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1 Introduction

Under the Water Framework Directive member states have to achieve good status of all of their surface waters and groundwaters. Good status is a combination of good chemical status and good ecological status. Good ecological status is defined as a slight deviation from reference status, based on populations of fish, macroinvertebrates, macrophytes and phytobenthos, and phytoplankton (Acreman and Dunbar, 2004).

Surface water abstraction pressures are currently subject to a national study commissioned by the Department of Environment Heritage and Local Government (DEHLG) under the Eastern River Basin District project. An initial abstraction pressure assessment was performed in Ireland by individual river basin district (RBD) projects and reported by the EPA in the national Article V report, *The Characterisation and Analysis of Ireland's River Basin Districts* (EPA, 2005). For surface waters, the risk assessments compared net abstractions (total abstractions minus total discharges) to an estimate of Q_{95} flows. Risk levels were set at threshold values for highly sensitive surface waters established in guidance documents from the UK and Northern Ireland; except in cases when a dam or weir was present which defaulted the assessment to "at risk." River water bodies were classified as "at risk" when the net abstraction compared to the Q_{95} flow was greater than 5%, and "probably at risk" when the net abstraction was between 5 and 10% of the Q_{95} flow.

Surface water abstraction is an important component of Ireland's water resources. It comprises some 70% of public and private water supplies across the country. There are over 530 surface water abstractions including those from rivers, streams, lakes and estuaries. Nationally the median surface water abstraction rate for individual abstraction points is 410 m^3/day (ERBD, 2007).

Environmental standards are needed to allow water managers to set ecological flow requirements for Ireland's surface waters. These flows will form a component of the actions needed to restore or maintain the surface waters at good ecological status. These ecological flows should be set in relation to ecological sensitivity of waters to changes due to abstractions.

The surface water abstractions project currently is developing a pilot of a methodology to look at the effects of abstraction on fish, and in particular, to define minimum flows that would need to be retained in streams to avoid effects on fish. This paper complements that study component by identifying available international methods for assessing non-fish biotic groups and assessing their usefulness in evaluating the effects of abstraction pressures on non-fish biotic groups in Irish rivers. The aims of this review were to:

1) Provide an brief overview of environmental flow methods to set a context for examining methods that incorporate ecological data in some manner
2) Summarise information on the effects of reduced flow, in particular caused by abstractions, on macroinvertebrates, macrophytes, phytobenthos, and phytoplankton

3) From the research in (2), identify if a specific species in Ireland is sensitive to reduced flow and determine if it could be used as an indicator of abstraction pressures
4) Consider whether it is sufficient use fish as the only indicator of abstraction pressures

As there have been few previous studies on the direct effects of abstraction pressures on non-fish species, results and conclusions from studies based on reduced and low flows have been included under the assumption that abstractions would have a similar effect. The International Glossary of Hydrology defines low flow as 'flow of water in a stream during prolonged dry weather' (World Meteorological Organisation, WMO, 1974), which means it is not necessarily a drought.

2 Environmental Flow Methods

One of river management's key areas of interest is the cost effective balance between the amount of water abstracted from rivers and the amount retained to protect the environment and instream needs. Only recently has environmental protection become a major factor in determining minimum flows in rivers, and previously a minimum acceptable flow was defined as whatever flow, level or volume is set having regard for particular circumstances (Petts, 1996).

Environmental flow is the determination of the quantity or volume of water through time required to maintain river health in a particular state. It has been given different names such as environmental flow regime, instream flow, environmental allocation, or ecological flow (Acreman and Dunbar, 2004). Tharme (2003) identified 207 environmental flow methodologies used in 44 different countries, and grouped them into four categories; hydrological, hydraulic rating, habitat simulation and holistic methodologies.

Table 1: Categories of Environmental Flow Methods (based on Tharme, 2003)

	Method Type	Description	Examples
Non-ecological	Hydrological index methods	Fixed percentages or look up tables	Tennant Method
	Hydraulic rating methods	Plotting the limiting biotic variable of concern against discharge	Wetted Perimeter Method
Ecological	Habitat simulation methodologies	Quantity and suitability of instream habitat available to target species	IFIM
	Holistic methodologies	Environmental flow regime of the entire riverine ecosystem	BBM DRIFT Expert Panel Benchmarking Methodology

2.1 Non-Ecological Methods

Hydrological environmental flow methodologies are considered to be the simplest, and are usually fixed percentages or look up tables used at a planning level. Worldwide these are the most commonly applied methods and are frequently based only on flow statistics. Often standard minimum flow is set as a proportion of long-term annual flow. Examples are the Q_{95} or median minimums. In some cases, the stream flow requirements were established based on

Hydraulic rating methodologies take a simple hydraulic variable assumed to be limiting to target biota. The environmental flows are determined by plotting the limiting biotic variable of concern against discharge. Such as the wetted perimeter or the maximum depth methods, where there is a threshold on the curve below which the habitat is significantly degraded.

