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Determination of flow regimes for protection of in-river values in New Zealand: an overview

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Abstract
Competition for water has intensified. Determining when, and how much, water needs to be left for in-river values is a challenge world-wide. In New Zealand there is now a well established connection between the flow regime, as defined by the magnitude and variability of flows, and suitability for in-river values. Physical habitat requirements of the biota have been defined and related to overall flow regimes (e.g., mountain fed, hill fed and lowland fed). Key to this is understanding both minimum flow and variability requirements of the biota. This paper overviews some of this science and illustrates how this knowledge has helped resolve river resource management issues in New Zealand.

Key words: environmental flows, water allocation, river ecology, trout, eels, invertebrates.

1. Introduction

The United Nations World Water Development Report – Water for People, Water for Life, released in March 2003, UN (2003), cited New Zealand as having the world's third best quality of water. New Zealand is also a country well endowed, by world standards, with water resources. This combination of high quality and plentiful supply of water generally supports ecologically healthy river systems (Biggs *et al.* 1990). It also leads to conflicts between those developments that use water in large quantities (e.g., hydro-power generation and irrigation), and those that wish to preserve the rivers in their natural state for intrinsic values or ecosystem services (e.g. tourism, recreational fishing). To assess the conflicting demands for natural resources, New Zealand has developed an 'effects-based' resource governance framework (the Resource Management Act; see http://www.mfe.govt.nz/rma/index.php) that enables potential users of a resource to present cases for development (or conservation) to a tribunal charged with making a decision in the interests of all stakeholders and the needs of future generations. This involves establishing what values might need to be maintained and the degree to which this is desired by stakeholders; a process which is heavily informed by objective eco-hydrological science. These panels are also charged with ensuring that the natural 'life-supporting capacity' of the waterway is preserved 'whilst' allowing for the economic needs of society. These are usually very difficult issues to resolve and inevitably the final decision involves some compromises.

There has been a long-held perception amongst many New Zealand water managers that the ecological health of a river can be preserved by establishing a minimum flow, and that all water above the minimum is available for other out-of-river uses. This perception leads to opposing parties in water allocation hearings arguing about what is the correct size for the minimum flow. However, new research (in New Zealand, Australia and North America) has demonstrated the importance of considering the whole flow regime in setting allocation limits, and not just the minimum flow (e.g., Biggs *et al.* 1990; Jowett 1990; Jowett, Richardson 1995; Biggs 1996; Poff *et al.* 1997; Biggs *et al.* 2001; Riis, Biggs 2003). This has been a major advance in the scientific support for water allocation in New Zealand. Information recently presented to water allocation hearings in New Zealand (e.g., the Waitaki River) has, for the first time internationally, applied such broad-based eco-hydrological approaches to enable more informed decisions. The novelty of these approaches centres around the eco-hydraulic research and monitoring of flow regime changes that has been carried out in New Zealand that has led to: 1) use of physical habitat modelling, in combination with flow modelling, to design a full 'flow regime' that caters for all life-history stages of key animal and plant species, 2) recognising that sediment movement is a key driver of ecosystem state, largely determining overall physical habitat conditions along a gradient from 'harsh' (frequent sediment movement) to 'benign' (infrequent movement) leading to the incorporation of sediment transport modelling as a tool to manage ecosystem health and allow some degree of mitigation of flow management effects (particularly following large scale activities such as impoundment); 3) incorporation of all levels of the food chain in effects analysis on the basis that good physical habitat for fish alone will not necessarily ensure healthy river ecosystems; 4) maintenance of invertebrate production is necessary for good salmonid populations (which are often food limited) so the 'quality' of invertebrate habitat, and the periphyton upon which they feed, needs to be catered for; and 5) identifying/avoiding/mitigating conditions that promote excess growth of weeds and periphytic algae. This paper overviews the above science, its application in New Zealand, and concludes with several recent examples demonstrating the above approaches for recommending flow regimes which have been targeted at maintaining desired in-river values.

2. Background on linkages between flow regimes and New Zealand river ecosystems

Broadscale relationships between flow variability and ecological state

Designing regulated flow regimes that preserve the character of a river, whilst enabling abstractions for out-of-river developments, requires an understanding of how the ecosystem in the river operates and is dependent on different components of the flow regime at different scales (Biggs *et al.* 2005). Ecosystems in New Zealand rivers have three main trophic levels: primary producers (periphyton or 'slimes' and 'macrophytes' which are large vascular plants), consumers (predominantly insects and snails) and predators (predominantly native and salmonid fish). Figure 1 shows a typical food chain involving these three elements in a healthy river environment.

Many New Zealand rivers are characterized by having a channel bed composed of sediments that often move during the moderate to frequent floods that many regions of New Zealand experience, creating quite 'harsh' environments (Jowett, Duncan 1990; Biggs *et al.* 2001). In such rivers the predominant food chain is from diatom-dominated periphyton to insects to fish (left side of Figure 1; Biggs *et al.* 1990). The thin, brown 'diatom' films that develop on the stones between floods provide good food for grazing mayfly and caddis-fly invertebrates. However, at the other end of the spectrum, where floods and freshes are infrequent (e.g., summer-time in foothills rivers) filamentous green algae ('slime') often proliferate, and where there are no bed-moving-floods then macrophytes and large bryophytes dominate the plant communities (these being classified as hydrologically 'benign' environments) (Biggs 1996). These primary producers are poor food for invertebrates and inhibit the development of diverse mayfly/stonefly/caddis fly dominated invertebrate communities (often resulting in a shift to a dominance by midges, worms and snails). River environments that are moderately harsh have predominantly diatom→insect→native fish food chains, but are usually the most diverse and 'healthy' ecosystems (e.g., Scarsbrook, Townsend 1993; Biggs 1996; Clausen, Biggs 1997; Biggs 2000; Biggs, Smith 2002; Jowett, Richardson 1995). Salmonid fish species (particularly rainbow trout) benefit from more 'benign' flow regimes, whereas brown trout do better in slightly harsher flow regimes (Jowett 1990; Jowett, Richardson 1989; McIntosh 2000). The 'benign' habitats with food chains comprising macrophytes→snails, worms and midges→fish are least common in New Zealand (Biggs 1996; Riis, Biggs 2003 in relation to macrophytes). Such environments are also usually less diverse (Clausen, Biggs 1997), but may still be

