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Flow Management in Marlborough's Small Streams

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Roger Young

Joe Hay

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MARLBOROUGH DISTRICT COUNCIL

Cawthron Institute
98 Halifax Street East, Private Bag 2,
Nelson, New Zealand.
Ph. +64 3 548 2319,
Fax. + 64 3 546 9464
www.cawthron.org.nz

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EXECUTIVE SUMMARY

Flow management in small streams is not easy, but increasing demand for water means that a robust process for flow management is required. In this report we review the approaches that could be used by the Marlborough District Council (MDC) to guide flow management and suggest a defensible process for making decisions on allocation limits and minimum flows from small streams. The approach we recommend will allow consistency in decision making across the district and ensure that environmental values are adequately addressed.

We believe that the overall approach to flow management in small streams should be the same as that used for larger rivers as outlined in the Ministry for the Environment Flow Guidelines (MfE 1998), with clear definition of the values to be protected and the instream management objectives. Critical values need to be defined so that sufficient flow is provided to sustain the most flow sensitive and important values, with the assumption that the flow requirements related to other significant values will also be met. A variety of technical methods can be applied to determine the flow regime required to meet the instream management objectives, through provision of critical, flow related, factors. Monitoring is also required to ensure that the flow regime is indeed meeting the objectives.

A review of the approaches to flow management by other councils indicated a diversity of approaches are being used, although most follow the broad approach outlined in MfE's (1998) flow guidelines. Management of flow in small streams has been given limited consideration in the past, but several councils are in the same position as MDC and currently thinking about the best approach to take.

Our recommended approach for managing flows in small streams in Marlborough is as follows: small streams throughout the region are grouped into the following classes – Ephemeral southern valley streams, Headwater streams, Wairau Plain spring-fed streams, North Bank Wairau streams, Marlborough Sounds streams. Instream values and management objectives are defined for each of these groups, along with critical values that, if protected, should sustain the other significant values. Habitat protection (or retention or maintenance) levels are suggested for each group of streams based on whether the instream values are considered to be high, medium or low.

We consider that hydrological analyses are the best approach for determining an appropriate flow regime for the Ephemeral southern valley streams, while generalised habitat models should be used for the Headwater, North Bank Wairau, and Sounds streams. A combination of a groundwater/surface water model (to prevent recession of the spring heads) and a water quality model (to predict the effects of flow on dissolved oxygen concentrations) should be used to manage flows in the Wairau Plain spring-fed streams. Detailed habitat analyses and modelling is justified only in the larger rivers throughout Marlborough on the basis of high instream values.

Sensible allocation limits are required for maintaining the security of supply for water users and for maintaining instream processes, habitat and values aimed at avoiding prolonged periods of low flow (i.e. 'flat-lining' of the minimum flow). The difference between the minimum flow and the summer 7-day Q_{95} (flow exceeded 95% of the time over summer) could be used as an allocation limit because it gives users a clear expectation of the security of their supply. Flow sharing is also an option that could

be considered to retain some variability in the hydrograph above the minimum flow. In this regard 1:1 flow sharing above the minimum flow is widely regarded as being inherently equitable (Jowett & Hayes 2004). Primary and secondary allocation limits and/or flow rostering can also be used to maximise the effectiveness of water use without compromising minimum flows.

Monitoring compliance with flow management rules is difficult in small streams since it is not possible to monitor flows in all systems. Water metering is the preferred approach, along with flow monitoring in key representative locations that can be used to trigger flow restrictions, if necessary.

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1. INTRODUCTION

Demand for water is increasing throughout the country and councils are being asked to balance abstractive demands against flows required for maintenance of instream values in small streams. In many cases these streams do not have flow data and there is limited information on instream values. Instream values associated with small streams often are perceived to be relatively low, despite these streams regularly providing important habitat for a variety of native fish, important spawning and juvenile rearing areas for sports fish, and providing a range of customary and landscape values. The volume of water abstracted from small streams and its value are also often relatively low and any benefits are often confined to one or few landowners. Therefore, water managers find it difficult to justify expensive habitat surveys for consent applications associated with small streams.

A range of technical methods are used for assessing flow requirements in larger streams and rivers. However, there may be difficulties applying these techniques in small streams (MfE 1998). The main reasons for this are:

1. That most research on flow requirements of aquatic life in New Zealand has been carried out on larger rivers,
2. Calibration of hydraulic models is often difficult in small streams because traditional current meters are too large to provide accurate information in shallow water,
3. Hydraulic models may perform poorly in small, shallow turbulent streams because the equations used in the models do not apply under turbulent conditions,
4. Hydrological records from larger streams and rivers may not be transferable to small streams.

Staff at the Marlborough District Council (MDC) have identified a need for better flow management in Marlborough's small streams and have asked Cawthron to review the approaches that could be used to guide flow management. The aim is to develop a robust and defensible process for making decisions on allocation limits and minimum flows from small streams in Marlborough. This approach will allow consistency in decision-making across the district and ensure that environmental values are adequately addressed. This report identifies a flow management approach which may be suitable for Marlborough.

2. MFE FLOW GUIDELINES FOR INSTREAM VALUES

As mentioned above, there are specific challenges for flow management in small streams. However, we believe that the overall approach to flow management in small streams should be the same as that used in other systems. The Ministry for the Environment's (1998) guidelines suggest the following approach to flow management (Figure 1). Key steps are the identification of the values present and an assessment of the Instream Management Objective for that stream. Once this is completed it is possible to identify a critical flow-related factor (or factors) which if maintained will ensure that the Instream Management Objective is achieved. A variety of technical methods can then be used to determine features of the flow regime (e.g. minimum flows, allocation limits, flow variability) that are required to sustain the Instream Management Objective. This general approach has been used widely throughout the country and appears to be useful, although there appears to be some overlap between determining the Instream Management Objectives and identifying critical factors.

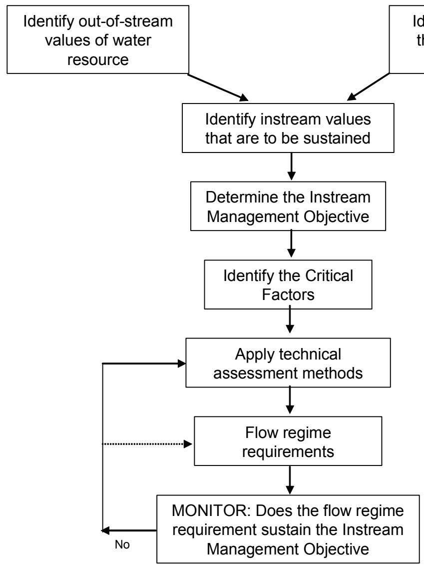

Figure 1. Approach to managing instream values in MfE (1998) guidelines.

