Review of methods for setting water quantity conditions in the Environment Southland draft Regional Water Plan

NIWA Client Report: HAM2004-018
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Prepared for

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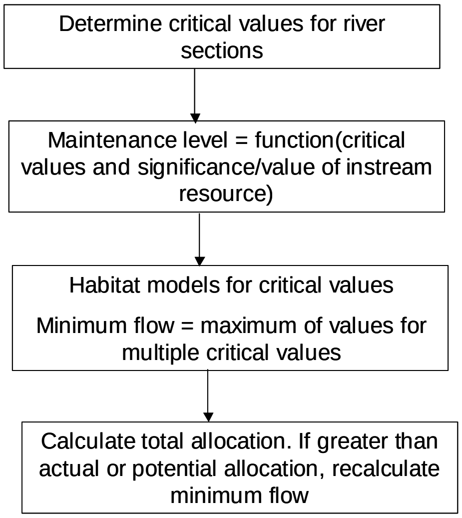
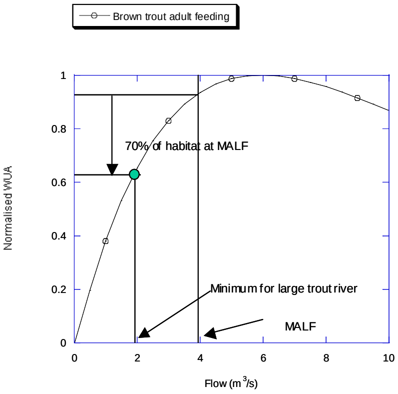
Executive Summary

This report reviews instream flow concepts and assessment methods and considers the process and approach undertaken by Environment Southland (ES) for defining instream values and water quantity conditions to sustain instream values in the ES Draft Regional Water Plan (ESDRWP).

We discuss water allocation strategies and flow assessments methods that could be used to implement flow management and allocation strategies. The flow assessment methods are based on the concept of retaining a percentage of suitable habitat for critical instream values in each river, as shown applied to a river with 70% habitat retention for adult trout in the example below.





We discuss the critical values that could be applied to Southland rivers and note that critical values and their associated habitat suitability criteria can be perceived in two ways. In most cases, they are applied in a specific sense for providing habitat for the target critical species/life stage and with the added aim of providing for taxa with lower flow requirements. However, in some cases the habitat criteria associated with the critical value are used in a generic sense – for providing general instream conditions that, based on experience, we consider appropriate for the ecological function and potential range of instream communities. Thus, the habitat criteria are substituting as general descriptors of instream conditions and stream size; the "target species" of the critical value may be secondary and may in fact not actually be present.

We suggest a method by which maintenance levels (the proportion of habitat retained) for critical values can be consistently assessed throughout the region. Although we have suggested critical values, maintenance levels, fishery and instream values, these are management goals and standards that should be decided by consultation with stakeholders.

We recommend four methods that could be used to define minimum flow regimes in Southland rivers, but do not specifically recommend minimum flows because we believe that some field information on flow and morphology is necessary to assess the effects of significant abstractions. The first three methods are tiered so that the first is the most conservative and will sustain instream values without any field investigations or knowledge of the biological community. The second method has limited data requirements and is aimed to retain critical values to achieve maintenance levels. The third method examines each case in more detail and provides the greatest flexibility for setting flow regime requirements.

We suggest:

1. a default method, where consents may be granted without further investigation if the total allocation is a small proportion of river flow (e.g., < 10% of the mean annual low flow, MALF) at any downstream point in the catchment;
2. application of generalised habitat models, by which consents can be granted with a minimum of site investigation in cases where the total allocation is moderate (e.g., < 30% of MALF), or where the instream values are low and;
3. detailed site instream habitat analysis and consideration of effects where total allocation is high (e.g., > 30% of MALF) and where the instream values are high;
4. the use of WAIORA to set flow requirements for small streams dominated by macrophytes where dissolved oxygen concentration is a limiting factor.

We define a method for setting total allocation according to the minimum flow, with total allocation managed in two ways – by limiting the amount of time that the flow is at the minimum by flow sharing or by establishing a relationship between minimum flow and total allocation. In the latter case, the relationship can then be used to specify the total allocation for a given minimum flow or a minimum flow can be specified for a given total allocation.

The application of the methods that we suggest requires some knowledge of the hydrology of the streams, particularly the frequency and duration of low flows. Such information is necessary for good water management and can be derived from specific flow records or from a regional analysis of flow regime characteristics.

We believe that application of these methods of flow allocation provide a transparent, equitable, and consistent system for the region.

PART I: CRITICAL VALUES AND FLOW ASSESSMENT METHODS FOR SOUTHLAND

1. Introduction

This report provides information to assist Environment Southland (ES) to define instream values and water quantity conditions to sustain instream values in their Regional Water Plan. Part I of the report considers the process and approach undertaken by ES for defining instream values and water quantity conditions to sustain instream values in the Draft Regional Water Plan (ESDRWP), and makes recommendations for revision of the ESDRWP. Part II is a review of instream flow concepts and assessment methods, and are presented to justify the methods recommended in Part I.

The approach taken by ES in the ESDRWP was to group rivers using the "Source of Flow" level in the River Environment Classification (REC). For each group of rivers, ES established significant values that define the purpose for management, and critical values that are the most flow sensitive.

The next step in the process is to set flow conditions for sustaining instream values. Because of limitations in time and resources for producing the ESDRWP, in situ assessments of the relationships between flow and instream habitat for Southland rivers were not undertaken. Environment Southland considered that a more cost effective and strategic alternative was, in partnership with the Ministry for the Environment, to seek advice from the authors on establishing relationships between Southland REC source of flow groups (i.e., lowland, hill, mountain, spring fed and lake fed) and instream habitat under various flow situations, using generalised habitat versus flow relationships based on existing data (e.g., instream habitat surveys) from around the New Zealand. The brief also included an assessment of the critical instream values identified in the ESDRWP and the appropriate REC spatial scale for classifying rivers with respect to instream values.

Management of water allocation involves a process of deciding upon management objectives (or critical values) and levels of maintenance, as described in the Flow Guidelines (Ministry for Environment 1998). We set out a rationale for deriving flow criteria for the ES Water Management Plan. The rationale focuses on minimum flows, and the associated flow variability required to maintain instream habitat. We do not deal with flows required to maintain channel structure (width, bed configuration, and substrate composition), which is controlled by flood flows and river control works.

Changes in flows that maintain channel structure can occur where there is a high degree of flow regulation, such as below dams for hydropower generation and large irrigation schemes. Such developments would be the subject of major river specific investigations in relation to resource consents requirements under the Resource Management Act (RMA).

In presenting this rationale, we are cognisant of the fact that regional councils have neither the time nor resources to undertake intensive river specific investigations of flow requirements of instream values except in situations where instream and out-of-stream values are very high. Alternative methodologies are needed that are based on existing or easy to acquire data that can be applied to streams with low to moderate instream values and/or where out-of-stream flow demands are low.

2. Summary of flow assessment process

The preceding sections have described the process that we recommend for flow allocation in the Southland region. The process (Fig. 2.1) follows that recommended in the instream flow guidelines (Ministry for the Environment 1998) in that it:

- identifies critical instream values (Section 3.3);
- establishes maintenance levels (Section 4.2); and
- calculates the flow requirements that will maintain those values (Sections 5 and 6).

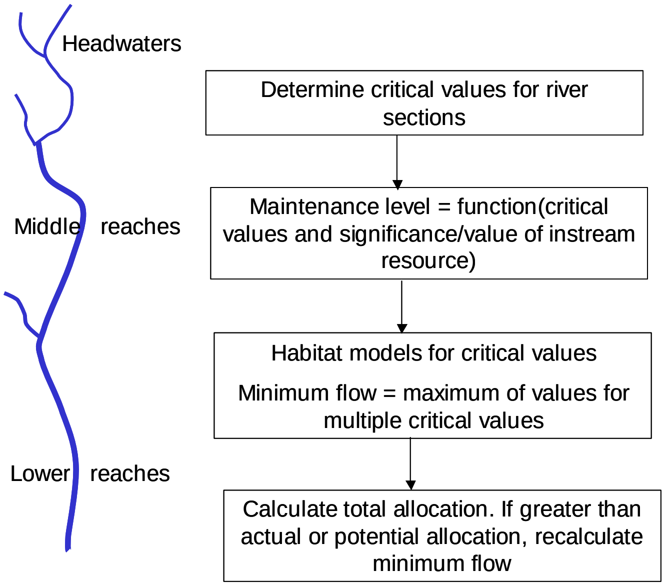


Figure 2.1: Flow chart for assessment of minimum flow requirements applied to morphologically similar sections of river (headwaters, middle and lower reaches).

Critical values are selected from a standard list (e.g., Table 4.1) after consultation with stakeholders. Note that the critical values should be appropriate for the stream/river size as in Table 4.2. Habitat criteria are identified for the critical values. The critical values and their associated habitat suitability criteria may be applied to provide for habitat for the target critical species/life stage, or in a generic sense to provide general instream conditions that, based on experience, should maintain a river's ecological function and potential range of instream communities. Maintenance (habitat retention) levels can then be associated with the critical value and value of the instream resource identified for the river or river section (Table 4.1). Habitat retention is based on retaining a proportion of the habitat available under normal low flow conditions. We acknowledge that in cases where instream values are considered to be low, the suggested levels of habitat retention could result in an effect on populations, but in most cases we believe there would be no measurable effect given the natural variability in flows and aquatic population densities. In order to limit the time that flows are at or below minimum flows, and thus the effect on aquatic communities, we propose an equation that can be used to balance total allocation and minimum flow.

The calculation of a minimum flow and total allocation requires some basic hydrological information, primarily estimates of the mean annual low flow (MALF) and flow duration statistics. We suggest four options for the assessment of flow requirements:

1. a default method (Section 5.1);
2. generalised habitat models (Section 5.2);
3. detailed instream habitat analysis (Section 5.3); and
4. the use of WAIORA where water quality is a limiting factor (Section 5.4).

The first three methods are tiered so that the first is the most conservative and will sustain instream values without any field investigations or knowledge of the biological community. The second method has limited data requirements and is aimed to retain critical values to achieve maintenance levels. The third method examines each case in detail and provides the greatest flexibility for setting flow regime requirements. The fourth method is for special cases, such as low gradient, macrophyte-dominated streams, where water quality rather than instream habitat limits ecosystem function.

The minimum flow would be calculated from habitat models (either using generalised or detailed habitat models) for the critical value, and the highest of the minimum flows for the appropriate habitat models selected as the appropriate minimum for the section of river (Fig. 2.1).

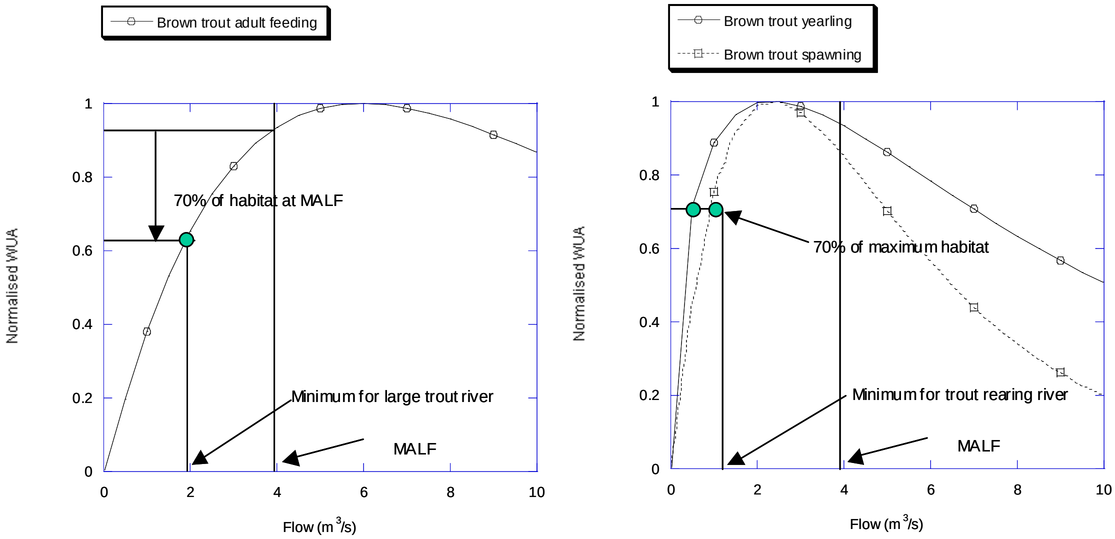


Figure 2.2: Calculation of minimum flow requirement for 70% habitat retention of critical values for a large trout river (left) and a trout rearing river (right).

After the minimum flow has been calculated, the amount of water available for allocation can be calculated (Section 6.1). This is water that is available at all flows above the minimum. If the allocation limit is not sufficient to meet the demand, the minimum flow should be increased, in order to meet that demand and achieve the same level of habitat retention. The possibility of flow sharing and a reduction in minimum flow (Section 6.2) can also be considered at this stage.

3. Critical values

In this section:

- § We discuss the critical values identified in the ESDRWP taking account of the role of stream size in community, species, and life stage habitat requirements and suggest some alternative goals.
- § Define surface water management units that could be used in the REC taking account of the scale appropriate for critical values in Southland rivers.

3.1 Critical values in the Draft Regional Water Plan

ES staff used the REC to categorise rivers according to source of flow: lowland, hill, mountain, lake fed, and spring fed rivers. Significant values, purpose for management, and critical values were then established for each "source of flow" group following consultation with stakeholders, ES planners and scientists. These are shown in Table 3.1.

Table 3.1: Significant values, purposes for management, and critical values that have been derived through meetings with stakeholders and Environment Southland planners and scientists.

Significant values identified for Management Unit	Purpose for Management (Derived by those values and uses sensitive to reduced flow that are also at risk from use (demand))	Critical value(s) (Key values that can be selected and will provide protection to other values)
Lowland		
In stream values Ecological (blackbilled gulls, terns, dotterels, silts, eels, inanga, kokopu, mayflies, trout) Recreational (angling, whitebating, rowing, sailing, jetboating, water skiing, swimming) Mauri Natural character Out of stream uses Industrial and city supplies Stock drinking Water harvesting (potential)	Trout Jet Boating Kokopu Mayflies Whitebaiting (recreational) Mauri Natural character	Maintain flow characteristics to sustain habitat required for trout. Manage flow variability to ensure abstraction does not adversely change general instream biological community compositions.
Hill		
In stream values Ecological (blackbilled gulls, terns, dotterels, silts, eels, non migrant galaxiids, kokopu, mayflies, trout) Recreational (angling, kayaking, swimming) Mauri Natural character Out of stream uses Industrial use and city supplies Domestic and stock drinking Irrigation Water harvesting (potential)	Trout Kayaking Kokopu Non migratory galaxiids Mayflies Whitebaiting Mauri Natural character	Maintain flow characteristics to sustain habitat required for trout. Manage flow variability to ensure abstraction does not adversely change general instream biological community compositions.
Mountain		
Ecological (blackbilled gulls, terns, dotterels, stilts, eels, non migrant galaxiids, mayflies, trout) Recreational – (angling, kayaking, swimming) Mauri Natural character Out of stream uses Domestic Stock drinking Hydro (potential)	Trout Kayaking Mauri Natural character	Maintain flow characteristic to sustain habitat required for trout
Lake fed		
In stream values Ecological (eels, non migratory galaxiids, caddisflies, trout, koaro, torrentfish, lake outlet community) Recreational (angling, kayaking, jet boating, swimming) Mauri Natural character Out of stream uses Industrial, domestic and stock drinking use Irrigation Hydro	Trout Caddis flies Torrentfish Lake outlet community Jet boating Kayaking Mauri Natural Character	Maintain flow characteristics to sustain habitat required for lake outlet communities
Spring fed		
In stream values Ecological (eels, non migratory galaxiids, sponges/crustaceans/macrophytes) Recreational (angling, hunting, shooting, plant gathering) Mauri Natural character Wetland interaction Out of stream uses Domestic and stock drinking	Trout Sponges, crustaceans and macrophytes Mayflies Non-migrant galaxiids. Wetland interaction Hunting/shooting Mauri Natural Character	Maintain flow characteristics to sustain habitat required for sponges, crustaceans and macrophytes Maintain flow characteristics to sustain habitat required for trout, and mayflies
Regulated		
There are two regulated rivers – the Monowai and the Waiau – that have been through extensive consent processes. As part of the work, the values used in the consent processes will be collated and checked with key stakeholders. Assuming those values are acceptable, then the project will look at whether the flow regimes under the existing consents allow for more water to be taken in the Waiau (downstream of the Manapouri outlet) while still protecting the values.		

3.2 Review of critical values

The concept of critical values is that by providing sufficient flow to sustain the most flow sensitive, important value (species, life stage, or recreational activity), the other significant values will be also be sustained. "Sustain" means different things to different people, and it is unrealistic to expect that all values will be maintained at original levels when flows change. For these reasons, "sustaining" instream values should be qualified by a more prescriptive definition. We suggest that it should be taken as meaning maintaining critical instream values at levels not noticeably different to existing levels and to the satisfaction of stakeholders. Identification of the critical instream values and appropriate standards of maintenance are an essential basis for the assessment of instream flow requirements. The critical values must be appropriate to the stream, particularly its size, and must be related to flow, particularly minimum flows, if the habitat-based methods that we recommend are to produce consistent and sensible results.

Critical values for water quantity in the ESDRWP were chosen by ES staff after consultation with DOC and Southland Fish and Game Council staff. The draft critical values included the following:

1. Trout.
2. General instream biological community composition.
3. Lake outlet communities.
4. Sponges, crustaceans and macrophytes.
5. Mayflies.

Instream ecosystem values and functions can be divided into those that are related to the biotic components of natural character (intrinsic and ecological values) (Section 6a RMA) and those related to exploitable ecosystem productivity (e.g., fisheries). Critical values 2 – 5 are all related to biotic natural character whereas critical value 1 (trout) has a fisheries value, which is dependent on ecosystem productivity. Mayflies (critical value 5) have also have value as food for trout and native fish that support fisheries, so they have both biotic natural character and exploitable ecosystem productivity functions. Maintenance of ecosystem productivity is more flow demanding than maintenance of biotic natural character. In this regard, managing a river for productivity of fisheries competes head on with use of water for out-of-stream productive purposes. An analogy is with farming. A farmer's focus is channelling the productivity of the land into meat or milk. Increasing the area of pasture, or increasing its productivity, will translate into more animal biomass for sale. Likewise, a fishery manager is interested in productive capacity of a river for producing fish biomass – either total biomass in the case of commercial fisheries, or numbers of legal size or trophy fish in the case of recreational fisheries. As with farms, the area and quality of habitat for the fish and for their foods underpins fishery productivity. Flow is a primary determinant of the area and quality of instream habitat for both the fish and their foods.