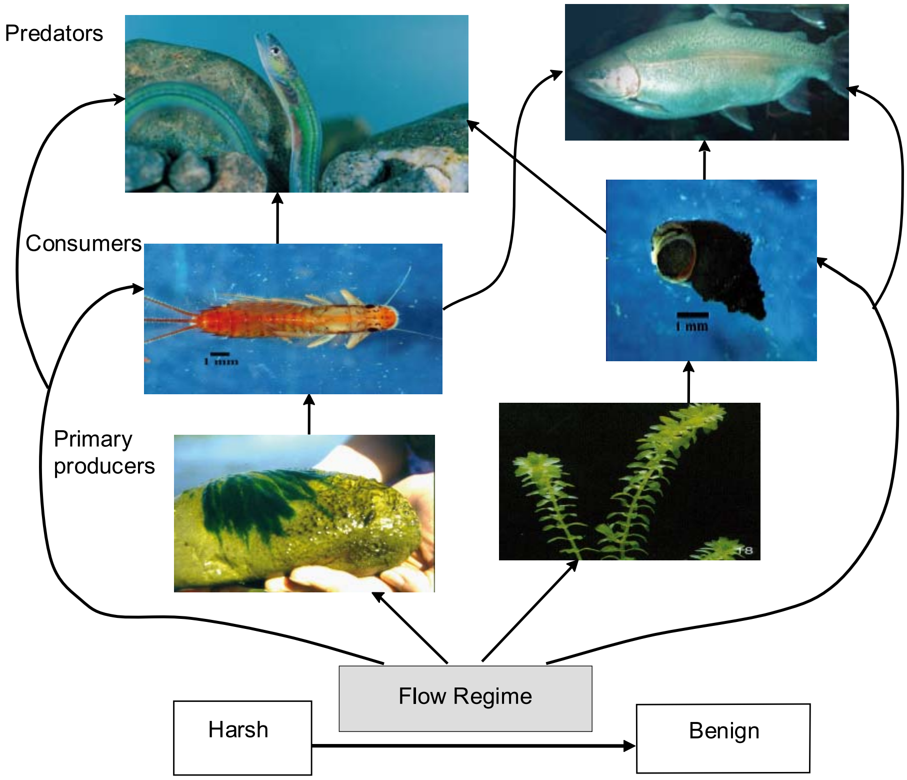

Fig 1. Typical food chains in New Zealand rivers. Harsh hydrological conditions (frequent floods and associated bed sediment movement) in rivers leads to a predominance of the left-hand food chain (mountain fed rivers) comprising periphyton as the main primary producer, insects as the main consumers and a predominance of native fish predators. Benign hydrological conditions (few floods and stable bed sediments) lead to a predominance of the right-hand food chain (lowland fed rivers) comprising macrophytes as the main primary producer, snails, worms and midges as the main consumers and salmonids as the predominant fish species. Hill fed rivers have a combination of both food chains and are particularly prone to filamentous green algal periphyton growth during summer low flows.

'healthy'. Terrestrial prey items can contribute a larger proportion to the diet of fish in small, stable streams. Where conditions are suitable for filamentous green algae to bloom (long periods of stable flow + nutrient enrichment of the water), then the food chain can (sometimes temporarily) shift to one dominated by snails, worms and midges (similar to that associated with benign environments) (Biggs 2000; Suren *et al.* 2003).

Thus, the type of ecosystem and the linkages between the trophic levels is usually strongly influenced by the overall nature of the flow regime (Fig. 1) (Biggs *et al.* 1990; Clausen, Biggs 1997). Determining what the strength and type of these linkages is, and their importance as drivers of in-river processes, has been a major focus of research in New Zealand over the last 25 years.

Ecologically important components of flow within a regime

We have identified three main components to flow regimes that are ecologically important in New Zealand:

Low flows: these set the limit to habitat quantity, providing that the duration of low flows is sufficient to engender a biological response (Jowett *et al.* 2005);

Small floods and freshes: these occur moderately frequently and contribute to maintaining habitat 'quality' through flushing away accumulations of silt and periphyton from coarse sediments. The magnitude of such flow perturbations is usually about 3 – 6 times the median flow (or low flow in a highly regulated river) (Biggs, Close 1989; Clausen, Biggs 1997) and they cause sand and fine gravel movement, but seldom move larger bed sediments such as cobbles where invertebrates and fish hide during such events. 'Flushing flow' events below storage dams often need to be higher in magnitude for removal of some periphyton and of silts deeper in the gravels because of the more armoured sediments in regulated rivers. The magnitude of change in flow compared with the low/median flow is very important, and not just the size of the flow. For example, a flow of 450 $m^3\ s^{-1}$ in a river after several months at 100 $m^3\ s^{-1}$ would have a good 'flushing' effect, where-