3. TECHNICAL METHODS FOR SETTING MINIMUM FLOWS

A range of different technical approaches are available for predicting how habitat availability is expected to change with flow. These approaches can be grouped into three types; historic flow methods, hydraulic geometry methods and habitat methods. Water quality models are also available and can predict how water quality (primarily dissolved oxygen and temperature) is expected to change with flow.

Historic flow methods assume that habitat availability is linearly related with flow, while hydraulic geometry methods assume that habitat availability is nonlinearly related to increases in river width with flow (Figure 2). In contrast, habitat methods look at how the distribution and occurrence of suitable depths and velocities for certain species will vary with flow. Depending on the channel geometry and stream size, habitat methods often identify a flow which provides maximum habitat availability, with habitat limited by shallow water/slow velocities at lower flows and by high velocities/deep water at higher flows (Figure 2).

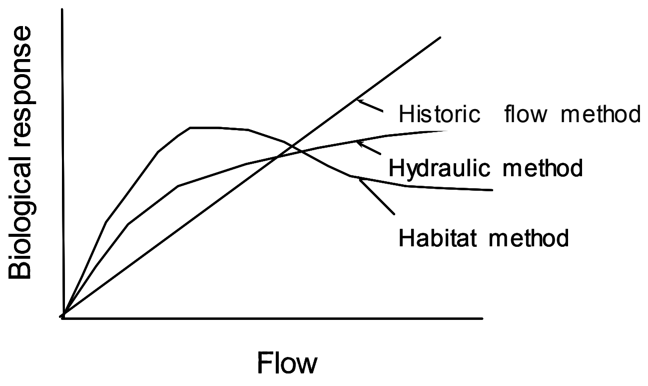

Figure 2. Hypothetical relationships between assumed biological response to flow for the historic flow, hydraulic and habitat methods. The biological response is assumed to be proportional to the flow, the wetted perimeter or width, and the weighted usable area, for the historic flow method, the hydraulic method, and the habitat method, respectively [From Jowett & Hayes (2004)].

Historic flow methods are the most simplistic and thus cheapest, while the cost of conducting a detailed habitat modelling exercise can be substantial (e.g. $30,000-50,000). Hydraulic models are somewhere in-between and generally require some field surveys, but not the detailed mapping of depths, velocities, substrate and/or bed topography that are required with standard habitat methods such as the Instream Flow Incremental Methodology (IFIM).

One relatively new approach that has some of the benefits of the traditional habitat methods (e.g. IFIM instream habitat modelling) but involves less effort, uses generalised habitat models (Lamouroux & Capra 2002; Lamouroux & Jowett 2005). These models are based on the relationship between the output of conventional instream habitat models (WUA) and simplified descriptions of the study reach (depth-discharge and width-discharge relationships, mean particle size and median flow). To use these models, all that is needed is information on the width of the site at a certain flow. It should be noted, however, that the dataset that was used to develop these models comprised gravel-bed streams/rivers with a mean annual discharge ranging from 0.6–54 m^3/s. The generalised models may not represent smaller streams and spring-fed streams (which have U shaped channels) and braided rivers (which have shallow, unconfined channels); prediction errors may be substantial for such streams/rivers that fall outside the character of the rivers in the original data set (Lamouroux & Jowett 2005).

As mentioned above, water quality models can also be used to set minimum flows that should help maintain water quality above thresholds limits. WAIORA is an example of a water quality model that is designed specifically for this purpose (Jowett et al. 2004). Measurements of diurnal variation in dissolved oxygen concentration and temperature are required before predictions can be made. Water quality is potentially affected in the Wairau Plains spring-fed streams as flow declines due to the abundant growth of aquatic plants. Respiratory demand from this plant biomass can cause substantial declines in dissolved oxygen concentration at night, and particularly if flows are reduced.

4. APPROACHES USED BY OTHER COUNCILS

4.1. Environment Southland

In 2004 Environment Southland, in conjunction with the Ministry for the Environment, contracted Ian Jowett (NIWA) and John Hayes (Cawthron) to review methods for setting water quantity conditions on a region-wide basis. The report that they produced is available at Environment Southland's website (http://www.es.govt.nz). This is a comprehensive report and provides a detailed review of the different technical methods that can be used. The approach suggested by Jowett & Hayes (2004) is broadly based on the MfE approach, but involves classifying streams into sensible groups (using local knowledge and/or the River Environment Classification system, Snelder & Biggs 2002) and then identifying typical values and critical values associated with each group (Figure 3). 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 also be sustained (Jowett & Hayes 2004). Candidates for critical value status might include flow sensitive rare or endangered species, or species with high fishery value. This region-wide approach incorporates the full range of river and stream sizes. Small streams draining lowland areas, hill/mountain areas, and the Hokonui/Catlins area were considered as separate groups with potentially different instream values. Jowett & Hayes (2004) also suggested applying 'significance rankings' to the critical value identified in each stream group and then setting appropriate habitat retention limits (Table 1).

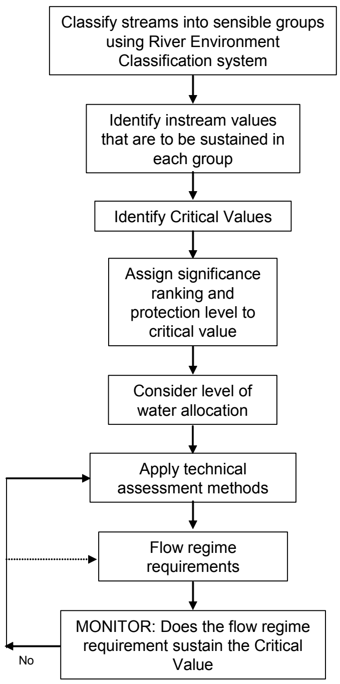

Figure 3. A summary of the flow management approach proposed for Environment Southland by Jowett & Hayes (2004).

Table 1. Significance rankings and suggested % habitat retention as proposed by Jowett & Hayes (2004) for Environment Southland.

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

Jowett & Hayes (2004) suggested four options for the assessment of flow requirements in Southland depending on the degree of water allocation:

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. In this case the minimum flow would be the MALF.
2. Application of generalised habitat models, where 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 1).
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 1).
4. The use of water quality modelling (e.g. WAIORA, Jowett et al. 2004) to set flow requirements for small streams dominated by macrophytes where dissolved oxygen concentration is a limiting factor.

4.2. Hawke's Bay Regional Council

Management of small streams is an issue for Hawke's Bay Regional Council, but not the highest priority at the moment. Many water users in the Hawke's Bay consider that the security of supply from small streams is not sufficient for their needs and prefer groundwater sources.

The approach that Hawke's Bay Regional Council is presently using for water management is to focus on catchments as groups, rather than investigating large numbers of individual sites. A default minimum flow of 80% of the MALF is applied unless specific investigations suggest an alternative is more appropriate. Allocation limits are based on the difference between the minimum flow and the summer 7-day Q_{95}, which is the seven day average flow that is exceeded 95% of the time during summer. The rationale behind this approach is that the Q_{95} directly relates to security of supply and the risk of flows being reduced to the minimum flow.

