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Setting Flows in Spring-fed Streams: Issues and Recommendations




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EXECUTIVE SUMMARY

This report examines the shortcomings of traditional methods for assessing flow requirements and setting minimum flows in spring-fed streams, and reviews alternative methods suggested in international scientific literature. It provides:

1. A review of the features that differentiate spring-fed streams from run-off streams,
2. An outline of how regional councils in New Zealand have managed flow in spring-fed streams,
3. A review of scientific literature addressing in-stream flow assessment and minimum flow setting in spring-fed streams, and
4. Recommendations for alternative flow setting methods and further study.

Traditional minimum flow assessment methods employed in New Zealand are based on hydraulic habitat and channel geometry (*e.g.* RHYHABSIM; WAIORA), and can be difficult to apply in spring-fed streams for several reasons. First, the stable flow regime may restrict calibration measurements to a relatively narrow range and hence reduce the scope for extrapolation, increasing potential for error. Second, high biomass of macrophytes, a common feature of spring-fed streams, can influence water level thereby confounding development of cross-section rating curves. The strong influence of macrophytes on water quality, especially diurnal dissolved oxygen (DO) cycles, may also result in flow related oxygen concentration sags supplanting flow related physical habitat as a critical factor affecting key ecosystem values. Applying currently available DO models to spring-fed streams is problematic because they do not account for the influence of groundwater, which is potentially low in DO.

Several minimum flow assessment methods have been applied in New Zealand spring-fed streams, the most common being hydraulic habitat modelling and expert panel. At least five regional councils have not yet experienced enough abstractive demand on spring-fed streams to warrant a minimum flow assessment, however there is potential for future increase. Most councils have not addressed spring-fed streams specifically in their regional plan, so by default they are likely to be assessed similarly to run-off streams. Given the difficulties of applying traditional hydraulic habitat models and the subjectivity of the expert panel approach, further research is needed to ascertain scientifically robust methodology.

To date there has been relatively little research to provide solutions to the challenges faced in assessing in-stream flow requirements of spring-fed streams and water allocation management. Future research efforts looking at an adapted habitat method (that takes into account seasonal macrophyte growth), complemented with a groundwater model and/or a refined DO model (that takes into account inflow from groundwater); look to be a useful approach.

Flow decisions should be science-based, but the effort put into the science ought to reflect the values of the in-stream resources. Flow management in groundwater dominated catchments is often complicated by a lag between groundwater abstraction and stream-flow depletion. There is an urgent need for reliable technical methods for in-stream flow assessment of spring-fed streams with high in-stream values and high abstraction demand. Research is required on physical habitat modelling and DO models to reduce the current uncertainty regarding the 'best' methods to apply to spring-fed

streams. In the meantime a conservative approach to minimum flow setting and water allocation management is warranted in high value spring-fed streams.

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1. INTRODUCTION

Environment Southland is currently exploring minimum flow and flow regime setting methods used in spring-fed streams, where traditional flow setting methods may not be appropriate.

Minimum flow and flow regime recommendations are frequently developed based on habitat modelling predictions, in an attempt to maintain habitat for valued fauna. Hydraulic habitat modelling using RHYHABSIM (River HYdraulics and HABitat SIMulation (Jowett 2004)) is probably the most widely applied approach in New Zealand rivers, particularly where there is a high degree of hydraulic alteration as well as high in-stream values. However, this approach requires water level versus discharge relationships to be developed for a series of cross-sections (Jowett *et al.* 2008), which can be problematic in spring-fed streams due to the influence of dense macrophyte beds and the relatively stable flow regimes on water level.

Generalised habitat models have been developed more recently as an alternative to hydraulic habitat modelling (as described by (Jowett & Hayes 2004)¹), requiring substantially reduced field effort and expense. However, while these generalised models have been found to perform reasonably well for streams with “average” channel shape (*i.e.* open U-shaped gravel bed streams), predictions using this method are likely to be inaccurate for statistical outliers in the channel shape distribution (Lamouroux & Souchon 2002). Outliers include extensively braided rivers and the relatively confined, deeply incised channels typical of many spring-fed streams.

Environment Southland recognised the potential shortcomings of these traditional methods when applied in spring-fed streams and found that other regional authorities faced the same issue. This led to the commissioning of the present report (under Envirolink Grant 905-ESRC234), to investigate other options.

This report provides:

1. A review of the features that differentiate spring-fed streams from run-off streams.
2. An outline of how regional councils in New Zealand have managed flow in spring-fed streams.
3. A review of scientific literature addressing in-stream flow assessment and minimum flow setting in spring-fed streams.
4. Recommendations for alternative flow setting methods and further study.

¹ Generalised models were developed by fitting a statistical response curve to predictions from a large number of hydraulic-habitat modelling applications in New Zealand.

2. FEATURES OF SPRING-FED STREAMS

Springs form where the water table intersects with the earth's surface, or where groundwater rises to the surface through fractures in the underlying geology. Springs are formally defined as points of natural, concentrated discharge of groundwater at a rate high enough to maintain flow on the surface (Van Everdingen 1991; Death *et al.* 2004)². They may have perennial or intermittent flow permanence, and can vary widely in size. Depending on the distance downstream from the source, spring-fed streams tend to differ from runoff-dominated streams in a number of ways.

Classic physical features of spring-fed streams that differentiate them from run-off streams include: a highly uniform annual temperature regime and, depending on the climate and underlying geology, a relatively constant flow regime (Death *et al.* 2004; Reiser *et al.* 2004). Spring-fed streams usually have small catchments and flow inputs are moderated by groundwater passage times, so they do not tend to experience floods that shape and maintain run-off river channels. As a result, spring-fed streams are often deeply incised, have relatively uniform rectangular channel form, and few bars (Arend 1999; Gordon *et al.* 2004; Griffiths *et al.* 2008). The stable flow regime cannot wash fallen vegetation downstream, so logs and branches usually remain in place and provide habitat that may otherwise not be present in run-off-fed streams (Reiser *et al.* 2004).

It is difficult to generalise about the nutrient status of spring-fed streams (close to the source) and it would be wise to look at them in a case by case manner. However, Reiser *et al.* (2004) state they are often low in nutrients, and other studies note that nutrient status is influenced by the underlying geology and type of aquifer that feeds the spring (Biggs & Close 1989; Biggs & Kilroy 2004). For example, streams fed via a spring from a shallow unconfined aquifer in an agricultural area would likely have quite a different chemical signature from those fed via a spring from a deep confined aquifer. Spring-fed systems in agricultural areas can have high nutrient levels, particularly nitrate, given its propensity to leach from soils. Also, springs in areas with volcanic geology may be enriched with phosphorus (Reiser *et al.* 2004). Spring water can be highly saturated with CO₂ and low in dissolved O₂ (DO) at the source, but these conditions will change with time and distance downstream.