2.2 Ecological Methods

Ecological methods directly include consideration of aquatic biota in setting environmental flows. Ecological methods range from those that establish minimum flow requirements to those that are designed to retain the natural flow variability of the river. This latter approach is known as the natural flow regime and it acknowledges that floods, medium flows and low flows are all important (Proff *et al.*, 1997).

Habitat simulation methods are considered to be more sophisticated than hydrological index and hydraulic rating methods, as they are based on detailed analysis of quantity and suitability of instream habitat available to target species. The variables usually associated with hydraulic habitat include depth, velocity, substrate and cover. Many researchers have observed the microhabitat characteristics of fish and invertebrates.

Instream Flow Incremental Methodology (IFIM) is a commonly used habitat simulation method. It attempts to integrate the planning concepts of water supply, analytical models from hydraulic and water quality engineering, and empirically derived habitat versus flow functions. It is used in the US and has been used in many European countries, including Northern Ireland, England, France, Austria and Czech Republic. The most common habitat simulation model is the Physical Habitat Simulation System (PHABSIM) which is part of the IFIM developed by the US Fish and Wildlife Service (Bovee, 1982). The end product of the habitat modeling is the production of habitat versus discharge functions for each target species and life stage. The output from the model can then be used in the assessment of ecologically acceptable flows.

Some environmental flow methods address more than a just a couple of target species. These methods are moving towards including consideration of the entire riverine ecosystem. Table 2 shows the countries that use these methods and the ecological data involved. These methods are discussed below in more detail; the South African and Australian holistic methods, the methods in United Kingdom, and the methods in other countries like the Netherlands and Spain.

Table 2: Summary of the Environmental Flow Methods – More than just one or two Target Species

Country	Method Name	Description	Ecological data used				
			Mammals	Fish	Invertebrates	Macrophytes	Phytoplankton
South Africa	Building Block Methodology	Expert Panel		✓	✓	✓	
Australia	Holistic Approach	Expert Panel		✓	✓	✓	
England & Wales	RAM	Look up tables and flow duration curves		✓	✓	✓	
Scotland & Northern Ireland	SNIFFER WFD48	Expert panel + authors developed lookup tables		✓	✓	✓	
Netherlands	Aquatic Outlook	Habitat Evaluation Procedure (HEP)	✓*	✓	✓	✓	
Spain	Basque Method	Compares downstream increase in species richness to increased flow		✓	✓		

* Unclear if related to establishing minimum flow requirements

2.3 Australia and South Africa

Holistic methodologies are focused on addressing the environmental flow regime of the entire riverine ecosystem, this includes the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary. Holistic methods took precedence over the habitat simulations methods in South Africa and Australia as they lack the high profile fisheries that other countries like North America [and Ireland] have (Tharme, 2003). Only 8% of the world's total methodologies are holistic methods (Tharme, 2003). If these holistic methods were based on actual data, the collection of data would be expensive and that is why there is often a reliance on experts (Acreman and Dunbar, 2004).

These approaches have been described as either 'bottom-up' methods, designed to construct a modified flow regime by adding flow components to a baseline of zero flows, or 'top-down' methods, addressing the question, "How much can we modify a river's flow regime before the aquatic ecosystem begins to noticeably change or becomes seriously degraded?" (Arthington *et al.*, 1998).

The South African Building Block Methodology (BBM) (King and Louw, 1998; King *et al.*, 2002) was the first structured approach of this type. It began as a bottom-up method. It is a rigorous and extensively documented method; a manual and case studies are available. It is based on a number of sites within representative and/or critical river reaches. The BBM involves a team of experts that follow a series of structured stages, using available data and model outputs. The holistic method in Australia was developed in close association with the South African BBM but is based on a set of more loosely structured methods (Tharme, 2003).

