MANAGING RIVER FLOWS FOR SALMONIDS: EVIDENCE-BASED PRACTICE

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EXECUTIVE SUMMARY

This report describes the proceedings of a Workshop in March 2010, organised by the Atlantic Salmon Trust, to draft advisory guidelines for setting flow standards and managing river flows from the perspective of salmonids, based on a review of available evidence. It was a follow-up to a symposium in York, January 2010, on managing river flows for salmonids. In the event, for reasons outlined here the Workshop did not feel able to produce definitive guidelines, but did review the status of the supporting science and make recommendations on the way ahead.

The chapters outline the science behind the river flow requirements of salmonids at different life stages, the impacts of artificial flows and approaches to setting standards in the British Isles. Also covered are the implications of climate change, approaches to monitoring and the potential offered by adaptive management for furthering scientific investigation of this topic. Five broad themes of enquiry emerged during the Workshop discussions:

- The nature of the perceived science base
- The nature of the required questions and methods to apply science to management
- The effectiveness of present day regulatory processes
- The effectiveness of present day standards in protecting salmonids
- The clarification of management objectives

The Workshop focused intentionally on salmonids, recognising that modern flow management needs to consider all ecosystem components, but arguing that this also required the individual components, such as salmonids, to be better understood. A dominant backdrop was the importance of the EU Water Framework Directive (WFD) in defining the approaches to flow standards in natural and modified waters, a driver considered to bring advantages (e.g. ecosystem approaches) and disadvantages (e.g. prescription). A further important driver was the responsibilities of industrial water users to regulate discharge regimes with due consideration to consequences for salmonids and the wider ecosystems. There is an important distinction to be made between the development and application of standards for restrictive management (i.e. the control of water abstraction to ensure that natural flows are not unduly reduced) and those for active management of heavily modified water bodies, i.e. the modification of flow regimes by release of water from impoundments for Hydroelectric Power (HEP), water supply or flood risk management. To date restrictive management has been the principal focus for the development of flow standards to support the WFD. However, it is apparent that such (generic) standards frequently lead to very different flow habitats and thus ecological protection, in different water types for the same notional standard. There has been no such application of generic standards for active management, nor has there been development of guidelines for matching discharge regimes locally to requirements of salmonids. Hence, key areas for attention are development of restrictive management standards that focus on local rather than generic reference flow indicators, and active management standards that specify local flow regimes that respect the needs of salmonid fishes.

The Workshop agreed that current standards for river flows are unsatisfactory because their evidence base is unclear, the suites of standards are inconsistently specified and applied by regulators. As a consequence, in different situations they may permit excessive take of water or be overly protective and wasteful of resources. However, the level, extent and consequences of

these shortcomings have not yet been objectively tested, by for example incorporating the lost production of salmonid fishes into cost-benefit analyses of water use.

The Workshop also agreed that the last twenty years has seen significant advances in our scientific understanding of some processes underlying flow-fish relationships. However, their complexity suggested that derivation of generic standards from first principles, in the sense of one set that would be effective for all rivers each with specific flow regimes, or even for a few categories of river types (*cf* WFD), might be inappropriate. Moreover, the variability in flow-fish relationships and difficulties in identifying flow-related impacts at the population level introduced uncertainties which needed to be taken into account in decision making.

Nevertheless, in spite of the difficulties, standards and clear guidance on the best approaches for managing water use to minimise impact on fish, fisheries and hydro-morphology are urgently needed. While some generic principles were necessary and appropriate, the specification of optimally protective regimes would ideally require river- or even site-specific study. However, this was perceived to be a clear case where adaptive management could be applied to refine the flow management regime in the light of locally measured responses of the fish populations.

While in most cases significant or persistent artificial deviations from natural flow regimes are regarded as deleterious to fish and other biota, this is not always the case. There are examples where artificial flow regimes, particularly from some impoundments, may lead to increased fish standing crop, production and, in the case of migratory species, increased smolt production. This may raise local opportunities for climate adaptation; but also raises challenging questions about the nature of "natural flows" and the environmental aims of flow management and regulation.

