Intl. J. River Basin Management Vol. 4, No. 3 (2006), pp. 179–189

Flow regime requirements and the biological effectiveness of habitat-based minimum flow assessments for six rivers

IAN G. JOWETT, *National Institute of Water and Atmospheric Research, P.O. Box 11-115, Hamilton, New Zealand. E-mail: i.jowett@niwa.co.nz*

BARRY J.F. BIGGS, *National Institute of Water and Atmospheric Research, P.O. Box 8602, Christchurch, New Zealand. E-mail: b.biggs@niwa.co.nz*

ABSTRACT
Sustaining instream values when there is demand for out-of-stream water use is challenging for water resource managers and often there is considerable debate about the methods used to assess flow requirements. Recommendations for flow regime requirements for benthic invertebrates, trout and indigenous fish were made using instream habitat analyses in six New Zealand rivers. We review the results of studies that were carried out to examine the response of aquatic communities to the flow changes. Although the biological data may not be scientifically rigorous in all cases, the weight of evidence from the various sources indicates that in 5 out of the 6 cases, the biological response and the retention of desired instream values, was achieved using the habitat-based methods for setting flows. Indeed, there were increases in trout and benthic invertebrate abundance and changes to the invertebrate community structure in the rivers with successful outcomes. In some cases, flows and flow variability were far from natural, yet excellent trout and invertebrate communities were sustained by the modified flow regimes. High (i.e., flushing) flows were beneficial for cleansing fine sediment deposits and filamentous algae in one river where this regime was recommended and in one case uncontrolled spring floods were necessary to open the river mouth and allow recruitment of diadromous fish species.

Keywords: Minimum flow assessment; instream habitat; flow regime.

Introduction

Rivers have high instream ecological, cultural, landscape, scenic, and amenity values such as angling, boating and other recreational activities. There are, of course, overlaps and linkages among various instream values and they differ in the extent to which they are influenced by variations in flow regime. However, all '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 [1]. '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 often the flow-related changes are small and sometimes 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 often there 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 and some decision-making is necessarily arbitrary and influenced by stakeholder politics as a result.

Long-term solutions to river flow management need to take a holistic view of the river system, including geology, fluvial morphology, sediment transport, riparian conditions, biological habitat and interactions, and water quality, both in temporal and spatial domains. The instream flow incremental methodology (IFIM [2]) 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. 1). Its use requires a high degree of knowledge about seasonal and life-stage habitat requirements of species and inter-relationships of the various instream values or uses.

Received on December 23, 2004. Accepted on June 1, 2005.

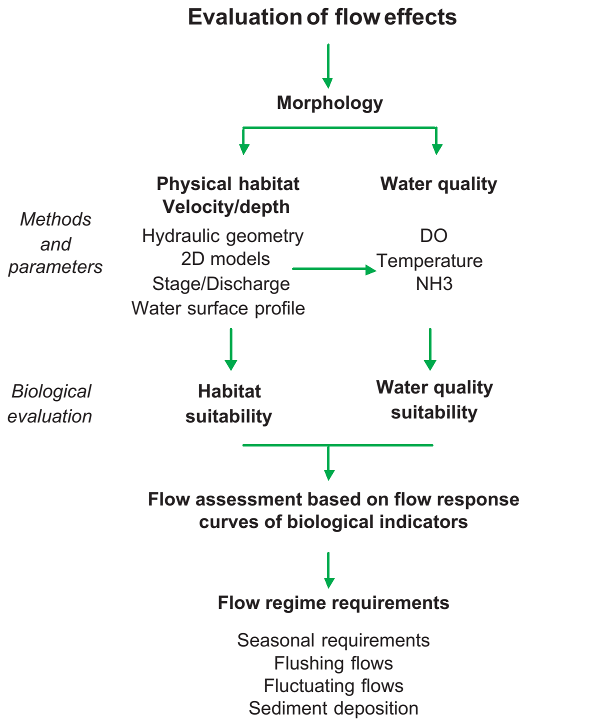

Figure 1 An IFIM framework for the consideration of flow requirements.

Other flow assessment frameworks are more closely aligned with the 'natural flow paradigm' [3] than IFIM. 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 [4]. 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.* [5] 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" [6]. 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 that contribute to target values. 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 low flows that are not characteristic of the river will constitute an atypical disturbance to the ecosystem and could fundamentally change its character. There is also an assumption that the biota are reliant on higher flow conditions [6].