The productive capacity of a trout stream may begin declining as flow falls below the optimal flow for invertebrate (fish food) habitat. By contrast, flow management for biotic communities may simply require maintenance of quite low levels of habitat.

There are three important components of an environmentally balanced flow regime: 1/ the magnitude of the minimum flow 2/ its duration, and 3/ flow variability. Of the five draft critical values listed above, maintenance of the productivity of trout populations is highly dependent on the magnitude and duration of the minimum flow, whereas maintenance of the other values is dependent mainly on the flow regime, in particular flow variability. However, trout also benefit from provision of a moderate degree of flow variability owing to the role that this plays in maintaining healthy invertebrate communities, which trout exploit for food. Furthermore, maintaining productivity of invertebrate communities (for fish food) may require higher flows than those required to maintain trout habitat.

The critical values listed in the ESDRWP have several deficiencies. The critical value "trout" is too vague. The depth and velocity and therefore the stream size and flow requirements of trout vary with fish size and life stage (Fig. 3.1). The habitat and drift feeding requirements of large adult trout are the most flow demanding. Medium to large rivers support these values. Small to medium streams support trout spawning and juvenile rearing values. If the ES critical value definition of "trout" were to remain as presently written, flow conditions would have to default to large adult trout which would result in minimum flows being overestimated in small, juvenile trout/spawning streams.

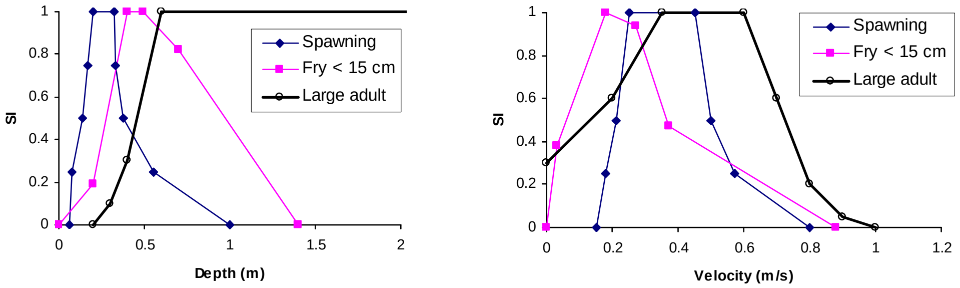


Figure 3.1: Depth and velocity suitability criteria for various life stages of brown trout: spawning (Shirvell & Dungey 1983), fry (Raleigh et al. 1986) and large adults (Hayes & Jowett 1994).

The critical value "general instream communities" is also too vague. There are various instream communities – some of which are valued more highly than others, mainly based on their contribution to ecosystem productivity exploitable by fish (e.g., mayfly/stonefly versus chironomid/worm/snail communities). Moreover, it is not clear whether "general instream biological community composition" refers to all trophic levels (i.e., periphyton, aquatic invertebrates and native fish communities) or just aquatic invertebrates. In addition, instream communities (especially periphyton and aquatic invertebrates) can vary in composition over time depending on the flow variability history. Target communities could be specified, but it is not practicable to do this for the various streams and rivers throughout Southland because it would require a detailed local knowledge of each stream. An alternative approach is to simply reference "general instream biological community composition" to the likely range of communities occurring under the natural flow regime according to the flow magnitude and "source of flow", and with provision for natural variation in the community over time. This avoids the situation where flow changes have resulted in a degraded community and that sets the standard for the stream. Implicit in this approach is the assumption that natural community composition is desirable. However, when dealing with trout, some communities are more desirable than others for maximising fishery productivity. For example, thin diatom, short green algal communities supporting mayfly/stonefly/caddis communities sustain highest trout production and best angling conditions. Rigid adherence to flow conditions that promote the natural range of instream communities might preclude the opportunity to manage a river's flow regime for enhancing a trout fishery (e.g., in the case of flow augmentation by irrigation companies or flow regulation for hydro-power generation).

Native fish have not been specifically listed as critical values in the ESDRWP because it was assumed that flow conditions set for trout would also provide for native fish and this is certainly true for some native fish species, such as eels, bluegill bullies, torrentfish, redfin bullies and common bullies that are commonly found in gravel bed rivers. However, other native fish species deserve specific consideration in the ESDRWP for the following reasons. Some streams may not support viable trout fisheries but may have significant native fish values. For example, slow flowing, entrenched lowland streams, which may support good populations of giant and banded kokopu. Farm drains are known to support giant and banded kokopu populations in Southland. These habitats can have quite low water quality conditions – too poor to sustain trout populations – yet can support kokopu as well as other native fishes, such as eels, inanga, and bullies. It would be inappropriate to apply flow conditions for trout in these waters because they would overestimate the flow needs of the native fishes defined by the critical values.

Two non-migratory galaxiid species are known to occur in mainland Southland – the gollum galaxias (*Galaxias gollumoides*) and an un-described flathead galaxias. They would probably be classified as threatened by the Department of Conservation (Tisdal 1994). These fish rarely coexist with trout (Allibone 2001), so it does not make sense to rely on flow conditions for trout to provide for their habitat requirements. Again, trout flow criteria would likely overestimate the flow needs of these species.

3.3 Alternative critical values

The critical values and their associated habitat suitability criteria can be perceived in two ways. In most cases, we apply them in a specific sense for providing habitat for the target critical species/life stage and with the added aim of providing for taxa with lower flow requirements. In some combinations of stream source and flow range, we use the habitat criteria associated with the critical value in a generic sense of providing general instream conditions that, based on experience, we consider appropriate for the ecological function and potential range of instream communities. In this latter situation, the habitat criteria act as general descriptors of instream conditions and stream size; the "target species" is secondary and may in fact not actually be present. Examples of these applications include:

§ trout spawning criteria which also provide good depths and velocities for invertebrate habitat (which sustains the fish food base) in small streams;

§ redfin and common bully habitat criteria that provide good general instream conditions for streams slightly larger than those dominated by diadromous galaxiids.

We recommend that the critical value "trout" be replaced by two alternative critical values related more closely to the various life history stages, sizes, and seasonal requirements of trout. Critical values should be included for non-migratory galaxiids and for some diadromous fishes. Ideally, specific definitions should be included for biotic natural character (instream communities), but a quantitative flow relationship for this does not exist. Instead, we propose using fish critical values in a generic sense to provide general instream conditions, which based on our experience, should support biotic natural character.

Finally, we consider that the critical value "mayflies" is unnecessary. In the ESDRWP, this critical value applies only to spring-fed streams, but mayflies usually are not the dominant component of spring-fed stream invertebrate communities. We believe that the intention behind a critical value for mayflies was mainly to support trout populations. Regardless, habitat for mayflies and other drift-prone invertebrates would be accommodated if trout were the critical value. Likewise, trout habitat could substitute for critical values 3 (lake outlet communities) and 4 (sponges, crustaceans and macrophytes) in the original list. Quantitative flow relationships do not exist for lake outlet communities, sponges and crustaceans. We suggest the following modified list of critical values:

1. Trout spawning and juvenile rearing.
2. Large adult trout.
3. Non-migratory galaxiids (gollum and other un-described species).
4. Diadromous galaxiids (inanga, giant and banded kokopu).
5. Redfin bully/common bully gravel bed community.

In slow-flowing environments, water quality may be a significant determinant of stream ecology. The effects of flow on water quality can be estimated using the decision support system WAIORA (Jowett et al. 2003).

3.4 Critical values as substitutes for other significant values

In New Zealand, it has generally been assumed that minimum flows set for salmonids will be adequate to maintain native fish populations. The rationale for this is that trout, because of their large size and drift-feeding requirements, have higher depth and velocity requirements than most native fishes. Many native fishes are most abundant in small streams or on the margins of larger rivers (e.g., upland bullies, redfin bullies, inanga). Therefore, habitat for these species is maximal at low flow. The river margins will still provide some habitat for these native fishes at the higher flows required by salmonids.

The fast water habitat native fish guild comprising torrentfish and bluegill bully have similar flow requirements to adult trout. Optimum habitat for these species, especially for torrentfish, typically occurs at high flows (Table 9.1, Fig 3.2). Similarly, optimum flows for some native invertebrate taxa occur at higher flows than trout (Table 9.1, Fig. 3.2). These species prefer riffle habitats that are very sensitive to flow changes. Nevertheless, flow conditions usually are not set for these fast water species alone because they do not have sufficiently high value. Torrentfish and bluegill bullies are relatively common and widespread and do not support fisheries (McDowall 2000). Furthermore, it is inappropriate to set minimum flows to maximise torrentfish and aquatic invertebrate habitat because such flows can not be sustained by the natural flow regime in smaller rivers or in rivers where the flow spreads out over a wide gravel flood plain. Flows that sustain maximum habitat for these fish usually are higher than the natural mean annual, or monthly, low flows and closer to the median flow.

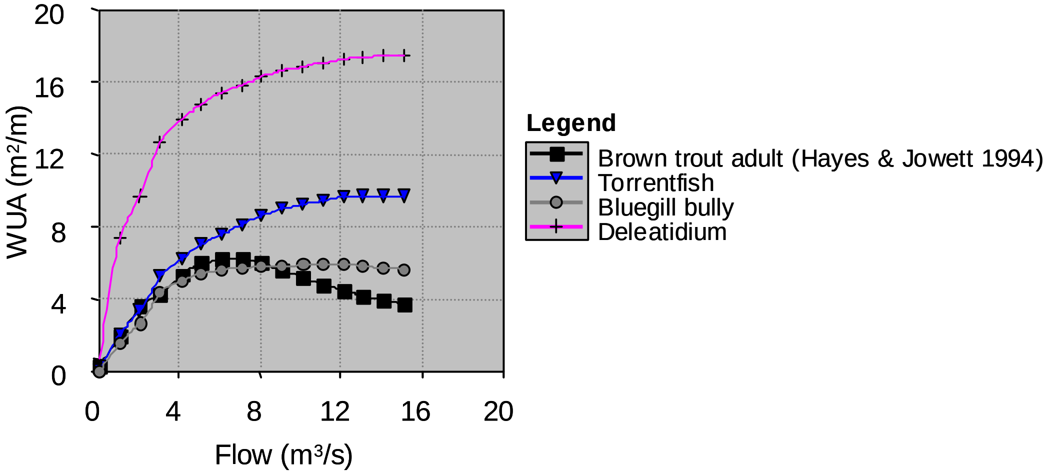


Figure 3.2: Relationships between instream habitat (WUA) and flow for fast water guild native fish (torrentfish and bluegill bully), adult brown trout and the mayfly *Deleatidium* for the Oreti River at Centre Bush.

The other native fish and invertebrate species are widespread and relatively common in most rivers, and many of the fish species do not have fisheries values. The relevant flow management aim for these species is maintenance of biotic natural character, perhaps using the native fish species as an indicator of biotic value. Therefore, it is not necessary to provide flows that sustain maximum habitat or potential maximum abundance. Moreover, many of the native fishes have life history features that impart resilience to environmental change. A large percentage of the native fish fauna in a given river reach is likely to be diadromous, especially close to the sea. These populations probably are recruited from a common gene pool – at least at the regional level. Therefore, environmental change in a given river may not necessarily affect recruitment of the population. Some of the common resident native fish species have a high intrinsic rate of increase, a feature that is well suited to variable flow conditions (e.g., upland bully).

Nevertheless, there are situations in which the conservation status of certain native fish species warrants special attention. These concern some of the non-migratory galaxiids and large diadromous galaxiids (giant, shortjaw, and banded kokopu). Usually these species do not co-occur with trout. For this reason, and because of their high conservation status, we have listed them as critical values. These galaxiids all have lower flow requirements than trout; and in addition to flow, they may require other features, including riparian and instream cover, and preferably native forest in the catchment or on the stream margins.

Habitat suitability curves have been developed for Otago flathead and roundhead galaxias (Baker et al. 2003) and so flow requirements could be based on these. They are small stream fishes; generally flows in the range 0.2 – 0.6 m^3/s provide maximum habitat for them (Table 9.1). The flathead and roundhead galaxiid adults live in riffles of gravel-bed streams. They spawn in the gravel and cobble substrate in the same locations. Reduction in wetted area of riffles due to water abstraction has the potential to threaten spawning success by stranding eggs. However, a mitigating feature is that spawning and egg incubation is confined to late winter – spring when irrigation demand is low. Reduction in wetted area at other times of the year could reduce the productive capacity for these fishes but, unless abstraction is extreme, it is unlikely to threaten population viability.

In Otago, a special flow management scenario has been discussed related to the preservation of some populations of non-migratory galaxiids. Historically maintained low flows (related to mining rights) in some streams and water races may have excluded brown trout and allowed non-diadromous galaxiids to persist. It has been suggested that the low flows could be maintained as a conservation measure to preserve these local fish populations (Baker et al. 2003). Whether similar flow management conservation opportunities exist in Southland should be discussed among the Department of Conservation, Southland Fish and Game and ES.

Other values listed in Table 3.1 include: birds (e.g., waders, terns, gulls, and shags), recreational values (angling, whitebaiting, boating, swimming), ecological character, and Mauri. Ecological character is equivalent to the critical value "biotic natural character".

Maintenance of trout habitat ought to favour shags by maintaining trout populations that shags can exploit for food. The feeding habitat requirements of wading birds, terns and gulls should be adequately provided for by the maintenance of adult and juvenile trout habitat – inasmuch as the habitat of aquatic invertebrates is taken into consideration in the maintenance of the latter. These birds and trout rely on aquatic invertebrate production in shallow riffles and runs for food. If the concept of sustaining productivity of trout populations is an integral part of a minimum flow regime then the food requirements of birds ought to be well catered for. The maintenance of a flat line minimum flow may not sustain invertebrate productivity at the same level as a natural flow regime (except in the special case of augmented minimum flows). This is because a flat line minimum flow excludes the potential for greater invertebrate production that may accrue in the greater wetted area during higher seasonal flows and prolonged flow recessions following floods. Where appropriate, the managed flow regime should include provision for maintenance of seasonal and flood variability (freshes) in order to maintain productivity of the river ecosystem for birds and fishes.

The breeding habitat requirements of wading birds, terns and gulls have been a matter of contention in recent Environment Court hearings (e.g., Rangitata National Water Conservation Order). However, these requirements are related to floods maintaining gravels free of vegetation for nesting birds. Flow management can only influence this matter where flow regulation is extreme – as occurs with dams for hydropower generation. For this reason, we have not considered it further in relation to our review which deals with regional minimum flows and minor to moderate flow variability in relation to the ESDRWP.

The flow requirements of recreational swimming are modest. A flowing river, with clean water and substrate, and swimming holes, is all that is required. Management of flows for trout habitat and natural character will provide for all of these requirements.

Provision for flow variability in those rivers which have naturally varying flows should sustain boating values. High flows, such as occur during flood recessions, are often required on smaller rivers for jet boating and kayaking. Provision for flow variability is an integral part of our recommended flow management rationale for maintenance of productive trout habitat. Maintenance of high levels of adult trout habitat, with flow variability, ought to provide sufficient depths over riffles to sustain boating values in larger rivers. The average depth of rivers that contain high levels of brown trout habitat is about 0.5 m or greater (that being the preferred adult trout depth). This average depth provides a passage depth of 0.25 m through riffle sections in the Oreti and Mataura rivers, which should be adequate for kayakers and jetboats, according to minimum criteria set out by Mosley (1983).

A recent study by Tipa & Teirney (2003) identified Maori values for streams in the Otago region. It showed that some of the values identified by Maori were highly correlated with biological measures of stream health, such as the macro-invertebrate community index (MCI) and a similar index described by Biggs et al. (1998). This relationship with biological indices of stream health suggests that flow recommendations that maintain healthy invertebrate communities would maintain Maori values, at least partly. However, Tipa & Teirney (2003) and the Ministry for the Environment's *Flow Guidelines* (1998) suggest iwi participation in the determination of a suitable flow regime.

4. Levels of maintenance

In this section:

- We suggest that levels of maintenance can be based on retaining a percentage of the habitat at mean annual low flow (MALF) for the critical values according to the value and significance of the instream resource.

The levels of maintenance are standards of habitat protection that aim to achieve consistent standards, with limited allocation and no flow sharing. In the following section (Section 5), we discuss the methods that can be used to determine minimum flows according to maintenance levels. However, the amount of water that is abstracted and the rules that govern the abstraction may alter the low flow regime, i.e., the duration and frequency of low flows. In Section 6, we discuss how minimum flows can be adjusted to achieve consistent levels of habitat maintenance under different low flow regimes, either where the total allocation extends the time that flows are at or below minimum flow (flat lining), or where flow sharing reduces the time that flows are at the minimum.

4.1 Levels of maintenance

Levels of habitat maintenance provided by minimum flows are usually set arbitrarily. This is partly because our state of knowledge on the effects of low flow is insufficient to predict the response of stream ecosystems, and particularly fisheries, and partly because instream habitat simply declines continuously as flow falls below the optimum value, at least in streams and smaller rivers. Therefore, there is no clearly identifiable point at which instream conditions become good or bad, but rather habitat simply gets worse as flow falls below the optimal value – although the rate of habitat change may vary with flow. When habitat modelling results are available, the rate of change of habitat is often used as a basis for setting a minimum flow. The point of greatest change in the rate (the breakpoint) is often selected as the minimum flow. This is based on the premise that higher flows offer diminishing benefits for instream habitat, although there is no scientific evidence that the breakpoint is correlated with biological response.

Instream habitat modelling can estimate the incremental (or percentage) reduction in habitat as flow declines. This can assist stakeholder negotiation over minimum flows where it is useful to consider the relative values of instream versus out-of-stream values in the negotiation. However, how much habitat reduction is enough is more a matter of arbitrary stakeholder choice rather than ecological science.

In the absence of habitat modelling results, the assumption must be made that habitat is proportional to flow for flows less than the MALF. In this situation, a cautious approach to flow setting would maintain the amount of habitat provided by the MALF. Where habitat modelling results are available, we suggest that minimum flows be based on retaining a percentage of the amount of habitat at MALF for the critical value (or a proportion of maximum habitat if it occurs at a flow less than MALF).