The Workshop exposed weaknesses in the current knowledge base, the principal reason why it was not able to come up with the guidance it felt was needed. It reached the view that, in spite of some areas of excellence, overall the current body of knowledge was patchy, incomplete and lacked focus in terms of what questions it was trying to answer. There was a strong case for gathering some of this knowledge through coordinated adaptive management, funded by water users. The Workshop's main recommendations are intended to enable an increase in the general knowledge base and promote more focus on local application of science. Given the current scarcity of funds and the urgent need to obtain better scientific information on flow regulation it is essential that research efforts are better coordinated and make full use of historical data sets. Experimental trials on this topic lend themselves to adaptive management and collaboration between industry, researchers and the regulators to apply our scientific understanding to the immediate management requirement of flow specification.

The Way Ahead

The individual chapters gave rise to nineteen specific recommendations listed in this report, the priorities amongst which are captured in the three overall recommendations shown below.

1. Review the evidence

The participants believed that there is considerably more information and knowledge in the grey and peer-reviewed literature than was available to the Workshop, which might help to answer some key questions. These questions are not always tightly specified and priorities vary between sectors, but there needs to be an agreed balance between the views of regulators and industry on what tools they need taking account of scientific realities. There was broad agreement that a review of this information should be undertaken, focussing on the following subjects:

- Explore the effectiveness of WFD flow standards for protecting salmonid fisheries (as e.g. abundance, structure, production, fitness) and the consequences of their use for lost water supply and power generation, through case studies across a range of river types. A particular issue lies in the use of Q95 as a low flow standard and what alternatives might be proposed.
- Investigate the uncertainties and decision risks implicit in the variability of fish-flow and flow-habitat relationships and means to incorporate them in to decision making.

2. Review and improve the mechanisms for coordination and funding fish-ecosystem-flow-related sciences.

There are major inconsistencies in objectives, practices and standards across the water use sectors and the regulators in the British Isles. The supporting science is also uncoordinated, leading to gaps, divergent approaches and failure to act on potential synergies. Coordination of research, the applied sciences (e.g. impact assessments, standards development) and monitoring is not being achieved under the current arrangements for aquatic environmental management. A discrete working group to take this forward is recommended, given the varied infrastructures and legislation across the regions and participating sectors (the sciences, operators and regulators). Current national economic constraints should not be taken as a reason to avoid setting out detailed needs and options for delivering this coordination and funding.

3. Promote adaptive management as a vehicle for collaboration

True adaptive fisheries management is still rare in the UK, but offers a potential route for some of the studies that are otherwise too expensive to pursue in conventional experimental formats. There is a clear precedent in the way uncertainties in the initial water body assessments for WFD are being followed up by 'investigations' to refine 'measures'. The lack of objective evaluation based on rigorous experimental design and statistical principles, of the effects of changing flow regimes, imposed licenses and standards remains a major omission, which is wasteful of national resources. Also required are procedures for reporting results of locally applied flow regimes and their incorporation in to more general developments of flow standards. However, adaptive management is a significant planning and financial burden that should be shared amongst industry and the regulators. This recommendation requires a national working group or similar that can explore funding, planning, implementation and reporting.

CHAPTER 1 - INTRODUCTION

1.1 Target readership and aims

This document is intended to inform those involved with the operational practice and planning of river flow management in the British Isles. It provides information on the current state of knowledge regarding the effects of changes in river flow on, primarily, salmonid fish and reviews river flow standards. It also highlights recent scientific developments. It was produced through a Workshop held in April 2010 which followed a wider Symposium held in January 2010. At the Workshop scientists and practitioners discussed the latest evidence and approaches to managing river flows for salmonids in the context of contemporary water use and regulation. The report offers background and technical advice on the current status of evidence-based approaches, recognising the integrated nature of ecosystem processes and the catchment scale of modern flow management.

As the Workshop proceeded it became apparent that the initial aim of enhancing evidence-based best practice advice would not be achieved. Partly, this was due to the difficulty of producing generally applicable models of flow requirements. However, more importantly, there have been very few tests and reports of instances where existing knowledge has actually been applied to prescribe local discharges. In the absence of such information there has been stagnation in the development of useful scientific knowledge. Nevertheless, the new information and understanding, coupled with evolving regulatory and environmental contexts, warrant consolidation into reappraisals of the topics here and lead to a number of recommendations.