Historically, the focus of instream flow studies has been on determining the low flow conditions required to maintain particular instream values, because low flow periods are the time of greatest competition for the limited amount of water that is available, and a time when 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. 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.
- Smaller floods and freshets, 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 often assist fish passage. 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'.
- 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 periphyton and macrophyte vegetation.
- Annual flow regime. The seasonal variation of flows also may have an important biological function, such as spring floods that open a river mouth and enable the spring migration of diadromous fish from the sea or annual floods in arid zones that sustain the flood plain ecosystem.
- 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.

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, freshets, 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.

Although methods of assessing flow requirements continue to be developed and debated, very few studies examine how well modified flow regimes have achieved their desired outcomes and there are few studies that describe the response of aquatic populations to flow changes. Armour & Taylor [7] surveyed 35 U.S. Fish and Wildlife field offices that had been involved in 616 IFIM applications of which only 6 had follow-up monitoring, the results of which were not reported. The survey found that opinions on IFIM were divided, with 40% considering the method technically too simplistic, 41% considering it too complex to apply, and 9% considering it not acceptable or biased. However with any flow assessment method, the critical test of whether the method worked or not is whether it was successful in achieving the desired maintenance of instream values. In the U.S. survey, half rated success as higher than neutral, while one-third rated it lower.

In this study, we review six New Zealand cases involving trout, benthic invertebrate and indigenous fish communities where minimum flow and flow regime recommendations have been made and implemented based on an IFIM approach, and examine the available biological data to determine whether these recommendations have been successful in achieving their desired goals. The assessment is based on information and data collated from a range of unpublished and published studies that were usually carried out on each river for other purposes, but allow evaluation of the success of the flow regime recommendations. All data and study methodologies were scrutinised and found to be adequate for the purposes of the present assessment.

Summary of methods

Instream habitat surveys and flow recommendations

Instream habitat surveys were carried out in reaches most affected by flow change, in all of the six study rivers and were used as a basis for recommending a flow regime to maintain the target values. The instream habitat surveys were either closely spaced cross-sections in representative reaches or cross-sections selected by a stratified-random sampling, without replacement (habitat mapping). This involves stratifying a section of river into categories with similar characteristics, such as pool, run, and riffle, and then randomly selecting cross-section locations in these categories. Instream habitat modelling was carried out using RHYHABSIM [8]. Flow recommendations were made after examination of the habitat (weighted usable area)/flow curves. Usually, minimum flow requirements were determined from a breakpoint determined by drawing a horizontal line through the maximum and extending a line through the low flow section of the curve (Fig. 2). The point where the two lines meet indicates the flow where habitat begins to reduce sharply with flow and was recommended as the minimum flow in most cases.

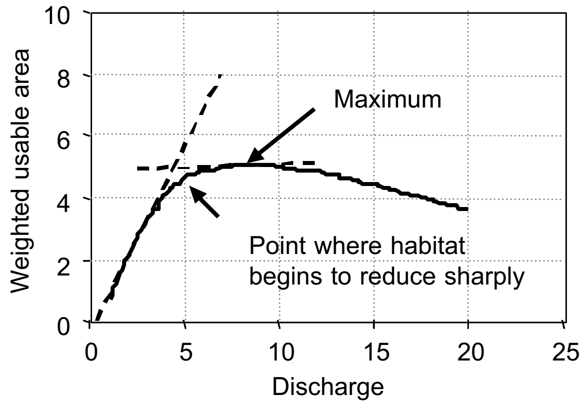

Figure 2 Selection of minimum flow at the point where habitat begins to decline sharply with decreasing flow for a hypothetical river.

Recommendations for extra flow releases as a means of flushing deposits of fine sediments or accumulations of filamentous algae were made where we considered it necessary and beneficial to the maintenance of the target instream values. The magnitude of these releases was calculated by the method of Milhous [9], as implemented in RHYHABSIM.

Biological responses

Information on the biological responses to flow changes were collected by a variety of methods including drift-diving counts of trout, quantitative benthic invertebrate sampling (mainly Surber samples), angler surveys, and electric fishing surveys. Details of these methodologies are available from the authors on request. In most cases, biological data were not collected specifically for the evaluation of flow changes. Where appropriate, trout densities in rivers with modified flow regimes were compared to national drift diving survey data [10] to show the relative magnitude of the response and how closely the trout density approached national maxima in unmodified rivers.