Habitat retention is an especially suitable method for use with generalised curves, because with these curves, the breakpoint is a function of the mathematical model that is fitted rather than a result of the stream geometry. In small streams and rivers, the flow that provides maximum habitat for many taxa will be higher than naturally occurring low flows (e.g., the MALF), as described earlier.

The suggested levels of habitat retention are conservative, in that we believe that they are unlikely to be proportional to a population response. Theoretically, a change in available habitat will only result in a population change when all available habitat is in use (Orth 1987). In most cases, we believe that because flows are varying all the time, population densities are at less than maximum levels. That being the case, a habitat retention level of, say 90%, would maintain existing population levels, whereas retention levels of 50% might result in some effect on populations, especially where densities were high.

4.2 Habitat retention levels

An argument can be made for varying the level of habitat retention according to the significance of instream and out-of-stream values. The assistance of Fish and Game staff would need to be obtained to prescribe trout fishery values, by size and life history stage, for the various rivers. Similarly, DoC staff could be asked to classify rivers according to native fish values. This could be done by reference to an REC map of the Southland region. For trout values, the REC map should present river size classes greater than 100 L/s median flow, which are likely to be intermittent or very small streams of no significant value to trout. This process would provide an overlay of greater detail than provided by the river size x critical value classification, and it would allow more prescriptive setting of minimum flow conditions. A suggested classification system for critical values and their significance is presented in Table 4.1.

An arbitrary habitat reduction from the maximum value might provide the basis for the minimum flow decision, taking into account the relative importance of instream versus out-of-stream values. We suggest that the habitat retention level could be varied depending on the perceived values of the out-of-stream use. As with critical values, the categories and levels by which habitat retention levels could be adjusted for each of the categories should be set in consultation with the community and stakeholders. In assessing the amount of habitat to be retained at low flow, it is important to realise that if the low flow were to provide maximum habitat, then higher flows would provide less than maximum habitat. Such a situation may be less than optimum for the species in question, although the risk of detrimental effect of increasing the flow above that which provides maximum habitat is not as great as decreasing the flow, and any habitat loss may be balanced by an increase in food production or the amount of cover. The “best” brown trout rivers, such as the Mataura and Motueka, have flows that provide near maximum habitat between the mean annual low flow and the median flow.

Critical values and out-of-stream uses will need to be assessed on a catchment basis, because the significance of critical values will often increase as the river flow increases. Small tributaries may have low significance ratings yet contribute to the flow of a river with high ratings. Maintenance of a minimum flow at the downstream site may depend on adequate flows in smaller tributaries. The procedure would evaluate flow requirements at points along the stream network to identify the most downstream location with the highest flow demands. Ideally, this would be used as a monitoring site so that when flows at this site reach a minimum, water restrictions would be applied to all upstream consents.

Table 4.1: Suggested significance ranking (from highest (1) to lowest (5)) of critical values and levels of habitat retention.

Critical value	Fishery quality	Significance ranking	% habitat retention
Large adult trout – perennial fishery	High	1	90
Diadromous galaxiid	High	1	90
Non-diadromous galaxiid	-	2	80
Trout spawning/juvenile rearing	High	3	70
Large adult trout – perennial fishery	Low	3	70
Diadromous galaxiid	Low	3	70
Trout spawning/juvenile rearing	Low	5	60
Redfin/common bully	-	5	60

ES's proposed REC surface water management units are too coarse to relate meaningfully to appropriate critical values. Classification needs to extend to the "river size" level to achieve an appropriate spatial scale. Table 4.2 shows five categories for "river size", in terms of median flow, that can be related to critical values and fish species that they are likely to support.

The rankings and levels should be seen as only a first cut. We recommend that Fish and Game and DoC staff be consulted for their local knowledge of the values in relation to stream size that streams throughout the Southland region possess. This information could be stored and viewed on a GIS data base linked with the REC. Local expertise will also be useful for identifying misclassifications of rivers (e.g., spawning/rearing sized streams that actually support seasonal or perennial adult trout fisheries). Misclassifications may occur because of local peculiarities in geology and hydrology influencing a stream’s channel morphology and flow regime. Geology interacts with flow regime to affect channel morphology. However, the relationships between these variables have not been quantified for New Zealand rivers so we excluded geology as an overall controlling REC factor for predicting instream habitat.

Interaction between source of flow and stream size also influences the size of trout able to be supported, and attendant fisheries values. This is related to the effect of the flow regime on channel morphology. For example, spring-fed streams will provide more adult trout habitat for a given flow than hill and mountain sourced streams because they are more entrenched (i.e., the stream is deeper for a given flow) and have more bank cover, producing conditions favourable for adult trout. A hill-sourced stream of the same size will be shallower and might only provide spawning and juvenile rearing habitat.

Table 4.2: River size categories (median flow) relevant to trout and instream community critical values by source of flow category.

Flow range	Lowland	Hill/Mountain	Hokonui/Catlin
20 – 300 L/s	Diadromous galaxiid	Non-diadromous galaxiid	Diadromous galaxiids (low elevation) and non-diadromous galaxiids at higher elevations
300 – 750 L/s	Redfin/common bully*	Trout spawning/juvenile rearing* or non-diadromous galaxiid if trout excluded	Trout spawning/juvenile rearing*
0.75 – 2.5 m^3/s	Trout spawning/juvenile rearing*	Trout spawning/juvenile rearing*	Trout spawning/juvenile rearing*
2.5 – 5 m^3/s	Trout spawning/juvenile rearing*	Large adult trout	Large adult trout
> 5 m^3/s	Large adult trout	Large adult trout	Large adult trout

*Note: trout spawning criteria also provide good depths and velocities for invertebrate habitat (which sustains the fish food base) in small streams, and redfin and common bully habitat criteria that provide good general instream conditions for streams slightly larger than those dominated by diadromous galaxiids.

5. Instream flow methods

In this section:

- § we recommend a suite of methods that could be used to define minimum flow regimes in Southland rivers.

- § We recommend a default method that can be used in cases where the level of abstraction is small and there are no data on stream morphology. For other cases, we recommend habitat based methods that can be used with minimal morphological and flow data in the case of relatively minor alterations to the flow regime, or with detailed surveys of instream habitat where the flow regime will be changed significantly by abstraction.

A sustainable aquatic ecosystem should consider the duration and frequency of minimum flows, as well as the magnitude of the minimum flow. In Section 6, we discuss how minimum flows, derived by methods described here, can be adjusted to achieve consistent levels of habitat maintenance under different low flow regimes, either where the total allocation extends the time that flows are at or below minimum flow (flat lining), or where flow sharing reduces the time that flows are at the minimum.

We suggest four options for the assessment of flow requirements:

1. a default method, where consents may be granted without further investigation if the water allocation level is a small proportion of river flow (e.g., < 10% of MALF) at any downstream point in the catchment;

2. application of generalised habitat models, by which consents can be granted with a minimum of site investigation in cases where the water allocation level is moderate (e.g., < 30% of MALF), or where the instream value significance ranking is low (> 2 in Table 4.1) and;

3. detailed instream habitat analysis and consideration of effects where water allocation level is high (e.g., > 30% of MALF) and where the instream value significance ranking is high (≤ 2 in Table 4.1);

4. the use of WAIORA to set flow requirements for small streams dominated by macrophytes where dissolved oxygen concentration is a limiting factor.

The first three methods are tiered; the first is the most conservative and will sustain instream values without any field investigations or knowledge of the biological community. The second method has limited data requirements and is aimed to retain critical values to achieve maintenance levels. The third method examines each case in detail and provides the greatest flexibility for setting flow regime requirements. Even though we suggest levels of abstraction (as a percentage of MALF) that might be appropriate for each method, we do not consider them mandatory, and flow regime requirements (i.e., Section 6) should be considered in all cases.

The fourth method is for special cases, such as low gradient, macrophyte-dominated streams, where water quality rather than instream habitat limits ecosystem function. Other aspects of water quality, such as nitrogen and phosphorous concentrations, can influence growth rates of plants, including periphyton, and the accumulation of periphyton can influence benthic invertebrate communities (Suren et al. 2003a). Although it has been suggested that nutrient concentrations be taken into account when assessing flow requirements (Suren et al. 2003b), methods for doing this have not been developed. In fact, in situations of low nutrient concentrations (dissolved inorganic phosphorus < 7.5 μg/L), periphyton growth increases as flow increases owing to higher nutrient transfer and higher water velocities (Horner et al. 1990; Biggs & Stokseth 1996). Suren et al. (2003b) found that algal biomass was higher in the Waipara River than in the Okuku River. They attributed this difference to higher enrichment in the Waipara River, although comparative analysis of nitrogen and phosphorus concentrations in the water ran counter to this conclusion. Average nitrogen levels were 22% lower in the Waipara than in the Okuku, and average phosphorus levels in the Waipara River (1.9 μg/L) were about half that in the Okuku. The flow in the Waipara was higher, and the water temperature was also 26% higher than in the Okuku River. Higher temperatures and higher nutrient transfer (because of slightly higher water velocities) in the Waipara River may have been more conducive to algal growth than conditions in the Okuku River. However, algae take up nutrients from the water, so it is possible that nitrogen and phosphorus concentrations without algae present might be higher in the Waipara than in the Okuku. Given these uncertainties and the present state of knowledge, we do not believe that it is possible to allow for nutrient concentrations in flow assessments.

The application of the methods that we suggest for instream flow requirements and total allocation require some knowledge of the hydrology of the streams, particularly the frequency and duration of low flows. Such information is necessary for good water management and can be derived from specific flow records or from a regional analysis of flow regime characteristics. For example, national low flow analyses have been published by Hutchinson (1990) and Pearson (1995), and a new method based on climate data and hydrogeology (Henderson et al. 2003) will soon be available and mapped on the REC. Less work has been done on the prediction of flow duration curves, but it is possible to develop regional relationships by fitting normal distributions to flow duration curves and then normalising to a flow statistic such as the median flow. If required, NIWA can provide assistance with these analyses.

We do not specifically recommend minimum flows because we believe that some field information on flow and morphology is necessary to assess the effects of significant abstractions. A variety of habitat based methods can be used for flow assessment. These include simple spreadsheets (see example in Section 9.5.1) and WAIORA (Section 9.6) for calculation of generalised relationships, and RHYHABSIM for more detailed habitat surveys and analysis.

In Part II, we describe the holistic frameworks that can and should be used to consider the effects of flow regime changes. These frameworks incorporate one or more of the three basic types of instream flow assessment method - historic flow, hydraulic geometry, and habitat methods. The holistic framework can be regarded as a checklist against which to evaluate flow changes. However, a holistic consideration of every aspect of flow and sediment regime, river and riparian morphology, and their associations with the life cycles of the aquatic biota requires a degree of knowledge about individual rivers that is rarely available. Fortunately, the large proportion of consents considered by regional councils in New Zealand involve changes to the low flows rather than the high flows, and the low flow regime has no significant effect on the sediment transport regime and river morphology. The aim of the minimum flow is to retain adequate water depths and velocities in the stream or river for the maintenance of the critical values. In assessing minimum flow requirements, we consider habitat at a meso- to macro-habitat level, rather than at a microhabitat level. The aim is to maintain suitable average depths and velocities in the river and these will be associated with a degree of habitat diversity that is generated by the morphology of the river, which is largely independent of the low flow regime. Although the geomorphological and flow related ecological processes that are associated with low to median flows are generally taken into consideration in instream flow methods, special issues, such as fish passage or seasonal flow requirements, may need to be investigated in some situations. Consideration should also be given to downstream effects. The effect of a flow abstraction is usually greatest immediately below the abstraction site and diminishes as the river flow is supplemented by contributions from tributaries and the proportional change in flow reduces. However, there may be situations where the critical effect is well downstream. This is most likely where the cumulative effect of abstractions from tributaries may result in unacceptably low flows in downstream reaches.

Of the three basic types of instream flow methods, historic flow methods are coarse and largely arbitrary, unless the natural flow paradigm is adopted and historical flows are specified so that they mimic natural flows. An ecological justification can be argued for the MALF, and the concept of a low flow habitat bottleneck for large brown trout has been partly justified by research (e.g., Jowett 1992), but setting flows at lower levels (e.g., the 7 day 5 year low flow $Q_{7,5}$) is rather arbitrary. Hydraulic methods do not have a direct link with instream habitat, and interpretation of ecological thresholds based on breakpoints or other characteristics of hydraulic parameters, such as wetted perimeter and mean velocity, are arbitrary and depend on rules of thumb and expert experience. On the other hand, habitat based methods have a direct link to habitat use by aquatic species. They predict how habitat (as defined by various habitat suitability models) varies with flow, and the shapes of these characteristic curves provide the information that is used to assess flow requirements. Habitat based methods allow more flexibility than historic flow methods offering the possibility of allocating more flow to out-of-stream uses while still maintaining instream habitat at levels acceptable to other stakeholders (i.e., the method provides the necessary information for instream flow analysis and negotiation). Nevertheless, habitat based methods are not without their critics (e.g., Kondolf et al. 2000; Hudson et al. 2002) and in the future, habitat suitability curves may be improved as more data are collected or our understanding of the linkage between hydraulics and biological response increases.

Generalised models take into account the relationship between habitat and channel shape, but do not require such detailed habitat surveys as a conventional instream habitat survey. Generalised models can be applied to a specific stream knowing only the average width at one discharge, as shown in the example in Section 9.5.1. However, within the suite of habitat-based models, it is possible to select the model that is appropriate to the situation. In many cases, the simple generalised model, with one measurement of width and flow, can be used to define a minimum flow for the appropriate critical values and habitat retention levels. If the stream morphology is unusual (i.e., substantially different from the range of rivers used to derive the generalised model) or if greater certainty is required, the width can be measured at two flows and WAIORA used to apply the generalised models. Finally, if the value of the instream or out-of-stream resource requires the most detailed level of consideration, instream habitat surveys and 1D, or even 2D, models can be used to predict habitat response curves for the critical values, or even net rate of energy intake and related fish abundance in the case of trout (Hayes et al. 2003).

In situ assessments of the relationships between flow and instream habitat for Southland rivers have not been carried out because of limitations in time and resources. Instead, we suggest that the regional plan set out the methods that are appropriate, the critical categories that are considered, and target habitat maintenance levels.

5.1 Default method - historic flows

We recommend that historical flows be used to set minimum flows in cases where the total level of abstraction is small and there are no data on stream morphology. In the default situation, we suggest that the minimum flow should be the mean annual low flow (MALF) and that this be applied in situations where the proposed abstractions do not exceed 10% of MALF at any downstream point in the catchment. The level of 10% of MALF was selected because we considered that the change in flow variability and the amount of time at MALF would be small and the effects on stream biota not perceptible. We considered 1:1 flow sharing as a default requirement, but thought that this would be unnecessarily difficult and expensive to implement in cases where abstractions were small. However, in cases where abstractions exceed 10% of MALF, a default minimum flow of MALF with 1:1 flow sharing would provide a high level of protection and would be an acceptable default in the absence of instream habitat information. However, it would constrain out-of-stream water use.

5.2 Generalised habitat models

Studies of flow and habitat requirements in more than 60 New Zealand rivers suggest that flow requirements can be generalised for particular species (Jowett 1996). For trout, these generalised relationships vary with fish size and life stage. Trout rivers, even of the same size, vary in the value of the fisheries they support. Moreover, different sizes of trout and life stages have different depth and velocity and related flow requirements. Jowett's studies indicate that maximum habitat for juvenile trout tends to be provided by flows of 1 – 2 m^3/s, whereas maximum habitat for adult brown trout is provided by flows of 6 – 15 m^3/s. More recently, a larger set of rivers (99) was examined by Lamouroux & Jowett (in press) to show that the shape of the relationships between habitat and flow per unit width was consistent between rivers. The results of this analysis allow us to more closely define the flows that provide maximum habitat for each species, and more importantly, quantify the habitat change that occurs with flow change.

The origins of the habitat suitability curves used to generate the generalised habitat models are listed in Table 9.2. We regard these as the best currently available, but further refinement is possible as more data on habitat use are collected or more refined methods of analysis are developed. The critical values and their associated habitat suitability curves must be appropriate to the stream, particularly its size, and must be related to flow, particularly minimum flows, if the habitat-based methods that we recommend are to produce consistent and sensible results.

Generalised models can be applied to a specific stream with simple spreadsheet calculations and knowing only the average width at one discharge, as shown in the example in Section 9.5.1. This assumes that the hydraulic geometry (relationship between width and flow) is typical of New Zealand rivers, as described in Jowett (1998). However, there are limitations. The generalised models were based on 99 New Zealand streams and rivers and so represent the results of habitat analysis in a river of "average" shape. This assumption breaks down where a river is unusually wide and shallow, as in extensively braided rivers, or where the river is narrow and deep, as in some spring-fed streams. If flow and width measurements are carried out at two flows, WAIORA can be used to apply the generalised relationships with greater certainty. The application and data requirements are described in the WAIORA user guide (Jowett et al. 2003).

Critical values can be associated with fish or invertebrate species, their habitat suitability curves, and the flows and flow classes that are most likely to provide the best conditions for those values (Tables 4.2 and 5.1). These critical values form a small stream to large river gradient according to the flow requirements of the various species. We believe that critical values of sections of rivers should generally fall in the same REC flow class listed in Table 4.2.

Table 5.1: Critical values and the generalised habitat models used to predict habitat values (see Section 9.5 for description of generalised models and their parameters).

Critical value	Species/life stage	*c*	*k*	Optimum discharge per unit width[1] (m^2/s)
Diadromous galaxiid	Inanga	0.19	19.74	0.01
Diadromous galaxiid	Banded kokopu (juvenile)	0.19	13.3	0.01
Non-diadromous galaxiid	Roundhead galaxias	0.31	10.64	0.03
Non-diadromous galaxiid	Flathead galaxias	0.28	9.11	0.03
Redfin/common bully	Redfin bully	0.26	7.39	0.04
Redfin/common bully	Common bully	0.39	6.51	0.06
Trout spawning/juvenile rearing	Brown trout fry	0.86	10.21	0.08
Trout spawning/juvenile rearing	Brown trout yearling	0.4	4.18	0.09
Trout spawning/juvenile rearing	Brown trout spawning	1.24	9.89	0.13
Trout spawning/juvenile rearing	Rainbow trout spawning	1.49	8.78	0.17
Large adult trout	Brown trout adult	1.17	4.35	0.27
Large adult trout	Food producing habitat	1.19	4.25	0.28
Large adult trout	Rainbow trout feeding (30-40 cm)	0.93	2.89	0.32

[1] i.e., optimum discharge per metre of river width

We have listed multiple species/life stages for each critical value. It is possible to select the appropriate species/life stage with some site knowledge, or alternatively calculate requirements for all listed species/life stages to determine which has the highest flow requirements. Because the shapes of the generalised curves differ, the species with the highest discharge per unit width is not necessarily the species with the highest flow requirement at less than maximum habitat.