1.2 The overall process and documentation

The combined Symposium and Workshop produced three principal outputs:

1. A Web-based Symposium Report (http://www.coastms.co.uk/conferences/426/show)
2. Peer- reviewed literature from the symposium presentations, to be published in Fisheries Management and Ecology
3. This Report

1.2 Scope and Rationale.

River flows affect almost every function of aquatic ecosystems in rivers, estuaries and even coastal zones; from structure of channels to energy cycling, from species diversity to movements and abundance. However, many of the early flow standards and protocols for rivers in the British Isles were based on the flows needed to maintain upstream migration of adult Atlantic salmon and sea trout (e.g. Stewart, 1969; Cragg-Hine, 1989). This seems to have resulted from the development of electronic fish counters and the deceptively simple and accessible relationships between adult fish counts and river flows. At the time, flow needs for juvenile stages were less well-developed, possibly because the data were fewer and process understanding less developed. However, a more prosaic reason is that adult fish need to migrate through rivers, including lower sections where cumulative flow effects may be more severe, in contrast to juveniles which are more uniformly distributed and often occur in channels with no evident flow impacts. Adult migration and fisheries, evidently responding to flow, were thus the initial concern of water managers.

The previous focus on salmonids was reasonable, given the contemporary management priorities. However, modern flow management recognises a wider remit through the notion of ecosystem health as a component of the Good Ecological Status criteria in the Water Framework Directive (WFD). In addition to embracing more species and multiple ecological groups it has been recognised for many years that flow management needs to move to integrated objectives reflecting flow regimes that consider responses over full life cycles and which encompass dynamics of flow on daily to seasonal scales. Seasonally varying standards have been adopted in the WFD (see Chapter 5).

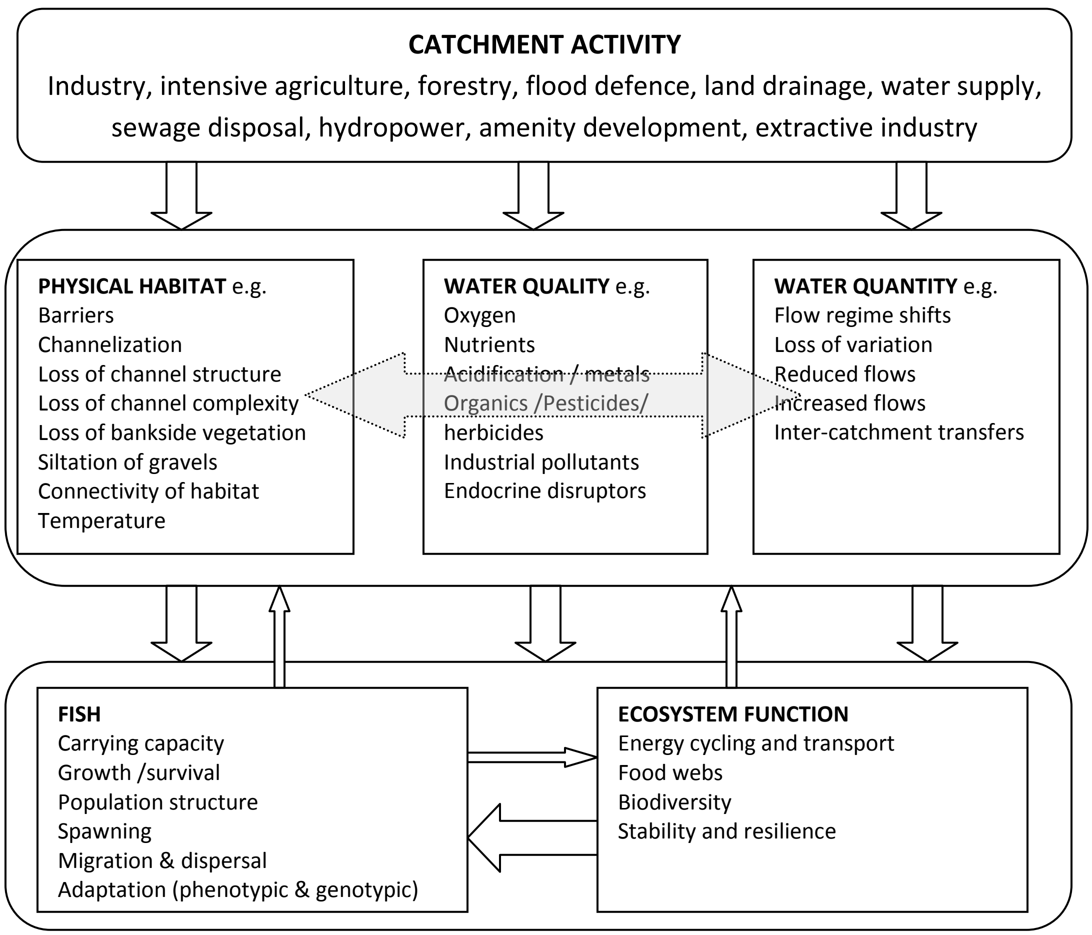

Fig 1.1 Some basic connections between human activities in catchments, geomorphological and hydrological processes and ecosystem (including fish) responses.