Case studies

Tekapo River

Flow assessment

The Tekapo River (mean flow 80 $m^3 s^{-1}$) was diverted at Lake Tekapo for the Waitaki Power Development in 1978, and was the first river in New Zealand where flow regime requirements for the maintenance of specific values were based on an analysis of instream habitat requirements [11]. There was no provision for a minimum flow in the river at the diversion point, but flows from tributary streams progressively increase the mean flow in the river to about 10 $m^3 s^{-1}$ at a point about 40 km down stream where it flows into a lake. The habitat analysis showed that a flow of about 10–13 $m^3 s^{-1}$ provided near maximum trout spawning and food producing habitat in the lower 20–40 km of the river [11], although flows in the section above this were less than optimum. Thus, the analysis suggested that a residual flow from Lake Tekapo was not necessary to supplement flows in the lower part of the river, and that the flow reduction would be beneficial to trout habitat and potentially increase the trout populations and the fishery in the lower part of the river. Apart from a slight intensification of landuse in the catchment (small increase in irrigated land and higher density holiday home development at the Tekapo village on the shores of Lake Tekapo), no changes have occurred to the river and channel environment over the last 50 years other than vegetation and morphological changes in the original 1978 river channel and flood plain.

Response of values to flow regimes

No monitoring was specifically carried out to test the predictions of the instream habitat modelling. However, other information can be used to make a confident judgement as to the relative success of the modified flow regime. Brown and rainbow trout were introduced into the downstream river system c. 1900 and extended their range into the Tekapo River without any stocking. However, there were no records of trout density prior to diversion as the Tekapo River was not considered an angling river and was not even mentioned in angling surveys of that time [12]. From this, we conclude that angling in the river was poor, probably because trout numbers were low and river conditions unsuited to angling.

Trout populations were surveyed by drift-diving in 1986 & 1989 [10], 8 and 11 years following the commencement of the modified flow regime. These surveys revealed densities of 94–240 brown (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) (> 20 cm) per km (Fig. 3). These trout densities are among the top twenty percent recorded in New Zealand rivers. These data are supported by angler use surveys that indicate that the river is one of the most popular angling rivers in the region, with angler use of 2400 days in 1994/95 and 4900 days in 2002/02. The modified Tekapo River is now the 'sixteenth' most popular angling river in New Zealand [13]. Six indigenous fish species are found in the Tekapo River. They are species commonly found in small upland streams and we have no reason to suspect that they have been detrimentally affected by the flow regime change.

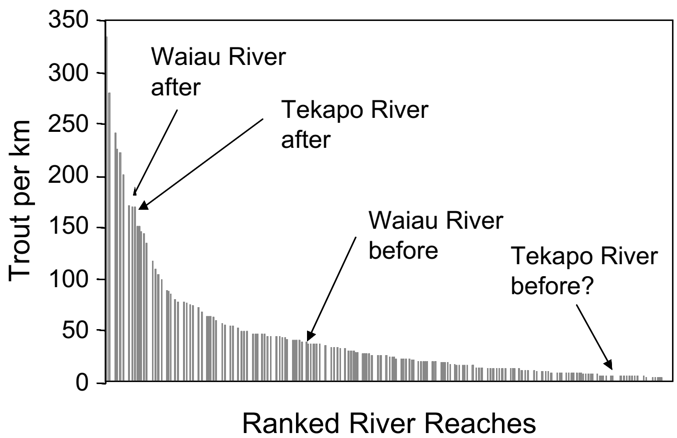

Figure 3 Total numbers of brown and rainbow trout (> 20 cm) per km in the Tekapo and Waiau rivers before and after implementation of minimum flow recommendations compared to national trout numbers from 300+ river reaches ranked in descending order (data compiled from [10]).

Waiau River

Flow assessment

Practically all of the natural flow of about 450 $m^3 s^{-1}$ of the Waiau River in Southland was diverted through the Manapouri Power Station in 1977. Tributary flows increased minimum flows in the 20 km reach below the diversion structure from 0.3 $m^3 s^{-1}$ immediately below the structure to about 3 $m^3 s^{-1}$ about 20 km down stream.

Instream habitat surveys and analysis of the hydraulic habitat of periphyton were carried out in a 20 km section of river immediately below the diversion structure to determine whether there should be flow releases from the diversion structure to improve trout fishing values. There was also a need to reduce the extent of periphytic algal proliferations and increase production of caddisflies and mayflies (fish food) in the stretch of river. An instream habitat analysis was carried out to determine flow requirements for trout [14] and this indicated that a flow of 12 $m^3 s^{-1}$ or greater would provide excellent brown trout habitat. An analysis of habitat used by benthic communities indicated that mean reach velocities of > 0.3 m s^{-1} were required to maintain a low periphyton biomass and the target invertebrate communities [15]. This equated to a flow of > 10 $m^3 s^{-1}$.

A flow regime was implemented in late 1997 that had a minimum of 12 $m^3 s^{-1}$ in winter and 16 $m^3 s^{-1}$ in summer. As a consequence flows are between 12 and 16 $m^3 s^{-1}$ for about 60% of the time (Fig. 4) but the frequency of high flows is unchanged (lower graph Fig. 4).