5.3 Detailed instream habitat analysis

We recommend that a detailed site instream habitat analysis and consideration of downstream effects be carried out where proposed flow allocation exceeds 30% of MALF and where instream values significance ranking is high (≤ 2 in Table 4.1). We believe that the flow regime warrants greater attention when allocation exceeds 30% of MALF. The reason for this is partly because it indicates relatively high water demand and partly because of the effect that high abstraction rates have on the duration of low flows ("flat lining").

This analysis should consider effects on stream morphology, water temperature, fish passage, as well as habitat for critical values and the need for flushing flows and flow sharing. Stalnaker et al. (1995) give an overview of the methods, and detailed descriptions of the methodology can be found in USGS publications (Bovee 1982; Milhous et al. 1989) and in notes prepared for New Zealand flow assessment courses (Jowett 1996).

5.3.1 Selection of reaches and cross-section locations

The selection of survey reaches and cross-section locations will depend on the river and the issues that are addressed. Reaches may be selected because they represent some critical aspect, such as a spawning area or potential barrier to fish passage, or they may be selected to represent the average conditions in a longer section of river. In the latter case, the best representation of a section of river is probably achieved through stratified random sampling without replacement (habitat mapping). This involves stratifying the longer section of river into categories with similar characteristics, such as pool, run, and riffle, and then randomly selecting cross-section locations in these categories. The cross-sections are selected without replacement within the categories to avoid bias caused by selecting cross-sections in similar riffles or in similar locations within a pool. The objective of the survey is to get the best possible representation of the characteristics of the section of river that is surveyed. Multiple reaches may be necessary if the morphological characteristics change. This is usually indicated by a change in gradient, flow, or geology.

5.3.2 Hydraulic modelling methods

Hydraulic modelling is used to predict water depths and velocities in a section of river over a range of flows. These predictions are then used to show how usable habitat varies with flow. Minimum flow assessments are based on the shape of the curves and the proportional changes engendered by a flow change. Either 1D or 2D modelling can be used, and if done well, there should be little difference between the results. 2D modelling can only be applied to a reach, the length of which is usually up to 1 km, a constraint imposed by survey costs. 1D surveys can be carried out over longer sections of river using the habitat mapping method, so that they can include a greater variety of habitats, although not at the same level of detail as a 2D survey. As discussed in

Section 9.3, 1D surveys do not require the same resources as 2D surveys, and usually produce similar or better accuracies. However, 2D models are better able to extrapolate beyond the calibration range in difficult river morphologies, give good graphic representation, and when the modelling is done well, they give better predictions of the direction and distribution of velocities.

The number of cross-sections in a 1D survey depends on the morphological variability within the river. An analysis of a 2D survey showed that similar results could be achieved with a 1D survey with 19 cross-sections (Tarbet & Hardy 1996). In another study, Payne (2002) sub-sampled several very large data sets to determine how many cross-sections are required to produce a robust weighted usable area function. He found that 15-20 cross-sections gave results nearly identical to results for 40 to 80 cross-sections per reach.

5.3.3 Interpretation of results

The most difficult and uncertain part of an instream habitat analysis is the biological interpretation of the results. The two key elements are the habitat suitability criteria that are used to calculate habitat and the linkage between available habitat and aquatic populations. These two issues can be discussed and argued without resolution, although the bottom line is that there must always be suitable habitat if an aquatic species or use is to be maintained. The flow assessment methods recommended in this report ensure that suitable habitat is provided for the critical values, to the specified levels of maintenance, although we acknowledge that there are still uncertainties in some trout habitat suitability criteria. We believe that application of these methods should provide a transparent, equitable and consistent method of flow allocation in the region.

5.4 WAIORA

The WAIORA decision support system can be used to calculate flow requirements based on water temperature, dissolved oxygen, and ammonia. Stream morphology and calibration data are required for the application of water temperature and dissolved oxygen models. This involves limited stream surveys and the collection of water temperature and dissolved oxygen data over a few weeks in mid-summer when flows are low, water temperatures are high, and dissolved oxygen concentrations low. Both water temperature and dissolved oxygen models are necessary because dissolved oxygen concentration depends on water temperature. When the models are calibrated, WAIORA can be used to predict how dissolved oxygen concentrations (and the associated water temperature) vary with flow, and a minimum flow that provides target oxygen concentrations can be selected. The default dissolved oxygen guideline in WAIORA is 6 g/m^3 and is appropriate for salmonid streams, but may be unnecessarily high for eels and some diadromous galaxiid species.

WAIORA can also be used to apply the generalised habitat models in cases where the stream morphology differs from the data set used to derive the generalised models (e.g., spring fed creeks) and/or to give greater certainty than can be obtained from one estimate of river width.

The application and data requirements are described in the WAIORA user guide (Jowett et al. 2003) and this can be downloaded from www.niwa.co.nz/ncwr/tools/waiora.

6. Total allocation

The total allocation, or total amount of water diverted or otherwise removed from the river channel, influences the flow regime of a river and the flow regime plays a critical part in determining the morphology, sediment transport, and biological communities.

The effects of flow regime on a river depend on the range of flows being considered, and can conveniently be divided into two components, the high flow regime and the low flow regime. The high flow regime affects sediment transport, river morphology, and biota. Large-scale projects like damming and major diversions that affect the frequency of high flows (≥ mean annual flood) will usually require detailed and specific studies to determine downstream flow requirements, such as minimum flows and their seasonal variation, and flushing and channel-forming flows. On the other hand, the low flow regime has practically no effect on channel forming processes, but does influence biota. The high flow regime and flow requirements for flushing flows and channel forming flows are not considered in this report.

In this report, we consider the total allocation of flows that directly affect minimum flows but note that it is possible to increase water use by diverting water into off-river storages during periods of relatively high flow and using this water when river flows are low. This is often known as water harvesting. Water harvesting operations can have minimal effects on aquatic biota provided they do not alter the low or high flow regimes.

From an ecological perspective, there is a relationship between the minimum flow and total allocation. The creation of a sustainable aquatic ecosystem requires both a minimum flow to retain the habitat and some restriction on total allocation to limit the amount of time the river is at that minimum. In this way, an assessment of minimum flow requirements considers the whole flow regime rather than just the minimum flow. In considering the relationship between total allocation and minimum flow, we have assumed that the ecological effect of a low flow increases with its duration. A short-term reduction in flow might have little effect on aquatic biota, whereas the same flow persisting for weeks or months would have more severe effects. For example, a minimum flow below a dam may persist for long periods and stream biota will be constrained by those conditions. However, if flows are reduced for a period of days or perhaps even weeks, stream biota may endure unsatisfactory conditions until flows increase. Thus, a low minimum flow with a small amount of water allocated may have similar ecological impacts as a higher minimum flow with greater total allocation. We recommend that this concept be taken into consideration in the ESDRWP.

Although the precise relationship between magnitude of low flow, duration of low flow and biological effect is unknown, it is probable that the detrimental effect of low flows increases linearly as the duration of the low flow increases. The duration of low flows can be limited in two ways:

- by limiting the amount of time that the flow is at minimum flow by flow sharing or;
- by relating the minimum flow to the total allocation so that the minimum flow increases with total allocation and the potential increase in suitable habitat offsets the increase in duration of low flows.

6.1 Minimum flow and total allocation

The minimum flow required to sustain aquatic ecosystems depends on the flow regime to some extent. For example, minimum flows below reservoirs are often held constant for long periods, so that the median or even mean flow is close to the minimum flow. However, in natural situations where there is no storage regulation, the minimum flow is considerably less than the mean and minimum flows. Higher than minimum flows play an important part in maintaining valued aquatic communities, and holding a stream or river at its minimum flow for an extended period would be like prescribing the worst state-of-health as an appropriate cure. For this reason, we suggest that minimum flows should be related to the total allocation, or alternatively the total allocation should be related to the minimum flow. This system has the benefit of giving maximum flexibility and responsibility to water users. Water rostering would be an efficient method of sharing a limited resource among the greatest number.

We have adopted a simple procedure assuming linear relationships between flow and habitat and between flow and exceedance duration (the percentage of time a flow is exceeded) (Fig. 6.1). We assume that the total abstraction should not increase the amount of time the river is at or below the minimum flow by more than 5%.

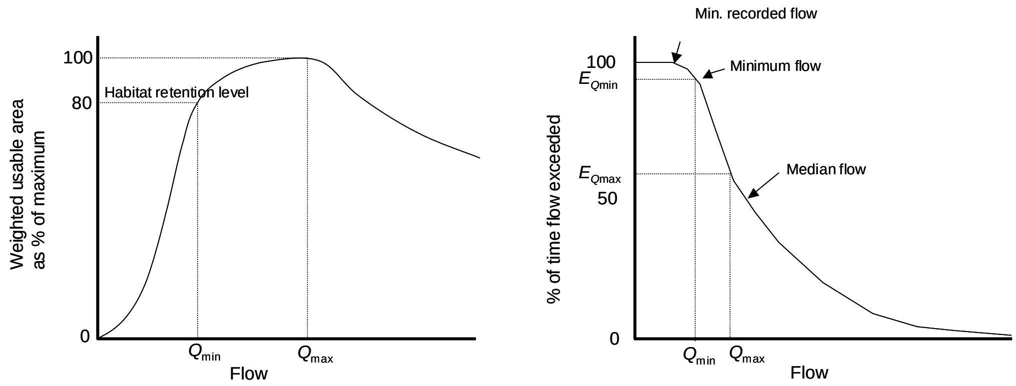


Figure 6.1: Normalised habitat-flow relationship showing the definition of minimum flow (Q_{min}) by habitat retention level and the flow (Q_{max}) that provides maximum habitat (left) and flow duration curves showing minimum flow(Q_{min}), maximum habitat flow (Q_{max}) and their associated exceedances, $E_{Q\min}$ and $E_{Q\max}$, respectively (right).

1. the minimum flow (Q_{min}) is calculated for the appropriate critical value and habitat retention level. The percentage of time that this flow is exceeded is $E_{Q\min}$. However, we are more interested in non-exceedance; the percentage of time that the flow is less than the minimum. The non-exceedance, $L_{Q\min}$, is 100 – $E_{Q\min}$.

2. the flow that provides maximum habitat (Q_{max}) is calculated. If this flow is greater than the median flow, the median flow is used as Q_{max}. The percentage of time that the flow is less than this is $L_{Q\max}$ and its value will be 50% or greater.

3. the rate of change of flow with flow non-exceedance (dQ/dL) is given by $$dQ/dL = \frac{(Q_{\max} - Q_{\min})}{(L_{Q\max} - L_{Q\min})}$$

4. if we limit the increase in non-exceedance to 5%, the allowable flow change is $5 \times dQ/dL$. Thus, when total abstraction (T) exceeds this amount, the flow will be at the minimum flow (Q_{min}) for 5% more time than it would naturally, and the minimum flow should be increased to prevent “flat lining”.

5. and the minimum flow (Q) for any total abstraction (T) that limits the increase in non-exceedance to 5% is given by $$Q = \mathrm{Max}[Q_{\min}, Q_{\min} + T - 5 \times dQ/dL].$$

When the total allocation (for a particular minimum flow) is exceeded, the minimum flow must be increased by an amount equivalent to the extra allocation. The following example illustrates the relationship between the point where the minimum flow must be increased, total allocation, minimum flow and exceedance at minimum flow. A minimum flow of 90 L/s is calculated for two streams with a median flow of 300 L/s (assuming that maximum habitat is at a flow greater than median flow). Stream A has a more stable flow regime than stream B and the flow exceedance statistic for the 90 L/s minimum flow is 80% in stream A and 60% in stream B, as shown on Fig. 6.2. The allowable total allocation (before the minimum is increased) of 105 L/s in stream B is relatively high because the stream is very "flashy" and abstraction causes relatively little change in the amount of time the stream is at minimum flow. Stream A is more like a spring-fed stream and the allowable total allocation (before the minimum is increased) is relatively low because abstraction would cause a large change in the amount of time the stream is at minimum flow.

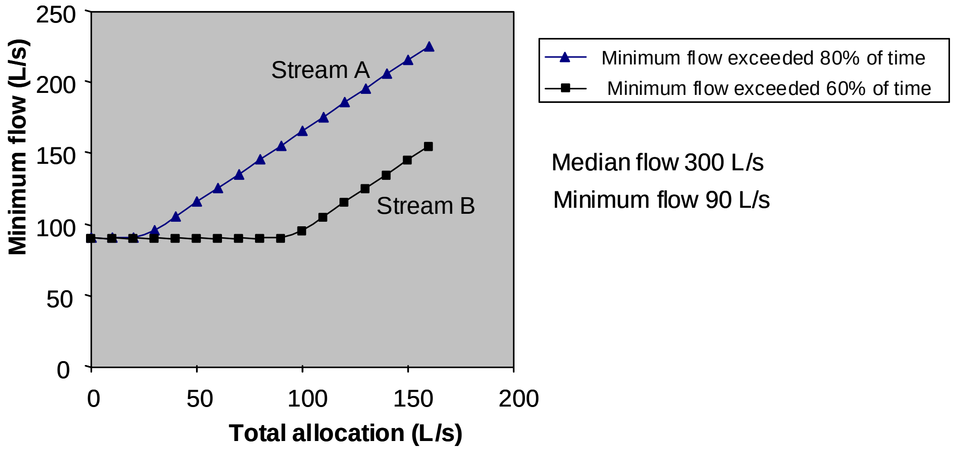


Figure 6.2: Relationship between minimum flow (L/s) and total allocation (L/s) for a stream where the minimum flow is exceeded 80% of the time and a stream where it is exceeded 60% of the time.

6.2 Minimum flow and flow sharing

The effect of flow sharing on the duration of low flows is opposite to the effect of increasing total allocation – it decreases the amount of time that flows are at the minimum flow. With flow sharing, it should be possible to decrease the minimum flow with maintenance levels equivalent to those with a higher minimum flow and no flow sharing. The principle is to maintain the same amount of habitat, averaged through time, under the two flow scenarios – a new minimum flow with flow sharing

(Q) and the minimum flow without flow sharing (Q_{min}). In doing this, we assume that there are linear relationships between flow and habitat and between flow and exceedance.

As with the calculation of total allocation, we calculate the minimum flow (Q_{min}), the percent of time ($E_{Q\mathrm{min}}$) that the flow is at or below that flow, the flow that provides maximum habitat (Q_{max}), and its associated exceedance ($E_{Q\mathrm{max}}$) (Fig. 6.1). For a given total allocation (T), it is possible to calculate the minimum flow (Q) with flow sharing so that the habitat with Q and flow sharing is equivalent to that with Q_{min} and no flow sharing. We have assumed a 1:1 flow sharing ratio, but any ratio could be used in the equations.

1. The minimum flow (Q_{min}) is calculated for the appropriate critical value and habitat retention level. The percentage of time that this flow is exceeded is $E_{Q\mathrm{min}}$. However, we are more interested in non-exceedance; the percentage of time that the flow is less than the minimum. The non-exceedance, $L_{Q\mathrm{min}}$, is 100 – $E_{Q\mathrm{min}}$.

2. The flow that provides maximum habitat (Q_{max}) is calculated. If this flow is greater than the median flow, the median flow is used as Q_{max}. The percentage of time that the flow is less than this is $L_{Q\mathrm{max}}$ and its value will be 50% or greater.

3. The rate of change of flow with flow exceedance (dQ/dL) is given by $\frac{dQ}{dL} = \frac{(Q_{\max} - Q_{\min})}{(L_{Q\max} - L_{Q\min})}$ and the percentage of time that the flow is at the new minimum flow (Q) is given by $L_Q = L_{Q\min} + (Q - Q_{\min})\frac{dL}{dQ}$

4. The minimum flow can be calculated by equating the products of flow and time below minimum flow ($Q_{\mathrm{min}}L_{Q\mathrm{min}}$) with flow and time below the new minimum flow (QL_Q) plus the flow sharing contribution. The flow sharing contribution is a proportion (half in this case) of the abstraction (i.e., $T/2$) above the minimum (Q), so that the average product of the flow and the time flow sharing is $\frac{\left(Q + \frac{T}{2}\right)\frac{T}{2}\frac{dL}{dQ}}{2}$ giving

$$Q_{\min} L_{Q\min} = QL_Q + \frac{\frac{dL}{dQ}\left(Q + \frac{T}{2}\right)\frac{T}{2}}{2}$$

5. This reduces to:

$$0 = QL_Q + \frac{QT}{4}\frac{dL}{dQ} + \frac{dL}{dQ}\frac{T^2}{8} - Q_{\min} L_{Q\min}$$

6. Replacing L_Q with $L_{Q\min} + (Q - Q_{\min})\frac{dL}{dQ}$

   gives a quadratic in Q

$$Q^2 + \left(L_{Q\min}\frac{dQ}{dL} - Q_{\min} + \frac{T}{4}\right)Q + \frac{T^2}{8} - Q_{\min} L_{Q\min}\frac{dQ}{dL} = 0$$

   that can be solved by setting

$$b = L_{Q\min}\frac{dQ}{dL} - Q_{\min} + \frac{T}{4}$$

   and

$$c = \frac{T^2}{8} - Q_{\min} L_{Q\min}\frac{dQ}{dL}$$

7. The new minimum flow (Q) is

$$Q = \frac{-b + \sqrt{b^2 - 4c}}{2}$$

The following example illustrates the relationship between minimum flow with 1:1 flow sharing (Q) and exceedance at minimum flow (E_{Qmin}). A minimum flow of 90 L/s is calculated for a stream with a median flow of 300 L/s (assuming that maximum habitat is at greater than median flow). With 1:1 flow sharing, the minimum is then adjusted depending on the amount of time that the minimum (90 L/s) would be exceeded naturally. Figure 6.3 shows how the adjusted minimum flow would vary with flow exceedance, assuming a total allocation of 60 L/s. In streams where the exceedance of minimum flow is close to the median flow (or flow that provides maximum habitat) in terms of exceedance, flow sharing is of little value and there is very little reduction in minimum flow. In this example, the natural flow regime of the stream (i.e., the % exceedance of the minimum flow) influences the amount of reduction in minimum flow, with no reduction for stable flow streams (low exceedance) and the amount of reduction increasing as exceedance and flow variability increases.