2.4 United Kingdom

2.4.1 England and Wales

The Environment Agency in England and Wales use an approach called the Resource Assessment and Management Framework (RAM). This framework aims to produce a consistent method and reflect the varying sensitivity of flow of different biota and habitats and by protecting low flows and flow variability (Dunbar *et al.*, 2004). For each assessment point the environmental sensitivity to abstraction is determined through consideration of four elements: physical characteristics, fisheries, macrophytes and macroinvertebrates. Each element is given a RAM score from 1 to 5 (least sensitive to most sensitive).

- For physical characterisation, photographs are used for typical river reaches.
- Expert judgement is used to interpret fisheries monitoring data and classify rivers using typical indicator fish species.
- For macroinvertebrates, available survey data that identifies them to species level is used. A system called LIFE (lotic invertebrate index for flow evaluation) correlates certain flow variables to community structure (Extence *et al.*, 1999). The LIFE score requires accurate daily flow records and at least twice-yearly species-level data that exist over the same time scale.
- Macrophytes recorded by the Mean Trophic Rank (MTR) type survey method were assigned flow sensitivities. The MTR is a numerical score assigned to a survey length on its macrophyte presence and abundance characteristics (Dawson, 1999). The MTR approach is more an indicator of water quality rather than flow. For this reason macrophytes may not be used as an indicator of flow in the next version of RAM in mid-2008. Holmes is working on the feasibility of using macrophytes as a flow indicator but it is early stages of the project (Mark Warren, 2007 *pers. comm.*).

The scores for each element are combined to give an overall environmental weighting (EW) score. The mean of the four scores is used, with each element being treated equally. These environmental weighting bands represent the ecological sensitivity to abstraction related flow reduction, whereby an EW of 5 the instream ecology is most sensitive to artificial reductions in river flow. The EW can be overridden by local knowledge and ground truths (Mark Warren, 2007 *pers. comm.*). The environmental weighting band is then used with long-term flow duration data to derive appropriate ecological river flow objectives (RFO) (Environment Agency, 2002). River flow objectives define the flow regime, including the minimum flows and flow variability. These figures are mainly based on professional judgement and previous applications such as the Surface Water Abstraction Licensing Procedure (SWALP – Kirmod and Barker, 1997); this means that critical levels have not been defined directly through scientific studies (Environment Agency, 2002).

Table 3 provides the guidelines on the percent abstraction of the natural flow that is permissible. Depending on the ecological sensitivity of the river (*i.e.* EW bands) between 1 and 30% of the natural Q_{95} flow can be abstracted. For flows above Q_{95}, between 15 and 75% of the natural flow can be abstracted depending on the interval between flow thresholds and the river's ecological sensitivity.

Table 3: Ecological River Flow Objectives based on Environmental Weighting Bands

Abstraction Sensitivity	EW Bands	Unconstrained (Protect Low Flows)	Interval between flow thresholds (Protect Flow Variability)			Licensable % of intervals
		% of Q95	1	2	3	
Very High	5	1-5	0.2	0.3	0.5	15%
High	4	5-10	0.2	0.3	0.6	25%
Moderate	3	10-15	0.2	0.4	0.7	50%
Low	2	15-25	0.2	0.5	0.8	75%
Very Low	1	25-30	0.3	0.6	0.9	75%

Note: QN50 minus QN95 (a measure of the median to low flow variability of the hydrograph) multiplied by the factors above give the flow band width of the flow intervals

"Hands-off" flow levels and volumes for abstraction licences can be set, with the aim of maintaining the flow regime above or at the ecological river flow objectives. These can also be translated into seasonally varying minimum acceptable flows if they are needed. The procedure provides the first-level classification, and the impact of any specific abstraction licence can be examined in more detail, for example, with habitat modelling. (Environment Agency, 2002). In order to maximise abstraction while maintaining the variability of flow, a tiered system of hands-off flows can be applied. Licences are generally granted with the lowest hands-off flow possible on a first come first served basis. As more licences are granted, the hands-off flow must be increased to maintain sustainable flows in the river (Environment Agency, 2004).

2.4.2 Scotland

Since April 2006, activities in Scotland that pose a risk to the water environment, including abstractions, impoundments, and discharges, as well as engineering works in freshwater, must be authorised under the Water Environment (Controlled Activities) Regulations 2005 (CAR). The Scottish EPA (SEPA) will use the WFD environmental standards to support the setting of conditions for CAR licences and to assess the capacity of the water environment to accommodate new water use activities without harming the ecology. Until CAR was introduced, Scotland had no comprehensive controls for abstractions or activities that alter water flow. New standards were proposed and are displayed in the Table 4. The standards aim to protect ecology from extremely low flows by restricting the permitted changes from natural flow patterns. (Natural Scotland - Scottish Executive, 2006).