Biological response to flow regimes

Drift-diving trout surveys were carried out over the 20 km section of river in the 2 years before and three years after the minimum flow was increased. These showed that numbers of brown and rainbow trout (> 20 cm) had increased six-fold (Fig. 5). The trout fishery in this river is now regarded as excellent, with high angler usage and high catch rates. In the 1994/95 fishing season just before the implementation of the minimum flow, angler usage in the whole river (c. 90 km) was 7700 days. After the flow was increased angler usage rose to 14600 angler-days in 2001/02 [13], against a national trend of declining usage. The Waiau is now the eighth most popular trout fishing river in New Zealand, as it was before diversion [12] and it has among the highest trout densities in New Zealand whereas previously it was in the lower range (Fig. 3).

A survey of the indigenous fish fauna [17] found 15 freshwater species typical of the rivers of southern New Zealand. Most species were diadromous and favoured cobble gravel substrates in edge habitats less than 0.25 m deep. The study concluded that the minimum flows would provide good native fish habitat.

The operation of the hydro-electric power development results in regular flood releases of high flows (100–200 $m^3 s^{-1}$) in spring/early summer and these are supplemented by releases of 45 $m^3 s^{-1}$ 4 or 5 times each summer for recreational purposes. These appear to help 'cleanse' the river going into summer. Subsequent monitoring has shown [18] that excess periphyton biomass

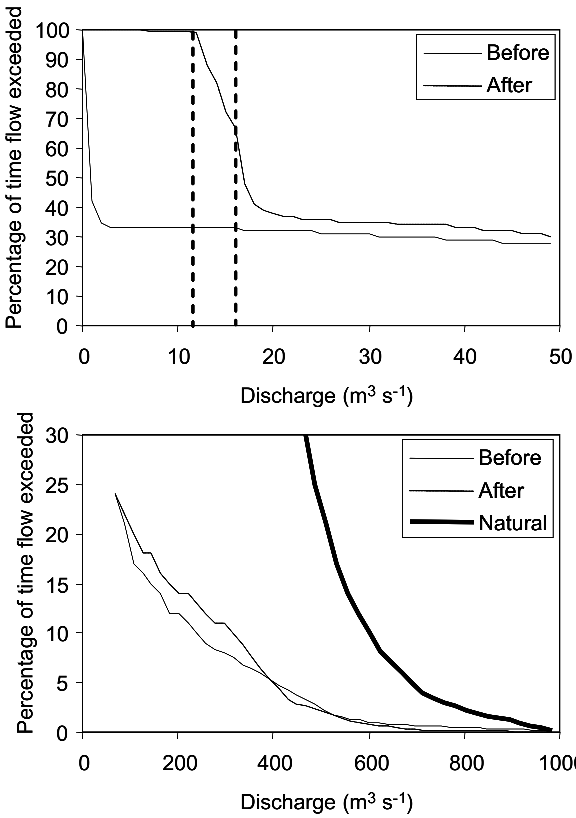

Figure 4 Flow duration curves before and after the implementation of minimum flow recommendations for flows in the low flow range (above) and in the high flow range (below) showing the natural and post hydro-electric flow duration curves before and after the implementation of minimum flow recommendations, Waiau River. The vertical dashed lines in the upper graph show the winter (left) and summer (right) minimum flows.

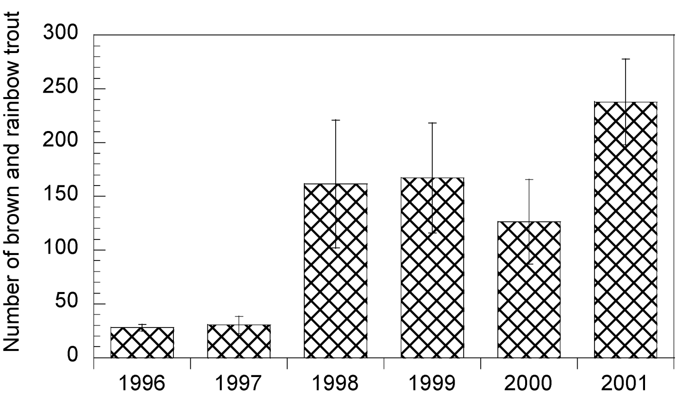

Figure 5 Numbers of large brown and rainbow trout (> 20 cm) in the Waiau River per km before and after the implementation of a minimum flow in 1997 of 12 $m^3\,s^{-1}$ in winter and 16 $m^3\,s^{-1}$ in summer. The error bars represent one standard error calculated from 4 trout survey reaches over 20 km (data from [16]).

can accrue if these spill flows do not occur. In such cases, additional flushing flows were recommended to maintain ecosystem health and benthic production.

