001$) between adult brown trout abundance and percentage suitable drift-feeding habitat (WUA) was found in 59 New Zealand rivers (Jowett 1993).

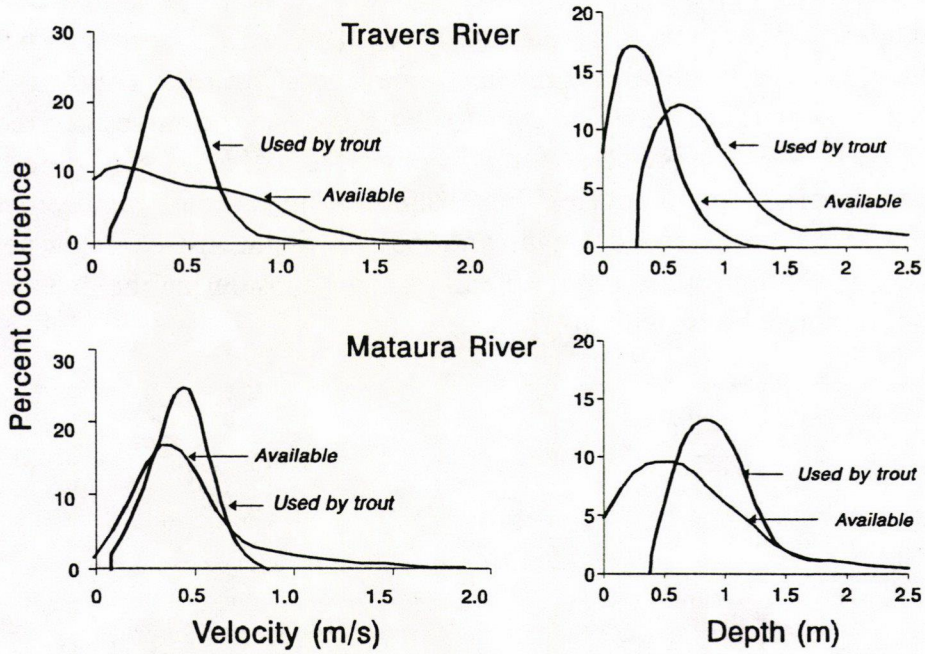


FIGURE A3. Comparison of water depths and velocities available in two rivers with those used by large brown trout when feeding on drifting invertebrates.

Hydraulic modelling and prediction of habitat suitability

The standard step method, used to model non-uniform steady flow in natural rivers, is well established in engineering practice (Chow 1959; Henderson 1966). This method is based on the principle of energy conservation and uses the flow, slope, hydraulic roughness, and the hydraulic properties of the cross-sections to calculate the longitudinal flow profile. An important assumption in the method is that the distance between cross-sections must be short enough that the hydraulic properties of the cross-sections approximate the hydraulic properties and slope between them. This means that cross-sections should be located sufficiently close that the cross-section area increases or decreases uniformly between cross-sections and that the change in slope

is kept to a minimum. In practice this means decreasing cross-section spacing at the heads and tails of riffles, where water slopes and cross-section areas change rapidly, and increasing the spacing when the hydraulic conditions are uniform. This sampling procedure is consistent with those used to sample instream physical habitat.

The hydraulic roughness (Mannings *N*) is determined from field data on discharge, cross-section area, hydraulic radius, and slope. Mannings *N* can vary with flow in an unpredictable manner (e.g. Hicks and Mason 1991) and this limits the range of flows for which the roughness calibration is valid.

The distribution of water velocities across a cross section can be calculated from its conveyance once the water level and flow are known (Figure A4) (Mosley and Jowett 1985; Jowett 1989). Each velocity can be adjusted for site specific features such as an upstream obstruction which might cause a reduction in velocity or a current on a bend increasing local velocities. Each measurement point represents a "cell" of the total river area (Figure A2) for which the suitability of the velocity, depth, and substrate is evaluated on a scale of 0 (unsuitable) to 1 (optimum). The point suitability is multiplied by the plan area of the cell it represents and summed over the reach to give the weighted usable area (WUA). An example of calculating point suitability is shown on Figure A5. Once a hydraulic model of the reach is derived, water velocities and depths can be predicted for any flow and the amount of suitable habitat at that flow evaluated. The computer programme RHYHABSIM (Jowett 1989) combines hydraulic simulation and evaluation of habitat suitability.