The physical characteristics described above provide habitat that is unique to springs and spring-fed streams. As a result, some springs provide semi-insular habitats that maintain isolated and unique fauna (Death *et al.* 2004; Scarsbrook *et al.* 2007). New Zealand has several species of invertebrate whose habitat may be solely confined to springs. Macroinvertebrate biodiversity and abundance in New Zealand springs (particularly perennial springs) can often be considerably higher than in run-off streams of similar size (Death 1995; Smith & Wood 2002; Death *et al.* 2004; Reiser *et al.* 2004; Wood *et al.* 2005; Scarsbrook *et al.* 2007). The relatively steady flow and temperature of spring-fed streams creates favourable

² For the purposes of this report, a 'spring-fed stream' refers to either cold-water springs or areas downstream of a geothermal spring where the mean temperature is less than 20°C.

conditions for spawning salmonids (Reiser *et al.* 2004). Due to their comparatively stable flows and water temperatures, spring-fed streams can also provide refuge from adjoining run-off streams during times of flood and extreme temperatures for a range of fish and invertebrate species.

Perhaps the most important feature of spring-fed streams, with regard to minimum flow setting, is the influence that aquatic macrophytes have on water depth and velocity. This has consequences for flow related habitat availability and for estimating rating curves for flow monitoring and hydraulic habitat modelling.

The comparatively stable flow regime and lack of flushing flows often promotes the accrual of dense beds of macrophytes. Not all spring-fed streams are dominated by macrophytes, but those with little or no shade (from riparian vegetation cover) usually are (Golder Associates 2010). Furthermore, some exotic macrophytes that have spread through New Zealand waterways are now classified as “noxious plants” given their ability to block waterways and create flood hazard (Coffey & Clayton 1988).

Recent research in New Zealand has shown that seasonal blooms of macrophytes can cause substantial changes in the hydraulics of spring-fed streams. For example, (Wilcock *et al.* 1999) found that, on average, water velocities decreased by 30% and depth increased by 40% due to high summer macrophyte growth in a New Zealand spring-fed stream (79% channel cover in summer *c.f.* 7% cover in winter), resulting in similar water levels despite a seven-fold decrease in discharge between seasons. A similar study at the same site found that summer velocities were reduced by 41% (Champion & Tanner 2000), and described submerged macrophyte beds as “semi-permeable dams” that increase stream depth and cross sectional area.

Macrophytes also consume oxygen from aquatic ecosystems at night and block the transfer of oxygen from the air to the water at depth (*i.e.* by reducing vertical mixing), which may result in low DO concentrations and consequent mortality of fish and invertebrates (Dean & Richardson 1999). This is especially relevant to spring-fed streams which may already be low in DO due to groundwater inflow.

3. CURRENT APPROACHES IN NEW ZEALAND

In this section we review the methods that have been recommended and/or used by New Zealand regional authorities for setting minimum flows. Where possible, the distinction is made between spring-fed streams and other stream types. Overviews of methods and recommendations on where they ought to be applied were presented by Beca (2007) and MFE (1998) and are not repeated here, although a table summarising some of the available methods and the pros and cons associated with them is attached as Appendix 1.

Young and Hay (2006) provided a brief review of the approaches used by a selection of regional councils for setting minimum flow in rivers in their jurisdictions. This review was not specific to spring-fed streams but rather an overview of methods and some aspects may have changed since it was published.

For the present report, regional councils were asked what flow setting methods have been used for spring-fed streams in their region; responses are summarised in Table 1. It should be noted that these are specific examples, and do not imply that this is the method used for all spring-fed streams.

Table 1. Methods used by various regional councils for assessing minimum flow in spring-fed streams.

Regional Council	Spring-fed stream	In-stream values	Level of abstraction	Method used
Environment Southland (pers. com. Steve Ledington) (Ledington 2008)	Meadow Burn	High <ul style="list-style-type: none"> • Brown trout fishery and spawning habitat • Native fish 	High	Expert panel (using minimum average velocity to derive minimum habitat)
Otago Regional Council (pers. com. Matt Dale) (Otago Regional Council 2010 draft)	Welcome Creek	High <ul style="list-style-type: none"> • Trout fishery and spawning habitat • Salmon spawning and juvenile habitat • Long-fin eels • Canterbury mudfish nearby (nationally endangered) 	High	Hydraulic-habitat modelling using RHYHABSIM
Environment Canterbury (pers. com. Andrew Parish) (Main 2001; Golder Associates 2009; 2010; 2010b)	<i>Waiau tributaries</i> Cold Stream Waiau East Stream	Medium/high <ul style="list-style-type: none"> • Salmonids - adult/juvenile habitat 	Not specified	Expert panel (based on ecological observation – no hydrological data available) using minimum average velocity to derive minimum habitat)
	<i>Lower Waimakariri tributaries Group A</i>	Medium/high <ul style="list-style-type: none"> • Salmonids spawning, juvenile and/or adult habitat 	Not specified	Hydraulic-habitat modelling using RHYHABSIM

	North Brook Cam River No. 7 Drain Ohoka Stream Courtney Stream Greigs Drain Kaputone Creek	<ul style="list-style-type: none"> • Longfin and short fin eel 		
	Lower Waimakariri tributaries Group B Middle Brook South Brook Kaiapoi River Styx River Otukaikino Creek	Medium/high <ul style="list-style-type: none"> • Salmonids spawning, juvenile and/or adult habitat • Longfin and short fin eel 	Not specified	<ul style="list-style-type: none"> • Expert panel • ‘General relationship’ habitat modelling (see text for details) using results from Group A
	Kaikoura spring-fed rivers Group A Middle Creek Lyell Creek/Waikawau	High <ul style="list-style-type: none"> • Trout fishery and spawning habitat • Native fish habitat • White baiting - Lyell Creek only 	Not specified	<ul style="list-style-type: none"> • Expert panel • Stakeholder involvement • Simplified 1D hydraulic-habitat modelling
	Kaikoura spring-fed rivers Group B Warrens Creek Ewelme Stream	Low <ul style="list-style-type: none"> • Trout and native fish habitat (both streams) • Trout spawning habitat (Warrens Creek only) 	Not specified	<ul style="list-style-type: none"> • Expert panel • Stakeholder involvement • Simplified 1D hydraulic-habitat modelling
Greater Wellington Regional Council (pers. com. Mike Thompson) (Watts 2008a; 2008b; Keenan 2009)	Papawai Stream	Medium <ul style="list-style-type: none"> • Historical significance, Recreation, • Brown trout • Long-fin eel • Giant kokopu (threatened) 	High	Expert panel (using 80% of MALF to provide habitat for longfin eel)
	Otukura Stream	Low to very low <ul style="list-style-type: none"> • Ecological value is low • Landscape and recreation value is very low 	High	WAIORA (used to predict critical flow to provide appropriate DO and temperature to increase ecological value)
Horizons Regional Council (pers. com. Jon Roygard)	“we have not specifically tackled this issue”	N/A	N/A	There are no examples of spring-fed streams being assessed for minimum flow
Marlborough District Council (Young & Hay 2006; Hay 2008)	No reply	N/A	N/A	Suggested method is WAIORA complemented with a groundwater/surface water model aimed at avoiding recession of spring heads (Young & Hay 2006). The use of the macrophyte habitat function within