The Q_{95} means that water users will be able to abstract for 95% of the time. This approach indicates that little water is available for abstraction from small streams and has therefore has been questioned by some. However, this is a fair reflection of reality.

Hawke's Bay Regional Council have identified the need to treat different types of streams differently (e.g. groundwater-fed streams), and to look at small streams and their connections with downstream rivers in more detail. They have also raised the issue that the majority of the habitat preference curves that are used for habitat modelling have been developed in larger river systems, and may not apply to small streams.

4.3. Horizons Regional Council

Horizons Regional Council is currently in the process of developing scientifically defensible minimum flows and allocation limits for the streams in their jurisdiction. The focus to date has mainly been on areas where abstraction demands are high, mostly affecting larger rivers. The latest approach has involved instream habitat analyses with habitat retention levels based on those outlined in Jowett & Hayes' (2004) report to Environment Southland. This approach has also been applied to some fairly small streams in the Upper Manawatu Catchment. However, Horizons are now considering what approach to take in smaller streams and rivers, where demands are lower. They are currently considering applying generalised habitat models (see Lamouroux & Jowett 2005), and are engaging in consultation with stakeholders, NIWA and Cawthron in the hope of achieving a consensus on an appropriate methodology. At this stage the Department of Conservation and Fish & Game New Zealand appear comfortable with the concept of applying generalised habitat models after testing these against predictions from full instream habitat models already applied in Manawatu and Rangitikei catchments.

The recent approach to setting allocation limits in conjunction with minimum flows has been to define what Horizons have called a "management flow", based on consideration of historic flow frequency and duration data. This is based on the approach taken by the Hawke's Bay Regional Council. The historic frequency of occurrence of the "management flow" indicates the expected frequency of occurrence of the minimum flow under the influence of allocation. The management flow can be set taking into account the acceptable level of risk to the environment and to resource users of the minimum flow occurring. The amount of water available for allocation is then derived from:

$$\text{Core Allocation} = \text{Management Flow} - \text{Minimum Flow}$$

Under this model, when the core allocation is fully allocated to users, and being fully used, the historical frequency of occurrence of the "management flow" becomes the frequency of occurrence of the minimum flow. The level of the management flow (and therefore the core allocation) can be set to control the risk of the minimum flow occurring.

In addition, Horizons have also adopted a 30% of MALF cumulative allocation limit for any point in the Upper Manawatu catchment, which provides some protection for small streams.

Part of the rationale for cumulative allocation at any point in the catchment not exceeding 30% of the MALF, was that, in their report to Environment Southland, Jowett & Hayes (2004) suggested this level of allocation as a trigger level for more in-depth consideration of instream habitat and possible downstream effects.

4.4. Tasman District Council

Water management in the Tasman District is conducted within water management zones identified by the council. These zones are largely defined by catchment boundaries and the approach to flow management varies to some extent from zone to zone depending on the degree of demand and values. For example, in systems with high perceived values and high irrigation demand, such as the Waimea and Riwaka, detailed instream habitat assessments and modelling have been conducted to guide the setting of minimum flows (Hayes 1998a; Hayes 1998b; Hay & Young 2005). Minimum flows have typically been based on inflection points in the flow versus habitat curves, or more recently related to % retention of habitat available at the MALF as suggested by Jowett & Hayes (2004). Specific flow management rules were developed for the Motueka Water Conservation Order and include minimum flows and a flow sharing approach. Compliance with flow management is generally controlled via a single flow (or groundwater level) recorder in each zone. Water metering is used to measure and manage abstraction rates.

Decisions on water allocation from small streams have been based on historical flow statistics derived from the nearest appropriate flow recorder. Minimum flows have been set at the estimated 1-in-5 year low flow. 'Rules of thumb' are also used to set default allocation limits and generally range from 10-33% of the 1-in-5 year low flow depending on the instream values present. A more intensive study on one of these small streams indicated that a minimum flow based on the 1-in-5 year low flow would result in a 15% reduction in yearling trout habitat availability compared with that available at the MALF (Young & Hayes 2002).

4.5. Nelson City Council

The Nelson City Council has recently revised its Freshwater Plan and defined the values associated with the waterways in the district. Detailed habitat assessments and modelling have been conducted in two major waterways (Maitai and Roding) and used to set minimum flows (Hayes & Stark 1995; Hayes 2003). An expert panel and working party was used to set minimum flows and allocation limits for the remaining waterways, including small streams. Historic flow statistics were used as the basis for these assessments with minimum flows ranging from the MALF for systems with high perceived values to the 1-in-5 year (seven day) low flow for systems with lower values. Similarly, allocation limits ranged from 10% of the 1-in-5 year low flow for systems with high perceived values to 33% of the 1-in-5 year low flow for systems with lower perceived values.

4.6. Otago Regional Council

The approach to flow management in the Otago Region is set out in the Regional Plan: Water for Otago. The Otago Regional Council (ORC) has focused on areas with high demand for water and set minimum flows and primary allocation limits for some catchments (e.g. Shag, Kakanui, Leith, Lake Hayes, Manuherikia, Waitahuna, Tuakitoto) or parts of catchments (e.g. Taieri upstream Paerau, Taieri between Paerau and Waipiata). Detailed habitat surveys and modelling were used to guide the minimum flow setting at some of these sites. The ORC initially proposed the use of historical flow statistics (1-in-10 year low flow) for setting minimum flows in other parts of the region. However, this approach and the flow statistic suggested was successfully challenged by stakeholders in the Environment Court. An outcome of the Environment Court decisions is that the ORC are now undertaking a programme of habitat surveys and modelling throughout the region to determine river specific minimum flows, although this has been primarily focused on moderate/large streams and rivers.

4.7. Auckland Regional Council

The approach to flow management in Auckland waterways is set out in the Proposed Auckland Regional Plan: Air, Land and Water. The need for minimum flows and flow regime requirements for high-use rivers and streams is identified in the plan. The plan refers to the MfE (1998) guidelines, along with other relevant publications and guidelines for setting flow requirements. The plan also refers to 'management flows' which can be used to determine the amount of water available for abstraction and the need for rostering and rationing abstractions. This appears to be similar to the 'management flow' approach used by Horizons Regional Council, as mentioned above.

The Auckland Regional Council (ARC) contributed to the initial development of the WAIORA system that can help guide minimum flow assessments and has used this system to define minimum flows downstream of some water storage reservoirs. The focus has been on low flow requirements for maintaining water quality owing to the prevalence of small streams with entrenched channels in the Auckland district in which mean velocity and water quality is more sensitive to flow reduction than wetted area. The ARC has also recently funded some work by NIWA on the values of small ephemeral streams. The results from this work are currently being written up and should be available shortly.