Although river flows have reduced from 450 $m^3\,s^{-1}$ to 12–16 $m^3\,s^{-1}$, there is no evidence of any detrimental effects on the fish community probably because there are no indigenous fish species that are found solely or predominantly in large rivers in New Zealand. However, while the high quality trout fishery and benthic community health has been reinstated with only 3% of the natural mean flow, the visual appearance of the river has changed with a loss of the large river character.

Monowai River

Flow assessment

Lake Monowai is regulated at the outlet for hydropower and flows from this lake varied frequently (usually daily) from near zero to full generation, depending on electrical demand. As with the Waiau and Tekapo rivers, tributaries enter downstream so that the river always has a small flow from not far below the control structure.

In 1994, instream flow assessments were used to determine that a minimum flow of 6 $m^3\,s^{-1}$ was required to provide habitat for a diverse benthic invertebrate community and 'healthy' river [19]. However, daily fluctuations in flow from 6 $m^3\,s^{-1}$ to 20 $m^3\,s^{-1}$ would still occur.

Biological response to flow regimes

Benthic invertebrate samples have been collected annually from a site in the lower Monowai River for 4 years prior and 4 years after the revised flow regime was instituted [20]. These data showed that the increase in minimum flow doubled benthic invertebrate densities (from 310 per m^2 to approximately 650 per m^2) and taxon richness (from 8 to an average of 17) (Fig. 6).

Although the new densities were less than the median from a range of other New Zealand rivers (1,903 per m^2 [21]), the taxon richness was slightly above the national median (14 [21]). Thus, an improvement in river ecosystem health and the objectives of the modified flow regime were largely achieved.

Moawhango River

Flow assessment

In 1979, the natural flow of the Moawhango River, about 9.6 $m^3\,s^{-1}$, was diverted out of catchment to the Tongariro River for hydro-power generation, leaving practically no flow from the hydro-impoundment dam. However, leakage and tributaries resulted in a 0.06 $m^3\,s^{-1}$, 9 m wide, slow flowing river 1 km down stream of the dam (previously 21 m wide and flowing

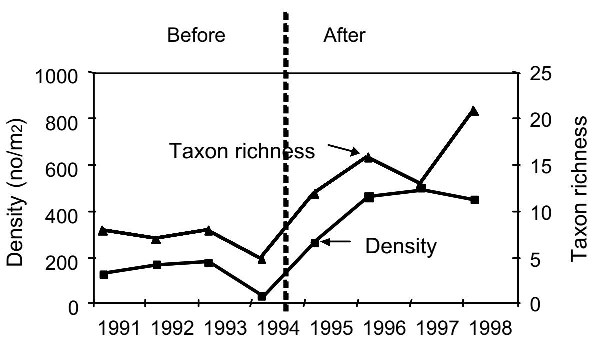

Figure 6 Density and taxon richness of benthic invertebrates in the Monowai River before and after implementation of a minimum flow control [22].

swiftly), and this increased to 4.7 $m^3 s^{-1}$ 39 km down stream at the Moawhango village. As part of the re-licensing process for the power scheme, benthic invertebrate surveys showed that the habitat below the dam was degraded with periphyton proliferations and an invertebrate community comprised of taxa commonly found in low water velocity environments [23]. An instream habitat assessment, together with trial flushing flows 4 times over the summer, were used to recommend flows required to establish benthic invertebrate communities below the dam that were typical of rivers in the region [24]. The residual flow that was accepted and instituted through the re-licensing process was 0.6 $m^3 s^{-1}$, which was 6% of the natural flow.

Biological response to flow regimes

Benthic invertebrates were sampled in the Moawhango River for 4 years before and one year after the minimum flow was implemented [23]. No other factors changed in the catchment as it is Army Reserve land. Over this period, the composition of the invertebrate community changed considerably. The relative abundance of 'desirable' taxa which are indicative of a 'healthy, high country lake-fed river' increased, whereas the relative abundance of non-target 'undesirable' taxa decreased. The proportion of the invertebrate community composed of mayflies + stoneflies + caddisflies (%EPT: a measure of the relative abundance of 'healthy' invertebrates) increased from 37% to 57% with the increase in flow, to the extent that it is now similar to the 60% EPT composition in the river upstream of the dam (Fig. 7). For all taxa, the relative abundance of target taxa increased with the increase in flow, whereas the relative abundance of non-target taxa decreased (Fig. 8). These results indicate that the modified flow regime succeeded in achieving the desired outcomes.