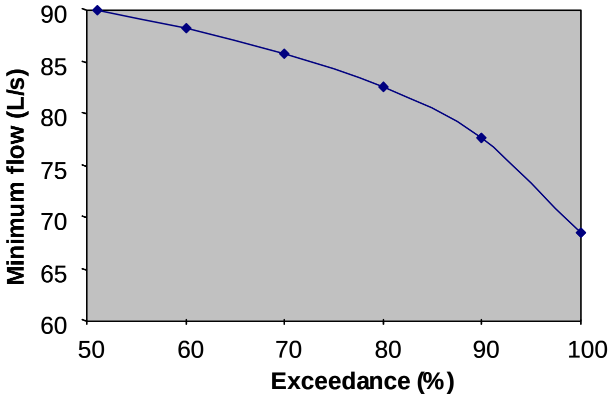


Figure 6.3: Variation of minimum flow with 1:1 flow sharing with % exceedance of the minimum flow of 90 L/s with no flow sharing, assuming a total allocation of 60 L/s.

PART II: REVIEW OF INSTREAM FLOW CONCEPTS AND ASSESSMENT METHODS

7. Instream values and their flow requirements

7.1 Defining instream values

Instream values may be grouped into:

- Ecological or intrinsic values.
- Landscape, scenic and natural characteristics of the river.
- Amenity values – recreational angling and fishing.
- Amenity values – boating and other recreational activities undertaken in, on or near the river.
- Maori values.

There are, of course, overlaps and linkages among these values and they differ in the extent to which they are influenced by variations in flow regime. “Flow-related values” change in a discernible way as flow changes. For example, the value of a particular river as a fishery may decline as flow declines, because the area of suitable habitat declines. At the other end of the scale, increasing flow also may make the river increasingly unattractive for angling, and there can be a range of flows that is preferred or optimal for the sport (Carlson & Palmer 1997; Hayes & Young 2001). “Flow-independent values” change to a minor or no extent as the flow changes. Factors like water quality, water temperature and the micro-distribution of turbulence and velocity also change with flow, but the flow-related changes are often small and the biological effects are difficult to predict because of the large natural variation in these factors and the tolerances of aquatic organisms.

Sustaining instream values when there is demand for out-of-stream water use is challenging for water resource managers. "Sustain" means different things to different people. Moreover, it is difficult to sustain all values at original levels when flows change. It is naïve to expect that instream habitat conditions and the stream ecosystem will remain exactly the same once a flow regime is altered. It also needs to be appreciated that there often is no clearly identifiable point at which instream conditions become untenable as flows are reduced, except when rivers cease flowing. In the face of this knowledge, the challenge is to determine the degree of change in flow and instream conditions before instream values are eroded noticeably and reach levels that dissatisfy community interests. Science presently can provide only partial answers for this problem. As a result, some of the decision-making is necessarily arbitrary and influenced by stakeholder politics.

7.2 Holistic flow assessment

Long-term solutions to river flow management need to take a holistic view of the river system, including geology, fluvial morphological, sediment transport, riparian conditions, biological habitat and interactions, and water quality, both in a temporal and spatial sense.

The instream flow incremental methodology (IFIM; Bovee 1982) 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, such as river morphology, physical habitat, water temperature, water quality, and sediment processes (Fig. 7.1). Its use requires a high degree of knowledge about seasonal and life-stage requirements of species and inter-relationships of the various instream values or uses.

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), allows 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 an “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.

In concept, the BBM is similar to the IFIM in aiming to maintain a prescribed condition based on a high degree of knowledge about flow requirements of the various aspects of the ecosystem. However, identification of flow requirements in the BBM is based more on the “natural flow paradigm” than an understanding of physical and biological relationships. A basic assumption of the BBM, and the major point of departure from IFIM, is that biota associated with a river can cope with naturally occurring low flows that occur often and may be reliant on higher flow conditions. Furthermore, flows that are not characteristic of the river will constitute an atypical disturbance to the ecosystem and could fundamentally change its character (King et al. 2000).

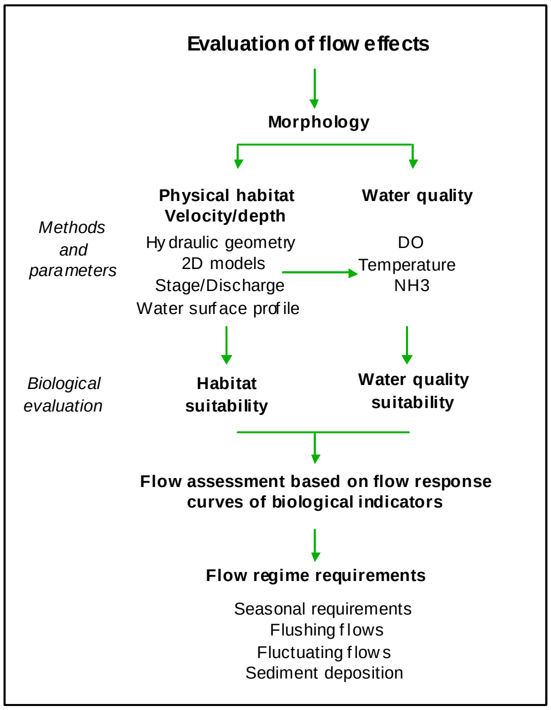


Figure 7.1: A framework for the consideration of flow requirements.

7.3 Significant elements of the flow regime

Historically, the focus of instream flow studies has been on determining the low flow conditions required to maintain particular instream values, because at this time there is the greatest competition for the limited amount of water that is available, and the river ecosystem is most under stress. However, several aspects of a river's flow regime may influence its ability to maintain particular instream values. These may be summarised as follows:

- Large floods, in the order of the mean annual flood and greater, are responsible for the overall form of an alluvial river channel. They are known as channel maintenance flows and also influence the nature of the river corridor – the floodplain surface, vegetation cover, and need for river control measures such as willow planting and groynes. Hence, large floods have a significant influence on the natural character of a river (RMA Section 6(a)), on the presence of areas of significant indigenous vegetation and significant habitats of indigenous fauna (RMA Section 6(c)), and on the amenity, intrinsic and heritage values of the river corridor (RMA Section 7(c), (d), (e)). Large floods also are a major cause of disturbance to the river ecosystem, with potentially significant impacts, at least for a time, on life-supporting capacity, as aquatic biota are displaced and their habitats temporarily destroyed. Large floods during October to December can be particularly disruptive of bird species that nest on river beds, such as the wrybill plover, although such birds may re-nest once or twice if not too late in the season (Hughey 1985). Similarly, floods that occur during incubation, emergence or early fry stages of salmonids (August-November) can severely affect a river fishery in subsequent years by reducing recruitment to the population (Hayes 1995).

- Smaller floods and freshes, with a frequency of a few times each year, are contained within the channel, and therefore have a more restricted effect than large floods. Nevertheless, they are able to mobilise sediment on at least some areas of the river bed, remove periphyton and other aquatic vegetation, and assist juvenile salmonids and larvae of diadromous native fish on their passage to the sea. They generally “flush” and “refresh” the river bed by removing silt and algal coatings, and inhibit vegetation from colonising the riverbed gravels that are not covered by flowing water and, in terms of flow requirements, are known as flushing flows. As with large floods, the effects of freshes can be both positive and negative; i.e., the effect of “flushing” and “refreshing” the river on the one hand, and the effect of disturbing and disrupting parts of the ecosystem on the other. Of particular significance may be the spacing of freshes, particularly from the point of view of flushing the river. The time required for aquatic biota to re-establish after disturbance by a fresh depends on the life cycle of the species. Macroinvertebrates tend to re-colonise streams within weeks (Sagar 1983), whereas trout may take years to re-establish.

- Flow recessions. The period during which flow is declining after a flood or fresh can be of particular significance for amenity values. For much of the time, flows in small to medium-sized rivers are less than desirable for recreational boating, and may restrict angling. During a flood recession, flows are higher than usual for a few days, and offer enhanced recreational opportunity.

- Low flows. As noted above, low flows are particularly important because they are the times at which there is greatest competition for water, the total wetted area of aquatic habitat is least, and the aquatic ecosystem is likely to be under greatest stress (apart from the catastrophic stresses that occur with large floods). On the other hand, stable low flows offer periods of high biological productivity, which permit recolonisation of the riverbed by macroinvertebrates and fish after a flood, and re-establishment of aquatic vegetation. Analysis of instream habitat requirements and general observations suggest that surprisingly low flows can support good native fish and benthic invertebrate populations in small streams, that higher flows are required for juvenile salmonids, and that adult trout and salmon are most numerous in larger rivers and have the highest flow requirements of all the fish species in New Zealand.

- The annual flow regime. Rivers have a distinctive flow regime, in which flows vary through the year in response to the annual distribution of rainfall, evapotranspiration, and snowmelt. This regime is an element of the natural character of a river, and in some cases may be so sufficiently distinctive, its maintenance is included as an instream management objective. The seasonal variation of flows may also have an important biological function, such as spring floods that open a river mouth and enable diadromous fish to migrate up stream.

- Flow variability. The way in which flow varies almost continuously in a river is a significant hydrological feature that has received much attention in designing flow management regimes. Many people consider that flow variations are an essential element of the regime that should be maintained, and that long periods of constant flow (“flat lining”), which could result from adherence to a minimum flow, should be avoided. A common management approach has been to establish “flow sharing” to prevent abstraction rapidly bringing residual river flows down to a particular minimum flow. Flow sharing limits the amount of time that flows are at minimum values, and so effectively ameliorates the biological effect of the minimum flow. There is no scientific evidence available that would justify one level of sharing over another, although 1:1 sharing between instream and out-of-stream uses is widely regarded as inherently equitable.

It can be seen that determining the river flows required to maintain particular instream values may present significant challenges, particularly if there are several values that have different, or even opposite, requirements. Depending on specific proposals for use of the river (e.g., damming, large-scale run-of-river abstraction, minor abstractions), it may be necessary to develop what might be called a “designer flow regime”, that considers the need to maintain floods, freshes, low flows, and aspects of flow variability. This, of course, means that the manager must have a clear idea of the outcomes that are desired, with regard to instream values, and the time and resources available to conduct an extensive environmental flow analysis.

7.4 Management objectives

A basic principle established in the *Flow Guidelines* (Ministry for the Environment 1998) is that instream values and their requirements must be identified and appraised within the context of definite instream management objectives (Fig. 7.2). Without these, instream values that are expressed in (non-monetary) environmental or amenity terms may receive less consideration than out-of-stream uses of water, whose values can be expressed in terms of dollars. However, where objectives have been developed consultatively to reflect community aspirations, they can be accorded appropriate weight, even though they might not be expressed in monetary terms. Resource management objectives have been defined by regional councils in their various regional policy statements, and an increasing number of councils are developing more specific objectives in regional or catchment water resources management plans. These objectives provide a reference point from which council officials, special tribunals, or the Environment Court can compare the merits of alternative uses of a given body of water, and in particular, the extent to which instream values must be provided for.

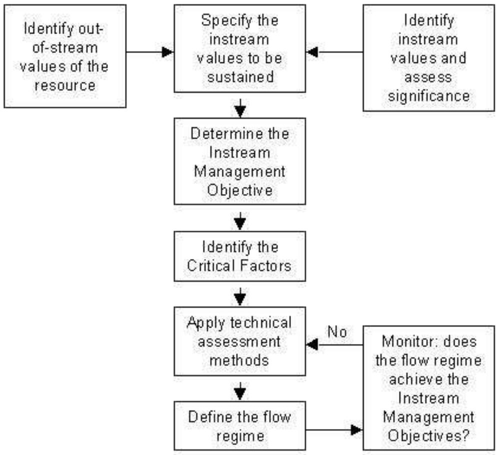


Figure 7.2: The process of setting objectives for management of instream flow regimes (from Ministry for the Environment 1998).

Instream flow management is a complex process, usually involving a combination of technical, public, and legal considerations. To be effective, the instream flow management process should consider the present status of the river and its ecosystem, and then, in consultation with public and institutional organisations, set goals and objectives before establishing appropriate flow requirements. Instream flow methods play a part in this process by showing how the requirements of instream uses, in terms of their various parameters such as wetted perimeter, instream habitat, and water quality, vary with flow. Once these relationships are established, the next important decision is the level at which instream values should be maintained. This is relatively simple where there are established water quality standards, such as for dissolved oxygen and ammonia. However, acceptable levels of instream habitat and even water temperature are more difficult to decide. The *Flow Guidelines* (Ministry for the Environment 1998) suggest that the level of maintenance should reflect the merits of instream values in a particular river (e.g., the quality of a recreational fishery, the biological diversity of a stream ecosystem, the conservation status of a breeding bird population on a river bed, the proximity to a large population centre of a kayaking river, the availability of alternatives or means of mitigation). The concept of retaining a percentage of the “natural” condition is one means of defining the level of maintenance, with the proportion of habitat retained varying according to the merits of the instream values and community aspirations.

7.4.1 Methods for choosing the level of habitat retention

The variation of habitat with flow (e.g., Fig. 9.3) can be used as a guide to selecting an appropriate minimum flow and various methods have been used. These range from selecting the flow that provides maximum habitat, selecting a breakpoint (the flow at which habitat begins to reduce sharply with flow), selecting a flow that retains a proportion of the maximum available habitat, to selecting a flow that provides a proportion of the habitat available under normal low flow conditions.

Environment BOP developed a standard method of selecting minimum flows based on habitat retention (Wilding 2002). They defined the maximum available habitat as the lesser of the habitat available at the natural mean annual low flow (MALF) and the flow that provides maximum habitat. They then selected a minimum flow that provided a proportion of the maximum available habitat and varied the proportion of habitat retained by the minimum flow according to the perceived value of the taxa present in the stream.

They used flow standards of 15%, 85% or 100% habitat retention depending on the perceived value of the taxa. Their approach was to:

1. Identify the maximum available habitat for each fish species present in the river. If maximum habitat occurs above the stream's median flow, maximum habitat is assumed to be the habitat available at MALF.

2. The level of maintenance is adjusted according to ecosystem significance. The minimum flow for the least "valued" species retains 15% of the maximum available habitat, while the minimum flow for the most "valued" species retains 100% of the maximum available habitat.

3. The minimum flows are examined for each species present, and the highest is chosen as the minimum flow for the stream.

4. Minimum flow assessments were then compared to the 5 year 7-day low flows of each stream and a general relationship between minimum flow and 5 year 7-day low flow was derived, so that existing hydrological estimates of 5 year 7-day low flow could be used to estimate minimum flows in streams where there were no instream habitat data.

Although we do not advocate following Environment BOP procedures exactly, the concept of setting flows to retain a proportion of either maximum habitat or habitat at MALF is an approach we recommend.

8. Flow abstraction and flow variability

8.1 Relative importance of flow variability and minimum flow

Before the effect of flow abstraction can be examined, it is necessary to appreciate the inter-relationships between flow variability and the magnitude and duration of low flows. Although flow variability is often thought an essential element of the flow regime that should be maintained, there is little published biological evidence that flow variability is essential. Similar biological communities are often found in streams and rivers with very different patterns of flow variability and valued biological communities can be maintained in rivers where the flow regime has been extensively modified by hydroelectric operations, such as in the Monowai, Waiau, and Tekapo rivers. The term "flow variability" also confuses the discussion, because high flow variability is often bad for the aquatic ecosystem and low flow variability good, depending on how flow variability is measured. Jowett & Duncan (1990) used hydrological indices, particularly the coefficient of variation, to define flow variability. They found that rivers with high flow variability had long periods of low flow and occasional floods, rivers with low flow variability were lake- or spring-fed, and rivers with moderate flow variability had frequent floods and freshes that maintained relatively high flows throughout the year. Rivers with high flow variability (i.e., long period of low flow interspersed with occasional floods) contained poorer "quality" aquatic communities than rivers with low to moderate flow variability. This suggests that the magnitude and duration of low flows is more important than flow variability *per se*. However, flow variability can also be associated with the frequency of floods and freshes. Clausen & Biggs (1997) used the frequency of flows greater than three times the median (*Fre3*) as an index of flow variability and showed, not surprisingly, that periphyton accumulation was less in rivers with more frequent floods (high *Fre3*) and that invertebrate densities in rivers with moderate values of *Fre3* (10-15 floods a year) were higher than those in rivers with high and low *Fre3* values. However, as with the Jowett & Duncan (1990) study, the rivers with low *Fre3* were also rivers in which there were long periods of low flow without floods.

The effect of flow abstraction on the frequency of floods and freshes and the duration and magnitude of low flows depends on the specific proposals for use of the river, such as damming, large-scale run-of-river abstraction, or minor abstractions. Potentially, damming can have the greatest effect both on the frequency of floods and freshes and the duration and magnitude of low flows. In fact, damming is the only way the flow regime can be modified sufficiently to affect the channel-forming floods that maintain the character and morphology of the river significantly. Large-scale diversions can increase the duration and decrease the magnitude of low flows significantly and can also reduce the frequency of freshes, but usually have little effect on the channel-forming floods. On the other hand, minor abstractions usually have little effect on the frequency of floods and freshes, even cumulatively, but certainly can reduce flows during periods of low flow.

Large-scale projects like damming and major diversions will usually require detailed and specific studies to determine downstream flow requirements, such as minimum flows and their seasonal variation, and flushing and channel-forming flows. Because minor diversions have little effect on floods and freshes, the main environmental concern is the minimum flow.

Flow variability and movement of bed sediments can have profound effects on stream ecosystems. Stable, spring-fed streams are subject to few floods, and the fish and plants that live in such streams are often unable to develop similarly or even to survive in less stable environments. On the other hand, gravel-bed rivers and their aquatic biota are in a constant state of change caused by extreme flows (floods and droughts) and mobile bed sediments. Floods are the most important element of flow variability, and flood frequency has been used in several biological models as the primary axis for classifying biological communities (Biggs et al. 1998). In streams with frequent floods, fish and invertebrates that are small and can colonise new areas rapidly are often dominant (Scarsbrook & Townsend 1993), and the periphyton community is usually sparse, with low species richness and diversity (Clausen & Biggs 1997; Biggs & Smith 2002). In streams with stable flow regimes, aquatic communities are thought to be influenced more by biological processes such as competition between species and grazing/predation than by external environmental factors (Poff & Ward 1989; Biggs et al. 1999).