4.8. Environment Canterbury

Environment Canterbury has been reviewing minimum flows in Canterbury over the last few years as part of their Natural Resources Regional Plan. The approach they are using includes a combination of expert and community advisory panels with technical input on the instream values and appropriate minimum flows for particular streams. The technical input has involved simplified habitat modelling (using either WAIORA or a simplified RHYHABSIM analysis) to assess how habitat is likely to change with flow. The technical inputs have also included reviews of water quality, invertebrate and fish distribution data to help assess the instream values of particular sites.

5. APPLYING THE APPROACH IN MARLBOROUGH

The approach we have applied in this report essentially follows the model suggested by Jowett & Hayes (2004), but with the additional step of explicitly identifying the critical, flow related, factors that must be provided to ensure that the critical values are protected, and therefore the instream management objectives are attained. Under Jowett & Hayes' (2004) suggested method the critical factor appears to have been assumed to be habitat availability, although there is recognition that water quality (particularly dissolved oxygen) may be a limiting factor in some small streams.

5.1. Grouping streams

When considering a regional approach to flow management for small Marlborough streams, it is helpful to group streams with similar values together so they can be managed in a similar fashion. In a meeting with staff from MDC (28th February 2006), four groups of streams were identified; ephemeral streams in the southern valleys (Southern Valleys), spring-fed streams on the Wairau Plain (Wairau Spring-fed), North Bank tributaries of the Wairau River (North Bank Wairau), and small streams flowing directly or indirectly into the Marlborough Sounds (Sounds Streams). After a preliminary assessment of the instream values associated with these groups of streams, we considered that it was also worth including a fifth group of streams – headwater streams in the inland parts of the district (Headwater Streams). Although probably facing little demand for water abstraction, these streams support a distinct native fish community including three types of non-migratory galaxiids which are absent or uncommon in other small streams in the district; alpine galaxias (*Galaxias paucispondylus*), Canterbury galaxias (*Galaxias vulgaris*) and dwarf galaxias (*Galaxias divergens*). At a national level, dwarf galaxias are considered to be in 'gradual decline', whereas alpine galaxias and Canterbury galaxias are considered 'not threatened' (Hitchmough 2002).

A summary of the typical instream values associated with each of these groups of streams is shown in Figure 4. The instream values associated with Marlborough's large rivers are also shown for comparison. The majority of these values are based on fish communities (as summarised in Hamill 2004), although wading birds, customary and landscape values are also shown. This summary is based upon our knowledge of Marlborough's streams (Young et al. 2000, 2002, 2004; Strickland et al. 2003), input from MDC staff, and the values identified in Appendix A of the Proposed Wairau/Awatere Resource Management Plan. Aquatic invertebrate communities will be present in all these streams, however we have not specifically listed them. Invertebrates obviously have intrinsic ecological values, as well as providing an important part of the food chain to fishes and birds. However, if flows are managed to protect critical fish habitats and water quality then the habitat for invertebrates should also be protected by default. This same situation applies for the algae and micro-organisms that also constitute an important part of stream communities.

5.2. Instream management objectives and critical values

There are a range of instream management objectives for the groups of streams. They are based on our experience and understanding of Marlborough's streams, but may need to be altered after input from stakeholders and the community. We have chosen what we believe is the primary instream management objective for each group of streams. We recognise that there are other instream objectives that may need to be considered. However, we believe that by providing sufficient flow to sustain the most flow sensitive, important value, the other significant values will also be sustained (see also Jowett & Hayes 2004).

The instream management objective for three groups of streams and the major rivers is based on retaining a proportion of the natural habitat for a particular species (Figure 4). The species chosen are those that are highly valued, and in the case of trout have high flow requirements meaning that values supported by lesser flows will also be protected. This is the most common situation and ideally suited to a habitat modelling approach.

The instream management objectives for the two other groups of streams – Southern Valleys and Wairau Spring-fed, are somewhat different. The landscape values of the Southern Valleys are probably more important than the ecological values of these sites and therefore the objective should be to maintain the natural frequency and duration of drying. For example, a reduction in the frequency or amount of time that these streams contain flowing water could cause vegetation encroachment into the stream channels and damage the existing landscape values that are present.

The Wairau Spring-fed streams on the Wairau Plain support a variety of values, however the biggest threat is probably associated with groundwater abstraction and recession, down the plain, of the spring heads. Many of these springs are already much shorter than they would have been prior to land modification and drainage of the Wairau Plain (Young et al. 2002). Therefore, the priority should be to maintain the length of permanently flowing habitats. If the heads of these spring-fed streams can be maintained then inputs of groundwater further down the Plain will support the values identified for these streams.

5.3. Protection levels

We have proposed a series of protection levels for each group of streams depending on whether the values are high, medium or low. These levels are based on our perception of the significance of the values present in each group and from classes indicating the relative value of different freshwater resources in Marlborough as listed in Appendix 1 of the Proposed Wairau/Awatere Resource Management Plan. It would be wise to consult with stakeholders and the community before finalising these protection levels. It might be appropriate to alter protection levels for some sites within groups if there is more detailed information on the relative values of some streams within a group. For example, Spring Creek is listed as having a high value in the Proposed Wairau/Awatere RMP and deserves a high level of protection, whereas the Pukaka Drain, which is also a Wairau Plain spring-fed stream, is considered to have only medium values and perhaps does not deserve the same level of protection.

For most of the groups we have suggested protection levels that are related to the amount of naturally available habitat at the mean annual low flow (MALF) following the approach of Jowett & Hayes (2004). The MALF is a commonly used hydrological statistic that represents the minimum flows that are likely to occur in most years. Other statistics, such as the low flow with an expected annual recurrence interval, may be even more useful as an index of annual minimum flows, but have not been typically used in the past. The existing ecological community has persisted under these conditions and the minimum annual flow may be the factor that limits the maximum size of the population. For example, there is some evidence that the habitat available at the MALF is an important factor controlling adult trout abundance (Jowett 1992). Whether the same is true for other species is debateable. However, it seems reasonable that the MALF should be similarly relevant to native fish species with generation cycles longer than one year, at least in situations where habitat declines toward the MALF. If the minimum flow restricts habitat for any species, there is potential for 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 native fish numbers increased with the magnitude and duration of low flow (Jowett & Hayes 2004).