Flushing flows were also recommended for the Moawhango River, because spill flows from the dam were relatively infrequent and sediment and periphyton were accumulating in the lower reaches. Hydraulic simulations showed that a flow of 20 $m^3 s^{-1}$ would cleanse more than 80% of the base flow streambed and disturb less than 20% of the armour layer (Fig. 9). Trial tests (Fig. 10) showed that flushing flows of 20 $m^3 s^{-1}$ were effective and these have been implemented.

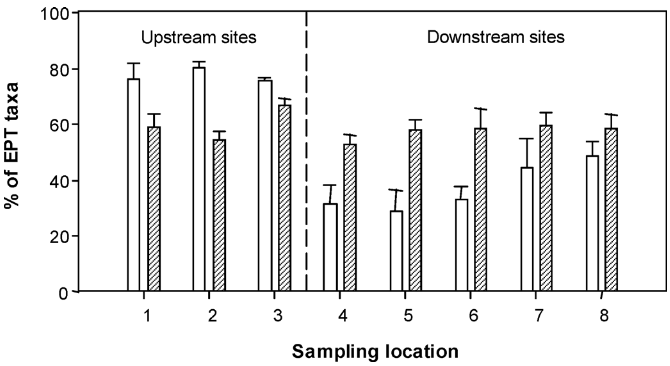

Figure 7 Total percentage of EPT taxa (mayflies + stoneflies + caddisflies) (x + 1se, $n = 5$) at the sampling sites at locations upstream and downstream of the Moawhango Dam, collected in 1997 (open bars) and in 2002 (hatched bars) (data from [23]).

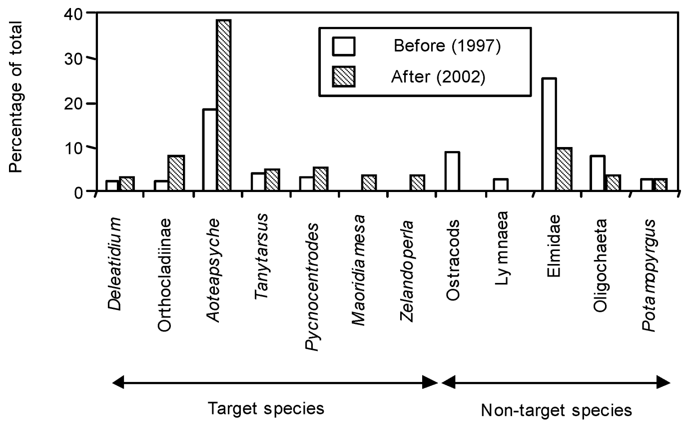

Figure 8 Benthic invertebrate species composition in Moawhango River before the minimum flow was implemented (open) and after (hatched) showing how dominance of target invertebrate species (left) increased and non-target invertebrate species (right) decreased as a result of a flow increase (data from [23]).

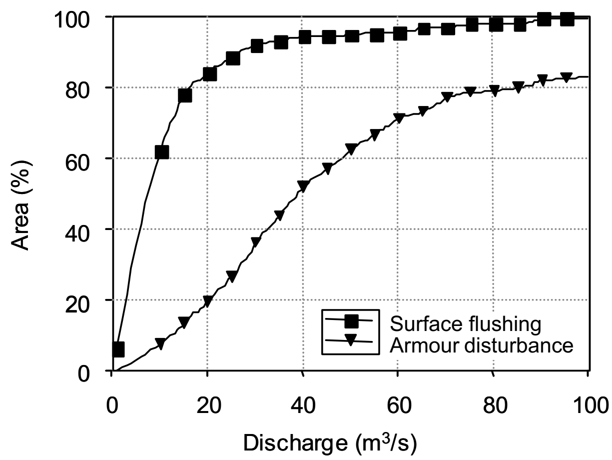

Figure 9 Percentage of the Moawhango River bed area flushed by flows of 0 to 100 $m^3 s^{-1}$ calculated using the Milhous [9] method.

Ohau River

Flow assessment

The Ohau River, South Island, drains Lake Ohau, a large, reasonably clear, glacial lake. Its mean flow was 80 $m^3 s^{-1}$ prior to diversion in 1979. The Ohau River begins with a low dam at the Lake Ohau outlet and an associated structure to release water. The river flows for about 11 km before it enters the artificially created Lake Ruataniwha. Following diversion, a flow of less than 1 $m^3 s^{-1}$ was left in the river and there were calls to reinstate flows sufficient to maintain a good trout fishery. An instream habitat survey was commissioned [25] and this showed that a flow of 10 $m^3 s^{-1}$ would provide excellent trout habitat. Increased flows (12 $m^3 s^{-1}$ in summer 8 $m^3 s^{-1}$ in winter) have been released from the lake since 1994. No flushing flows were recommended because there was no facility for controlled release of high flows.