				WAIORA was later deemed inappropriate by Ian Jowett (NIWA) (Hay 2008)
Environment Waikato (pers. com. Mark Hamer & Edward Brown)	Not specified	N/A	N/A	There are no examples of spring-fed streams being assessed for minimum flow
Hawkes Bay Regional Council (pers. com. Kolt Johnson)	Not specified	Not specified	Not specified	<ul style="list-style-type: none"> • Historical flow method (% of MALF) • Expert panel
Tasman District Council (pers. com. Trevor James)	“we don’t have a lot of abstractive pressure on spring-fed streams, so the issue has not been addressed”	N/A	N/A	There are no examples of spring-fed streams being assessed for minimum flow
West Coast Regional Council	No reply	No reply	No reply	No reply
Northland Regional Council (pers. com. Dale Hansen)	“...not aware of studies / analysis on this issue”	N/A	N/A	There are no examples of spring-fed streams being assessed for minimum flow
Auckland Regional Council	No reply	No reply	No reply	No reply
Environment BOP (pers. com. Janine Barber) (Bloxham 2005)	<i>Rotorua area spring-fed streams</i> Awakaponga Mangakakahi Miller Rd Stream Ngongotaha Utuhina Waingaehe Waipa Waiteti	High • Trout – spawning, juvenile & adult habitat	Not specified	Hydraulic-habitat modelling using RHYHABSIM
Gisborne District Council (pers. com. Dennis Crone)	“the only...spring-fed stream (in this region) has a very small take (4L/s)...there is no minimum flow management on this stream”	N/A	N/A	There are no examples of spring-fed streams being assessed for minimum flow
Taranaki Regional Council (pers. com. Chris Spurdle) (Jowett 1993; Taranaki Regional Council 2005)	Spring-fed streams not specifically addressed in freshwater plan Three catchments were identified as being spring-fed.	Not specified	Note specified	Regional generalised habitat model (2/3 habitat rule of thumb, which sustains 67% of adult brown trout habitat at the MALF (based on Jowett 1993)

3.1. Environment Southland

The Meadow Burn is the only spring-fed stream in Southland that has been assessed for minimum flow. It has a high fishery value (salmonids and Gollum galaxias) and a high degree of hydraulic alteration due to abstraction. The assessment began in response to marked stream depletion effects due to groundwater abstraction (Steve Ledington, pers. com.). A simple hydraulic method was applied, based on expert advice from Ian Jowett (private consultant – formerly with NIWA). Jowett made the suggestion that maintaining a minimum average velocity of 0.2 to 0.3 m/s would act to ensure that flows will be at levels where adequate habitat for large adult brown trout would be retained (Ledington 2008). He based this advice on his experience that 0.2 – 0.3 m/s is sufficient velocity to prevent deposition of fine sediment, as well as being the preferred velocity range for a number of native fish species and juvenile trout (Jowett pers.com). He also pointed out that an average of 0.2-0.3 m/s means that there should be areas of higher, as well as lower, velocities thus encompassing habitat requirements of most species, and is probably adequate (sighting his own field data) for adult trout in a spring-fed stream. Jowett noted that this was a generalisation and assumes that water depths are adequate, which they usually will be in a spring-fed stream.

Water velocities of 0.2-0.3 m/s are too low to sustain high aquatic invertebrate drift rates and drift feeding by trout, but benthic invertebrate densities are usually higher in spring creeks (Death 1995; Wood *et al.* 2005), so trout should be able to compensate by browsing invertebrates off macrophytes and the stream bed. Trout are frequently seen foraging in this manner in spring-fed streams (John Hayes, Cawthron Institute, pers. com.). A full assessment of minimum flow would require hydraulic habitat modelling, which would include a more detailed habitat analysis; a species list; and confirmation of habitat suitability criteria.

3.2. Otago Regional Council

The only minimum flow assessment that has been carried out on a spring-fed stream in Otago was on Welcome Creek in 2009-2010. Noted for its high in-stream values (salmonids, longfin eel and Canterbury mudfish) as well as a high degree of hydraulic alteration (abstraction for irrigation), Welcome Creek is different from many spring-fed streams in that the flow is heavily influenced by irrigation by-wash, where summer flows are artificially maintained above that which would occur naturally (Otago Regional Council 2010 draft). An in-stream habitat model (RHYHABSIM) was used to assess minimum flow for the stream. The report noted the likelihood of macrophyte growth significantly effecting fish and macroinvertebrate habitat, but did not mention if this was a problem when carrying out the habitat modelling.

3.3. Greater Wellington Regional Council

Two spring-fed streams in the Wellington region were identified as having been assessed for minimum flow. One is the Papawai Stream, which has high abstraction pressure and medium in-stream value status. Minimum flow requirements were assessed through an expert panel approach. Eighty per cent of the MALF was considered appropriate for maintaining habitat for the most valued species, longfin eel, as well as providing sufficient flow to avoid contributing to low DO levels in the stream (Keenan 2009).

The other is the Otukura Stream, which has low to very low in-stream value status and high abstraction pressure. WAIORA was used to predict the minimum flow necessary to provide a minimum DO percentage (no less than 80% - based on Schedule Three of the Resource Management Act 1991). No specific species were targeted as most valued; rather the method aimed to increase the ecological value of the stream as a whole. Given the potential issues of using WAIORA DO modelling in spring-fed streams (Hay 2008; Young & Doehring 2010), this application may be questionable.

3.4. Marlborough District Council

In 2006 Cawthron Institute was commissioned to produce a report recommending flow management regimes for small streams managed by Marlborough District Council. “Wairau Plain Spring-fed Streams” was one of five stream classes recognised in the report (Young & Hay 2006). Streams within this class were perceived to have highly significant in-stream values. Ephemeral sections are thought to undergo seasonal downstream migration of the upstream wetted front at a rate far beyond what would have occurred prior to land modification and drainage of the Wairau Plain (Young *et al.* 2002). The recommended approach for minimum flow assessment of spring-fed streams was to use a groundwater/surface water model to assess groundwater levels required to prevent recession of the spring heads; combined with a flow related water quality model (WAIORA) to predict flows required to maintain minimum DO concentration.

The recommendation to use WAIORA to model the effect of flow variation on DO concentration was based on previous studies on oxygen dynamics in some of the Wairau spring-fed streams and on studies on the tolerance of native fish to low DO concentration (Young & Hay 2006). This recommendation was later withdrawn by Cawthron, sighting several shortcomings with the DO modelling process within WAIORA. Ian Jowett (formerly of NIWA), who developed the model, recommended not using the macrophyte function for DO modelling until further testing has been carried out (Hay 2008). These problems have not yet been resolved (see section 4).

3.5. Environment Canterbury

Environment Canterbury has been reviewing minimum flows for various river types (including several that are spring-fed) as part of its Natural Resources Regional Plan. The approach it has taken includes a combination of expert and community advisory panels with technical input on the in-stream values and appropriate minimum flows for particular streams (Young & Hay 2006).

A report by Golder Associates (2010) for Environment Canterbury is one such technical input. It assessed the ecology of 17 tributary streams in the Waiau catchment, recommending minimum flows using a variety of methods. The report gave a detailed description of the ecology and values of each stream, but did not consider the level of abstraction pressure. All seven spring-fed stream minimum flow recommendations were made using an expert panel approach, probably in part due to a lack of hydrological data (in six out of the seven streams). Of the seven streams that are spring-fed, five have high summer flow due to the influence of irrigation seepage to groundwater from the Waiau Irrigation Scheme. Determining minimum flow in these streams was problematic (though arguably unnecessary) because low flows occur over winter, when demand for abstraction is low. The two spring-fed streams that are not influenced by irrigation, Cold Stream and Waiau East Stream, are listed and described in Table 1.