Stream Type

	Ephemeral Southern Valleys *e.g. Fairhall, Omaka*	Headwater Streams *e.g. Tributaries of Branch/Leatham, Clarence, Awatere*	Wairau Plain Spring-fed *e.g. Drain N, Fultons, Doctors, Roberts*	North Bank Wairau *e.g. Onamalutu, Are Are, Waikakaho*	Sounds Streams *e.g. Waikawa, Umungata, Whatamango*	Major Rivers and their Tribs *e.g. Pelorus, Rai, Wairau, Goulter, Branch, Spring Creek, Awatere*
Typical Instream Values	Eel Upland bully Trout spawning/rearing Landscape values	Eel Upland bully Koaro Non-migratory galaxiids Trout spawning/rearing Native biodiversity Landscape values	Eel Common bully Migratory galaxiids Trout spawning/ rearing Bird habitat Customary values Watercress Whitebaiting/Angling Native biodiversity Landscape values	Eel Redfin/Common/Bluegill/Upland bully Inanga Migratory galaxiids Lamprey Trout spawning/rearing Angling – early season Bird habitat Native biodiversity Landscape values	Eel Redfin/Common/Bluegill bully Migratory galaxiids Dwarf galaxias Whitebaiting Bird habitat Native biodiversity Landscape values	Eel Common/Bluegill/Upland bully Inanga Non-migratory galaxiids Torrentfish Large adult trout Trout spawning/rearing Bird habitat and corridor Customary values Whitebaiting/Angling Kayaking/Rafting Landscape values
Instream Management Objective	Maintain the natural frequency and duration of drying	Maintain available natural habitat for trout spawning/rearing and non-migratory galaxiids	Halt any further recession of spring heads and maintain water quality to protect aquatic life	Maintain a proportion of available natural habitat for trout spawning/rearing and migratory galaxiids	Maintain a proportion of available natural habitat for migratory galaxiids	Maintain a proportion of available natural habitat to sustain a productive trout fishery
Critical Value	Landscape values	Non-migratory galaxiids And trout spawning/ rearing	Landscape values trout spawning/ rearing And native biodiversity	Trout spawning/rearing	Migratory galaxiids	Large adult trout
Critical Factor	Duration and frequency of drying	Habitat for non-migratory galaxiids and trout spawning/ rearing	Wetted stream length and minimum dissolved oxygen concentration	Trout spawning/ rearing habitat	Migratory galaxiid habitat	Large adult trout habitat
Protection level	Low (<20% change in natural duration and frequency of drying)	High (90% of habitat retention at natural MALF)	High (No recession of spring heads beyond current levels and maintain minimum dissolved oxygen above 60% saturation)	Medium (70% of habitat retention at natural MALF)	Medium (70% of habitat retention at natural MALF)	High (90% of habitat retention at natural MALF)
Technical Method	Hydrological analysis	Generalised habitat models	Water quality modelling – WAIORA plus Ground/surface water model to control recession of spring heads	Generalised habitat models	Generalised habitat models	Detailed instream habitat analysis and modelling

Figure 4. Potential stream groupings in Marlborough, their associated values and a suggested technical methods for flow management.

Jowett & Hayes (2004) recommended maintaining a proportion of the habitat available at the MALF or of the habitat optimum, whichever occurs at the lower flow (Figure 5). This approach aims to retain a proportion of the habitat that the stream is naturally capable of providing during periods of low flow, thus providing for some allocation of water to out-of-stream uses, with the proportion of habitat retained depending on the relative significance of the instream values.

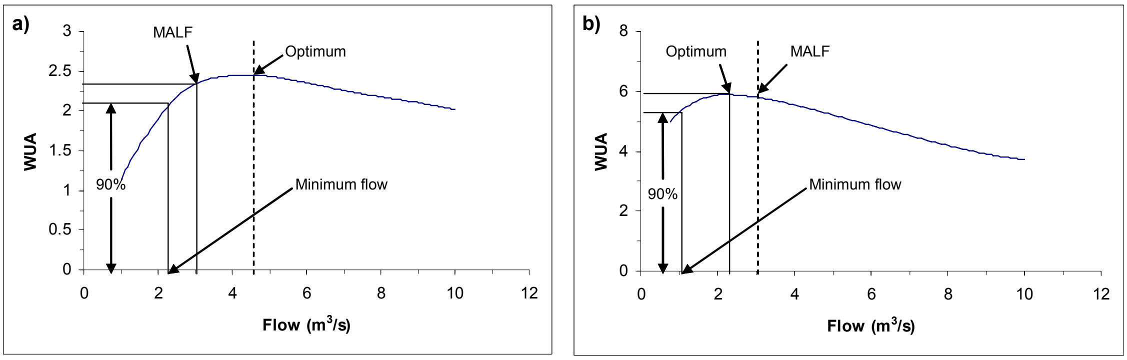

Figure 5. Derivation of minimum flow based on retention of a proportion (90% in this case) of available habitat (WUA) at a) the MALF, or b) the habitat optimum, whichever occurs at the lower flow, as recommended by Jowett & Hayes (2004).

Most small streams will not have hydrological records, which makes assessments of habitat availability at the MALF problematic. Nevertheless, some estimate of the MALF is required so any changes in flow can be referenced back to 'natural' conditions. A description of the range of methods that could be used to estimate natural MALF in streams with no hydrological information is beyond the scope of this report, but could include developing flow relationships between the site of interest and a nearby flow recorder, or alternatively through estimates involving catchment area and specific discharge.

We believe that the values supported by the Headwater streams and Major rivers are highly significant and deserve a high level of protection. We have suggested that 90% of the habitat naturally available at the MALF, or habitat optimum, should be retained to meet the instream management objectives for these groups (Figure 4). This level of protection aligns with the protection level that was suggested by Jowett & Hayes (2004) for critical values with high significance rankings. A 90% protection level allows for some abstraction during normal flow years, but it is unlikely that this reduction in habitat would cause a noticeable reduction in fish abundance or other instream values given the high natural temporal and spatial variability in fish populations. For example juvenile trout abundance in the Kakanui River, North Otago, varied by a factor of 5–92 between sites and by a factor of 3.6–23 between years (Hayes 1995), and adult trout abundance varied by a factor of 10 between sites and by a factor of four between years (Jowett 1995). Our suggestion of 90% protection level is a conservative guide and ultimately the decision rests with MDC after consultation with stakeholders

The spring-fed streams on the Wairau Plain also support some highly significant instream values that deserve a high level of protection (e.g. migratory galaxiids - Young et al. 2002). Therefore, we have suggested that no loss of wetted stream length should be allowed. Minimum dissolved oxygen criteria (>60% saturation) should also be used to ensure that water quality in the wetted areas does not harm aquatic life. This water quality criterion is based on our knowledge of oxygen dynamics in some of these spring-fed streams (Young et al. 2000) and on studies of low dissolved oxygen tolerance of native fish (Dean & Richardson 1999). If a less conservative approach was deemed necessary to enhance security of supply for abstractors under dry conditions, a small reduction in wetted stream length (e.g. 1%) could be considered.

We consider that the values in the North Bank Wairau and Sounds Streams are of moderate significance and following Jowett & Hayes (2004) have suggested that 70% of the available natural habitat should be retained for certain species or life stages (Figure 4). This protection level would involve a greater risk that impacts on the instream values may be observed, but would allow a greater security of supply for water abstraction even in dry years.