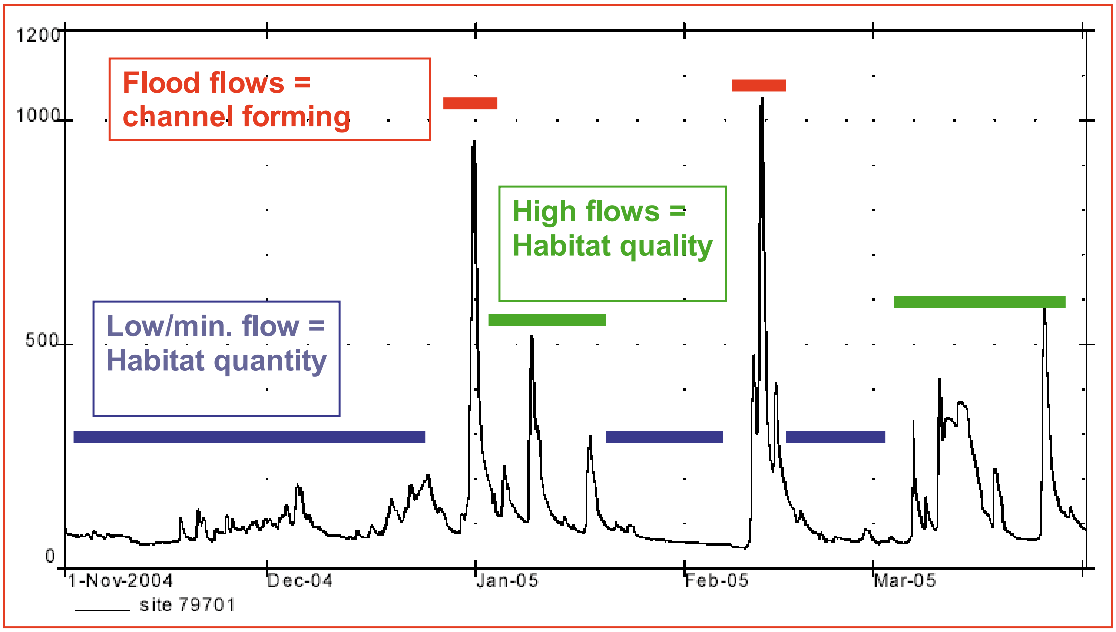

Fig. 2. Different flow components in the Waiau River in southern New Zealand.

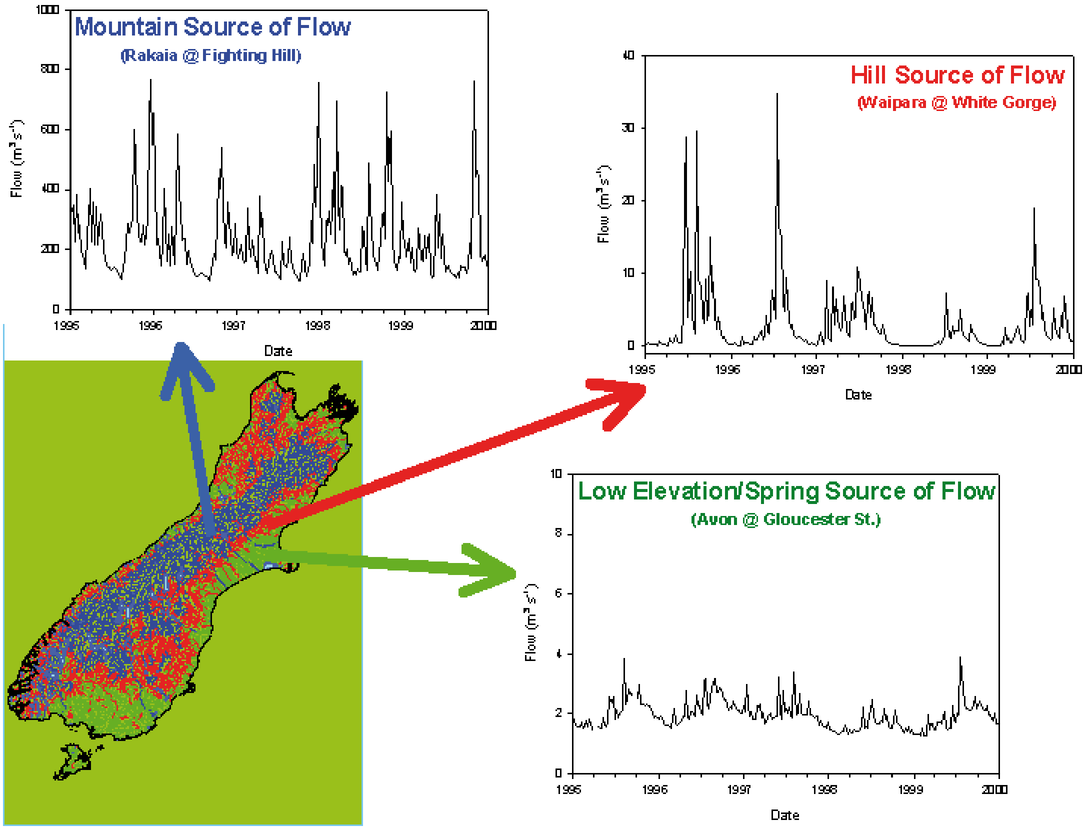

Fig. 3. Use of the New Zealand River Environmental Classification to identify the main flow regimes of all the rivers in the South Island. The map shows the distribution of the three types of rivers, while the hydrographs show typical, near-natural flow regimes for each river.

as a flow of 450 $m^3 s^{-1}$ after several months at 300 $m^3 s^{-1}$ would have little effect on periphyton unless a critical threshold for bed sediment stability was exceeded. This is because the periphyton would have equilibrated to the flow of 300 $m^3 s^{-1}$. A long period (e.g., 2 – 3 months) of constant minimum flow in summer will usually reduce invertebrate production and diversity through accumulation of periphyton and silts.

Large floods: these are floods that fill the whole channel to near the top of the banks and occur only about once a year. They are termed 'channel forming' or 'channel maintenance' flows. These cause large disturbances to the river ecosystem and often wash most periphyton, macrophytes and invertebrates from rivers (e.g., Biggs, Close 1989; Riis, Biggs 2003), together with a large proportion of young introduced fish species (McIntosh 2000). Most native fish species appear to have evolved to cope with these floods and may take temporary refuge in more sheltered bank areas (e.g., Jowett, Richardson 1989).