Lowland tributaries to the Waimakariri River in Canterbury have undergone two minimum flow assessments in the past ten years. The first was by Main (2001), in a report that aimed to assess the adequacy of minimum flows set in the then current regional plan. Minimum flows were determined with an expert panel approach, complemented with fish passage modelling for critical reaches (the shallowest section of river) (Main 2001; Golder Associates 2009). Main's recommendations were based on the minimum depths required for the upstream passage of adult salmonids. This was established as the critical in-stream value, requiring the greatest depth for passage. Diffusion of effluent was also considered in one case. The report did not differentiate between spring-fed and run-off streams, hence it was not directly relevant to our review.

The second report on minimum flow requirements for 14 lowland Waimakariri tributaries (Golder Associates 2009), assessed the effectiveness of the existing minimum flows (recommended by Main 2001) and made new recommendations using more comprehensive 1D hydraulic-habitat modelling (RHYHABSIM). Twelve of the fourteen lowland streams are spring-fed. Of these twelve, seven had sufficiently robust stage/flow relationships to enable physical habitat modelling using RHYHABSIM. These are listed in Table 1 as "Waimakariri tributaries Group A". In the remaining five spring-fed streams, changes in river flow were inconsistent with changes in water level. This was attributed to the influence of macrophyte growth and clearance of macrophytes upstream (Golder Associates 2009). Hence, habitat modelling was not possible at these sites, so "general relationships" between flow and habitat availability were derived by combining the data from all 14 sites into one RHYHABSIM model. These general relationships were then used for sites where modelling habitat above and below the survey flow was hampered by a poor stage/flow relationship. The report

concluded that the summertime clearance of macrophyte beds for flood protection results in a drop in water levels which “may worsen the effects of low flows,” depending on stream size and channel morphology.

Minimum flow requirements for seven streams in the Kaikoura area were recently assessed by Environment Canterbury and Golder Associates using an expert panel approach coupled with stakeholder input and simplified 1D habitat modelling. Four of these streams are spring-fed – namely Middle Creek, Lyell Creek/Waikawau, Warrens Creek, and Ewelme Stream. The report noted that the methods used were, in hindsight, somewhat “lacking in scientific rigor” given recommendations in the proposed National Environment Standard on Environmental Flows (NES) framework (Beca 2007 – see Appendix 1), which was published after the assessment took place (Golder Associates 2010b). For example, the report states, “water quality modelling (especially temperature and DO) and fish passage analysis...would have been desirable, particularly...for rivers such as Lyell Creek that have both high ecological value and a high degrees of hydrological alteration” (Golder Associates 2010b).

3.6. Taranaki Regional Council

Minimum flow requirements of spring fed rivers in the Taranaki region were assessed using a rule of thumb applied to a regional generalised habitat modelling approach, developed by Jowett (1993). The “2/3 habitat” rule of thumb results in the minimum flow sustaining 67% of adult brown trout habitat at the MALF (Taranaki Regional Council 2005). Spring-fed streams are not assessed any differently than run-off streams.

3.7. Hawkes Bay Regional Council

Similar to Taranaki Regional Council, Hawkes Bay has identified several spring-fed streams in the region and has assessed them in the same way as streams that are run-off fed – using either a percentage of the MALF or an expert panel approach.

3.8. Environment Bay of Plenty

Spring-fed streams are not specifically addressed in Environment Bay of Plenty’s Operative Regional Water & Land Plan. Streams that are under significant abstractive pressure and have significant in-stream value are assessed using hydraulic-habitat modelling using RHYHABSIM. A default minimum flow of 90% of MALF is set for all other streams. Spring-fed streams are assessed similarly to run-off streams.

3.9. Other regional councils

Several regional councils (Northland, Waikato, Horizons regional councils; Tasman and Gisborne district councils) indicated that they do not have abstractive pressure on spring-fed streams, so the challenge of assessing minimum flow requirements for them has not yet been addressed. Hence, no examples were forthcoming from these regions. Young and Hay (2006) gave a description of the approach to water allocation followed by Tasman District Council and Horizons Regional Council, among others.

No response was received from the Auckland and West Coast regional councils.

4. REVIEW OF INTERNATIONAL RESEARCH

4.1. Hydraulic-habitat methods

While the relationship between flow and in-stream habitat has been studied and modelled extensively in run-off streams, there has been very little research on appropriate flow setting methods specifically for spring-fed streams.

Our literature search revealed a total of ten relevant published papers (Appendix 2). However, most of these were merely examples of habitat modelling on spring-fed streams, while only three (Hearne *et al.* 1994; Elliott *et al.* 1999; Reiser *et al.* 2004) provided a critique of the appropriateness of using habitat methods for spring-fed streams. These studies all suggest potential adaptations of habitat modelling methods to make them more suitable for spring-fed streams.

The most commonly recognized shortcoming was the influence of aquatic macrophytes on habitat modelling predictions. As discussed in Section 2, it is well known that seasonal blooms of macrophytes are capable of substantially altering water depth and velocity. This is problematic when calibrating habitat models (*e.g.* RHYHABSIM), since depth/water level is influenced by the macrophyte biomass, rather than solely by flow (as these methods assume). In an experimental application of the habitat model PHABSIM, weighted usable area results were found to differ by up to 34% between seasons, due to the influence of aquatic macrophytes (Hearne *et al.* 1994). While this is problematic with respect to interpreting modelling results for flow management, it clearly illustrates that macrophytes can have a substantial influence on physical habitat. Consequently, in some cases it may be necessary to select transects that include macrophyte beds to provide results that are representative of prevailing conditions.

Both Hearne *et al.* (1994) and Elliot *et al.* (1999) agreed that the timing of the calibration fieldwork, with regard to seasonal macrophyte growth, is important. Hearne *et al.* (1994) recommended minimising extrapolation error by collecting calibration data at a time that

coincides with maximum macrophyte growth, but they thought that some of the calibration data may need to be discarded. Presumably they intended for outliers to be omitted from rating curve calibration. Elliot *et al.* (1999) sensibly suggested collecting data when macrophyte growth is at a level which is consistent with the period of interest – *i.e.* during the irrigation season. They further suggested that it may be possible to manage the density of macrophytes at a more consistent level by harvesting (cutting or spraying) weeds during the study, if the in-stream conditions produced represent the area of river being assessed and the usual management of the river. However, it is hard to imagine how this could be done in a consistent manner such that the macrophyte management itself did not artificially influence water level.

Alternatively, if macrophytes are harvested carefully so that sediments are not disturbed or targeted at a time of year when macrophyte abundance is minimal, flow requirements could be assessed solely on physical bed form hydraulic controls, which will return environmentally conservative minimum flows (assuming that depth will be greater when macrophytes grow, producing more wetted habitat. However, this assumes that depth rather than water quality or food is the key habitat variable). The cross sections could continue to be monitored over the macrophyte accrual period and rating curves revised. Habitat surveys could be repeated over the same period (say two more times – in the middle of the accrual period and at the end), and rating curves could be compared over this period to see whether a predictable pattern is evident. It may be possible to analyse rating curves and habitat survey data to see whether a correction factor could be applied to the survey data (based on rating curve changes). If this works then the method may be transferable to other streams, or else the recalibration process would need to be repeated for each stream.