We suggest that the values in the ephemeral Southern Valleys streams are relatively low compared to the values in the other streams. Again, this would need to be checked with stakeholders/community and perhaps also considering the results from recent work on ephemeral streams in Auckland commissioned by ARC. The Instream Management Objective and critical value is related to landscape values, and the critical factor required to preserve this value entails maintaining the duration and frequency of drying. We suggest allowing only a small change (<20%) in the duration and frequency of drying. The 20% level is arbitrary, but seeks to set a level where the change in landscape values is minimised while still allowing a reasonable security of supply for water abstraction during most years. Hydrological analyses and modelling would be required to determine the amount of water allocation that could occur without changing the duration and frequency of drying by more than 20%.

5.4. Technical methods

5.4.1. Hydrological analysis

The technical methods chosen to determine the flow requirements within each group will differ according to the critical factors identified. For the ephemeral Southern Valley streams the critical factors are based on hydrological statistics, so a hydrological analysis would be required to determine how much water could be allocated without changing the frequency or duration of drying by more than 20%. Existing hydrological data and records of current abstraction levels would be required to determine the existing frequency/duration of drying and predict the natural frequency/duration of drying in the absence of abstraction.

5.4.2. Generalised habitat models

Generalised habitat models have been suggested as the appropriate technical method for three of the stream groups (Headwater Streams, North Bank Wairau tributaries, Sounds Streams) for several reasons, including:

- At its simplest this method requires only the measurement of stream width at one flow. Therefore, implementation of the method is relatively cheap and feasible for a large number of sites.
- The method is expected to provide a better estimate of the effects of flow on habitat availability than simpler historic flow statistics or hydraulic methods.
- In the case of the North Bank Wairau tributaries and Sounds streams, the instream values are considered to be only moderate and therefore not sufficient to justify detailed instream habitat surveys and modelling.
- Although the values of the Headwater Streams are considered to be high, the level of demand for water abstraction in these systems is expected to be low and so less likely to cause substantial impacts on instream values. Therefore, we believe that detailed instream habitat surveys and modelling are not justified.

The minimum requirement for using generalised models is a measurement of stream width at a single known flow. A New Zealand average hydraulic geometry relationship (Jowett 1998) can be used to estimate how width will change with flow. This relationship works reasonably well for unconfined gravel-bedded rivers, but will not provide accurate estimates of changes in width with flow in streams/rivers with different shaped channels. To overcome this, measurements of width at several different flows can be used to calculate a site-specific hydraulic geometry relationship. Once the relationship between flow and width is calculated, a dimensionless index of habitat value over a range of flows can be calculated for particular species using the following equation:

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

where HV is the habitat value (dimensionless; the equivalent of RHYHABSIM's HSI, or WUA% in earlier versions, and can be converted to the equivalent of WUA m^2/m by multiplying by river width at a given flow), Q is the discharge (m^3/s), W is the width (m), and c and k are coefficients that describe the shape of the curve and have been derived for particular species (Jowett & Hayes 2004; Table 2). The dataset that was used to determine the c and k coefficients for particular species included streams/rivers with a mean annual discharge ranging from 0.6–54 m^3/s. Therefore, there may be substantial error in applying these models to small streams with flows outside this range (Lamouroux & Jowett 2005).

Table 2. Coefficients that can be used to determine the shape of flow habitat value (*HV*) curves for particular species of fish or invertebrates that are found in Marlborough (modified from Jowett & Hayes 2004).

Species	*c*	*k*
Inanga	0.19	19.74
Shortjaw kokopu[+]	0.19	16.35
Upland bully	0.11	8.63
Banded kokopu (juvenile)	0.19	13.3
Galaxias vulgaris	0.03	2.29
Longfin eel (<30cm)	0.07	2.07
Redfin bully	0.26	7.39
Shortfin eel (<30cm)	0.13	2.32
Common bully	0.39	6.51
Brown trout fry	0.86	10.21
Brown trout yearling	0.4	4.18
Nesameletus[*]	0.26	2.62
Brown trout spawning	1.24	9.89
Bluegill bully	1.01	6.13
Deleatidium[*]	0.33	1.92
Torrentfish	0.88	4.05
Brown trout adult	1.17	4.35
Food producing habitat	1.19	4.25
Coloburiscus humeralis[*]	1.35	4.17
Aoteapsyche[*]	1.44	3.17
Zelandoperla[*]	1.71	3.4

* large river habitat suitability curves (see Jowett 2000), + suitability for cover locations only

A comparison of the output from generalised habitat models and detailed habitat modelling at the same sites showed broadly similar habitat response to flow for given species (Jowett & Hayes 2004). However, there were some differences in the shapes of the curves which could lead to different interpretations of suitable minimum flows. This presumed inaccuracy of the generalised models must be weighed up against the reduced requirements for fieldwork and modelling when using this approach.

5.4.3. Water quality modelling - WAIORA

The U-shaped channel of the Wairau Plains Spring-fed streams means that a large change in flow would be required to cause a significant change in the availability of habitat. However, the nocturnal respiration of abundant aquatic plants in many of these spring-fed streams, combined with the relatively low dissolved oxygen concentration of the groundwater inflows, means that flow reduction could cause regular and severe breaches of dissolved oxygen guidelines. Diurnal changes in pH may also be a concern.

WAIORA is a model that has been designed to predict the impacts of flow reduction on habitat availability (using hydraulic and generalised models), temperature, dissolved oxygen and ammonia concentrations (Jowett et al. 2004). The dissolved oxygen component of the model requires habitat and water temperature data and an estimate of the ecosystem respiration rate, production/respiration ratio, and the reaeration coefficient, which describes the rate at which oxygen is exchanged between the atmosphere and the stream. These latter values can be calculated from analyses of the change in oxygen concentration over 24 hours at a reference flow using the model itself or alternative approaches (e.g. Young & Knight 2005). If oxygen data are not available to calibrate the model, default values from similar stream types can be used as a last resort.

The model assumes that changes in the concentration of dissolved oxygen are the result of oxygen production from photosynthesising plants, oxygen uptake via respiration from all the members of the ecosystem, and oxygen exchange through the water surface as described by the following equation:

$$\frac{dO}{dt} = P - R + kD$$

where *dO/dt* is the rate of change of oxygen concentration, *P* is the rate of gross primary production, *R* is the rate of ecosystem respiration, *k* is the reaeration coefficient and *D* is the oxygen deficit (or difference between the observed oxygen concentration and the concentration at 100% saturation).

The model assumes that with reduced flows the rates of gross primary production and ecosystem respiration remain the same, while the reaeration coefficient will either increase (shallower water) or decrease (less current and turbulence). The habitat data is used to predict the direction and degree of change in the reaeration coefficient. The daily fluctuations in oxygen concentration are generally expected to increase in amplitude with decreased flows because the same amount of biological activity is limited to a smaller volume of water.