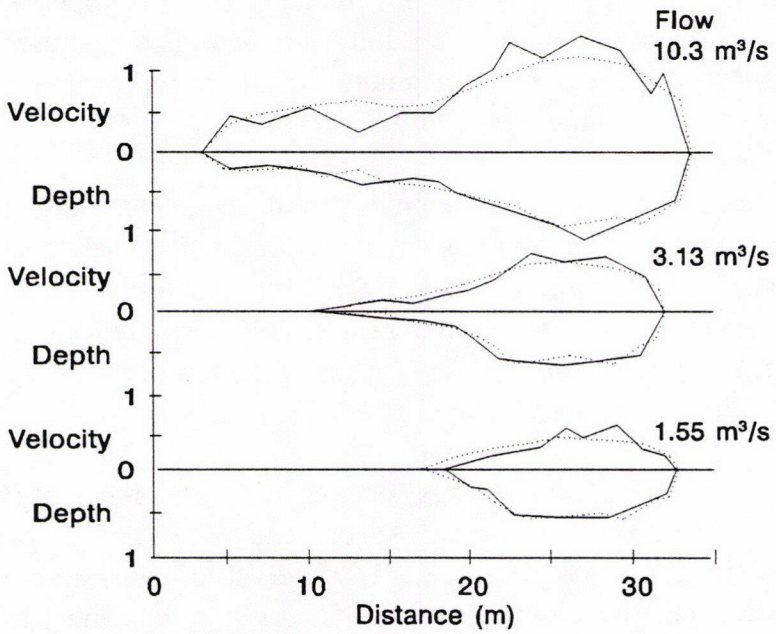


FIGURE A4. Comparison of measured water velocities and depths across a channel (solid line) with those predicted from measurements (dotted line) taken at a flow of 13.2