Fish are not the only biological receptors in rivers. Contemporary aquatic environmental management recognises that the whole ecosystem needs to function properly for its constituent parts to be in good health; hence the notion of environmental flows (e.g. Poff *et al*, 1997, Acreman and Dunbar, 2004). This paradigm is unquestionably important; it is enshrined implicitly in the WFD (Acreman and Ferguson, 2010) and other recent environmental legislation and is the backdrop to this report.

Equally, modern "flow management" is more than simply adjusting the tap at a dam or controlling abstraction. The complex interactions of hydrological and geomorphological processes, land use and climate governing channel structure and habitat (Fig 1.1) act at all scales. The simple pathway CATCHMENT ACTIVITY ⇨ WATER QUANTITY ⇨ FISH in Figure 1.1 addresses just one aspect of a far wider environmental challenge to our understanding and practice in flow management.

However there are practical limitations, given the current state of knowledge, in actually delivering an evidence-based flow management strategy based solely on the ecosystem approach. In part this is because there is still a lack of process understanding sufficient to inform practical protection of ecosystem function. Moreover, "ecosystem function" may be too high a level to be a useful entity on its own to evaluate and manage a river's flow regime. Indeed, even to propose management of (just) the flow regime falls short of the holism inherent in ecosystem management, which should take into account the full range of hydromorphological and ecological processes (Fig 1.1). Physical habitat management has become a major focus in the UK following the successful regulatory campaigns from the 1970s onwards to reduce point-source chemical pollution.

There is a balance to be struck between the aspiration for a fully holistic approach and the need to manage practically the constituent parts of ecosystems. This report addresses only one, but significant, aspect of the overall management of river flows. It focuses on the migratory salmonids, salmon (*Salmo salar* L.) and trout (*Salmo trutta* L.), because:

- for historical social and economic reasons these species have been comparatively well-studied and thus a large body of knowledge exists;
- they are ubiquitous across most of the British Isles (trout more so than salmon), although salmon not naturally present in some lowland catchments of eastern England;
- as migratory species, they make extensive use of whole catchments and estuaries to complete their life cycles and are demonstrably dependent upon adequate flows for their well-being. Thus they may be considered sentinel species for their environments.

While this last assumption might appear reasonable, it remains to be thoroughly tested and demonstrated. It is therefore considered important to refer to other fish species or ecosystem components in order to expose conflicts resulting from inter-specific or inter-taxa water requirements. The guidance is not intended to provide an overview of all aquatic ecosystem flow requirements, however desirable that may be.

There is an important distinction to be made between the development and application of standards for <u>restrictive</u> management (i.e. the control of water abstraction to ensure that natural flows are not unduly reduced) and those for <u>active</u> management (i.e. the increase in flows by release of water from impoundments for HEP, water supply or flood risk management). The distinction matters because restrictive management has been the main focus for the development (through UK TAG) of generic standards for flow to support implementation of the

Water Framework Directive. However, attempts to do this for active management, which is a major application, have been less developed or successful (Acreman and Ferguson, 2010).

The Workshop focused on standards to combat the presumed negative effects of manmade changes in natural flow regimes, although in some circumstances flow modifications may actually be beneficial for fish production (Chapters 2 and 4). Moreover climate change is already affecting flow patterns in many rivers. Therefore, the possibilities of positive flow management to attain some improvement on the natural state and to offer adaptation to climate change (e.g. Wilby *et al.*, 2010) are additional perspectives for modern flow regulation to consider.