Biological response to flow regimes

Although the river now provides what is regarded as excellent angling water and trout habitat, trout numbers and angler usage have remained low, with 636 anglers-days in 1994/95

Figure 10 Moawhango River after 8 months of nearly constant flow (above) and 7 days after a flushing flow (below).

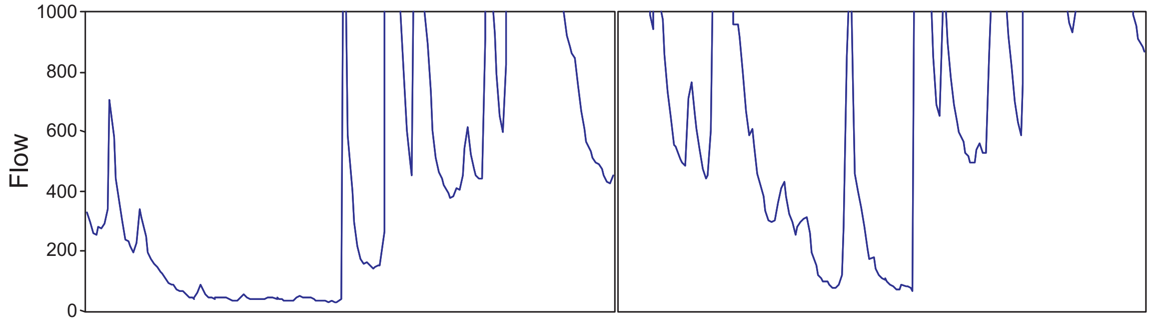

Figure 11 Waipara River flows (L s^{-1}) over the dry December 1998 to May 1999 summer (left) and the normal December 1999 to May 2000 summer (right).

[26] and 500 angler-days in 2001/02. Historically, the fishery may have been poor, as there is no mention of angling use in the Ohau river in an early angling diary scheme [12]. The lack of trout in the river may be related to poor food production because of glacial silt deposits on the substrate and lack of flow variation, and/or problems with recruitment and fish passage between the lake and river or simply a preference for the lake environments.

This is the only case where predictions of trout abundance and maintenance of an associated fishery based on the quality of habitat were not successful.

Waipara River

Flow assessment

The Waipara River, a small gravel bed river north of Christchurch, is under considerable pressure from irrigation abstraction. An instream habitat analysis was carried out and recommended a minimum flow of 120 L s^{-1} for the maintenance of indigenous fish biodiversity values [27]. This was based on consideration of habitat for common bullies (*Gobiomorphus cotidianus*), a species with habitat preferences that were intermediate between the fast-water species (torrentfish (*Cheimarrichthys fosteri*) and bluegill bullies (*G. hubbsi*)) and the edge-dwelling species (upland bullies (*G. breviceps*) and Canterbury galaxias (*Galaxias vulgaris*)), as suggested by Jowett & Richardson [28].

Biological response to flow regimes

Following the flow assessment, fish populations were surveyed seasonally by electro-fishing 8 reaches along 20 km of river for three years. In the first December to May (inclusive) summer (1998/99), flows were extremely low, but were relatively normal in the following year (Fig. 11).

The fish surveys showed that the effect of low flows on fish populations increased with the magnitude and duration of low flow (Fig. 12). In the first December to May (inclusive) summer (1998/99) when the mean flow was 647 L s^{-1}, daily mean flows were less than nominated minimum flow of 120 L s^{-1} for 31% of the time and fell to a minimum of 32 L s^{-1} [29]. These low flows led to a substantial decline in the abundance of 3 of the 4 common indigenous fish species in the river. The following summer (1999/00) when the mean flow was 1069 L s^{-1}, daily mean flows were less than 120 L s^{-1} for only 10% of the time, with a minimum of 69 L s^{-1}. These conditions resulted in little change in indigenous fish abundance. These results support the recommended minimum flow, and even suggest that the minimum flow recommendations for these indigenous fish species may have been unnecessarily high.

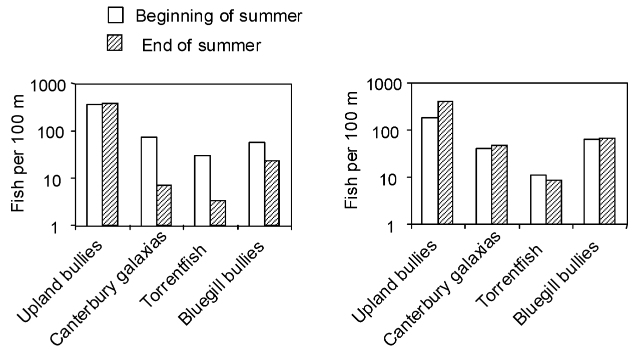

Figure 12 Indigenous fish abundance in the Waipara River at the beginning and end of a dry December 1998 to May 1999 summer (left) and normal December 1999 to May 2000 summer (right).