The values in Table 4 are from the SNIFFER WFD48 report (Acreman *et al.*, 2006) and were determined by expert opinion, which was then modified by the study's investigators. Separate expert teams firstly derived standards for invertebrates, macrophytes, and fish. The standards are given in the form of allowable abstraction as the percentage of natural flow. It assumes that Q_{95} is the critical flow below which more stringent standards are required. In addition certain standards are more stringent during certain periods, covering macrophyte reproduction, cyprinid (*e.g.*, minnows) spawning, and salmonid spawning (Acreman *et al.*, 2006).

Table 4: Proposed Water Flow Standards for Rivers in Scotland (Natural Scotland - Scottish Executive, 2006)

<table>
<tr><th colspan="6">Water flow (% permitted change from natural flow) – rivers</th></tr>
<tr><td colspan="6">'High' Status</td></tr>
<tr><td rowspan="2">River type</td><td rowspan="2">Season</td><td colspan="4">Flow decreasing ⇒</td></tr>
<tr><td colspan="3">Flow > QN95</td><td>Flow < QN95</td></tr>
<tr><td>ALL</td><td>ALL</td><td colspan="3">Up to 10</td><td>Up to 5</td></tr>
<tr><td colspan="6">'Good' Status</td></tr>
<tr><td rowspan="2">River type</td><td rowspan="2">Season</td><td colspan="4">Flow decreasing ⇒</td></tr>
<tr><td>Flow > QN60</td><td>Flow > QN75</td><td>Flow > QN95</td><td>Flow < QN95</td></tr>
<tr><td rowspan="2">A1</td><td>Summer: Apr-Oct</td><td>30</td><td>25</td><td>20</td><td>15</td></tr>
<tr><td>Winter: Nov-Mar</td><td>35</td><td>30</td><td>25</td><td>20</td></tr>
<tr><td rowspan="2">A2 (downstream), B1, B2, C1, D1</td><td>Summer: Apr-Oct</td><td>25</td><td>20</td><td>15</td><td>10</td></tr>
<tr><td>Winter: Nov-Mar</td><td>30</td><td>25</td><td>20</td><td>15</td></tr>
<tr><td rowspan="2">A2 (headwaters), C2, D2</td><td>Summer: Apr-Oct</td><td>20</td><td>15</td><td>10</td><td>7.5</td></tr>
<tr><td>Winter: Nov-Mar</td><td>25</td><td>20</td><td>15</td><td>10</td></tr>
<tr><td rowspan="2">Salmonid spawning and nursery areas (not chalk rivers)</td><td>Summer: Apr-Oct</td><td>25</td><td>20</td><td>15</td><td>10</td></tr>
<tr><td>Winter: Nov-Mar</td><td>20</td><td>15</td><td>Flow > QN80
10</td><td>Flow < QN80
7.5</td></tr>
</table>

Standards identified by the expert teams for each biota group sometimes differed. Table 5 compares the different expert standards for macrophytes, invertebrates, and fish (prior to adjustments by the study investigators). The macrophyte and invertebrate standards are given as the percent of natural flow on one day and the fish standards are given in terms of percent of abstraction of flow left when Q_{95} has been protected. Overall Acreman *et al.* (2006) concluded that the standards provided for fish are less stringent than those for macrophytes and invertebrates at high flows but that the fish standards are more stringent at low flows near Q_{95}.

Table 5: Comparing Expert Standards for Macrophytes, Invertebrates and Fish (Acreman *et al.*, 2006)

	Macrophytes		Invertebrates		Fish	
	%	Period	%	Period	% > Q_{95}	Period
A1	10	Mar - May	30	All year	50	Jul – Apr HOF Q_{98}
	20	Jun - Feb			20	May – Jun HOF Q_{98}
A2	10	Mar - May	10	All year	20 $>Q_{95}$ 10 $<Q_{95}$ 5 $<Q_{99}$	All year
	20	Jun - Feb				
B1	10	Mar - May	10	All year	50 $>Q_{90}$ 25 $<Q_{90}$ 20 $<Q_{95}$	Rheophilic cyprinids Jul – Jan HOF Q_{99}
	20	Jun - Feb				
B2	20	All year	20	All year		
C1	20	All year	20	All year	50	Feb – Jun HOF Q_{90}
C2	10	Mar - May	10	All year		Adult salmonids All year HOF Q_{95}
	20	Jun - Feb			50	
D1	10	Mar - May	20	All year		Salmonid spawning and nursery
	20	Jun - Feb				
D2	10	Mar - May	10	All year	20	May – Sep HOF Q_{95}
	20	Jun - Feb			20	Oct – Apr HOF Q_{80}
	Hands-Off flow is Q_{95} March - May		Hands-Off flow is Q_{97} All year			

2.4.3 Northern Ireland

In Northern Ireland, a new abstraction and impoundment licensing system came into effect in February 2007. The amount of water that can be taken from a river is site specific and risk orientated. As with Scotland, Northern Ireland incorporated the environmental standards from the SNIFFER WFD48 (Acreman *et al.*, 2006) findings.