1.3 Standards, objectives and models

In the UK a common approach to managing flows for aquatic ecosystems is to set protective flow standards for key species or taxonomic groups and to develop flow controls and management protocols to meet these standards. In all cases, setting protective standards or threshold flows requires the stages of (Fig 1.2):

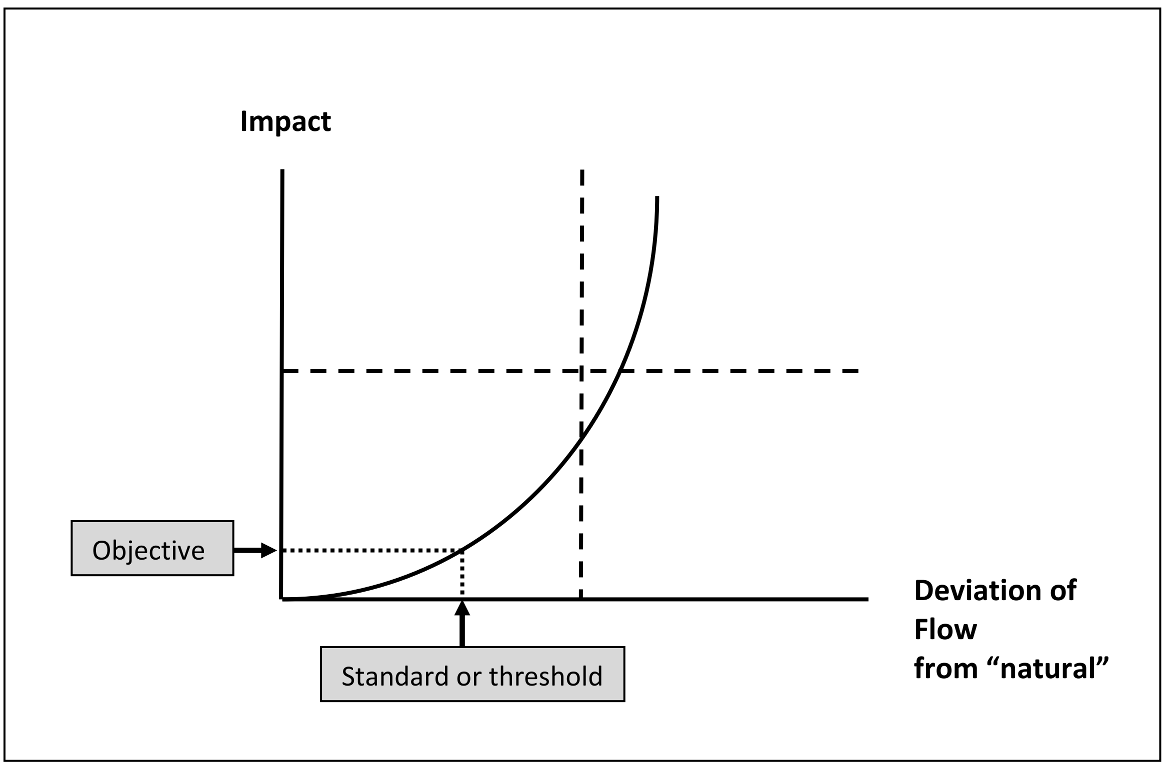

Fig 1.2 Diagrammatic representation of relationships amongst a fish-flow model (impact against –ve or +ve deviation from natural flow), management objective and the protective standard, or threshold. See text.

(1) the specification of the objective, being the point of acceptable impact, with risk aversion included as appropriate,
(2) some form of modeling of impact *vs* deviation from the natural condition and
(3) the estimation of the protective flow standard or threshold, being the level of deviation (from natural flow metric) associated with the objective.

Here the natural flow regime (*sensu* Poff *et al*., 1997) is taken as the reference point for two reasons. First, it has scientific acceptance, on basic Darwinian principles of fitness and selection, as the flow regime that is likely to provide optimal conditions for biota, because it gave rise to present day adaptations that maximise lifetime fitness (Lytle and Poff, 2004; Stearns, 1990). Second, all forms of flow alteration involve some deviation (increase or decrease) from the natural hydrograph, which restorative or protective management tries to ameliorate; so it is helpful to express the independent variable (and standards or thresholds) in these terms. Poff *et al*. (1997) give five criteria of flow which have impacts on both biota and physical habitat (hydromorphology); these might individually or in combination form the x-axis:

Magnitude (e.g. mean or other central tendency, over a period: hour, day, month, year etc)
Frequency (how often a given flow occurs over a time period)
Duration (e.g. how long a specified flow or an exceedance value occurs e.g. Q95 is the flow that is exceeded for 95% of the time over the assessment period)
Timing, or predictability (the regularity with which a particular flow occurs)
Rate of change ("flashiness", how quickly flows change)