Hearne *et al.* (1994) offered an algorithm intended to account for variations in macrophyte biomass when calibrating PHABSIM. This algorithm aimed to adapt the water surface profile (WSP) module of PHABSIM by varying roughness as a function of both biomass and discharge. It may be possible to incorporate a similar approach in RHYHABSIM, either within its WSP modelling option, or by allowing for bivariate rating curves predicting water level based on both flow and macrophyte biomass. In either case the calibration data requirements would be substantially higher than in the standard application, because calibration water level data would have to be gathered over a range of both flow and macrophyte biomass.

An increase in macrophyte biomass in spring-fed streams results in an increase in roughness, decrease in velocity and increase in depth (Wilcock *et al.* 1999; Naden *et al.* 2006). Champion and Tanner (2000), citing several papers, gave a range of Mannings n coefficient values (a measure of roughness) for low and high macrophyte biomass ($n = 0.02$ to 0.04 and $n = 0.25$ to 2.25 respectively). These coefficients could be used in a WSP model as described above, although they still represent a broad range roughness even within each biomass category. A positive linear relationship between biomass and n was shown in the shallower channels surveyed, but deeper channels showed poor correlation. This was thought to be attributable to velocity being controlled by downstream shallow zones rather than bed roughness (Champion

& Tanner 2000). This violates the assumptions of uniform flow required to calculate Mannings n , hence hydraulic modelling predictions based on WSP modelling may still be less reliable in the deeper sections of macrophyte dominated natural streams.

The relatively stable and predictable seasonal flow regime in spring-fed streams was recognised as a potential benefit for habitat modelling by Elliott *et al.* (1999), by facilitating the collection of hydraulic and habitat suitability data under specific flow conditions (*e.g.* high, medium or low discharges). Conversely, stable flow could be problematic for habitat modelling. Habitat modelling (PHABSIM) was developed on run-off streams, where seasonal flow regimes and flow recessions following storm events provide a relatively wide range of flows and water levels for calibration. This enables prediction of water level, depth, and velocity in the selected cross-sections, as well as the ability to extrapolate flow (and habitat) above and below the highest and lowest measured calibration flows. The ability to extrapolate flow and habitat availability in spring-fed streams will be limited because the range of measured calibration flows is relatively narrow (Reiser *et al.* 2004).

Reiser *et al.* (2004) suggested that a two dimensional (2-D) model would allow a greater range of extrapolation in spring-fed streams, because the changes in water level through most of the modelled reach are predicted based on computational fluid dynamics calculations, rather than empirical rating curves. However, bed roughness plays an important role in these calculations so the influence of seasonal macrophyte growth on bed roughness would need to be taken into account. Reiser *et al.* recognise this difficulty and go on to note that 2-D modelling would be no better than 1-D modelling at estimating velocities within the macrophyte clumps, where fish may often reside. Consequently, 2-D modelling certainly does not represent a “silver bullet” for the issues of habitat modelling in spring-fed systems dominated by macrophyte growth.

One issue concerning the influence of macrophytes on water level not addressed in the literature is that a given biomass and coverage of macrophytes may restrict water velocity differently, depending on the discharge (*i.e.* the roughness influence of macrophyte beds may be dependent on flow). When discharge is high, macrophytes are depressed by high water velocities. Whereas when discharge and water velocities are lower, the macrophytes tend to ‘stand up,’ effectively increasing bed roughness and potentially resulting in similar water levels for lower discharge. This phenomenon has been observed in spring-fed streams in Marlborough (see Appendix 3), where there is evidence to suggest that as flow increases between about 3000 and 5000 L/s there is a decrease in depth (as macrophytes are pushed down by the water flow). Further flow increase (of between 5000 and 7000 L/s), corresponds with an increase in depth, similar to that measured at a lower flow (Young *et al.* 2002). Further reduction in flow would ultimately lead to a reduction in water level, so the overall response of water level to flow would have a hump. This problem would presumably be more difficult to find a solution to than the issue of macrophyte beds growing during the period of survey and calibration data collection.

One possible solution to this would be to target habitat modelling at shallow, fast, riffle or fast run sections, where water velocity is adequate to limit macrophyte growth. Depths and velocities in these habitat types are more sensitive to flow change than in deeper, slower, habitat types (*e.g.* pools, and slow runs). Focusing habitat modelling on these habitat types ought to result in conservative minimum flow recommendations and would largely avoid the problems with macrophytes influencing water levels and velocity. However, these habitats are generally rare or absent in spring-fed streams, and such assessments would only be relevant to species that use/prefer these habitat types. Hydraulic models developed for these fast, shallow habitats could also be used to assess adequate flows to maintain fish passage.

Another potential issue with applying habitat modelling to spring-fed streams is the transferability of habitat suitability criteria (HSC) developed in run-off streams. This does not appear to have been discussed in the literature relating to spring-fed streams. However, HSC transferability has long been recognised as an important consideration in the broader habitat modelling literature (*e.g.* Thomas & Bovee 1993). It has often been recommended that habitat use or preference data should be river specific. Development of HSC can be prohibitively expensive and time consuming, so HSC are commonly transferred between streams. In doing so, it is assumed that HSC developed on streams with similar physical characteristics to the study river should be more applicable than HSC developed on physically different rivers. However, organisms may exhibit different behaviours in the relatively stable habitats provided by spring-fed streams, particularly in those where macrophytes dominate. For example, trout may supplement drift foraging by browsing invertebrates from macrophytes or the stream bed. Consequently, habitat suitability criteria developed based on observations in run-off rivers in the absence of macrophytes may not truly reflect habitat use or preference in spring-fed streams. If in-stream habitat modelling is to be used to inform on minimum flow for spring-fed streams, it may be necessary to develop new HSC curves for spring-fed/macrophyte dominated streams.

Generalised habitat models³ have recently been developed to provide a simplified, lower cost, estimate of the relationship between habitat and flow (Jowett & Hayes 2004; Lamouroux & Jowett 2005). Unfortunately, these are unsuitable for most spring-fed streams (Beca 2008) because they assume a stream has a typical hydraulic geometry (mean depth-discharge and mean width-discharge relationships), within the range of the 99 stream reaches used to develop the generalised models (Lamouroux & Jowett 2005). This assumption does not hold for streams that are statistical outliers and this includes spring-fed streams which are typically deep and narrow.

³ Lamouroux & Jowett (2005) developed generalised habitat models by fitting a statistical response curve to predictions from a large number of full hydraulic habitat (RHYHABSIM) applications in New Zealand. They did this for a range of species and life stages commonly modelled in New Zealand applications. Generalised models simply require a width/discharge relationship which can be based on measurement of width at a single discharge and an assumption that the hydraulic geometry conforms to the typical relationship for New Zealand rivers described by Jowett (1998), or, preferably, measurement of the average width of the modelled reach at two or more known discharges to fit a width discharge relationship. The models provide HV (habitat value, equivalent to HSI in the full habitat models) and WUA versus flow response curves that can be interpreted in a similar way to conventional ones.