The licensing authority is obliged to examine protected areas when granting the licences. They investigate whether there are Special Areas of Conservation (SACs), Special

Protected Areas (SPAs), Areas of Special Scientific Interest (ASSI – from the Nature Conservation and Amenity Lands Order in Northern Ireland, which prevents the continuing decline of habitats and species) or specific fish classified rivers. These areas are all available in Geographical Information System format and the effects can be modeled if required (Close, 2007 *pers. comm.*).

2.5 Other Countries Methods

Other countries have been found to use environmental flow methods that consider more than just one or two target species. The Netherlands and Spain are an example of these; both countries have developed their own methodology.

2.5.1 The Netherlands

The Netherlands has a method called the "Aquatic Outlook" project. This project aims to develop water management strategies to reinstate the ecological conditions and values of water systems while improving opportunities for functional use (Duel *et al.*, 1996). The Habitat Evaluation Procedure (HEP) is the standard approach for impact assessment and evaluation of measures causing changes in environmental conditions of habitats for flora and fauna species. HEP is a set of habitat suitability index models and analytical procedures to use the models for habitat evaluation. The habitat suitability curves for more than 60 species of flora and fauna are used, including species of macroinvertebrates, fish, waterfowl, wetland birds, mammals and flora. The models include only the main environmental factors limiting the population of the species reviewed. Examples of such factors are water quality, water depth, stream flow and vegetation cover. Duel *et al.* provide a graph of average stream velocity requirements for spawning barbel, but does not document what other target species and flow related habitat suitability curves are used.

2.5.2 Spain (Basque Country)

The Basque Method uses two different equations depending on the pollution level of the river (Docampo and Bikuna, 1995). The biotic equation relates the ecological diversity of macroinvertebrates and fish species with natural runoff. It is based on the "river continuum concept" i.e. in the upper/ middle ranges of a river, species diversity increases with discharge and therefore drainage area. The optimum instream flow is calculated from the natural flow, as that which gives a reduction in species diversity. The absolute minimum instream flow is calculated as above, only considering summer autumn conditions.

It is not possible to obtain diversity spectra in polluted rivers or in rivers particularly affected by human activities. In these situations the second equation the hydraulic equation is used.

2.6 Data Availability

The environmental flow method that is chosen often depends on the scale of the assessment and the data available (Acreman and Dunbar, 2004). Environmental flow methods have a high requirement for extensive ecological datasets. Many countries do not have the resources to gather such datasets. This is why expert opinion is now often used (Acreman and Dunbar, 2004), like for example in South Africa, Australia and now Scotland. Even under the data-driven RAM framework in England and Wales, there is expert judgement used to define the river flow objectives.

In Ireland, there are currently few biological datasets. The only national biological dataset is the invertebrate sampling for the biological Q value. However the individual rivers are only sampled once every three years, and the invertebrates are not identified to species level. Under the new Water Framework Directive monitoring programme, the biological quality elements will continue to be sampled once every three years (see Table 6). This frequency will not add much to the understanding of the effects of low flows and abstractions on the ecology of rivers, as for example the LIFE score used in the UK uses invertebrate data that is identified to species level and sampled at a frequency of three times per year (Extence *et al.*, 1999).

Table 6: Frequency of Sampling of Biological Quality Element under the Water Framework Directive Monitoring Programme (EPA, 2006)

Biological Quality Elements	Minimum Frequency	
Macroinvertebrates	**1**	Times in each 3-year cycle
Phytobenthos	**1**	Times in each 3-year cycle
Macrophytes	**1**	Times in each 3-year cycle
Phytoplankton	**1**	Times in each 3-year cycle
Fish	**1**	Times in each 3-year cycle
Seriously polluted sites - i.e. Bad status	**1**	per year macroinvertebrates

Black *et al.* (2002) states that hydro-morphological data may in some cases be used as a partial proxy for ecological status assessments, not least for the 'characterisation reports' that Member States must first complete by December 2004 (Article V) and at intervals thereafter. The Dundee Hydrological Regime Alteration Method (DHRAM) for example uses the Indicators of Hydrologic Alteration (IHA) approach of the US Nature Conservancy to classify the risk of damage to instream ecology using a five-class scheme (Black *et al.*, 2005). However it is insufficient just to use hydrological data for assessing the status of surface water quality under the Water Framework Directive.