The above points show that variability above that minimum is required to maintain healthy ecosystems. Flow variability is determined from the overall pattern of low and high flows during the year. Figure 2 shows the relative magnitude of the different high flow events during 2004/05 in the Lower Waiau River, southern New Zealand. In the reach of the recorder site, low flows that set habitat quantity are in the range of 70 – 100 $m^3 s^{-1}$, whereas high flows that help maintain habitat quality are in the range of 300 – 600 $m^3 s^{-1}$ (i.e., 3 – 6 times the low flows). Flood flows that can alter channel morphology and transport bed sediments are greater than about 1000 $m^3 s^{-1}$ (i.e., more than about 10 times the low flows).

The importance of low/minimum flows in determining habitat quantity is fairly clear, as are the effects on channel structure of large flood flows. However, through extensive laboratory and field experimental studies we have now begun to understand the link between habitat quality and ecosystem productivity/health of New Zealand rivers, and how these are driven by the magnitude, frequency and duration of small floods/flushing flows (e.g. Scarsbrook, Townsend 1993; Biggs, Thomsen 1995; Clausen, Biggs 1997, 1998; McIntosh 2000; Biggs *et al.* 2005; Jowett *et al.* 2005; Francoeur, Biggs (2006); Jowett, Biggs (2006).

Geographic distribution of different flow regimes in New Zealand

To help utilize the concepts illustrated above in water resources management, we need to define what the natural flow regimes are for most rivers in New Zealand. As it is impractical to field survey every reach of every river, an alternative approach was required. The approach adopted uses the New Zealand River Environment Classification (Snelder, Biggs 2002; Snelder *et al.* 2005). The River Environment Classification (REC) organises information about the physical characteristics of New Zealand's rivers (for example, their climate, the source of flow for the river water, the geology of the catchment and catchment land cover, e.g., forest, pasture, urban) and maps this information by river segment for New Zealand's entire river network which has more than 500,000 km of streams and rivers. The REC system groups rivers into classes at a variety of levels of detail and scales. Rivers with the same class have similar physical environments and areas expected to have similar ecosystems, similar environmental values, and similar responses to human disturbance, despite the possibility that they are geographically separated. (For more information on the REC see: *http://www.maf.govt.nz/mafnet/publications/rmupdate/rm14/rm14-04.htm*).

Figure 3 shows broad geographic distributions of three main types of natural flow regime over the period 1995 – 2000 in the South Island using the REC. The variations between river segments occur as a result of the interaction between altitude and interception of predominant weather patterns and associated precipitation. Three flow regimes are depicted (after Biggs *et al.* 2005):

Mountain source of flow – characterised by a relatively high minimum flow (about 100 $m^3 s^{-1}$ for this example from the Rakaia River), with very frequent high flows of 3 to 6 times the low flow. Large amounts of gravel derived from the upstream glaciers are usually transported during these higher flows. Low flows typically occur in winter and seldom last for more than 6 weeks. There were no large floods during this period, but channel forming flows greater than 1000 $m^3 s^{-1}$ occur. Overall, these rivers provide 'harsh' conditions for riverine communities with periphyton being dominated by low-growing diatoms, and invertebrates being dominated by rapidly colonising insects (e.g., mayflies). Native fish compete relatively well with introduced fish in such environments.

Hill source of flow – characterised by relatively low minimum flows (about 0.2 $m^3 s^{-1}$ for this example from the Waipara River) compared with the high flows, with moderately frequent high flows of greater than about 6 times the low flow. Low flows typically occur during late summer/autumn and can last for 12 to 16 weeks, with high flows in late winter. Flood flows can have a very high magnitude (about 3000 times the lowest flows) and 're-set' the river bed ecosystem back to almost a 'zero state'. These rivers are prone to filamentous periphyton blooms during periods of low flow. Periphyton usually re-colonise rapidly after high flow events and may bloom 6 to 8 weeks after a flood. Often there are insufficient invertebrates to impart significant ‘grazing’ losses, and invertebrates change from insect domination to worms and midges during the late summer low flows (e.g., Suren *et al.* 2003). Low flows can severely restrict or reduce fish communities. Native fish appear better adapted to survive such conditions than introduced salmonids (Jowett *et al.* 2005). Overall, the environment in these rivers for riverine communities is intermediate between ‘harsh’ and ‘benign’.

Low elevation/spring source of flow – characterised by relatively high minimum flows (about 1.8 $m^3 s^{-1}$ in this example from the Avon River), with a moderate frequency of low intensity high flow events (greater than about 1.5 times the low flows). The lack of relatively high magnitude flood events results in very long periods of stable velocities and stable bed sediments, which often allow slow-growing and long-lived plants (i.e., macrophytes) to grow. These change the whole nature of the river environment and associated invertebrate communities (dominated by snails, worms and midges). Also, rainbow trout are better adapted to these low flow variability habitats (this also includes lake outflow rivers) than brown trout, which tend to perform better in the hill source of flow rivers (Jowett 1990). Overall, the environment in lowland/spring source of flows is considered physically ‘benign’ for riverine communities.

3. The process of setting flow regimes in New Zealand and application of scientific methods

Meeting the purpose of New Zealand’s Resource Management Act (RMA) requires the setting of flow regimes that will protect riverine values, whilst allowing for development of part of the water resource for out-of-river uses. The underlying principle is that not all elements of the ecosystem require all elements of the flow regime.

The challenge is to determine the degree of change in flow that could occur before riverine communities and associated values change to levels that dissatisfy stakeholder interests (i.e., ‘sustainability’ under the RMA).