5.4.4. Groundwater surface water model

In order to halt the recession of the heads of the spring-fed streams on the Wairau Plains, a groundwater model is required to help to understand the relationship between groundwater levels and spring-fed stream flows. We understand that MDC has developed such a model and it should be useful for this purpose.

5.4.5. Detailed instream habitat analysis and modelling

We suggest that detailed instream habitat analysis and modelling is required to determine appropriate minimum flows for the major rivers in Marlborough. Detailed habitat analysis and modelling is often referred to as the Instream Flow Incremental Methodology (IFIM). There is a large amount of information on this approach available in the literature, and we suggest that readers requiring more information consult Jowett & Hayes (2004) for a thorough summary of the approach. A summary is given below.

The first step in this process involves selecting the river reach of interest. Detailed surveys of the river bed are then required although the type of survey depends on whether a 1-dimensional (1-D) or 2-dimensional (2-D) approach to habitat modelling is followed. The 1-D approach includes measurements of depth, velocity and substrate composition across marked cross-sections throughout the study reach at the 'survey' flow. Cross-sections are selected to represent the range of habitat types available in the reach. Water levels are measured at the survey flow and again at one or more calibration flows to establish rating curves at each cross-section. A hydraulic model (e.g. RHYHABSIM) is then used to predict depths and velocities at each measurement point on the cross-sections over a range of simulated flows. These depth and velocity predictions are related with habitat suitability criteria for particular species to predict how habitat availability for that species will change with flow.

The 2-D approach to habitat modelling is a more recent development and involves a detailed survey of the bed topography throughout a river reach. Substrate composition also needs to be mapped throughout the reach. Water levels at the top and bottom of the reach are measured at the survey flow and at calibration flows. In order to test the model further water level measurements should be taken at the survey and calibration flows either across cross-sections or at random points in the survey reach. A 2-D hydraulic model (e.g. River2D) is then used to predict the depths and velocities occurring at any flow in the reach. Available habitat is then predicted with habitat suitability criteria using similar calculations as for 1-D modelling.

There has been some discussion of the pros and cons of 1-D and 2-D approaches to habitat modelling in recent consent and environment court hearings throughout New Zealand. The recent Trustpower hearing on the Wairau River is a good example. The 2-D approach is particularly appropriate in a braided river where the 1-D approach would struggle to cope with the complexity of the channel. The 2-D approach is also expected to perform better than the 1-D approach for flows outside the calibration range, although there is little evidence to either support or refute this. On the other hand, the 1-D approach requires less field and modelling effort and can be applied to a longer reach of river. The 1-D approach is also considered to be more accurate within the range of calibration flows than the 2-D approach. This is because its predictions are constrained by actual measurements of water level (at the calibration flows). Inaccuracies in 2-D model predictions arise mainly from errors in the measurement of bed topography and these are sensitive to the spatial resolution of the topographical survey

5.5. Allocation limits

Appropriate allocation limits are an important component of flow management, otherwise there is the potential for abstraction to result in 'flat-lining' of the hydrograph at the minimum flow. Maintaining some degree of flow variability is generally considered to be important, especially maintaining moderate and large floods that are sufficiently powerful to scour periphyton from the stream bed. The physical habitat for benthic invertebrates sustained by flow recessions following these events is also expected to benefit a river's productivity [i.e. those that elevate the base flow for 30 days or more which is sufficiently long for benthic invertebrates to fully colonise previously dry or scoured river bed (Sagar 1983)]. However, there is currently little scientific evidence supporting the need to maintain small scale flow variability.

The allocation limit is also important for determining the security of supply for abstractors. As more water takes are consented, the security of supply for existing consents is reduced.

There is little clear guidance on appropriate allocation limits. As mentioned in Section 4 above, many councils use 'rules of thumb' to define allocation limits (e.g. 33% of the MALF, or 10% of the MALF). Hawke's Bay Regional Council use the difference between the minimum flow and the summer 7-day Q_{95} as the allocation limit, since the frequency of this flow is clearly defined (exceeded 95% of the time in summer) and gives users clear expectation of their security of supply. Some councils have also adopted a flow sharing approach to try and maintain some of the natural flow variation. For example, the Motueka River Conservation Order provides for 12% of the residual flow at a key recording point to be abstracted in part of the catchment. In this case there is no minimum flow and irrigators and instream values are expected to suffer equally in periods of drought.

Jowett & Hayes (2004) also considered allocation limits in their report to Environment Southland. They suggested that there is a relationship between allocation limits and minimum flows. If demand for abstraction is high then conservative minimum flows should be used. However, if demand is low then lower minimum flows could be set. This approach may have merits, and assumes that both the minimum flow and its duration are important in limiting instream values. However, this approach is relatively complicated and would require considerable analysis on a site-by-site basis for implementation. Environment Southland have not used this approach in their plan.

An alternative approach that is commonly used by several councils involves primary and secondary allocation limits, where abstraction related to secondary permits must cease at higher minimum flows than abstraction related to primary allocation. This approach allows for water harvesting under high flow conditions. Environment Southland has used the mean flow as the minimum flow for these secondary allocations to ensure that natural flow variation is not dampened at medium to low flows.

Flow rostering is another approach that can be used to maximise the number of abstractors that are able to get some water without compromising minimum flows. Water user committees are usually required in these circumstances to find agreement on who can take water and when under particular low flow conditions. An example of a 'one day on, one day off' rostering scheme is given in the Proposed Auckland Regional Plan: Air, Land and Water.

Allocation limits for small streams should be small. Hawke's Bay Regional Council have suggested that the 'rules of thumb' for setting allocation limits are not appropriate in small streams (e.g. the 7-day Q_{95} in a small stream is almost nothing). However, given that instream habitat in small gravel-bed streams is highly sensitive to flow reduction (because they are shallow) allocation of only small volumes may be realistic – although this depends on the value of the instream values in question. In this regard Hawke's Bay Regional Council is interested in better understanding the instream services that small streams supply, such as thermal refuges for fish from mainstem rivers during summer (Geoff Wood pers. com.).

5.6. Monitoring compliance

Some mechanism is needed to monitor compliance with flow management rules in major rivers or small streams. In general, flow monitoring is not undertaken at all abstraction points, but rather abstraction is based on flow records from key recorder sites. The location of these sites is important especially if there is political pressure against water metering, which appears to be the case in many regions. One approach is to have an upstream site above any abstraction points, so allocation limits can be based on natural flows. However, without water metering it is impossible to know if abstractors are following any water use restrictions or if abstraction is dropping flows below acceptable levels downstream. The alternative, and preferred, approach is to monitor flow at a site downstream of all abstractions. However, without water metering it is difficult/impossible to determine what the natural flows would be at the site in the absence of abstraction, which is what is needed to determine the degree of impact compared to natural conditions. In many cases, flow recorders are installed above and below the main areas of abstraction to deal with these concerns. However, even with this approach difficulties can remain related to predicting natural versus induced 'loss' of surface water to aquifers where groundwater pumping is the main mechanism of abstraction.