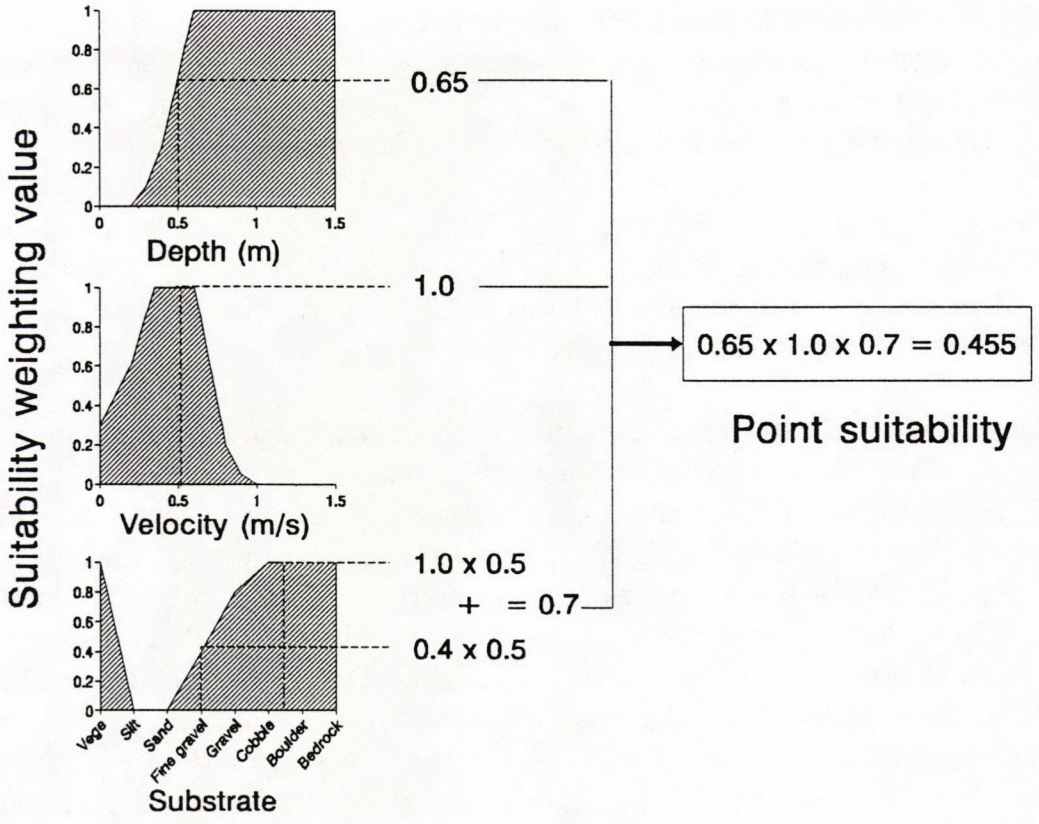


FIGURE A5. Calculation of point suitability for a point with 0.5 m/s velocity, 0.5 m depth, and a substrate of 50% boulders and 50% fine gravel.

Brown trout model

Using data collected for the "100 rivers" survey, Jowett (1993) developed a model of the abundance of large brown trout in New Zealand rivers. This model is based on water temperature, weighted usable areas for "food and space", instream cover, and six other variables which relate to the production of "food".

The water temperature requirements in the model are derived from biological information. Brown trout spawn in winter and egg mortality begins to increase when water temperatures exceed 11°C (Scott and Poynter 1991). A comparison of the distribution of brown trout with respect to river water temperatures shows an absence of trout when winter water temperatures exceed about 10.5°C. Thus, water temperature is one factor which limits their distribution and abundance.

The amount of "food and space" in a river is also known to be important (Chapman 1966). Weighted usable area for trout habitat, "space", and WUA for food production, "food", plus seven other variables explained 87.7% of the variation in numbers of large brown trout in 59 New Zealand rivers (Figure A6). The most important variables were WUA for trout habitat, WUA for food production, instream cover, and water temperature as an overriding factor. Of the other variables, sand substrate is very poor food producing habitat and it is rare to observe brown trout in areas where the predominant substrate is sand; lake outlets are well known for their high trout stocks; headwaters

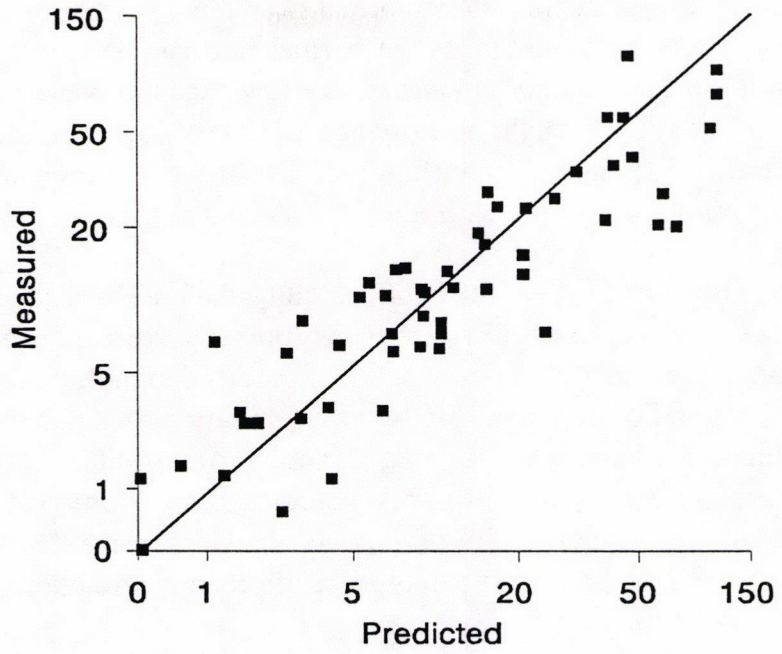


FIGURE A6. Comparison of measured numbers of large brown trout per hectare in 59 New Zealand rivers with numbers predicted by the brown trout model (Jowett 1993).

usually contain lower trout densities than the lower reaches of a river; trout populations in high gradient rivers are severely depleted by floods (Jowett and Richardson 1989); and pastoral development appears to have an adverse impact on trout.