The process is critically dependent at the outset on defining environmental and social objectives. If the objective is to maintain all elements of all riverine values at their current levels without any change, then there can be no change in the flow regime. This is easy.

What is much more difficult is to define a flow regime that changes flows significantly to allow some out-of-river water use, but that continues to maintain riverine values. For this, the total flow regime must be considered. Most abstractions only affect minimum flows and have negligible effects on variability and flood flows unless there are large upstream storage dams.

The National Institute of Water and Atmospheric Research (NIWA) has worked extensively with the New Zealand Ministry for the Environment (MfE) and a range of stakehold-

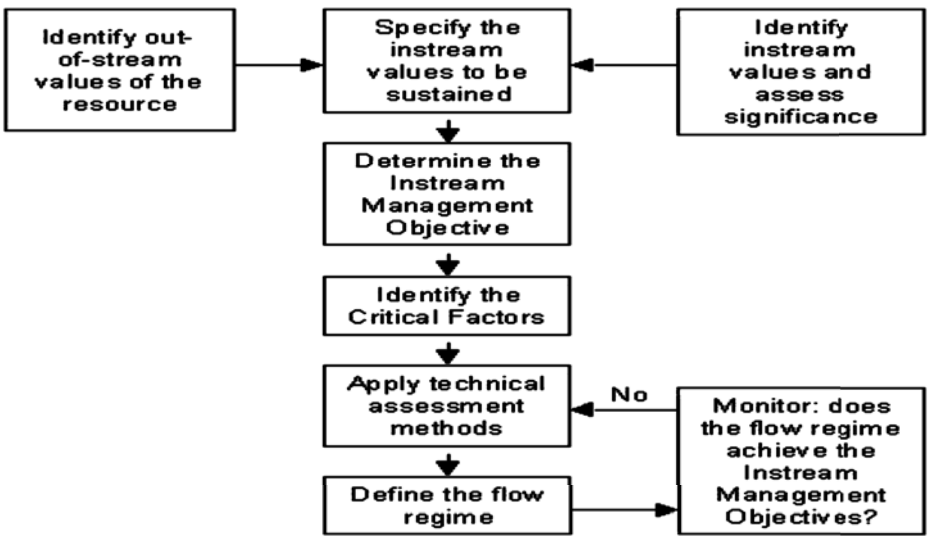

Fig. 4. The key processes required for setting flow regimes (from MfE 1998). (“Instream” is equivalent to the term “in-river” used in the text.)

ers to write the technical methods of the MfE Flow Guidelines (MfE 1998). These methods encompass a 'values-based' assessment system that are driven by societal expectations for water ways, with scientific methods being used to 'design' the flow regime necessary to fulfil those expectations.

The essential steps of this New Zealand methodology for setting flow regimes are (Fig. 4):

Simultaneously define 'out-of-river values' of the resource and 'in-river values' and their significance, taking into account the following broad areas of values:
- ecological/intrinsic
- landscape
- amenity
- cultural

Determine in-river management objectives (i.e., what does society want to protect in the river?). In this step there is also a need to consider the 'level of protection' of the values (i.e., to what extent do the values need to be protected, such as 60% or 90% of that occurring under natural flows/conditions. In some situations the flow based habitat can be enhanced so that values can be enjoyed at a level more than would occur naturally – e.g., 120% of natural: see Jowett, Biggs (2006).)

Identify the critical factors needed to sustain the selected values.

Apply technical assessment methods to determine the flow regime needed to provide the necessary habitat. These methods must be underpinned by a knowledge of:
- hydrology
- hydraulics
- in-river biota

The technical assessment methods for a particular circumstance need to reflect the nature of the question, the value of the resource, how close to some critical threshold the flow might move to, etcetera. They must consider:
- Standards and guidelines (for water quality)
- Physical habitat availability (for biota and non-biological uses)
- Focus on key values
- Link to the whole 'in-river community'
- Identify 'bottlenecks'
- Include the magnitude of low flows, and the timing, duration and frequency of high flows (i.e., the total flow regime).

Small decisions (relatively small water requirement with likely small effects) can use simple methods that are cheap to employ. Major decisions require in-depth, quantitative assessments involving one and two-dimensional hydraulic modelling for habitat simulations, as well as population modelling of riverine biota (if possible). Many of the predictions can only be semi-quantitative, or even qualitative, so it is important to know the structure and general temporal variability of the key riverine organisms (i.e., there is a need to have well informed projections based on a thorough knowledge of what is growing in the river in question).

It is most important to consider low/minimum flow habitat, then flow variability, then water quality for different aspects comprising the key values (e.g., spawn + rearing + adult resting + feeding habitat for trout fish). Often populations are limited by specific 'bottlenecks' (e.g., passage from the sea through lagoon bars for diadromous fish; Jowett *et al.* 2005). Such bottlenecks need to be identified and resolved in the analysis.