Richter *et al*. (1997) took the list further, into 'indicators of hydrological alteration' and there have been several attempts to refine indices of the 'rate of change' category, justified by the vital importance to ecosystems of disturbance (Archer and Newson, 2002; Clausen and Biggs, 1997)

The impact (y-axis, Fig 1.2) is the dependent variable, the indicator, which responds to the flow deviation and which the management objective seeks to protect. It might be expressed at different levels, for example, in terms of:

Individual (e.g. migration rate, growth or other fitness indices, by life stage, by species)
Population (e.g. abundance, structure, rate of change)
Community (e.g. distribution, diversity, resilience)
Socio-economic (e.g. catches, demand, participation, availability, value)

In Fig 1.2 the illustrative relationship between flow change and impact is a simple one; in reality it is likely to be more complex and will always have high uncertainty attached, which should also be estimated. One can see immediately the large variety of ways (i.e. the combination of x,y axes metrics) to present such models and equally the impossibility of covering all of them; but the principle (objective/indicator-model-standard) is the same in all cases and offers a framework for reviewing data and knowledge. The discussion of what is appropriate and practicable occupies much of this report.

There is a special case not covered by Fig 1.2 in which deviation from natural flows may enhance fish population performance, through for example supporting flow at times of natural damaging drought or cropping extreme spates. Such significantly modified sustained flows, while comparatively rare, are likely to arise in the context of active flow management, for example from discharges regulated by dams.

Defining the management objective in ways that can be conveyed through the quantitative terms of fisheries assessment is a critical part of the process and often a stumbling block. Examples include the WFD Ecological Status classification and the Environment Agency's Conservation Limits for salmon (Chapter 3). It may be impossible or impracticable to set quantitative objectives formally in many cases, but it is essential to consider the various options and select the best quantitative or qualitative basis for both setting standards and assessing the impacts of flow modification.

The two activities of (a) setting standards and (b) assessing the impacts of perturbed flow regimes have the common feature of needing a fish impact-flow model (Fig 1.2), but thereafter rely on different types of supporting science. The former is usually about precautionary limits or bands, often set to protect the ecosystem as a whole, is typically associated with regulatory legislation, licensing and enforcement and tends to be presented in categorical form (see examples in Chapter 4). The latter may involve no predetermined standards and is about observed, continuous relationships between flow change and impacts on designated ecosystem parts, species or species traits, communities or processes (See Chapter 2). The key to both lies in having the appropriate models. The limited availability and scope of such models and their considerable uncertainty will be seen throughout this report to be major constraints on providing a scientifically robust evidence base for flow management (See Chapters 3 and 6). Sometimes, due to circumstances or system complexity, flow definition techniques involving expert opinion may be the only option and are increasingly used (Acreman and Dunbar, 2004; Ahmadi-Nedushan *et al*., 2006).

It is necessary to strike a balance between, on one hand, the inclination for detailed understanding of ecosystem processes, and on the other hand the limits that variability and uncertainty introduce, compounded by the comparatively crude controls available to managers through, for example, licensing and operational practice. This has led to adoption of simple rule-based systems which are sometimes at odds with the actual complexities of the systems being managed. Reconciling and amalgamating these contrasting perspectives is an important challenge for collaboration between science and management.

1.4 Outline legislative background

Historically, there were wide differences in the ways that river flows and abstraction were controlled in the different parts of the United Kingdom, although there is now a common legislative framework derived from EU directives, in particular the Habitats Directive and the Water Framework Directive. In England and Wales, abstraction of water was largely uncontrolled during the first part of the 20th century, apart from public water supply developments under Acts of Parliament. However, falling groundwater levels led to concerns over excessive abstraction and resulted in the introduction of the Water Act 1945, which provided control through licenses for defined groundwater areas. The legislative control of water resources has further developed largely in response to crises in public water supply during major droughts and the Water Acts of 1963, 1991 and 2003 brought regulatory control to abstractions and discharges. In Scotland and Northern Ireland abstractions remained uncontrolled until legislation was introduced to implement the requirements of the Habitats Directive

Regulation of abstraction (and hydropower) is the responsibility of:

- Environment Agency – in England and Wales,
- Scottish Environmental Protection Agency,
- Northern Ireland Environment Agency.