Perhaps the most interesting concept in the brown trout model is the flows at which the instream habitat variables (WUA) are calculated. In a natural river, flow and the amount of suitable instream habitat vary with time. The amount of habitat was calculated at mean annual low flow, median flow, and mean flow. (The mean annual low flow is the average of the instantaneous minimum flows for each year of recorded flow, the median flow the instantaneous flow which is exceeded 50% of the time, and the mean flow is the average of instantaneous flow for the whole period of record.) The amount of adult trout habitat at mean annual low flow was more closely related to trout numbers than the habitat available at the higher flows. This suggests that the amount of suitable trout habitat at low flow is one of the limiting factors in the system - a kind of "bottleneck". The amount of habitat for food production at median flow was more closely related to trout numbers than the amount at either low or mean flow. Thus, even if there is adequate habitat at low flows, a trout population is controlled by the average food producing capacity of the river rather than the capacity during more extreme events. Ideally, the average food producing capacity should be derived by integrating the amount of habitat for the full flow regime of the river, however for most natural flow regimes the habitat at median flow appears to be a reasonable estimate.

Management of instream habitat

Instream flow requirements for brown trout can be predicted using the model just described. Winter water temperatures must be maintained at less than 10.5°C and

summer temperatures should not exceed the lethal limit of 25 to 27°C. Adult trout habitat at low flow and food production under normal flow must be maintained at adequate levels. For most natural flow regimes the normal flow can be taken as the median flow. However, if the flow regime is modified severely, such as severe abstractions at less than median flow, then it might be more appropriate to integrate the food producing habitat for the various management options. The other factors which influence trout abundance usually alter little with flow.

In the "100 rivers study" (Biggs *et al.* 1990) the habitat quality in 63 rivers around New Zealand was evaluated. Assuming that the 63 rivers are a representative sample of New Zealand rivers, they can be ranked and then divided into groups depending upon the quality of the instream habitat. For instance, 15% of the rivers surveyed had more than 60% of their area providing "food and space" habitat for adult brown trout (Figure A7). This group of rivers represents examples of rivers where naturally occurring flows provide excellent trout habitat. Similarly, 15% of the rivers had less than 32% of their area as trout "food and space" habitat. Rivers in this group are examples of poor quality rivers when it comes to trout habitat.

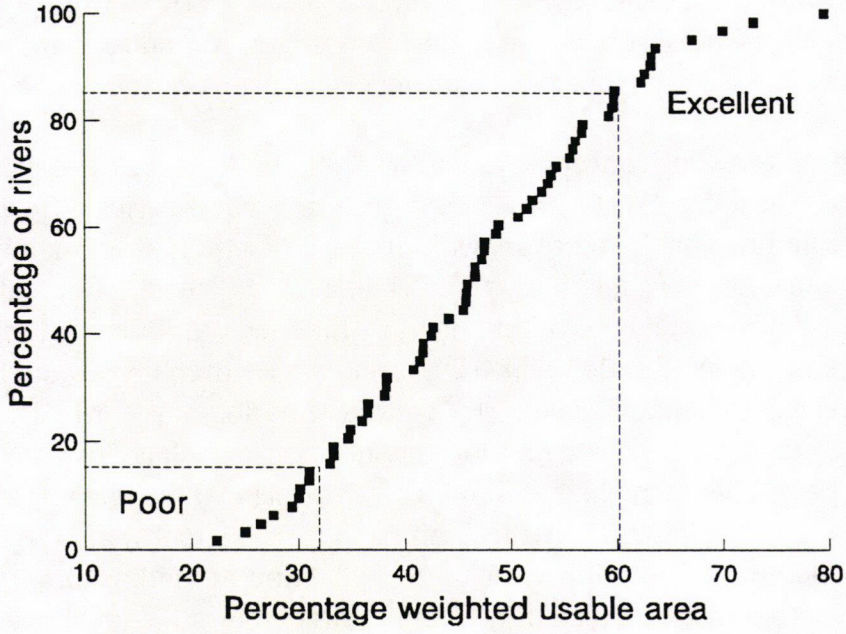


FIGURE A7. Total "food and space" habitat for adult brown trout in 63 New Zealand rivers.

Proposals to modify river flows can be assessed against this background – showing both the extent of the impact and the relative value of the resource.

This concept can be extended to other habitat types which are appropriate to the river, region, and management objectives. However, before this is done, relationships between the habitat suitability curves, WUA, and the aquatic biota to which they apply

should be established. At present, such relationships have been established for brown trout, a number of benthic invertebrate species, and for total benthic invertebrate biomass. Weighted usable area for food production was significantly correlated with total benthic invertebrate biomass in the 40 rivers of the "100 rivers" survey where there were data (unpublished data) and WUA for brown trout habitat was significantly correlated with brown trout numbers in 59 rivers (Jowett 1993).