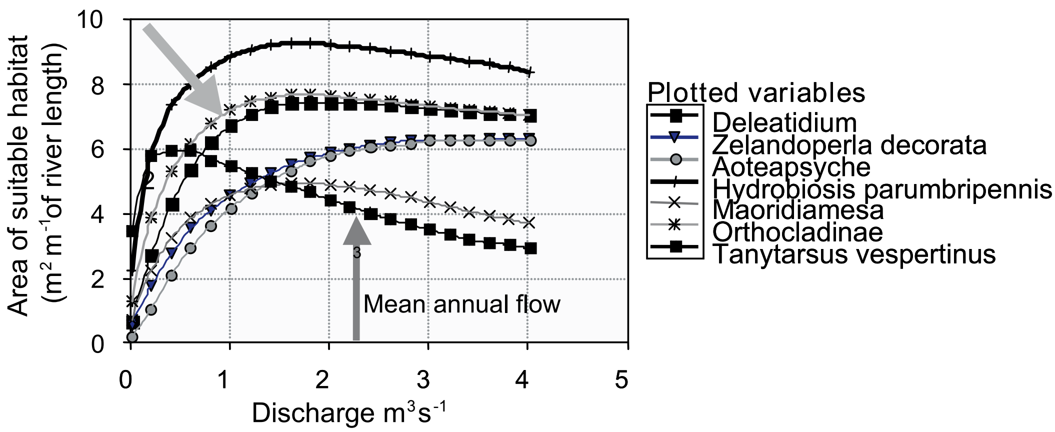

Fig. 5. Variation of habitat suitable for benthic invertebrates with flow (Moawhango River) (from Jowett, Biggs 2000). Note that in this example, the point of 'diminishing returns' for many of the species is less than the mean annual low flow, suggesting that the natural low flows in this particular river are greater than optimum for a productive benthic invertebrate community. This is not uncommon in moderate to large rivers. By using curves such as those shown in this diagram, time series of habitat suitability can be generated so that variations in available habitat can be tracked through the year as a function of temporal changes in flow regime. See text for a discussion of the arrows.

Minimum flow determination: rules-of-thumb

There are many situations where comprehensive scientific assessments to closely link the requirements of river management objectives to a flow regime are not required or possible. In such situations two approaches are often used in New Zealand (in combination) to regulate abstractions and help protect riverine values:

1) A 'standard' minimum flow, which is usually some proportion of the median flow or mean annual 7-day low flow (MALF). This is often a useful 'surrogate' measure of the flow that sets the upper limit on viable living space. However, using this is not the best approach for many circumstances. In particular, while this approach usually gives some adequate habitat in small to medium sized rivers, it may not create the best conditions for the given values in larger rivers, (e.g., see Fig. 5). For large rivers best conditions for key values can be at flows well below the median or MALF (e.g., 3% of median flow in the Waiau River, in southern New Zealand has created an excellent trout fishery; Jowett, Biggs (2006)).
2) Flow sharing between abstractions and riverine needs is useful where the minimum is well below the optimum flow for a target value as it gives an added measure of protection for values in such situations. The ratio between what is abstracted versus what is left in the river has no specific basis in science (similarly the flow threshold below which flow sharing commences). There are no set formulas for these numbers. The theory is that flow sharing enables a greater level of protection for riverine values if the minimum flow is poorly defined. In practice, if flow sharing is adopted, a much lower minimum flow can be set as this method gives a large degree of precaution. Flow sharing is also viewed as a mechanism by which some flow variability can be retained as flows approach the minimum, but in reality variability at such levels is likely to be ecologically trivial. Flow sharing is designed to be used on unregulated rivers where there is little flow control and little knowledge of flows required to maintain riverine values. In particular, it is useful where minimum flows are well below the optimum for key values. Before applying flow sharing, it is important to think carefully about the purpose it is being used for.

Minimum flow determination – quantitative methods

When major decisions are to be made, and where simple methods are inappropriate, habitat simulation is one of the useful tools (as is used in the Instream Flow Incremental Methodology; Bovee 1982). Figure 5 shows an example of using hydraulic habitat simulation to determine how habitat availability (the vertical axis) for some common New Zealand invertebrates changes as a function of flow in the Moawhango River, central North Island, New Zealand (from Jowett, Biggs 2000). The hydraulic habitat for some species such as the midge *Tanytarsus* peaks at low flows (i.e., they prefer lower velocities), whereas other species require higher velocities and associated higher flows (e.g., the stonefly *Zelandoperla*).

Such analyses are only one of the tools in our 'tool kit' for assessing flow regimes. They are most commonly used to define minimum flows based on what species are 'desirable' (often the mayfly *Deleatidium*). For the example shown, the dark (red) arrow in Figure 5 defines the minimum flow (1 $m^3 s^{-1}$) that might be recommended if only *Deleatidium* were to be considered. This flow might be recommended because:

That is the point at which an increase in habitat per unit of flow starts to decrease on the habitat suitability – flow curve (i.e., there is a sharply diminishing return in terms of habitat for any further increase in flow: - a 100% increase in the minimum flow would only result in a 10% increase in suitable habitat)

Flows in unregulated rivers are usually greater than a proposed regulated minimum for most of the time, and if the proposed minimum is set at the optimum for a target species/value, then the actual regulated flows may be beyond the optimum for most of the year and will not result in the best conditions for the target species/value.

Flow variability determination – quantitative methods

The degree and timing of flow variability to maintain riverine values is usually not well known. However, a long period (e.g., 2 to 3 months) of a constant minimum flow in summer will often reduce invertebrate production and diversity, particularly in enriched rivers (e.g., Suren *et al.* 2003). As discussed earlier, a wise goal to assist with maintaining habitat quality is to prevent excessive build up of periphyton and silt that long periods of constant flow encourage.

To investigate the implications of flow variability we have used detailed 1-dimensional or 2-dimensional hydraulic modelling, together with laboratory and field experiments to define the velocities required to remove periphyton and silt from river beds. Where fish spawn in the bed of a river the penetration of the flushing flows into the gravels needs to be carefully set to help, but not damage, the fishery.

Fig. 6. The Moawhango River before an experimental flushing flow (from Jowett, Biggs 2006). Copyright: Journal of River Basin Management.

4. Case studies

Parts, or all, of the technical assessment methods have been used in New Zealand for the last 25 years and New Zealand has an international reputation for some of the best and most successful ‘holistic’ assessments in the world (e.g., Jowett, Biggs 2006).