4.2. Alternatives to hydraulic habitat modelling

While there is little literature on the application of habitat methods to spring-fed streams, there appears to have been even less published on other approaches to minimum flow setting.

Spring-fed streams are arguably most limited by water quality, since there is generally adequate depth (because of the U shaped channel form) and there are typically abundant benthic invertebrates for fish to feed on. The abundance of aquatic plants in many spring-fed waterways, combined with the relatively low dissolved oxygen concentration of the groundwater entering these systems, means that reductions in flow can increase fluctuations in the concentration of DO, allowing potentially lethal diurnal DO sags to develop (Keenan 2009; Young & Doehring 2010). If these assumptions are true, then the effects of flow changes on water quality are likely to be more important in spring fed streams than any effects of flow changes on habitat availability. Therefore water quality modelling may be the best method for assessing minimum flows in spring-fed streams. The concentration of dissolved oxygen is a critical component of the life supporting capacity of a river system and, therefore, any effects of water abstraction on dissolved oxygen concentrations need to be considered in flow management decisions (Young & Doehring 2010).

Also, using a DO model by-passes the problems associated with habitat models, namely HSC transferability, the influence of macrophytes on stage – flow relationships, and the limited flow range for extrapolation.

Water quality modelling has occasionally been recommended in New Zealand as a method for setting flow requirements for small streams dominated by macrophytes where dissolved oxygen (DO) concentration is a potential limiting factor (Jowett & Hayes 2004; Young & Hay 2006; Young & Doehring 2010).

However, predicting relationships between DO concentration and flow in spring-fed systems is currently problematic because the available models do not account for large inputs of groundwater, which are prevalent in spring-fed streams, by definition (Hay 2008; Young & Doehring 2010). Further research is required to develop models that take account of this. Another consideration with setting minimum flows using dissolved oxygen is that some sites naturally exhibit DO concentrations that are lower than the recommended minimum guidelines (such as >80% saturation or >6mg/L) (ANZECC 1992; Young & Doehring 2010). These streams may have large inputs of low DO groundwater rather than excessive uptake of DO by stream biota, so organisms that are sensitive to low DO may be absent from these streams naturally. Young and Doehring (2010) give an excellent summary of the DO tolerances for various native and introduced fish.

A recommended initiative would be to conduct DO monitoring in spring-fed streams during summer low flow to see what natural DO concentrations currently exist and to see if DO is affected by flow variation due to abstraction. This data could be used for future minimum flow assessment when the models are able to account for groundwater input as discussed.

Using a simple hydraulic method may also be an applicable and cost effective method for assessing minimum flow in spring-fed streams. As outlined in Section 3.1, maintaining a minimum average velocity of 0.2 – 0.3 m/s should prevent deposition of fine sediment and provide adequate habitat for adult brown trout. This assumes that water depths are adequate, which they usually will be in a spring-fed stream. This method was used by Environment Canterbury for spring-fed tributaries of the Waiau River, as well as Southland Regional Council for the Meadow Burn. However, if the stream is DO limited, not habitat and food limited as may often be the case in spring-fed streams, then this method will not provide the best estimate of minimum flow. Also, ascribing an average velocity in a stream that is characterised by macrophytes that retard flow may not be entirely satisfactory, since there will be areas of practically nil flow among macrophyte beds and areas of concentrated high flow around them.

Both Elliot *et al.* (1999) and Petts *et al.* (1999) suggested that groundwater and/or groundwater-surface water models may need to be developed to effectively manage flows in spring-fed streams under high abstraction demand. These authors discussed stream depletion due to groundwater abstraction and the lag response of flow to groundwater abstraction. Whilst these issues may not be exclusive to spring-fed streams, the typically high permeability of groundwater dominated catchments and often large spatial separation between groundwater abstractions and the stream channel make the definition of impacted reaches more difficult (Elliott *et al.* 1999). The lag of stream-flow response can mean that stopping abstraction has no initial effect on flows. It is conceivable that flow may continue to decline after abstraction ceases, due to the lag response to previous abstraction. Recovery may take months, depending on the hydraulic properties of the underlying geology and aquifer (Petts *et al.* 1999).

Several authors have addressed the issue of lagged flow response to groundwater abstraction, suggesting that a simple minimum flow and abstraction cut-off model for managing water allocation is not suitable for groundwater dominated catchments (*e.g.* Petts *et al.* 1999; Boulton & Hancock 2006). This potential issue is more in the realm of flow management, rather than flow assessment, so is outside the scope of this report. Ultimately though, as stated by Petts *et al.* (1999, p 512), “*the key to successful management of groundwater dominated catchments is to be able to predict groundwater contributions to river flow*”.

Reiser *et al.* (2004) discussed the potential use of a water temperature model alongside a physical habitat model, suggesting they be given “equal priority” when assessing flow regimes for spring fed streams - particularly in situations when large flow reductions are anticipated. The potential impacts of abstraction on water temperature probably depend to some extent on the method of abstraction in addition to the magnitude of abstraction. Abstractions from groundwater may reduce the cooling effect of groundwater inputs to the in-stream flow; whereas water taken directly from the channel may have less impact (Olsen & Young 2008).

Alternatives for deriving minimum flows and/or flow regimes for spring-fed streams include historical flow methods, expert panels, and the demonstration flow method (Railsback & Kadvany 2008). However, each of these also comes with caveats. Those for the historical and

expert panel approach were discussed in Beca (2007) and are summarised in Appendix 1 of this report. The demonstration flow method (Railsback & Kadwany 2008) is essentially an extension of the expert panel approach, where the panel of experts view the study stream under a range of flows and decide which is appropriate for maintaining the values of interest. It has the same shortcomings as the standard expert panel approach aside from the difficulty in visualising how the stream's characteristics will change with flow. However, it can only be applied in situations where the full range of flow options can be readily attained and consequently it still lacks predictive power for flows outside the natural range (or range of manipulation, for regulated systems).

4.3. The need for further research

As alluded to above, there is a need for further research to provide effective predictive models to inform minimum flow setting in spring-fed streams (Boulton & Hancock 2006). *Reiser et al.* (2004) suggested several hypotheses on the possible ecological effects of hydrological changes in spring-fed streams through abstraction, with a particular focus on potential impacts on salmonids. These (and other) hypotheses, summarised in Table 2, provide possible direction for future study into flow-ecosystem relationships in spring-fed streams. The hypothetical effects on salmonids are largely negative.

Table 2. Hypotheses on the possible changes in habitat for salmonids given a reduction in flow due to abstraction in spring-fed streams.