The biological effects of flow variability usually refer to the effects of floods or the effects of long periods of low flows. However, we are not aware of any studies that demonstrate that small-scale flow variation is biologically important. In fact, frequent flow variations are usually considered detrimental. Daily and weekly flow fluctuations are often a feature of rivers downstream of hydropower stations. These fluctuations in flow create a varial zone that is wetted and dried as water levels rise and fall. With frequent flow fluctuations, this zone will not sustain immobile plant and invertebrate species. Mobile species such as fish, and probably some invertebrate species, can make some use of this zone, especially for feeding in recently inundated areas, where there may have been some terrestrial invertebrates in the substrate. However, a varial zone that is wetted and dried at more frequent intervals than a week is unproductive and can be regarded as lost habitat.

8.2 Minimum flows for minor diversions and flow variation

When a minimum flow condition is applied in a river below abstraction points, the abstraction of flow reduces the river flow to the minimum flow as long as the capacity to abstract flow (i.e., the allocation limit) exceeds the water available above the minimum flow, and this prolongs the time that the flow is at the minimum. If the minimum flow restricts habitat for any species, there is potentially a detrimental effect on that population. NIWA research in the Waipara River, where habitat is limited at low flow, showed that the detrimental effect on fish numbers increased with the magnitude and duration of low flow. An instream habitat survey (Jowett 1994) showed that fish habitat began to decline sharply when flows fell below 120 L/s, slightly greater than the 7-day MALF of 112 L/s. In the first summer (1998/99 mean flow 1190 L/s), daily mean flows were less than 120 L/s for 31% of the time and fell to 32 L/s. In this year, there was a substantial decline in abundance of three of the four common native fish species in the river (Fig. 8.1). The following summer (1999/00 mean flow 1243 L/s) there was little change in native fish abundance when daily mean flows were less than 120 L/s for 10% of the time and fell to 69 L/s (Fig. 8.1). In the third year, flows were less than 120 L/s for 61% of the time and fell to 47 L/s, and two of the four common fish species declined in abundance (Jowett unpublished data).

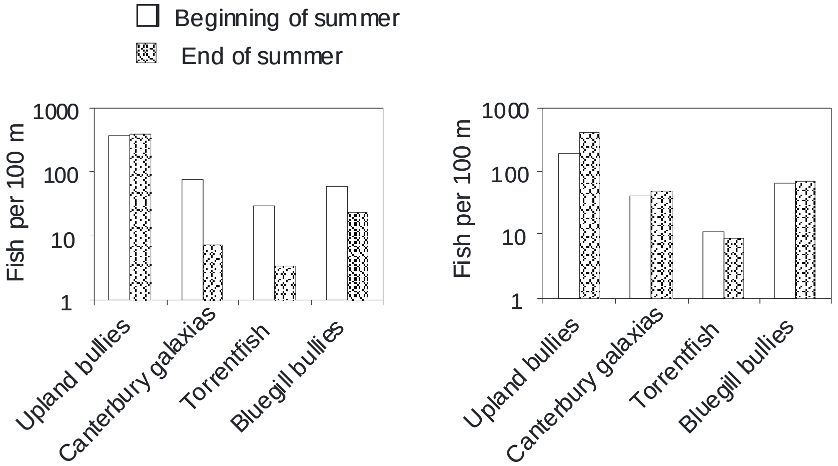


Figure 8.1: Native fish abundance in the Waipara River at the beginning and end of the dry 1998/99 summer (left) and wet 1999/00 summer (right).

Minor flow variations appear to ameliorate the detrimental effects of low flow by limiting the time that the flow is at the minimum, and conversely abstraction of water prolongs the time that flows are less than naturally occurring minimums. For example, the Mokau River at Totoro has a median flow of 23.3 m^3/s and a MALF of 3.4 m^3/s. If 10% of the median flow were abstracted from the river, the amount of time that the river was at or below the mean annual low flow would increase from 0.6% to 5%. Any further increase in the amount of water abstracted would further increase the amount of time that the river is at low flow.

The rise and fall in level, and consequent increase and decrease in water velocities associated with minor flow variations, could have a small beneficial cleansing effect along the stream margins. Along the margins, a small part of the stream bed will be alternatively wetted and dried and the fine sediment in this zone could be removed by wind when dry. Where the margins remain wetted, the small variations in velocity that occur could redistribute fine sediment from the margins of riffles to pools. However, these effects are hypothetical and very much smaller than those that occur during freshes.

Increasing the amount of water abstracted can also influence the reliability of the supply. If we assume a hypothetical minimum flow of 2.76 m^3/s (80% of MALF) in the previous Mokau River example, and assume that total abstractions are 5% of the median flow (i.e., 1.165 m^3/s). The total allocated flow of 1.165 m^3/s can be abstracted whenever the river flow is above 3.925 m^3/s (2.76 + 1.165). According to the flow duration curve, 3.925 m^3/s is exceeded 99% of the time, so that abstraction will only be restricted for 1% of the time. If the total abstraction were increased to 2.33 m^3/s (10% of the median flow), then abstraction will be restricted whenever flow falls below 5.09 m^3/s (2.76 + 2.33). The flow duration curves shows that with this scenario there would be restrictions for 5% of the time.

The environmental effect of low flow obviously varies with the duration of that flow. A near zero flow for a short time may have no adverse effects, whereas if it were in place for weeks or months, there would probably be serious effects. Such an argument suggests that the minimum flow should be varied with the percentage of time that flows are at or below the minimum. For example, where there is a major diversion or dam, flows can be controlled to such an extent that the minimum flow is effectively the median flow. In this situation, the minimum flow requirement is higher than in semi-natural situations where the minimum flow only persists for a short time.

8.3 Flow management strategies

There are several strategies for managing minor flow abstractions. Subject to minimum flow requirements, it is possible to:

- limit or cap the total amount of water abstracted from the river;
- allow a “free-for-all”; or
- have a flow sharing arrangement.

Water abstraction can also be restricted below various flow levels, so that the total allowable abstraction increases with flow. Such a strategy allows diversion into storage reservoirs during high flows, so that water can be used for irrigation or other purposes during periods of low flow without affecting river flow.

The management of water resources within a catchment is complicated by the need to consider the rights of existing consent holders to a reliable supply against equitable and efficient water use both instream and out-of-stream.

8.3.1 Allocation limits

A limit on total abstraction limits the amount of time the river is at low flow and guarantees a certain level of reliability of supply to consent holders, but prevents further water use.

8.3.2 No allocation limits

If no limit is placed on abstractions, other than the indirect limit posed by the reliability of supply and the effect that has on the economics of developing new schemes, the allocation of water amongst the various users becomes a problem when restrictions are in place. The relative rights of the “old” versus “new” consent holders, allocation policies and compliance monitoring become challenging issues for water managers. In some situations, it may be possible to form local management committees that roster the days on which each user is allowed to take water. However, if there was no limit on total allocation, increasing the allowable take would increase the amount of time that flows are at the minimum flow. In such cases, the minimum flow should be increased to compensate. Although changing minimum flow requirements as a result of increased abstraction may provide the best balance of water use and environmental protection, it may be difficult to implement because of the effect it would have on existing water users.

8.3.3 Flow sharing

Flow sharing alleviates the need to increase the minimum flow as the amount of abstraction increases by limiting the amount of time that flow is at the minimum, effectively ameliorating the detrimental environmental effect of the minimum flow. This suggests that the minimum flow with flow sharing could be less than the minimum flow without flow sharing.

There is no empirical ecological evidence for deciding by how much the minimum flow could be reduced in such circumstances, but it is possible to reduce the minimum so that the amount of habitat with flow sharing integrated over time is similar to that at a higher flow without flow sharing. Similarly, there is no evidence to justify any particular level of sharing, although 1:1 sharing between instream and out-of-stream uses is widely regarded as inherently equitable.

8.4 Flow related habitat limitation

When setting minimum flows for instream values the assumption is made that low flow is a limiting factor. Research in New Zealand indicates that the MALF and median flows are ecologically relevant flow statistics governing trout carrying capacity and stream productivity. Jowett (1990, 1992) found that the amount of adult instream habitat at MALF was correlated with brown trout abundance in New Zealand rivers. The habitat metric that he used to quantify instream habitat was percent weighted useable area (WUA), the flow related habitat index used in the Instream Flow Incremental Methodology (IFIM) (Bovee 1982; Stalnaker et al. 1995). WUA is calculated from channel cross-section surveys of depths, velocities, and substrate composition matched with trout suitability of use curves derived for those physical variables. The adult brown trout habitat suitability curves used in Jowett’s analysis were developed by Hayes & Jowett (1994). The inference arising from Jowett’s research was that the percentage of adult trout habitat (WUA%) at the mean annual low flow MALF acts as a bottleneck to trout numbers. He also found that the percentage of invertebrate food producing habitat at the median flow was strongly associated with trout abundance (Jowett 1990, 1992). These two habitat metrics are surrogate measures of space and food, which are considered to be primary factors regulating stream salmonid populations (Chapman 1966).

Jowett’s research provides empirical and conceptual support for the validity of WUA as a habitat index for brown trout populations in New Zealand rivers. The insights gained from this research can also provide a basis for identifying hydrological statistics that are ecologically relevant to brown trout populations.

The reason why the MALF and median flows are likely limiting factors is related to the generation cycles of trout and benthic invertebrates. Brown trout are usually mature at between two and five years of age, with age three for first spawning being most common in rivers. On average, a trout makes the greatest reproductive contribution to the population over the first two or three years of spawning. Because of their large size and feeding habits, adult trout have amongst the highest flow requirements for living space of all New Zealand's freshwater fish species. The lowest flow that a river falls to each year sets the lower limit of physical space available for adult trout. This annual limit to living space potentially sets a limit to the average numbers of trout. This concept is intuitively sensible to anyone who has spent a lot of time looking for trout in rivers. Rivers that fall to very low flows each year hold few trout while those that sustain higher flows hold more trout. Anglers subconsciously gravitate to the latter type of rivers.

In contrast to long-lived species, such as trout, most benthic invertebrates have generation cycles less than or equal to one year, although some have 2-3 year life histories. Invertebrate recolonisation is rapid, in the order of weeks in most cases. In other words, benthic invertebrate populations can respond relatively quickly to medium term improvements in habitat conditions. The invertebrate WUA at median flow provides an approximation of invertebrate habitat conditions prevailing most of the time. This is an important consideration for maintenance of stream ecosystem and fisheries productivity. A flat line minimum flow will reduce invertebrate production that would otherwise accrue during times when natural flow exceeds the minimum flow for weeks at a time. This could be considered as a reduction in life supporting capacity, as the resultant potential reduction in food resources could affect fish production.

The above rationale provides a conceptual ecological basis for interpreting flow statistics, such as the MALF (and 1 in 5, 1 in 10 year low flows etc.), in terms of trout habitat conditions. If protecting trout habitat (and populations) is the overriding factor in setting a minimum flow condition, then the flow that provides maximum habitat or the MALF is an ecologically defensible choice for a conservative minimum flow. However, this may leave little or no flow available for existing out-of-stream users during critical dry periods in most years.

Jowett (1992) developed habitat based regression models, incorporating the above ecological concepts, to predict adult trout abundance in New Zealand rivers. Independent tests have shown that the models successfully predict adult trout distribution and abundance, albeit at a fairly coarse level (Jowett 1995; Hayes & Stark

1997). When the models are used in conjunction with IFIM analyses, they routinely predict declines in trout abundance in small/shallow rivers as a consequence of flow abstraction below the MALF. This occurs because optimal adult trout instream habitat (WUA) in small/shallow rivers usually occurs at flows greater than the MALF. When abstraction causes a reduction in the effective MALF, it will result in a reduction in annual habitat capacity for adult trout. Jowett's models translate this reduction in habitat to reduction in predicted trout abundance.

River size, channel morphology, and hydrology affect the relationship between trout habitat and flow. In very large rivers with confined channels, optimal adult trout habitat conditions may occur at flows at or even below the MALF as a consequence of high mean water velocities at normal flows. In smaller, shallower rivers, it is much more likely that adult trout habitat, and even juvenile trout habitat, will decline linearly from the MALF through to zero at zero flow. This means that a minimum flow condition, say equivalent to the 1 in 5 year (or even 1 in 10 year) low flow, on a large, confined river channel may provide the same relative level of habitat protection as a more conservative minimum flow such as the MALF would on a small, shallow river.

No studies have been undertaken in New Zealand that have tested whether low flow limits trout populations. This was an intention of a three year study of the spatial and temporal variation of trout abundance in the Kakanui River (Hayes 1995; Jowett 1995). However, low flows during the study were not extreme, the lowest being 0.9 m^3/s which was 1.6 times higher than the MALF (0.56 m^3/s). Floods in late winter to early spring appeared to affect recruitment, affecting juvenile year-class strength, the legacy of which could be tracked in the adult population in later years. Stable flow through one winter-spring period, followed by stable flow the following summer, resulted in excellent recruitment and high juvenile abundance.

Unfortunately, most of the published studies on the effects of low flow on salmonids and other aquatic life have been undertaken in a manner that does not allow the effects to be quantified with respect to hydrological magnitude and return frequency of low flow events. An outstanding exception is an intensive, long-term (30 year) study of a sea-run brown trout population in Black Brows Beck, a small stream in north-west England in the southern English Lake District (Elliott et al. 1997; Bell et al. 2000). The stream was only about 0.8 metres wide and was not subject to flooding. Droughts in Black Brows Beck were found to have significant impacts on the trout population. The effects of sustained drought were to reduce the stream area available as habitat and retard trout growth, both factors contributing to high mortality of juvenile trout

(0+ and 1+); adult trout were not resident in this stream. Constant drought conditions were predicted to reduce the population growth rate, abundance, and variability in abundance from year to year; these effects being dependent on the severity of the drought (i.e., rainfall or flow reduction). The effects were not limited to juvenile trout rearing in the stream, they were even manifest in the number and reproductive investment of returning adults. Severe constant drought conditions, equivalent to about a 1 in 10 year drought or worse, were predicted to result in a chaotic or declining population (Bell et al. 2000), especially when they occurred in successive years (Elliott et al. 1997; Bell et al. 2000). Even droughts with a return period of five years (c. the 1 in 5 year low flow) had a measurable impact on the population. Hayes & Young (2001) more extensively reviewed this study and low flow effects on salmonids in general.

The study on the Waipara River referred to in the previous section indicated that some native fish species were detrimentally effected when flows were less than the MALF for more than 10% of the time and that both the magnitude and duration of low flow were important (Jowett unpublished data).

9. Instream flow methods

A large number of methods have been used to determine flow requirements and "new" methods continue to be suggested, only a few of which are discussed here. The method or methods used to develop an appropriate minimum flow or flow regime will depend on the case being considered, and can vary from a quick rule-of-thumb assessment to detailed studies over several years. Even though methods have been applied for more than 30 years, there is no universally accepted method for all rivers and streams, and there are very few case studies of ecological response to flow changes that can be used to judge the success or failure of different methods. Traditionally, instream flow methods have been used to define a minimum flow, below which no human influences should take place. However, the current trend is away from methods that set one "minimum flow" towards methods that consider the flow regime, with some degree of flow variability incorporated to maintain the natural morphology and ecosystem.

Instream flow methods can be conveniently divided into three types: historic flow, hydraulic, and habitat methods. The methods were described by Jowett (1997) and are summarised in the following sections.

9.1 Historic flow methods

These methods are based on flow records and are the simplest and easiest to apply. Stalnaker et al. (1995) describe this type of method as "standard setting" because they are generally desktop rules-of-thumb methods that are used to set minimum flows. A historic flow method is based on the flow record and uses a statistic to specify a minimum flow, below which water cannot be abstracted. The statistic could be the average flow, a percentile from the flow duration curve, or an annual minimum with a given exceedance probability. For example, a method might prescribe that the flow should never drop to 30% of MALF, or it could recommend that the average flow should stay above 80% of MALF. The percentage used is referred to as the "level of maintenance".

The aim of historic flow methods is to maintain the flow within the historical flow range, or to avoid having the flow regime deviate widely from the natural flow regime. The underlying assumption is that the ecosystem has adjusted to the flow regime and that a reduction in flow will cause a reduction in the biological state (abundance, diversity, etc.) proportional to the reduction in flow; or in other words, that the biological response is proportional to flow (Fig. 9.1). It is usually also assumed that the natural ecosystem will only be slightly affected as long as the changes in flow are limited and the stream maintains its natural character. It is implicitly assumed that the ecological state cannot improve by changing the natural flow regime.

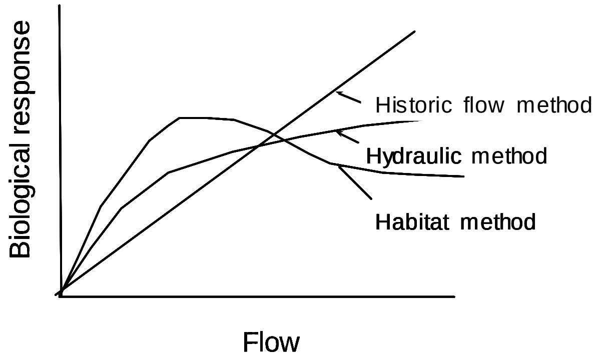


Figure 9.1: Hypothetical relationships between assumed biological response to flow for the historic flow, hydraulic and habitat methods. The biological response is assumed to be proportional to the flow, the wetted perimeter or width, and the weighted usable area, for the historic flow method, the hydraulic method, and the habitat method, respectively.

The most well known historic flow method is the Tennant (1976) method, also known as the Montana method, which specifies that 10% of the average flow is the lower limit for aquatic life and 30% of the average flow provides a satisfactory stream environment. The Tennant method was based on hydraulic data from 11 U.S. streams (including streams in Montana) and an assessment of the depths and velocities needed for sustaining the aquatic life. Tennant found that at 10% of average flow the average depth was 0.3 m and velocity 0.25 m/s, and he considered these lower limits for aquatic life. He found that 30% of average flow or higher provided average depths of 0.45-0.6 m and velocities of 0.45-0.6 m/s and considered these to be in the good to optimum range for aquatic organisms. This is an example of a “regional method”, applicable to a region that has the same type of streams as the streams used for developing the method. However, the Tennant method has been adopted in many different parts of the world, including New Zealand, and in some cases, its recommended minimum flows have been similar to IFIM predictions (e.g., Allan 1995, Hayes 2003). In New Zealand, Fraser (1978) suggested that the Tennant method could be extended to incorporate seasonal variation by specifying monthly minimum flows as a percentage of monthly mean flows.