The first example is that of the Moawhango River in the central North Island of New Zealand where ecosystems values, including a trout fishery, were recreated after 25 years of degraded conditions below the Moawhango dam (see Jowett, Biggs 2000 for the full analysis). The changes were brought about by a small increase in the minimum flow (16%), supplemented with flushing flows. Figure 6 shows the condition of the Moawhango River after about 8 months of constant flow. Note the blurred outline of stones beneath the water surface caused by a build up of silt in all the lower velocity areas of the channel, and the associated heavy accumulations of peri-

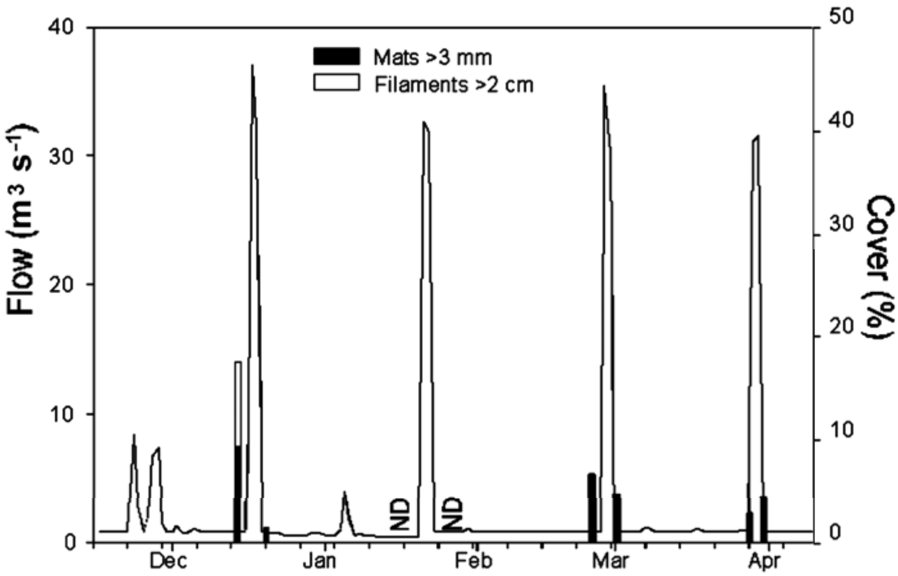

Fig. 7. The flushing flow regime designed for the Moawhango River and its effect on periphyton 1 km below the regulating dam (from Kelly, Biggs 2005). ND = not detectable.

Fig. 8. The Moawhango River after an experimental flushing flow (from Jowett, Biggs 2006). Copyright: Journal of River Basin Management.

phyton, the even more blurred areas. We used numerical hydraulic simulations, and information from laboratory studies on the shear stress required to dislodge and remove excess periphyton growth, to design a flushing flow regime for the river. The flushing flow regime implemented, and its effects on periphyton cover, is shown in Figure 7.

Figure 8 shows visually the result of the new flow regime. After the first flushing event the silt and periphyton had been largely removed, as indicated by the much clearer outlines of stones beneath the water surface. The flushing flow used was about 17 times the baseflow and it was designed to disturb the gravels to a depth of more than 10 cm so as to rejuvenate the surface and sub-surface habitat to allow for spawning by trout (an introduced fish species). The flushes have been designed to last for 9 hours each (to allow

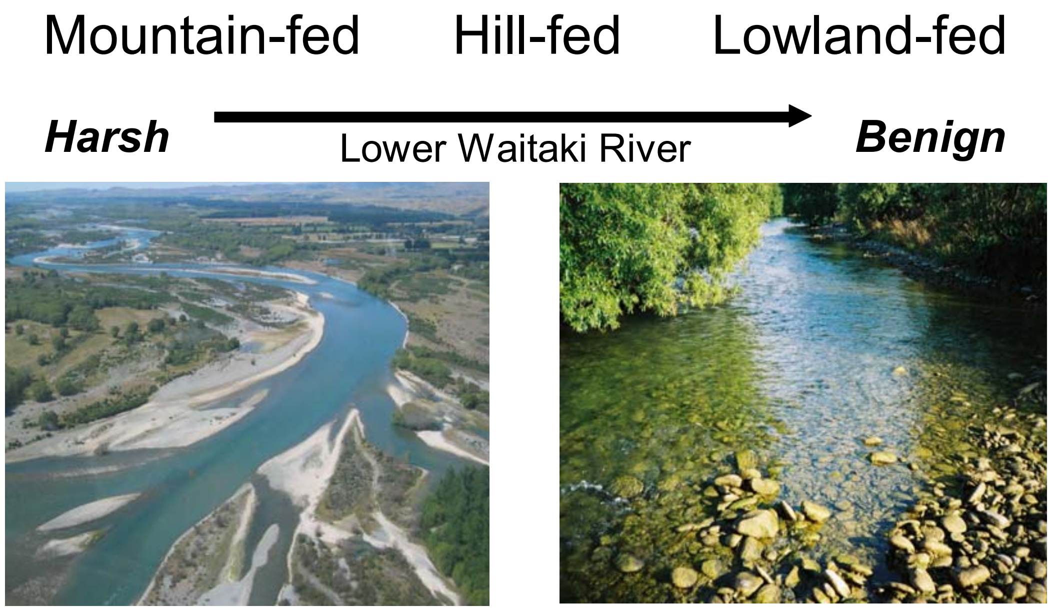

Fig. 9. The ‘harshness’ gradient for the Waitaki River. A large proportion of the river is currently braided with mobile gravels. However, the number of braids has been reduced by 50% over the last 70 years because of riparian willow invasion (right picture) and this is creating an ecologically more benign environment for riverine communities. This trend is predicted to accelerate under a proposed new water plan.

for full transport of the suspended material out of the system) and are repeated 4 times over the summer (about 6 weeks apart). These flushing flows, together with the small increase in the minimum flow, have resulted in an enormous improvement in ecosystem health (increased benthic invertebrate diversity), removal of foul odours in summer, and the creation of an excellent rainbow trout fishery where one did not previously exist.