3 Effects of Reduced Flow on Biota

Predicting the effects on biota is still somewhat difficult to do due to the regional ecological controls (Castella *et al.*, 1995). It has been found that flow-biota relationships are site specific with particularly complex responses at intermediate sites (*i.e.* middle course of the river), which is the case for macroinvertebrates observed by Bickerton (1995).

Dewson *et al.* (2007b) summarises that the ecological community changes with reduced discharge are probably as a result of changes of the instream environment. With decreasing discharge there is commonly loss of wetted area, reduced water velocity and depth, changes to nutrient concentrations, increased water temperatures, and lowered dissolved oxygen levels.

Some studies on the effects of reduced flows on macroinvertebrates, macrophytes and phytoplankton are discussed below. The effects of an abstraction in a river are expected to be similar.

3.1 Macroinvertebrates

Dewson *et al.* (2007a) reviews the different studies and summarises the conflicting results of the effects of reduced discharge on invertebrates, which are summarised in the Table 7. Reduced flow can affect invertebrate density, taxonomic richness and drift. These variables have been found to either increase, decrease or remain the same with decreased flow.

Under reduced flow conditions, some researchers have observed invertebrates to decrease in density. One theory is that the decrease in habitat area also reduces food quality and quantity are also reduced which leads to changes in competition and predation (McIntosh *et al.,* 2002). In other situations, the density of invertebrates increases as flow decreases, because the reduced wetted area and concentrates individuals in a smaller area (for example Gore, 1977). Some studies that have shown no change in invertebrate density, while others have shown variable density. Suren *et al.* (2003a) for example state that macroinvertebrate density increased in rivers with high nutrients, whereas the density was unchanged in rivers with low nutrients. This was due to the food response to low flows as algal blooms were observed during low flow in enriched streams.

A reduction in taxonomic richness is sometimes observed after reduced flows, due to a decrease in habitat types (McIntosh *et al.*, 2002). The severity of the reduced flow will influence invertebrate responses because it affects the amount of habitat loss and the magnitude of change of instream conditions (Dewson *et al.*, 2007a). In times of reduced flow no change in taxonomic richness has been observed but it does not increase.

Dewson *et al.* (2007a) explains how drift enables organisms to escape unfavourable conditions and how active drift has been found increase during periods of low flow. Armitage (1995) found that refugia are available even at the lowest discharge as long as the adverse conditions are not prolonged. This is because invertebrates are small and mobile. The hyporheic zone however (a region beneath and lateral to a stream bed, where there is mixing of shallow groundwater and surface water) has not been found to be used by invertebrates as refugia when surface conditions become undesirable due to low flow conditions.

Castella *et al.* (1995) studied the effects of abstractions on invertebrates on 22 streams across the United Kingdom. They found that in upland rivers invertebrates may have adapted to high flow variability as this is naturally more characteristic of upland stream. Lowland streams appear to be more degraded (Armitage and Petts, 1992; Castella *et al.*, 1995). Castella *et al.* (1995) also noted that increased sedimentation and loss of macrophyte cover are important factors in contributing to invertebrate community changes.

Table 7: Summary of the Effects for Decreased Stream Flow on Habitat Conditions and Invertebrates; and the Number of Times they have appeared in the Literature (Dewson *et al.*, 2007a)

Variable	Increase	No Change	Decrease
Velocity	-	-	8
Depth	-	-	9
Wetted width	-	3	10
Temperature	5	2	3
Dissolved O_2	-	3	-
pH	2	1	1
Nutrient concentration	-	-	2
Electrical Conductivity	4	-	-
Sedimentation	9	1	-
Suspended Sediment	-	-	2
Algae	6	1	1
Invertebrate – Density	7	2	12
Invertebrate – Taxonomic richness	-	3	9
Invertebrate – Drift	10	-	3

Dewson *et al.* (2007b) directly tested the hypothesis that short-term abstractions would decrease habitat availability and suitability for invertebrates, by constructing weirs and diversions that reduced discharge in three small streams. Samples were taken four times within the month after the diversion. When the diversions were in operation the discharge was 89-98% lower at impacted sites and the velocity decreased by an average of 57%. They found that there was an increase invertebrate density, drift peaked in the first few days following discharge reduction and there was no change in taxonomic richness. They noted the importance of considering the timing and severity of water abstraction.