This study in the Waipara River also demonstrated the resilience of the indigenous fish community, as it redeveloped strongly after the first year of the study even though it had been severely reduced in numbers. Some large floods during the study that caused extensive disturbance of bed materials had little effect on fish abundance, and diadromous species (torrentfish and bluegill bullies) were dependent on spring floods for recruitment. Low flows were more detrimental to the fish community than floods, with prolonged low flows reducing the abundance of fish species that prefer high water velocities, and favouring those that prefer low velocities. During periods of low flow proportionally more fish were found in riffles. This implies that riffle habitat is important in the maintenance of fish stocks and biodiversity during periods of low flow. The key elements of the flow regime were the magnitude and duration of low flows, as well as the occurrence of spring floods that allowed recruitment of diadromous species [29].

Discussion

The case studies described here are the only New Zealand cases that we know of where the biological effects of flow recommendations based on instream habitat assessments can be evaluated, even though flow regimes in more than 100 streams and rivers have been set based on instream habitat requirements. The predominant flow management focus was on minimum flow requirements in all six rivers and although the biological data may not be scientifically rigorous in all cases, the weight of evidence indicates that the biological responses were as expected and successful in 5 out of 6 cases. In particular, trout abundance in the highly modified Waiau and Tekapo Rivers was close to the highest recorded in any New Zealand rivers, suggesting that the modified flow regimes were near optimum for trout. There are no fish species in New Zealand that are found only in large rivers, and deep and swift waters in the large rivers probably limited fish production prior to flow modification.

The study in the Waipara River showed that it is necessary to appreciate the inter-relationships between flow variability and the magnitude and duration of low flows. Although flow variability often is thought an essential element of the flow regime that should be maintained [3], there is little published biological evidence that flow variability is essential for ecosystem maintenance or even the maintenance of specific components. Similar biological communities are often found in streams and rivers with very different patterns of flow variability (e.g., brown trout thriving in mountain headwater streams and lowland spring-fed streams) and valued biological communities can be maintained in rivers where the flow regime has been extensively modified by hydro-electric operations, such as was the case in most of the study rivers. The term 'flow variability' also confuses the discussion, because high flow variability can be bad for the aquatic ecosystem and low flow variability good, depending on how flow variability is measured. Jowett & Duncan [30] 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 freshets that maintained relatively high flows throughout the year. Rivers with high flow variability (i.e., long periods 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 be defined by the frequency of floods and freshets. Clausen & Biggs [31] 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) [30] 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 freshets 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 freshets 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. Dams and associated storage capacities were sufficient to reduce floods in two of the six cases described here. Flushing flows were necessary in one of those cases to remove fine sediment carried into the river by tributaries with particularly high sediment loads.

We suggest that these case studies do not support commonly held views that more flow is better and that all aspects of a natural flow regime are important. The flow regime in rivers controlled or diverted for hydro-electric generation were far from 'natural', particularly in the Waiau and Monowai rivers, yet these rivers contain excellent trout and invertebrate populations.

However, some aspects of the flow regime can be important. At certain times of year floods can play a role in fish migration, either by allowing passage through shallow sections of river or by opening the river mouth and allowing recruitment of diadromous fish species from the sea, as occurs in the Waipara River. However, spring floods are not advantageous in every New Zealand river system. The Kakanui River is located on the east coast of the South Island like the Waipara River, but is slightly larger. In this river, a year without spring floods allowed the successful recruitment of juvenile trout, with a subsequent 3–4 fold increase in adult trout numbers 3 years later, whereas in other years floods during spring prevented successful emergence of trout fry [32,33].

Rivers are often different and have different flow requirements depending upon the species that are supported by the river and their life cycle requirements. This was evident within New Zealand, which is relatively heterogeneous in terms of climate and river type, and although the general principles used to establish a satisfactory flow regime would apply to most rivers, absolute flow requirements for a given river will be unique and probably will be dictated by different biological requirements. The challenge for biologists is to determine the aspects of the flow regime that are important for the various biota associated with their rivers, and to develop flow regimes that meet those needs.

Acknowledgments

We thank the two anonymous referees for their constructive comments and the Foundation for Research, Science and Technology (New Zealand) for funding under contract C01X0308.

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