The second example arises from a recent Waitaki Water Allocation Board hearing to decide on how best to allocate the water in the Waitaki River, a large gravel bed river in the South Island of New Zealand with very high values for trout and salmon fishing (see http://www.mfe.govt.nz/publications/water/waitaki-regional-plan-jul06/). Key questions included: what is the current state of the Waitaki River (i.e., flow regime and associated instream communities) and what should the flow regime be to protect instream values such as salmon fishing, trout rearing, jet boating and eel harvest? The river downstream of the Waitaki hydro-power dam presents a special case as it currently spans a range of conditions, and is migrating progressively toward becoming a more benign habitat for instream biota through the effect of willow migration onto the floodplain (which is removing braids and channelising the flow), exacerbated by low bed sediment supply as a result of upstream reservoirs. Overall, a physically 'harsh' flow regime, and associated productive/healthy ecosystem, still predominates, but there are extensive areas of quite benign habitat in side braids of the channel and in backwaters (Fig. 9), and the extent of these areas is increasing (Hicks *et al.* 2003).

As the Lower Waitaki River is such a large, braided, river, see Fig. 9, with a diversity of physical habitats, setting a suitable flow regime to maintain present riverine values was not simple, and required the application of a full complement of quantitative methods and mitigation (e.g. Jowett 2003; Hicks *et al.* 2003). Simply maintaining the current flow regime will not in fact maintain all in-river values without change because of the current trend towards a more stable, less braided channel. This makes the identification of environmental and social objectives all the more critical, and necessitates a truly holistic approach to flow regime setting and river management in order to achieve the identified objectives.

To initiate discussion a draft proposal for the future river regime in the Lower Waitaki River was prepared by the Waitaki River Water Allocation Board. This was completed without reference to scientific methodologies (the regime was drafted through a political process). A major point of concern for this draft regime was that it would result in a near constant minimum flow in many summers that would have further degraded the habitat and could have reduced the life-supporting capacity of the river (river ecosystems require flow variability to stay healthy; Biggs *et al.* 1990; Poff *et al.* 1997; Biggs *et al.* 2001; Biggs *et al.* 2005) and these effects would have been difficult to mitigate (e.g., flushing flows of 3 to 6 times the minimum flow would be required = 1000 $m^3\ s^{-1}$ which cannot be generated artificially through the upstream hydro dam). Thus, there would have been a tendency under the proposed regime for the river to become more physically benign (Fig. 9). Consequently mats of unsightly periphyton 'slime' may have become a feature of the Lower Waitaki and benthic invertebrate communities were predicted to shift from healthy mayfly/caddisfly dominated communities to snail/midge/worm dominated communities.

Scientifically based technical assessment methods were used to recommend a different flow regime to that arrived at by the Water Allocation Board. The proposed regime consisted of seasonally varying minimum flows (120-150 $m^3\ s^{-1}$) and flow variability (e.g., four flushing flows lasting for at least one day each) during summer to sustain riverine values. Further mitigation by better management of riparian vegetation was also recommended as being required (I.G. Jowett and D.M. Hicks, Statements of Evidence to the Waitaki Water Allocation Tribunal). The final regime determined by the Water Allocation Board was close to the above recommendations.

5. Discussion

The current 'state of the art' for setting flow regimes in New Zealand rivers goes well beyond just setting a minimum flow. It involves developing overall 'regimes' with ranges in minimum flows to meet seasonal life-history requirements of critical species and short term higher magnitude variability to maintain habitat quality. The methodology provides scientifically defensible reasons for adding a flow variability component to regulated flow regimes to simulate some of the important hydro-ecological processes. Two examples of the application of these methodologies have demonstrated how they can assist with maintaining riverine values and, thus, sustainable water management.

A key step in the New Zealand flow regime setting process is definition of the values that stakeholders want retained in a waterway, and to what level. Definition of this requires comprehensive community consultation and resource planning. The consultation is usually sponsored by the applicant for water use, whereas the resource planning is carried out by the Regional Council (a statutory regional body established to implement the RMA at regional and watershed scales). Once the competing demands have been established, then a range of scientific methodologies may be nominated for use by the development agency and/or Regional Council to quantify impacts, input to development of design specifications, and design mitigation where negative impacts cannot be avoided.

Where low impacts of a proposed development are expected, then simple methods can be used to help identify the most appropriate residual flow regime. However, where large impacts are expected then a 'basket of quantitative methods' is usually required. These more complex methods require several key capabilities: 1) good information and modelling capability to define how reach hydraulics might change with a change in flow; 2) good historical hydrological information to identify the magnitude, frequency and duration of naturally occurring high and low flow events; 3) knowledge of, and ability to model, the sediment transport regime; 4) hydraulic habitat requirements of the different life-history stages of the key biota; and 5) food and habitat quality (including water quality) requirements of the key biota. These capabilities require extensive regional understandings of ecosystems, but given the value of water to society it should be possible in most developed countries to justify such investment in data collection thereby allowing more rational decisions.

Future research needs to focus on: 1. required duration and frequency of flushing flows and channel maintenance flows, 2. the effect of duration of low flows on fish, invertebrates and periphyton. Better knowledge in these areas will also help answer questions regarding the effect of flow regimes on invertebrate production (e.g., how low should the flow be for how long? How high should the flushing flows be without totally destroying the ecosystem?, What is the best balance of low and high flows?). We believe that studies that compare ecological, hydrological, and hydraulic data over a range of geographic and climatic scales, such as described here, are necessary to provide the understanding of the physical processes and their relationships to aquatic biota for predicting the effects of flow changes. The selection of an appropriate flow regime for a river requires clear goals and targeted objectives, with levels of protection set according to the relative values of the in- and out-of-stream resources and community aspirations. The challenge 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. This requires an interdisciplinary approach that is in the best interests of both river conservation and sustainable water resources use.

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