(After - Reiser *et al.* (2004) with additions)

Hypothesis	Change in physical characteristics	Resulting change in habitat and ecosystem	Effect on Salmonids
Increased variation in flow may disturb the historically stable channel shape and substrate conditions, to become more similar to run-off dominated streams.	Changes to channel geometry and bed conditions with a higher proportion of finer sediments	Less salmonid spawning habitat	Negative
Shallower water may decrease the habitat provided by large woody debris and the channel cross sectional area over which macrophytes can grow.	Less water for aquatic species	Less habitat available	Negative
Shallower water may result in increased water temperature variation downstream from the source.	Greater seasonal, and steeper longitudinal, temperature variation	<ul style="list-style-type: none"> • Less habitat available • Species adapted to cold water may be especially sensitive in summer; the longitudinal extent of suitable habitat will contract • Poorer water quality 	Negative

Shallower water may result in increased oxygenation through diffusion where macrophytes beds have not dominated.	Increased mixing of dissolved gases through the water column	Better water quality	Positive
Lower water velocities may decrease water turbulence.	Reduced mixing of dissolved gases (<i>e.g.</i> DO) through the water column	Poorer water quality	Negative
Lower water velocities may increase water turbulence in the shallows.	Increased mixing of dissolved gases through the water column	Better water quality	Positive
Aquatic macrophytes that are suited to a stable flow regime may be less likely to thrive, resulting in lower productivity and biomass.	<ul style="list-style-type: none"> • Less substrate and food available for invertebrates • Less carbon sequestered 	<ul style="list-style-type: none"> • Fewer aquatic invertebrates • Less food available for fish 	Negative
Aquatic macrophytes that are suited to warmer water temperatures and lower velocities may result in higher productivity and biomass.	More food available for invertebrates	<ul style="list-style-type: none"> • More aquatic invertebrates • More food available for fish • More habitat available 	Positive
Substantially reduced flows could lower adjacent groundwater levels and change the composition of riparian plant communities. Drying riparian soils may oxidize and lead to bank instability.	Increased sediment loading on stream with a higher proportion of finer sediments	Less spawning habitat	Negative
Reduced flow could encourage filamentous algae to proliferate, especially if accompanied by increased nutrients from intensified farming.	<ul style="list-style-type: none"> • Reduced water velocities • Reduced water quality (greater pH and DO fluctuations) • Smothering of macrophytes and stream bed 	<ul style="list-style-type: none"> • Poorer water quality • Entrainment of invertebrates and small fishes (leading to death by suffocation, starvation or predation) • Increased mortality of aquatic invertebrates and fish due to diurnal pH and DO variation • Less large aquatic invertebrates • Less fish 	Negative
Reduced flow will reduce physical habitat and populations of some species.	Reduced wetted area and water velocities	<ul style="list-style-type: none"> • Less physical habitat for most aquatic invertebrates and fishes (since water velocities are rarely too high naturally for most species in spring-fed streams) 	Negative
Reduced flow will reduce stream power resulting in less invertebrate food for fishes.	<ul style="list-style-type: none"> • Reduced water velocities • Lower shear stresses • Increased siltation of the stream bed 	<ul style="list-style-type: none"> • Less benthic invertebrates, by number and diversity • Less salmonid spawning habitat • Reduced invertebrate drift • Less food for fish 	Negative
Multiple stressor environments resulting from reduced flow may increase susceptibility of invertebrates and fishes to	<ul style="list-style-type: none"> • Reduced water velocities • Increased siltation of the stream bed • Increased nutrients and contaminants (if flow 	<ul style="list-style-type: none"> • Multiple stressors include: <ul style="list-style-type: none"> –siltation –filamentous algal proliferation –increased diurnal variation in temperature, pH and DO 	Negative

disease.	changed accompanied by increased intensity of farming) • Increased diurnal variation in pH and DO	–reduced water quality –contaminants (<i>e.g.</i> , nitrate, agricultural chemicals ...) • Less invertebrates • Less fish • Reduced biodiversity	
Reduced flows may decrease the concentration of DO in the stream.	Larger diurnal fluctuations of DO	• Increased stress on fauna • Loss of less tolerant species • Less food available	Negative

Issues and ideas discussed in Sections 4.1 and 4.2 also highlight the need for further study. Further research into adaption of habitat methods to take macrophyte biomass into account, and developing specific habitat suitability criteria, would be beneficial, as would improvements to DO modelling to account for the influence of groundwater inflow on DO dynamics.

Research on the relative importance of drift- versus benthic foraging and piscivory to fishes, especially trout would also be helpful in order to understand the effects of reduction in stream power (through reduced flow) and associated drift transport.

There is also a big gap in our understanding of multiple stressors on aquatic invertebrates and fishes. In order to advance this subject significantly the disciplines of ecotoxicology and fish health need to be developed in New Zealand.

5. SUMMARY AND CONCLUSIONS

The stable flow regime and high biomass of macrophytes that characterise spring-fed streams can present difficulties for traditional hydraulic-habitat modelling. The stable flow regime may restrict calibration measurements to a relatively narrow range and hence reduce the scope for extrapolation, increasing potential for error. The high biomass of macrophytes can confound development of stage-discharge relationships on survey cross-sections, introducing substantial error into water level, and therefore habitat, predictions. Even if these hurdles can be overcome and minimum flow requirements can be assessed with hydraulic-habitat modelling, flow response lags to groundwater abstraction complicate minimum flow management in spring-fed streams.

To date there has been relatively little research into potential solutions to the challenges to in-stream flow assessment and water allocation in spring-fed streams. In the absence of appropriate technical methods, it appears that an “expert panel” approach has been widely used in New Zealand, despite its subjectivity. Traditional habitat modelling methods have also been widely applied in New Zealand streams and, in many cases, spring-fed systems have been assessed no differently to run-off streams.

With the present state of knowledge it is not clear whether physical habitat or water quality (especially DO) is the critical factor in spring-fed streams. However, given that generally there is likely to be adequate depth (because of the U shaped channel form) and there are typically abundant benthic invertebrates for fish to feed on, arguably spring-fed streams are likely to be most limited by water quality. If this assumption is true, then water quality modelling may be the best method for assessing minimum flows. This raises doubt over whether physical habitat modelling is appropriate or necessary in many cases. A sensible (though more costly and potentially difficult) approach for these streams may be to conduct a pilot study before deciding to undertake physical habitat surveys, to attempt determine what the critical limiting ecological factor is likely to be: physical habitat, water quality, or food.

However, DO modelling is challenging in spring-fed streams/groundwater dominated catchments because currently available models do not account for the in-flow of groundwater that (typically) has a relatively low concentration of DO. Also, groundwater inflow and DO concentration will vary from stream to stream, so further research is required to develop models that take account of this.

The adapted habitat methods discussed in Section 4.1 present some possible solutions that could be experimentally applied, but the solutions are invariably further complicated by knowledge gaps in this subject. Aside from the high cost and potential for being subjective, the adapted habitat modelling methods described are inherently flawed in that the HSC data may not be transferable to spring-fed streams. New HSC curves would be required to develop this approach. Any harvesting of macrophytes is likely to alter the physical bed-form due to changes in water velocities, and these will introduce significant error when calibrating RHYHABSIM.

If a spring-fed stream is deemed to be habitat limited in a pilot study, then a simple and cost effective approach may be to determine the critical average velocity necessary to preserve in-stream values/ecological indicators such as maintaining fish (velocity) preference and/or prevention of fine sediment deposition. Minimum flow could be set to maintain this velocity, as was done in the Meadow Burn and Waiau River.

Potential technical methods for situations with high in-stream values and/or abstraction pressure include an adapted habitat method, ideally complemented with a groundwater model, and/or a refined DO model (that takes into account inflow from groundwater). However, all of these modelling tools require further development to overcome recognised shortcomings.