3.2 Macrophytes

Research that has been carried out on macrophytes has shown that different types of macrophytes have different flow tolerances. The UK Vegetation Classification (Rodwell, 1995) assigns broad flow tolerances to 24 communities of aquatic macrophytes. Kirmond and Barker (1997) ranked 50 macrophyte species and groups in order of their sensitivity to flow reduction.

Biggs (1996) found that macrophyte colonisation is enhanced by low velocities, and growth rate and organic matter accrual can be enhanced by moderate velocities. However, high velocities retard colonisation and organic matter accrual. For mature communities, the peak biomass of macrophytes can be negatively correlated with velocity. This is in contrast with bryophytes, which are often restricted to areas of high velocity on stable substrata.

Abstractions can also lead to an impoverished macrophyte community and exclusion of rheophilic species (prefer to live in fast moving water) (Holmes *et al.*, 1998; Westwood *et al.*, 2006). One such macrophyte is *Ranunculus* species which is characteristic of Chalk streams in England, but some species are also found frequently in Ireland rivers and streams (Webb *et al.*, 1996).

Ladle and Bass (1981) observed *Apium nodiflorum* (water cress) gaining a competitive advantage over *Ranunculus calcareous* (water crowfoot – not present in Ireland) as a result of the dying of the stream in summer. A marked reduction in macrophyte cover has also been observed in other studies as a result of abstractions or lower flow conditions. For example Bickerton (1995) noticed a detrimental short term effect on *Ranunculus* as a result of low flow.

The figure of 10 cm/sec is often quoted as the point below which there would be a limit on *Ranunculus* growth but there are no absolute values. Velocity is driven by discharge influenced by channel dimensions and abstraction (Cranston and Derby, 2002). Cranston and Derby (2002) suggested that the target flow regime for *Ranunculus* species is that at least 90% of the naturalised daily mean flow should be maintained throughout the year at all points in the river system.

3.3 Phytoplankton

In times of low flow phytoplankton (unicellular algae and cyanobacteria, both solitary and colonial, that live, at least for part of their lifecycle, in the water column of surface water bodies) there is a succession of species. It changes from being dominated by low-biomass diatom to high-biomass filamentous algae, that is algal blooms occur in times of low flow. This is due to increased temperatures, higher nutrient concentrations and reduced current velocity (McIntire 1966; Proff *et al.* 1990; Suren *et al.* 2003b).

Suren *et al.* (2003b) found that in nutrient enriched streams there was a substantial increase of filamentous algae during low flow conditions, however in unenriched streams low biomass diatoms remained dominant. They state that the shift to filamentous algae could result in potential deleterious effects to the invertebrate and fish community and concluded that setting minimum flows according to specific hydraulic habitat requirements of target species is likely to provide more adequate protection for these organisms in unenriched rivers and that enriched streams are more sensitive to flow abstractions.

3.4 Individual Species as Indicators of Reduced Flow

There have been some suggestions in the literature of species of biota that could be indicators of reduced flow. These suggestions have arisen from site specific studies and there is no record to date of an attempt to regionalise them as indicator species.

Some researchers have found that some species are particularly sensitive to reduced flow and can decline in numbers or disappear altogether. Gore (1977) suggested using a mayfly as an indicator of adequate stream flow conditions because of its strong drift response to flow reduction. Armitage and Petts (1992) also suggested that absences of species that favour clean stone surfaces such as some heptageniid mayflies and stoneflies may indicate that siltation is occurring which may be associated with reduced flow. Extence (1981) found that two species briefly disappeared during the 1976 drought in Essex, England, *Sigara dorsalis* (leach) and *Dryops* (beetle) species.

It has also been found that some species thrive in times of low flow. This was the case found by Extence (1981) for *Asellus aquaticus* (waterlouse). It was relatively scarce prior to the 1976 drought and the numbers expanded significantly during the drought summer. *Asellus* is usually associated with slower flowing stretches of river.