Historical flows can also be used to define “an ecologically acceptable flow regime”; for example, Arthington et al.'s (1992) holistic method that considers the magnitude of low flows, and the timing, duration and frequency of high flows. Such a flow regime would not only sustain biota during extreme droughts, but would also provide high flows and flow variability needed to maintain the diversity of the ecosystem. The building block method (BBM; King et al. 2000) is a similar approach. The range of variability approach (RVA) and the associated indicators of hydrologic alteration (IHA) identify 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 holistic, BBM and RVA methods are conservative and maintain the ecosystem by retaining the key elements of the natural flow regime. These are low risk approaches aimed at maintaining an ecosystem in its existing state and preclude the possibility that a river ecosystem could be enhanced by other than a natural flow regime. They are probably most appropriate for river systems where the linkages between ecosystem integrity and flow requirements are poorly understood.

9.2 Hydraulic geometry and channel mapping methods

Hydraulic methods are more time consuming in that they are based on measurements of hydraulic data (wetted perimeter, width, depth or velocity) from one or several cross-sections in the stream. The aim of hydraulic methods is to maximise food production by keeping as much of the food-producing area below water. Because the streambed is considered the most important area for food production (periphyton and invertebrates), it is usually the wetted perimeter or the width that is used as the hydraulic parameter.

The variation of the hydraulic parameter with flow can be found by carrying out measurements at different flows, or from calculations based on rating curves or Manning’s equation. The graph of the hydraulic parameter versus flow (Fig. 9.1) is used for prescribing recommended flows or to specify a minimum flow. The minimum flow can be defined as the flow where the hydraulic parameter has dropped to a certain percentage of its value at mean flow, or the flow at which the hydraulic parameter starts to decline sharply towards zero (the curve’s breakpoint). If the wetted perimeter or width is used, the breakpoint is usually the point at which the water covers just the channel base. However, wetting of the channel base might not be enough to fulfil the depth and velocity requirements of some species.

Gippel & Stewardson (1998) suggest an objective method for defining a breakpoint in wetted perimeter/flow (*P/Q*) relationships that could be very useful for maintaining consistency in flow assessments between rivers. They suggest the breakpoint could be selected as either the point of maximum curvature or the point where the slope

(dP/dQ) is 1, after first normalising wetted perimeter and flow by dividing by their respective values at an index flow, such as the median flow.

9.3 Habitat methods

Habitat methods, including the habitat component of the Instream Flow Incremental Methodology (IFIM), are an extension of the hydraulic methods. Their great strength is that they quantify the loss of habitat caused by changes in the natural flow regime, which helps the evaluation of alternative flow proposals. According to a review by the Environment Agency in the U.K. on river flow objectives, “Internationally, an IFIM-type approach is considered the most defensible method in existence” (Dunbar et al. 1998). The Freshwater Research Institute of the University of Cape Town in South Africa states, “IFIM is currently considered to be the most sophisticated, and scientifically and legally defensible methodology available for quantitatively assessing the instream flow requirements of rivers” (Tharme 1996). A review of flow assessment methods in the book “Instream flows for riverine resource stewardship” (Annear et al. 2002) described IFIM as the “most appropriate for relative comparisons of habitat potential from among several alternative flow management proposals” and as “the method of choice when a stream is subject to significant regulation and the resource management objective is to protect the existing healthy instream resources by prescribing conditions necessary for no net loss of physical habitat”. Nevertheless, controversy has accompanied development of the IFIM, in particular the hydraulic and habitat models (e.g., PHABSIM) (Mathur et al. 1985; Scott & Shirvell 1987; Kondolf et al. 2000; Hudson et al. 2003). A multi-authored review exposed divergent opinions regarding the scientific defensibility of PHABSIM (Castleberry et al. 1996).

While many of the shortcomings highlighted in the recent reviews have been recognised and debated for many years, intense debate over them in the recent Tongariro Power Development resource consents hearings triggered a wave of distrust of the IFIM; first within the Taupo fisheries staff of the Department of Conservation, and then among some Fish and Game Council staff. These concerns lead to a review of the IFIM in New Zealand (Hudson et al. 2003) and a workshop in Nelson in early 2004. Both the review and workshop served to air concerns over the IFIM and how it is applied in New Zealand. No clear consensus emerged from the workshop other than the need for continued improvement of the science of instream habitat assessment. Those who have been working with WUA based models within the IFIM, and integrating them with developing environmental science in New Zealand, support their application, while others still distrust conventional WUA models.

Regional councils are caught in the middle of this debate. They require cost effective, science based approaches to setting minimum flows for instream values and allocating water to out-of-stream use. In our opinion, regional councils interests are best served by proceeding with IFIM based habitat models because there are no viable alternatives that are as cost effective and scientifically advanced. There is a good foundation of science underpinning the use of IFIM habitat based models in New Zealand and new advances are making them more cost effective (e.g., the generalised habitat models presented in this report).

Nevertheless, the recent IFIM debate is a timely reminder that further advancement of environmental flows science in New Zealand should be encouraged. Regional councils should not view the current instream flow assessment methods and models as being static. The models are simplifications of the real world and the algorithms and data used in them have varying degrees of certainty. Messages from the Nelson IFIM workshop were for research to:

- better understand habitat use by fish and aquatic invertebrates (i.e., better habitat suitability criteria and ways of modelling these data),
- develop flow related models that are more biologically realistic and intuitive than habitat index (WUA) models (e.g., models that predict spatially explicit growth potential and fish numbers and which can assist in validating conventional WUA models (Hayes et al. 2004)),
- validate and monitor model predictions, so that we can learn from experience.

Regional councils need to recognise that IFIM predictions are not perfect and they need to work with the various stakeholders and science providers to improve the science of environmental flow assessment. They can encourage research in all three of the above areas and can contribute directly to monitoring model predictions. Furthermore, review of regional plans and water resource consents should be scheduled to allow uptake of improvements in the science within reasonable time frames to provide equitable outcomes for all stakeholders.

9.3.1 Habitat models

Several computer models have been developed for the evaluation of physical habitat, water temperature and sediment processes. More recently, individual-based fish models (Railsback & Dixon 2003) and models based on energetic concepts (Addley

1993; Guensch et al. 2001; Hayes et al. 2000, 2003) have been developed to the stage where they can be used for flow assessment. Current software includes:

- PHABSIM (physical habitat simulation; Bovee, 1982; Milhous et al. 1989).
- RHABSIM (river habitat simulation) used in the United States.
- RHYHABSIM (river hydraulic habitat simulation; Jowett 1989) used in New Zealand.
- EVHA (evaluation of habitat; Ginot 1998) in France.
- CASIMIR in Germany (Jorde 1997).
- RSS (river simulation system; Killingtviet & Harby 1994) in Norway.

More recently, 2D and 3D modelling software has been used to predict flow patterns in complex rivers (e.g., River2D: www.river2d.ualberta.ca, and NIWA's 2D model – Beffa 1996; Duncan & Carter 1997; and SSIIM a 3D model: www.bygg.ntnu.no/~nilsol/ssiimwin). In braided rivers, a 2D model has the advantage of being able to predict braiding patterns and the proportion of flow in each of the braids, whereas a 1D model is limited to the range of flows that are contained within the surveyed channels. However, 2D models do not necessarily predict water velocities accurately. Williams (2001) pointed out that velocity prediction was poor (r^2=0.09) in a 2D model of a 1500 m reach of shallow pools and riffles that was developed by Guay et al. (2000). Guay et al. (2001) later attributed inaccuracy to highly turbulent currents, shallow waters, complex riverbanks, and a riverbed of highly variable roughness on a small spatial scale. Tarbet & Hardy (1996) developed a 2D model of the Logan River, and then compared measured and predicted depths and velocities at 136 points at a flow of 7.7 m^3/s, and 150 points at a flow of 4.2 m^3/s. They found that at 4.2 m^3/s, the modal error in velocity was 0.6 m/s with a modal depth error of 0.25 m, and at 7.7 m^3/s the velocity error was 0.15 m/s and depth error 1 m.

In any model, the quality of the results will depend on the quality of the fieldwork and calibration. This is especially true of 2D models where the accuracy of the topographic model has a major effect on the accuracy of depth and velocity predictions. In gravel bed rivers, the accuracy of velocity prediction using a 2D model (Duncan & Hicks 2001) and a 1D model (Mosley & Jowett 1985) were similar. In the Ashley River, Mosley & Jowett (1985) predicted depths within ±0.03 m and velocities with an average absolute error of about ±0.15 m/s at flows ranging from 14.4 m^3/s to 0.083 m^3/s. Duncan & Hicks (2001) compared measured and predicted depths and velocities in the Rangitata River and found average absolute errors of 0.063 m and 0.18 m/s, respectively. In a 1D model, replication of measured water depths and velocities is exact when the measured flow is simulated (with RHYHABSIM). In a 2D model, it is difficult to calibrate the model so that measured water surface levels are modelled precisely, and any error in water surface level translates to an error in predicted depth and mean cross-section velocity. 1D models are easier to calibrate and predict water surface level more accurately than 2D models, at least within the range of rating curve calibration. Within a reach, a 2D model requires more data points than a 1D model and therefore gives a better measure of the longitudinal variations in depth and velocity. As predicted flows depart from the flow used to calibrate a 1D model, uncertainty in velocity distribution increases because it can change with flow. 2D models are likely to predict such changes in velocity distribution more accurately than 1D models, although in both cases, predicted depths and velocities will be incorrect if water surface levels are not modelled accurately.

The aim of habitat-based methods is to maintain, or even improve, the physical habitat for instream values, or to avoid limitations of physical habitat. They require detailed hydraulic data, as well as knowledge of the ecosystem and the physical requirements of stream biota. The basic premise of habitat methods is that if there is no suitable physical habitat for the given species, then they cannot exist. However, if there is physical habitat available for a given species, then that species may or may not be present in a survey reach, depending on other factors not directly related to flow, or to flow related factors that have operated in the past (e.g., floods). In other words, habitat methods can be used to set the “outer envelope” of suitable living conditions for the target biota.

Biological information is supplied in terms of habitat suitability curves for a particular species and life stage. A suitability value is a quantification of how well suited a given depth, velocity or substrate is for the particular species and life stage. The result of an instream habitat analysis is strongly influenced by the habitat criteria that are used. If these criteria specify deep water and high velocity requirements, maximum habitat will be provided by a relatively high flow. Conversely, if the habitat requirements specify shallow water and low velocities, maximum habitat will be provided by a relatively low flow and habitat will decrease as the flow increases. The suitability curves in Figure 9.2 were developed for large, feeding adult brown trout in New Zealand (Hayes & Jowett 1994) and specify higher depth and velocities than curves for adult brown trout developed in the U.S.A. (Raleigh et al. 1986). Whether this is due to differences in the sizes of fish has not been clarified. However, it is clear that it is important to use suitability curves that are appropriate to the river and were developed for the same size and life stage of fish, and behaviour, as those to which they are applied.

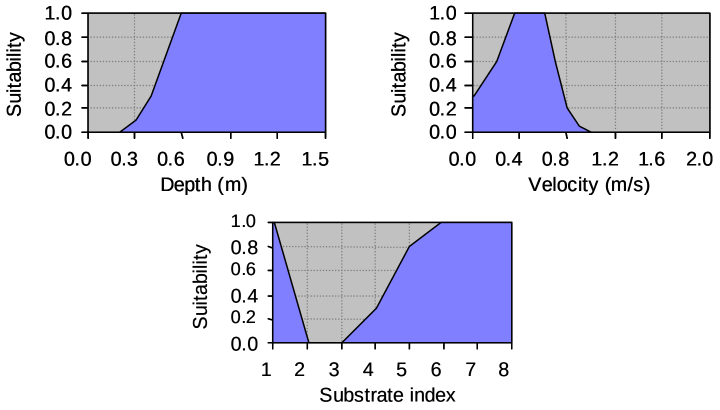


Figure 9.2: Habitat suitability curves for adult brown trout (adapted from Hayes & Jowett 1994).

Habitat criteria have more influence on flow assessments than any other aspect of the analysis. Failure to use appropriate criteria can result in inappropriate flow assessments. Therefore, habitat criteria need to consider all life stages and, where appropriate, include suitability criteria for the production of food for those life stages. Selection of appropriate criteria and determination of habitat requirements for an appropriate flow regime requires a good understanding of the species' life cycles and food requirements (Heggenes 1988; 1996).

The analysis can be separated into a hydraulic component and a habitat component. The hydraulic analysis (Fig. 7.1 shows some of the available techniques) predicts velocity and depth for a given flow for each point, represented as a cell in a grid covering the stream area under consideration. In addition, information on bed substrate and other relevant factors such as shade, aquatic vegetation and temperature, can be recorded for each cell.

The habitat analysis starts by choosing a particular species and life stage, and a particular flow. For each cell in the grid, velocity, depth, substrate, and possibly other parameters (e.g., cover) at the given flow are converted into suitability values, one for each parameter. These suitability values can then be combined (usually they are multiplied) and multiplied by the cell area to give an area of usable habitat (also called weighted usable area, WUA). Finally, all the usable habitat cell areas can be summed to give a total habitat area (total WUA) for the reach at the given flow. Although WUA is often interpreted as the area of usable habitat, it only represents an area when binary habitat suitability curves are used (i.e., habitat variables are either suitable (1) or unsuitable (0)). This whole procedure is then repeated for other flows until eventually the outcome has been produced: a graph of usable habitat area versus flow for the given species. This graph has a typical shape as shown in Figure 9.3 with a rising part, a maximum and a decline. The decline occurs when the velocity and/or depth exceed those preferred by the given species and life stage. Thus, in large rivers, the curve may predict that physical habitat will be at a maximum at less than naturally occurring flows. Thus, in contrast to the historic flow method, the habitat method does not automatically assume that the natural flow regime is optimal for all aquatic species in a river.

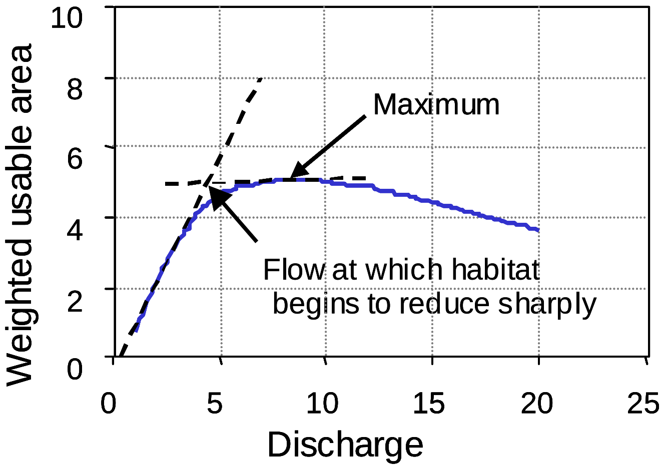


Figure 9.3: Selection of minimum flow at the breakpoint where habitat begins to decline sharply with decreasing flow.

The relationship between habitat and flow (Fig. 9.3) can be used to define a preferred flow range, a minimum flow, or a preferred maximum flow. As with hydraulic methods, the minimum flow can be defined as the breakpoint or as the flow at which the habitat has dropped to a certain percentage of its value at mean or median flow. It can also be defined as the flow that has the lowest acceptable minimum amount of habitat in absolute terms. If the recommended minimum flow is at or above the habitat maximum for a particular species or instream use, the area of habitat available to that species will be less than maximum for most of the time. Often this does not matter because the rate of change in habitat with flow is less at high flow than at low flow (Fig. 9.3) and the difference between maximum habitat and the amount of habitat at a high flow is relatively small. Most New Zealand native fish are found in shallow water along the edges of large rivers (Jowett & Richardson 1995) and there is usually some edge habitat available over a large range of flows. However, if maximum habitat for all species and instream uses occurs at less than the minimum flow, it suggests that a reduction in flow might enhance those values.

Habitat suitability curves have been developed for threatened species (e.g., blue duck; Collier & Wakelin 1995), for species of special interest (especially trout and salmon; Hayes & Jowett 1994) and even for recreational activities (Mosley 1983). When many fish species and life stages are present in a river, there are usually conflicting flow requirements. For example, young trout are found in water with low velocities, and adult trout are found in deep water with higher velocities. If the river has a large natural variation with pools, runs and riffles, some of the different requirements may be provided for. Still, even in these rivers, and especially in rivers with small habitat variation, one species may benefit greatly from a reduction in depth and velocity, whereas habitat for another species may be reduced. If a river is to provide both rearing and adult trout habitat, there must be a compromise. One such compromise is to vary flows with the seasonal life stage requirements of spawning, rearing, and adult habitat, with the optimum flow gradually increasing as the fish grow and their food and velocity requirements increase. Biological flow requirements may be less in winter than summer because metabolic rates and food requirements reduce with water temperature. If flow requirements of individual species are different, a solution may be found by choosing one with intermediate requirements (Jowett & Richardson 1995) or to define flow requirements for aquatic communities.

Habitat methods and water quality models can be integrated, although usually the results of hydraulic models are transferred into water quality models. For example, a water temperature model (SSTemp; Bartholow, 1989) uses water depth and velocity for each flow and these data are then used to model how water temperature varies with distance downstream. The integration of stream geometry and water temperature, dissolved oxygen and ammonia models has been implemented in the decision support system WAIORA (Jowett 1999).

9.4 Regional methods

Tennant’s (1976) method is a good example of a regional method that combines the best features of historic flow methods and habitat methods, resulting in a biologically defensible method of minimum flow assessment – for the region. Once established, regional methods can be easily applied to rivers within the region using a formula based on the proportion of natural flow, either recorded or estimated. The formula can be as simple as a fixed proportion of flow or the proportion can vary with river size, possibly retaining a higher proportion of the flow in small rivers than in larger rivers, as used in formulae for maintenance of trout and food producing habitat in Wellington and Taranaki rivers (Jowett 1993a,b). Similar methods could be developed for regions that are hydrologically and morphologically similar, with criteria that apply to trout, native fish, stream insects, or periphyton. By analysing habitat variation with flow for rivers within a region, it is possible to determine the level of flow as a proportion of median or MALF that maintains adequate or optimum conditions for various target communities. Variation in levels of maintenance could be achieved by assessing requirements for optimum habitat and minimum habitat, as in the Tennant method. Application of the method would involve selecting an appropriate target community and level of maintenance for the river in question and then applying a formula based on flow.

The benefit of regional methods over historic flow methods is that they can have explicit environmental goals, making water management more transparent. Thus, regional methods can be established as biologically defensible, and discussion and consultation can focus on whether the target and flow standards of maintenance are appropriate.