The Tasman District Council has a comprehensive system of compliance monitoring and uses key hydrological recording sites at the downstream end of water management zones to monitor compliance and instruct users on water rationing. Water meters are required on all water takes. Therefore, exceedance of permitted takes, or failure to abide by water restriction orders, can be detected and followed up. Naturalised flow regimes can be easily synthesised using records of observed flows and measured rates of abstraction, so the effects of existing abstraction can be determined. A system like this would be useful in Marlborough.

6. SUMMARY

An approach to managing flows in small streams in Marlborough is suggested. Small streams throughout the region can be grouped into the following classes – Ephemeral southern valley streams, Headwater streams, Wairau Plain spring-fed streams, North Bank Wairau streams, Marlborough Sounds streams. Instream values and management objectives have been defined for each of these groups, along with critical values that, if protected, should sustain the other significant values. Critical, flow related, factors required to maintain these values, and protection levels are suggested for each group of streams based on whether the values are considered to be high, medium or low.

Hydrological analyses are considered to be the best approach for determining an appropriate flow regime for the Ephemeral southern valley streams, while generalised habitat models should be used for the Headwater, North Bank Wairau, and Sounds streams. A combination of a groundwater/surface water model to prevent recession of the spring heads and a water quality model, to predict the effects of flow on dissolved oxygen concentrations, should be used to manage flows in the Wairau Plain spring-fed streams. Detailed habitat analyses and modelling is really only justified in the larger rivers throughout Marlborough.

Sensible allocation limits are required to maintain the security of supply for water users and avoid ‘flat-lining’ the hydrograph at the minimum flow. The difference between the minimum flow and the summer 7-day Q_{95} (flow exceeded 95% of the time over summer) could be used as an allocation limit because it gives users a clear expectation of the security of their supply. Flow sharing can also be used to retain some variability in the hydrograph above the minimum flow. Primary and secondary allocation limits and/or flow rostering can also be used to maximise the effectiveness of flow use without compromising minimum flows. Monitoring compliance with flow management rules is difficult in small streams since it is not possible to monitor flows in all systems. Water metering is the preferred approach, along with flow monitoring in key representative locations that can be used to trigger flow restrictions, if necessary.

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8. REFERENCES

Dean T, Richardson J 1999. Responses of seven species of native freshwater fish and a shrimp to low levels of dissolved oxygen. New Zealand Journal of Marine and Freshwater Research 33: 99-106.

Hamill P 2004. Marlborough’s Freshwater Flora and Fauna – a field guide. Marlborough District Council. 94 p.

Hayes JW 1995. Spatial and temporal variation in the relative density and size of juvenile brown trout in the Kakanui River, North Otago, New Zealand. New Zealand Journal of Marine and Freshwater Research 29: 393-407

Hayes JW 1998a. Wairoa/Waimea/Wai-iti River instream flow study. Prepared for Tasman District Council. Cawthron Report No. 414. 32 p.

Hayes JW 1998b. Riwaka River minimum flow study. Prepared for Tasman District Council. Cawthron Report No. 400. 19 p plus appendices.

Hayes JW 2003. Maitai River instream habitat flow analysis. Cawthron Report No. 795. Prepared for Nelson City Council. 22 p.

Hayes JW, Stark JD 1995. Benthic macroinvertebrate and fish communities in the Roding River and their minimum flow requirements. Prepared for Nelson City Council. Cawthron Report No. 288. 31 p. plus appendix.

Hitchmough R 2002. New Zealand Threat Classification System lists 2002. Threatened Species Occasional Publication 23. Department of Conservation, Wellington. 210 p.

Jowett IG 1995. Spatial and temporal variability of brown trout abundance: a test of regression models? Rivers 5: 1-12.

Jowett IG 1998. Hydraulic geometry of New Zealand rivers and its use as a preliminary method of habitat assessment. Regulated Rivers: Research and Management 14: 451-466.

Jowett IG 2000. Flow management. In Collier, K. J.; Winterbourn (eds) New Zealand stream invertebrates: ecology and implications for management. Hamilton, New Zealand Limnological Society. Pp. 289-312.

Jowett IG, Hayes JW 2004. Review of methods for setting water quantity conditions in the Environment Southland draft Regional Water Plan. NIWA Client Report: HAM2004-018. Prepared for Environment Southland. 81 p.

Jowett IG, Kingsland S, Collier KJ 2004. WAIORA User Guide – Version 2.0. National Institute of Water & Atmospheric Research Ltd., Hamilton.

Lamouroux N, Capra H 2002. Simple predictions of instream habitat model outputs for target fish populations. Freshwater Biology 47: 1543-1556.

Lamouroux N, Jowett IG 2005. Generalized instream habitat models. Canadian Journal of Fisheries and Aquatic Sciences 62: 7-14.

MfE 1998. Flow guidelines for instream values. Volumes A & B. Ministry for the Environment, Wellington.

Sagar PM 1983. Invertebrate recolonisation of previously dry channels in the Rakaia River. New Zealand Journal of Marine and Freshwater Research 17: 377-386.

Snelder TH, Biggs BJF 2002. Multiscale river environment classification for water resources management. Journal of the American Water Resources Association 38: 1225-1239.

Strickland R, Crowe A, Young R 2003. A pilot study of the ecology of small streams in the Marlborough Sounds. Prepared for Marlborough District Council. Cawthron Report No. 827. 47 p.

Young RG, Strickland RR, Harding JS, Stark JD, Hayes JW 2000. The Ecology of Spring Creek - Awarua. Prepared for Marlborough District Council and Fish & Game NZ – Nelson Marlborough Region. Cawthron Report No. 611. 52 p. plus appendices.

Young RG, Crowe ALM, Strickland RR 2002. Ecological assessments of spring-fed streams on the Wairau Plain. Prepared for Marlborough District Council. Cawthron Report No. 737. 34 p. plus appendices.

Young RG, Keeley NB, Shearer KA, Crowe ALM 2004. Impacts of diquat herbicide and mechanical excavation on spring fed drains in Marlborough. Science for Conservation 240. Department of Conservation, Wellington. 50 p.

Young RG, Hay J 2005. Instream habitat flow analysis for the Waimea River and provisional minimum flows for proposed dam sites in the upper Wairoa and Lee catchments.

Young RG, Hayes JW 2002. Assessment of some potential techniques to guide management of water abstraction from small streams. Cawthron Report No. 743. Prepared for Tasman District Council, Fish & Game New Zealand, and the Motueka Integrated Catchment Management Program. 18 p.

Young RG, Knight BR 2005. RiverMetabolismEstimator. Version 1.2. Developed for Ministry for the Environment SMF Project 2208. Available at: http://www.cawthron.org.nz/news/news-2006/functional-indicators-new-approach-river-health.html.