4 Discussion

Environmental Flow Methods

Many different environmental flow methodologies are used worldwide. The most commonly used methods are still hydrological methods that do not involve any ecological data or even any verification using ecological data. These methods are not sufficient under the Water Framework Directive as its implicit assumption is that the combined degradation of the four quality elements fish, invertebrates, macrophytes and phytoplankton can be related to the degree of modification of the flow regime. One of the principal challenges of water managers is to be in a position to measure departure from the natural flow regime in terms that reflect the degree of ecological degradation (Bragg *et al.*, 2005).

For several decades, water managers have used habitat simulation methods to establish instream flow requirements for target or sensitive species. More recently methods have been developed that typically consider the range of aquatic flora and fauna; however, these have been used in only a few countries (Sections 2.3 to 2.5 describe these methods). These methods often require comprehensive datasets and/or expert opinions on the different biota groups. The need for such extensive datasets is often why there is a reliance on expert opinion, as the data can be expensive to generate and long time series of data is usually required.

Effects of Reduced Flow on Biota

The literature has shown that there is an effect on biota during times of reduced flow or abstractions. No literature was found regarding the sensitivities of different biota types to reduced flow, as much of the research to date has been focused on individual biota types by experts in that field.

During times of reduced flow, in general terms, the invertebrate density increases, taxonomic richness remains the same, and invertebrate drift increases. However different studies have found different results, as discussed in Dewson *et al.* (2007a). In the case of macrophytes, they are seen as having enhanced growth in times of reduced flow, with the exception of some rheophilic species. The composition of the phytoplankton community is also seen to change in times of low flow, from being low-biomass diatom dominated to high-biomass.

Many of these effects of reduced flow on biota are regionally specific and sometimes even site specific, which could account for the varied results found in studies. Macroinvertebrates, in particular, have been found to have much more conflicting evidence as to the effects of reduced flow has on them. This could also be due to larger number of studies carried out on the effects of reduced flow on macroinvertebrates than on macrophytes or phytoplankton. Nevertheless studies would have to be carried out in Ireland to see what effects reduced flows and abstractions would have on the biota.

Individual Species as Indicators of Reduced Flow

There have been some suggestions in the literature of species of biota that could be indicators of reduced flow. These suggestions have arisen from site-specific studies and there is no record to date of an attempt to regionalise them as indicator species.

Is it Sufficient to use Fish as the Only Indicator?

Our review identified fish as the most commonly used biotic group used to establish environmental flows (among the methods that considered the ecology), with the habitat simulation methods being the most widely used. While habitat preferences for use in habitat simulation models have been defined for species in many species, the preponderance of habitat preferences have been defined for fish.

The exceptions are the few countries that use ecological methods that consider more than one or two target species, like the holistic methods in the South Africa and Australia. These holistic methods were developed in the southern hemisphere countries that do not have high profile fisheries (Tharme, 2003). The methods used in the UK also consider multiple biotic groups to establish environmental flows, however, they do have high profile fisheries.

Also another item to note is that in the SNIFFER WFD48 report, the authors interpreted the expert opinion on fish were found to be the more sensitive biota group at times of reduced flows. However this has not been stated in any other literature and there are no studies to back up the statement as it is just based upon expert opinion. Also the experts involved in SNIFFER WFD48 stated that macroinvertebrates and macrophytes are more sensitive in times of high flow, so if flow variability was to be considered as the new paradigm of natural flow regimes suggests it should be, it would be necessary to in turn consider macroinvertebrates and macrophytes.

5 Conclusions

- Little literature is available to addresses the effects of reduced flow or abstraction pressures on non-fish biotic groups; most of these tend to be site specific. No indices were found in the literature that use biotic groups or individual species as indicators of reduced flow.

- The hydrological methods are the most commonly used environmental flow methods used worldwide. The methods tend simply select a flow metric, while others are based on observations of aquatic habitat conditions, however, they do not explicitly consider biotic groups as required under the Water Framework Directive.

- Fish appears to be the most common ecological indicator used for setting minimum flows, by means of the widely used habitat simulation models.

- The environmental flow methods that are moving towards looking at the entire riverine ecosystem appear to be the exceptions rather than the norm. In the long term, this appears to be a way forward. However, these methods would not be able to be adopted directly into Ireland as the ecological data required is not available, which would also hinder the use of expert opinions.

For Ireland to be on par with other countries, minimum flow requirements for rivers need to be determined. To be compliant with the Water Framework Directive ecological data needs to be used as the degradation of the ecology can be related to the degree of modification of the flow regime and not just low flows. So the habitat simulation method PHABSIM that is being used is the first important step along the path to creating an environmental flow methodology for Ireland.

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