References

Biggs, B. J. F., Duncan, M. J., Jowett, I. G., Quinn, J. M., Hickey, C. W., Davies-Colley, R. J., and Close, M. E. 1990. Ecological characterisation, classification, and modelling of New Zealand rivers: an introduction and synthesis. *New Zealand Journal of Marine and Freshwater Research 24*:277-304.

Bovee, K.D. 1978. Probability of use criteria for the family Salmonidae. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-78/07, *Instream flow information paper 4*. 80 p.

Bovee, K.D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-82/26, *Instream flow information paper 12*. 248 p.

Brierly, G. J. undated. River reach analysis of the Waiau River, Southland, from Mararoa Weir to Te Waewae Bay. Southland Regional Council. 144 p.

Chapman, D.W. 1966. Food and space as regulators of salmonid populations in streams. *The American Naturalist 100*:345-357.

Chow, V. T. 1959. Open channel hydraulics. McGraw-Hill, Kogakusha, Japan. 680 p.

Glova, G. J., Duncan, M. J. 1985. Potential effects of reduced flows on fish habitats in a large braided river, New Zealand. *Transactions of the American Fisheries Society 114*:165-181.

Hayes, J. W., Davis, S. F., Jellyman, D. J., Jowett, I. G. 1992. Review of fish distribution in the Waiau River catchment, Southland. New Zealand Ministry of Agriculture and Fisheries, *New Zealand Freshwater Fisheries Miscellaneous Report 109*, Christchurch. 33 p.

Henderson, F. M. 1966. Open channel flow. Macmillan, New York. 522 p.

Hicks, D. M., and Mason, P. D. 1991. Roughness characteristics of New Zealand rivers. Water Resources Survey, DSIR Marine and Freshwater, Wellington. 329 p.

Hill, L., and Marshall, G. Stalking trout. The Halcyon Press, Auckland. 148 p.

Jowett, I.G. 1987. Fish passage, control devices, and spawning channels. *In*: Henriques, P.R. (Ed.), Aquatic biology and hydroelectric power development in New Zealand. Oxford University Press. pp. 138-155.

Jowett, I.G. 1989. River hydraulic and habitat simulation, RHYHABSIM computer manual. New Zealand Ministry of Agriculture and Fisheries, *Fisheries Miscellaneous Report 49*, Christchurch. 39 p.

Jowett, I.G. 1990. Factors related to the distribution and abundance of brown and rainbow trout in New Zealand clear waters. *New Zealand Journal of Marine and Freshwater Research 24*: 429-440.

Jowett, I.G. 1993. Models of the abundance of large brown trout in New Zealand rivers. *North American Journal of Fisheries Management 12*:417-432.

Jowett, I.G., and Richardson, J. 1989. Effects of a severe flood on instream habitat and trout populations in seven New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research 23*:11-17.

Jowett, I.G., Richardson, J., Biggs, B.J.F., Hickey, C.W., and Quinn, J.M. 1991. Microhabitat preferences of benthic invertebrates and the development of generalised *Deleatidium spp*. habitat suitability curves, applied to four New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research 25*:187-199.

Mathur, D., Bason, W.H., Purdy, E.J. and Silver, C.A. 1985. A critique of the in-stream flow incremental methodology. *Canadian Journal of Fisheries and Aquatic Sciences 42*:825-831.

Mosley, M.P., and Jowett, I.G. 1985. Fish habitat analysis using river flow simulation. *New Zealand Journal of Marine and Freshwater Research 19*:293-309.

Raleigh, R.F., Zuckerman, L.D. and Nelson, P.C. 1984. Habitat suitability index models and instream flow suitability curves: Brown trout. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-82/10.71. 65 p.

Scott, D., and Shirvell. C.S. 1987. A critique of the instream flow incremental methodology with observations on flow determination in New Zealand. Pages 27-43 *In:* B. Kemper, and J. F. Craig, editors. Regulated streams: advances in ecology. Plenum Press, New York.

Scott, D., and Poynter. M. 1991. Upper temperature limits for trout in New Zealand and climate change. *Hydrobiologia*.