The rationale for habitat based regional methods is the same as that of habitat methods. Within a region, it is possible to develop formula that predict when hydraulic conditions are optimum or become limiting for a range of aquatic species. For instance, most native fish are small stream species. Few are found in swift, deep water. In contrast, adult trout are rarely found in water less than about 0.4 m deep. Stream insects are most abundant in shallow swift habitats.

It is also possible to generalise velocity and depth criteria as levels of protection within a region, based on a data set from rivers in the region. For instance, average velocities of less than 0.1 m/s might be considered poor, 0.1-0.3 m/s adequate, and 0.3-0.5 m/s good for aquatic organisms such as trout and benthic invertebrates. Similarly, average depths greater than 0.15 m might be considered suitable for native fish and depths greater than 0.4 m suitable for adult trout.

These methods are potentially useful in that they combine the best features of habitat and flow methods and are likely to result in flow assessments that provide life sustaining flows whilst retaining some degree of the river’s character.

9.5 Generalised instream flow models

Habitat methods and instream habitat models have been used for many minimum flow studies in the last two decades (Gore & Nestler 1988; Reiser et al. 1989; Gallagher & Gard 1999; Guay et al. 2000). Conventional instream habitat models link a traditional hydraulic engineering model to habitat suitability curves for water depth, velocity and bed particle size. The hydraulic model predicts the values of point habitat variables (velocity, depth, particle size) for the discharge in a stream reach. Suitability curves are used to calculate point habitat values for each combination of point habitat variables. Their product is a habitat value (*HV*, ranging between 0 and 1), and when summed over the reach surface area, *HV* gives the weighted usable area (WUA). Therefore, the major reach-scale outputs of these models are relationships between WUA and discharge.

Applying conventional instream models in a stream reach requires considerable field effort and experience. It involves a complete survey of bed topography and precise measurements of current velocities and water depths along several geo-referenced cross-sections, depending on the form of hydraulic model. The hydraulic model also requires calibration at 2 or more flows.

Several approaches have been proposed for reducing this effort. Some are based on a simplification of the hydraulic complexity within the reach by using hydraulic geometry relationships and considering point velocities as equal to their average (Jowett 1998), or simplifying their statistical distribution (Singh & Broeren 1989; Lamouroux et al. 1998). Others try to identify general patterns in existing applications of the models (Hatfield & Bruce 2000). Lamouroux & Capra (2002) proposed to model directly the output of conventional instream habitat models using simplified and cost-effective reach descriptions (depth- and width-discharge relationships, particle size, median flow). The advantage of the resulting generalised habitat models is that no simplifying hypothesis is made on the distribution of hydraulic variables within reaches. Their use requires little experience and field effort, and the models provide *HV* and WUA curves that can be interpreted in a similar way as conventional ones.

Tests of generalised models in France (Lamouroux & Capra 2002) and New Zealand (Lamouroux & Jowett in press) found that habitat values for taxa were predictable from simplified hydraulic data. Reach hydraulic geometry (mean depth and mean width-discharge relationships), average bed particle size and mean natural annual discharge could be used to provide reliable estimates of habitat values in natural stream reaches. Key physical variables driving habitat values were found to be similar in New Zealand and France. The Reynolds number of reaches (discharge per unit width) governs changes in habitat value of all species within reaches. The Froude number at the mean natural discharge, which indicates the proportion of riffles in stream reaches, was generally the major variable governing overall habitat value in the different reaches. This is consistent with the preference of benthic fauna, such as many of the native New Zealand fish species and benthic invertebrates, for riffles (Jowett & Richardson 1995; Jowett 2000), and non-benthic aquatic fauna for runs or pools (e.g., Jowett 2002).

The generalized habitat models were robust. Tests of the French models of Lamouroux & Capra (2002) in New Zealand rivers were very satisfactory, and most New Zealand models gave reasonable accuracy when applied in rivers larger or smaller than those used to calibrate them (with some loss of accuracy for some taxa). This suggests that the generalised model equations can be used to model habitat quality anywhere in the world for taxa with comparable microhabitat suitability, at least within their calibration range. Generalised models necessarily lose some information compared to conventional models such as PHABSIM. This loss must be balanced against the requirement for fieldwork and experience in conventional modelling. In particular, hydraulic geometry relationships in reaches can be easily obtained from field measurements made at two different discharges or using regional models (Leopold et al. 1964; Jowett 1998; Lamouroux et al. 1998). By combining generalised models and hydraulic geometry relationships, estimating habitat values in multiple streams is possible from few field measurements and detailed topographies of stream reaches, associated velocity measurements and hydraulic model calibration are not required.

9.5.1 Derivation and application of a generalised method

Generalized habitat models suggest general, simple rules can be used to improve flow management or to estimate regulation impacts over whole river networks.

The generalised model takes the form:

$$HV = a \times \left(\frac{Q}{W}\right)^{c} \times e^{-k\frac{Q}{W}}$$

The values c and k describe the shape of the relationship between habitat (HV, weighted usable area m$^{2/}$m as a proportion of river width, dimensionless) and discharge (Q m^3/s) per unit width (W m), and the parameter a is a scaling factor that varies from reach to reach. The values c and k are of most interest, because the assessment of flow requirements is based on the shape of the curve, rather than the absolute values. The equation has a maximum at c/k, so that this ratio specifies the discharge per unit width that provides maximum habitat.

The values of model coefficients for each taxa were derived from a dataset of 99 reaches. The reaches in this dataset have mean flows varying from 0.6 m^3/s to 53.8 m^3/s (the same data were used by Lamouroux & Jowett (in press). Lamouroux & Jowett (in press) fitted a non-linear mixed effects model to these data for habitat and flows from 0.05 times the mean flow to the mean flow. This model described a common shape for each taxa (i.e., *c* and *k* were held constant), but *a* was allowed to vary between reaches.

For some taxa, generalised curves could not be developed by the method used in Lamouroux & Jowett (in press) because the flow range that was modelled did not include the flow that provided maximum habitat. An alternative method of deriving generalised curves was used to avoid the problem of modelling an inappropriate flow range. Instead of fitting one value of *c* and *k* to all reaches, values of *c* and *k* were fitted to each reach. Values for *c* and *k* were then examined and reaches with negative values and outlying values of *c*/*k* were excluded.

The median values of *c* and *k* are shown in Table 9.1. The origins of the habitat suitability curves used for the calculation of generalised curves are shown in Table 9.2.

Table 9.1: Generalised habitat models used to predict habitat values (*HV*) from average characteristics of stream reaches. Model parameters *c* and *k* are developed for each reach and the median value selected, excluding reaches with negative values of *c* and *k* and outlying values of *c*/*k*.

Species	***c***	***k***	**Optimum discharge per unit width[1] (m^2/s)**
Inanga	0.19	19.74	0.01
Shortjaw kokopu[2]	0.19	16.35	0.01
Upland bully	0.11	8.63	0.01
Crans bully	0.09	6.84	0.01
Banded kokopu (juvenile)	0.19	13.3	0.01
Canterbury galaxias	0.03	2.29	0.01
Roundhead galaxias	0.31	10.64	0.03
Flathead galaxias	0.28	9.11	0.03
Longfin eel (< 30cm)	0.07	2.07	0.03
Lowland longjaw galaxias	0.33	9.35	0.04
Redfin bully	0.26	7.39	0.04
Shortfin eel (< 30cm)	0.13	2.32	0.05
Common bully	0.39	6.51	0.06
Brown trout fry	0.86	10.21	0.08
Brown trout yearling	0.4	4.18	0.09
Nesameletus[3]	0.26	2.62	0.1
Brown trout spawning	1.24	9.89	0.13
Bluegill bully	1.01	6.13	0.16
Rainbow trout spawning	1.49	8.78	0.17
Deleatidium[3]	0.33	1.92	0.17
Torrentfish	0.88	4.05	0.22
Brown trout adult	1.17	4.35	0.27
Food producing habitat	1.19	4.25	0.28
Rainbow trout feeding (30-40 cm)	0.93	2.89	0.32
Coloburiscus humeralis[3]	1.35	4.17	0.32
Aoteapsyche[3]	1.44	3.17	0.45
Zelandoperla[3]	1.71	3.4	0.5

[1] i.e., optimum discharge per meter of river width
[2] suitability for cover locations only
[3] large river habitat suitability curves (see Jowett 2000)

Table 9.2: Source of habitat suitability criteria used for the development of generalised habitat curves.

Species	Reference
Aoteapsyche	Jowett et al. 1991
Banded kokopu (juvenile)	McCullough 1998
Bluegill bully	Jowett & Richardson 1995
Brown trout adult	Hayes & Jowett 1994
Brown trout fry	Raleigh et al. 1984
Brown trout spawning	Shirvell & Dungey 1983*
Brown trout yearling	Raleigh et al. 1984
Coloburiscus humeralis	Jowett et al. 1991
Common bully	Jowett & Richardson 1995
Crans bully	Jowett & Richardson 1995
Deleatidium	Jowett et al. 1991
Flathead galaxias	Baker et al. 2003
Food producing habitat	Waters 1976
Canterbury galaxias	Jowett & Richardson 1995
Inanga	Jowett 2002
Longfin eel (< 30cm)	Jowett & Richardson 1995
Lowland longjaw galaxias	Baker et al. 2003
Nesameletus	Jowett et al. 1991
Rainbow trout feeding (30-40 cm)	Bovee pers. comm.
Rainbow trout spawning	Jowett et al. 1996
Redfin bully	Jowett & Richardson 1995
Roundhead galaxias	Baker et al. 2003
Shortfin eel (< 30cm)	Jowett & Richardson 1995
Shortjaw kokopu	McDowall et al. 1996
Torrentfish	Jowett & Richardson 1995
Upland bully	Jowett & Richardson 1995
Zelandoperla	Jowett et al. 1991

* Although Shirvell & Dungey (1983) measured water velocities 2 cm above the top of the redd, their velocities were within the range of mean water column velocities measured in North American rivers.

Instream habitat data from an anonymous river (18.53 m wide at a flow of 5.58 m^3/s) are used to illustrate an application of the generalised method.

Ideally, field measurements of stream geometry and its variation with flow would be used to calculate the relationship between width and discharge. However, in this case the generality of the method is tested by using the average New Zealand hydraulic geometry relationship $W = bQ^{0.176}$ (Jowett 1998) between width (*W*) and discharge (*Q*) to calculate the width for flows of 0 to 10 m^3/s. The generalised model is then applied in the following steps:

1. the hydraulic geometry width constant *b* is calculated as $W/Q^{0.176}$ or 13.69;
2. the width is then calculated for each flow as $13.69Q^{0.176}$;
3. the discharge per unit width (*Q/W*) is calculated for each flow;
4. the habitat value (*HV*) is calculated for each flow using the appropriate values of *c* and *k* for each species $HV = \left(\frac{Q}{W}\right)^{c} \times e^{-k\frac{Q}{W}}$;
5. the values are then normalised (i.e., divided by the maximum value) so that the maximum value is 1.

The habitat value (*HV*) is the dimensionless habitat value and is equivalent to expressing weighted usable area as the proportion of river width. The habitat value (*HV*) can be converted to the equivalent of WUA in m^2/m by multiplying by the river width at each flow.

Figure 9.4 shows the curves of dimensionless *HV* predicted using the generalised relationship compared to those predicted using the instream habitat data and RHYHABSIM and Figure 9.5 shows the same set of curves with *HV* multiplied by the river width at each flow.

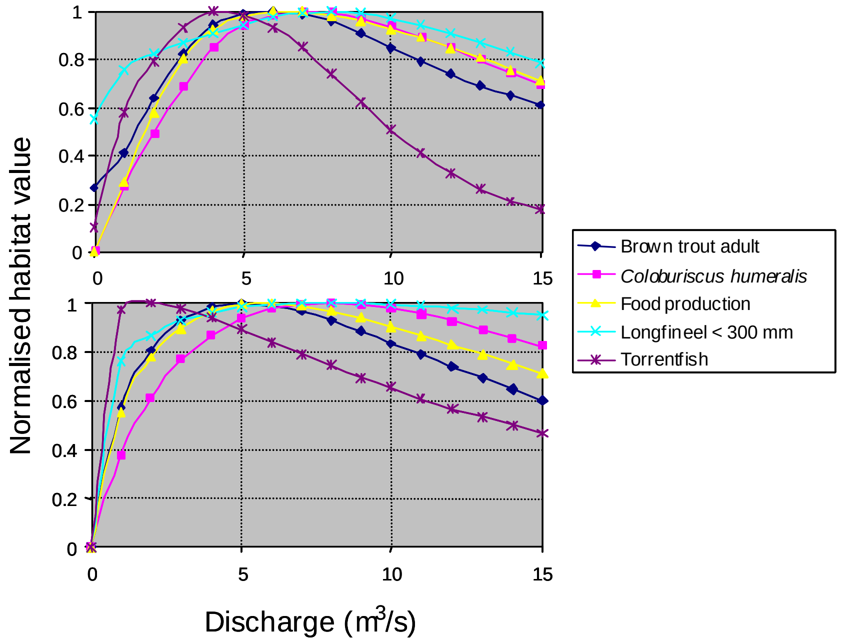


Figure 9.4: Comparison of normalised habitat per unit width predicted by habitat modelling in RHYHABSIM (above) and the generalised method (below).

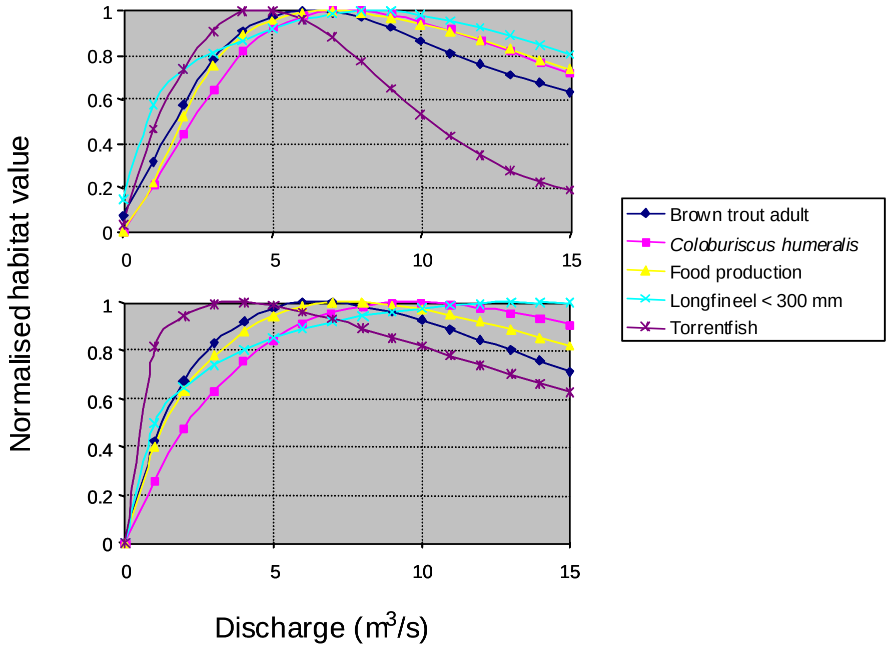


Figure 9.5: Comparison of normalised habitat area predicted by habitat modelling in RHYHABSIM (above) and the generalised method (below).

9.6 WAIORA

WAIORA, Water Allocation Impacts on River Attributes, is a decision support system developed by NIWA that uses information on stream morphology, either from simple measurements at two flows or from a RHYHABSIM dataset, to predict how instream habitat, dissolved oxygen, total ammonia, and water temperature change with flow. The generalised models described in the previous section can be implemented in WAIORA. WAIORA calculates the effects of flow on instream habitat, dissolved oxygen, total ammonia, and water temperature, and links the output to environmental guidelines (that can be specified by the user) to determine if an adverse effect is likely to occur. A number of assumptions have been made during model development and these are detailed in a manual and help file that can be downloaded from www.niwa.co.nz/ncwr/tools/waiora. The outputs of WAIORA reflect the nature of these assumptions and the quality of the data entered by the user. The models are better at predicting the relative amount of change associated with flow scenarios than at predicting absolute changes. Some guidance on the expected accuracy of models and comfort zones associated with guideline thresholds is provided in the help file and the summary plots.

WAIORA provides:

- information on environmental criteria that can be used;
- predictions of the absolute and relative change associated with a proposed new low flow and whether specified environmental guideline thresholds are exceeded;
- where possible, predicted effects of avoidance/mitigation options; and
- an audit trail of the procedures followed.

To use WAIORA you should:

- have knowledge of the existing stream conditions above and below the proposed abstraction; and
- either collect data from two site visits to assess changes in habitat or carry out a more detailed instream habitat survey and calibration using RHYHABSIM.

The steps in the assessment process are:

1. select parameters to evaluate (stream geometry is required for all);
2. data collection;
3. calibration (water temperature and DO models);
4. calculation of effects;

5. evaluation of effects.

The quality and scope of the instream habitat survey data will determine the reliability of the results, particularly the degree to which you can extrapolate beyond the flows that were surveyed. Two levels of survey are available. For quick assessments, stream widths and depths can be measured at two flows in at least 3 locations in each habitat type (e.g., pool, run, and riffle). Stream width, depth and velocity are then estimated assuming logarithmic hydraulic relationships (Jowett 1998). These data can then be used to calculate the discharge per unit width for each discharge and apply generalised habitat models. In cases where you want to extrapolate to flows higher or lower than those surveyed, cross-section data can be collected and calibrated in RHYHABSIM. The normal procedure is to survey at least 5 cross-sections in each mesohabitat type (e.g., pool, run, and riffle) and re-measure water levels at two or more flows.

Calibration data can also be collected for water temperature and dissolved oxygen models. These calibration data should be collected at times of maximum stress, normally mid summer. DataSondes can be deployed to measure diurnal variation in water temperature and dissolved oxygen concentration and inexpensive temperature loggers are available. Water temperatures are required at both the start and end of the section of river for calibration of the water temperature model. Although it is possible to model water temperature and dissolved oxygen without calibrated models, calibration is desirable to calculate appropriate parameters and coefficients for the dissolved oxygen models and to set appropriate initial water temperatures for the water temperature model.

Once the models have been calibrated, WAIORA calculates how stream width, depth and velocity, water temperature, and dissolved oxygen and ammonia concentrations vary with flow and displays the values of these parameters for the current low flow and the low flow that will result from the proposed abstraction or flow discharge.

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