Spring-fed streams may be more sensitive to a reduction in flow than run-off streams, largely because of their naturally stable flow regime (Reiser *et al.* 2004). Abstraction may result in changes to the ecosystem and habitat of residing fauna and flora, and will likely have a net negative effect on salmonid populations (Table 2). Death *et al.* (2004) note several possible crenobionts (organisms restricted to spring ecosystems) in New Zealand whose populations could also be impacted by abstraction.

Conversely, the narrow U shaped channel profile typical of spring-fed streams would minimise depth reduction, so if flow was reduced due to abstraction, spring-fed streams may be less susceptible to dropping below a depth perceived as critical for fish passage. Also, the stabilising influence that macrophytes have on water level/depth may allow considerable leeway before abstraction has adverse effects on suitable physical habitat and spring-fed stream ecosystems.

The above points highlight the need for a conservative approach to water allocation in spring-fed streams until further research provides guidance on the 'best' technical method(s) and reduces some of the uncertainty in assessing effects of flow change. It would also be prudent to consider minimum flow in spring-fed streams independently from that of run-off streams. Regardless, it is clear that the technical toolbox will have to be augmented in order to confidently assess minimum flow requirements in most spring-fed streams.

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8. APPENDICES

Appendix 1. Pros and cons of common flow assessment methods.

After: (MFE 1998; Beca 2007).

Method	Description	Pros	Cons
Historical Flow Method 1	Proportion of recorded or estimated flows (e.g. retain at least 80% of natural flow). Can be adjusted seasonally.	Quick and easy, uses existing data, results in flow variability without going into detailed level of analysis. Some abstraction allowed during times of low flow.	Assumes a linear relationship between flows and habitat, inconsistencies in estimating flow data, difficult to apply in un-gauged systems without accurate hydrological models, natural mistrust of method due to being too simple, doesn't target needs of specific values. Not applicable where in-stream values are high or there is a large change to the natural flow regime.
Historical Flow Method 2	Minimum flow based on a proportion of a flow statistic (e.g. minimum flow 90% of MALF). Can be adjusted seasonally.	Quick and easy, uses existing data. Widely used and well understood. Abstraction ceases when flows are less than minimum.	
Expert Panel	Panel of experts to advise on flow requirements based on bankside inspection.	Quick, cheap, has credibility (depending on the experts), useful political tool to help overcome mistrust if well managed and inclusive of stakeholders. Can be used to support other methods.	Not predictive, it is difficult for experts to determine how characteristics of river change with flow. Subjective and consensus can lead to poor environmental outcomes.
Generalised Habitat Models	Describes average relationship between habitat and flow, simplified versions of detailed 1D models	Don't require full in-stream habitat surveys, could be used more widely.	Models lack information that could be gathered using a 1D habitat survey, not as precise, relatively new technique, some restrictions to stream types; present models have been developed for single-thread gravel rivers (i.e., they do not apply to braided rivers and spring-fed streams)
1D Hydraulic Habitat Model	Predicts water depth, velocity, and habitat suitability as a function of flow.	Widely used and understood, relatively easy modelling, gives a specific relationship, most closely links hydraulic habitat availability with a range of flows.	Interpretation of results variable, modelling can be applied without consultation of biology and context, and limitations of habitat model are not well appreciated.
2D Hydraulic Habitat Model	Predicts water depth, velocity, and habitat suitability as a function of flow.	When working outside boundaries of current wetted channel, extrapolating beyond calibration data provides good 2D graphics for visualization of predictions. Can extrapolate further than 1D model, especially suitable for braided rivers and rivers where flow patterns change significantly with flow. Well-suited to accommodation of spatial habitat metrics.	Requires significant and expert data inputs and analysis, difficult and expensive to apply on shallow boulder rivers. Calibration and validation often inadequately undertaken. Depth and particularly velocity prediction errors can be high (much larger than 1D models). Interpretation of results is variable, modelling can be applied without consideration of biology and context, and limitations of

			habitat model are not well appreciated.
Water Quality Models	Includes temperature and DO. Use generalized habitat or 1D hydraulic model above.	Requires some data and links flow to critical parameters (temperature and DO). Application is relatively simple	Complicated to calibrate models. Require training in application of principles.
Connectivity / Fish Passage Assessment	Habitat model applied in a critical reach, identified by survey. See 1D and 2D hydraulic models above.	Addresses specific issue at specific locations.	Need to view entire affected river segment to identify critical reach for modelling, requires significant field investigation. Biological interpretation can be difficult; don't know what length of time is sufficient for fish passage or how the length of a critical reach interacts with a critical passage depth.

Appendix 2. National and international literature relevant to flow in-stream flow assessment and setting in spring-fed streams.

Paper	Brief outline	Spring-fed stream	In-stream values	Level of abstraction	Method used / considered	Method intended for (local or general)
(Champion & Tanner 2000) New Zealand	Investigates effects of aquatic macrophytes on the hydraulic and physico-chemical variables of a New Zealand spring-fed stream by removing vegetation cover.	Whakapipi Stream	N/A	N/A	Not considered	N/A
(Elliott <i>et al.</i> 1999) United Kingdom	Outlines some of the issues related to the application of habitat models to groundwater dominated rivers.	Various	N/A	N/A	Habitat methods (IFIM with PHABSIM)	General use (UK)
(Hardy <i>et al.</i> 1983) United States	Uses an early physical habitat model to assess habitat – flow relationships in a spring-fed stream in Nevada.	Ash Spring	High	High	Habitat methods	This river only
(Hearne <i>et al.</i> 1994) United Kingdom	Published data on in-stream macrophyte growth in chalk streams were used to test the seasonal effects of plant growth in a hypothetical channel. The results show how these effects can significantly distort PHABSIM results.	Non specific	N/A	N/A	Habitat methods (IFIM with PHABSIM)	General use (UK)
(Johnson <i>et al.</i> 1995) United Kingdom	Investigates the historical effect of abstraction on salmonid habitat	River Allen	High (trout and salmon)	High	Historic and habitat methods (IFIM with PHABSIM)	This river only
(Petts 1996) United Kingdom	Case study for the implementation of a proposed “ecologically acceptable” water allocation policy	River Babingley	Medium-High (adult trout)	High	Historic and habitat methods (IFIM with PHABSIM)	General use (UK)
(Reiser <i>et al.</i> 2004)	Summary of typical features of spring-fed streams and hypotheses on the consequences of increased flow variability. Also presents ideas for	Non specific	N/A	N/A	Habitat methods (IFIM with PHABSIM) 1D and 2D	General use (North America)

United States	improving and developing flow setting methods for spring-fed streams.				Water quality (temperature modelling)	
(Wilcock <i>et al.</i> 1999) New Zealand	Investigates the seasonal variation of macrophyte abundance, its influence on flow and channel volume, and the implications of this on stream habitat and function.	Whakapipi Stream	N/A	N/A	Not considered	N/A
(Young & Doehring 2010) New Zealand	DO and water temperature were continuously monitored in six streams (some spring-fed, some run-off) over summer to observe the relationship between flow and water quality.	Papawai Dock Parkvale Taueru Kopuaranga Mangaterere	N/A	N/A	Water quality model (DO and temperature modelling)	N/A

Appendix 3. Relationships between flow and hydrological habitat variables at the Motor Camp site on Spring Creek. From (Young *et al.* 2002).