Various other bodies and organisations are also responsible for the operation of their own schemes within the limits of their licenses. This can include water companies and navigation authorities, hydropower operators, fish and water cress farmers and industrial users.

In 1992 the European Council adopted the Habitats Directive (Council Directive 92/43/EEC) which aims to promote the maintenance of biodiversity. In the UK the Habitats Directive has been transposed into national laws by means of the Conservation (Natural Habitats, & c.) Regulations 1994 (as amended), and the Conservation (Natural Habitats, & c.) Regulations (Northern Ireland) 1995. Under the Habitats Directive, in order to meet obligations to avoid deterioration to designated sites and to protect designated species, bodies are required to review existing consents, permissions or authorisations which may affect the integrity of these sites or species and undertake an appropriate assessment of new proposals where they can cause a significant effect to a European site. In the case of the Environment Agency this includes existing abstraction licenses. In Scotland and Northern Ireland the flow-related Habitats Directive objectives are delivered through the new legislation to control abstraction.

Box 1: Background on Water framework Directive Good Ecological Status and Good Ecological Potential

The ***Ecological status*** (ES) classification for each water body (WB) is based on four broad quality ***elements*** (Biological, Hydro-morphological, Physico-chemical, Specific pollutants). There are four components to the ***Biological element*** of rivers: Fish, Invertebrates, Macrophytes and phytobenthos (phytoplankton is an additional element in lakes). There is also a ***Chemical status*** classification, adapted from traditional methods, that does not concern us here.

The Ecological status of surface water of a WB falls into one of five categories: High, Good, Moderate, Poor and Bad. "High" status corresponds to and defines the ***reference condition*** of a WB for its particular ***river type***. River type is a predetermined characterisation based on a suite of ecological and geomorphological features giving 18 different river types, deemed (by expert opinion) to be in reference conditions. It is necessary to band rivers in this way because natural faunal composition and ecology vary so much across the variety of rivers types, that no one scoring system would be applicable to all waters. The reference conditions are demonstrably different amongst the Types. Note that in the case of the Fish classification used in England and Wales by the Environment Agency EA the reference conditions are not based on banded typologies, but on a continuously varying gradation of habitat indexed by altitude and channel width, variables which have strong association with, amongst other things, flow.

The WFD (Annexe V, 1.4.) requires that the ES be expressed as the ***Ecological Quality Ratio*** (EQR), being the ratio of the observed value of the biological parameter (e.g. fish abundance) presence and that predicted under reference conditions for the particular water body. Moreover, the ratio "... shall be expressed as a numerical value between zero and one, with high status represented by values close to one and bad status by values close to zero." The reason for insisting on the common EQR approach is to provide a common scale of ecological quality and to enable future inter-calibration between Member States

In two other categories of water, Artificial (AWBs) or Heavily Modified (HMWBs) water bodies, classification goes no higher than moderate and, because ES is already compromised (although it may be mitigated by compensatory mechanisms, e.g. stocking) the status is expressed as ***Ecological Potential***.

One of the aims of the WFD is to achieve "Good" or better ecological status in all rivers by 2015 (or by 2027, if there are overwhelming difficulties). By Directive definition, a failure in any one of the elements triggers failure as a whole for the water body. Furthermore, failure of any of the biological components, e.g. fish, triggers failure of the biological element (and thus the WB) as a whole - the one-out-all-out principle.

Conservation objectives and protection of a nationally designated network of sites is achieved through the Site of Special Scientific Interest (SSSI) Network. These underpin Natura 2000 (N2K) sites, but also have objectives in their own right. Designation of these is under the Wildlife and Countryside Act (1981), but that provision has been strengthened by the Nature Conservation (Scotland) Act 2004 and, by the Countryside and Rights of Way Act 2000 (in England and Wales).

In 2000 the introduction of the Water Framework Directive (WFD) established a new framework for the management and protection of rivers, lakes, estuaries, coastal waters and groundwaters. The composition, abundance and age structure of fish fauna are part of the biological element required to meet WFD's Good Ecological Status (GES) in rivers, lakes and transitional waters and Good Ecological Potential (GEP) in Heavily Modified Water Bodies (HMWBs), see Box1.

Hydromorphological conditions in each water body gaining GES must be sufficiently good to support the biological status and are an integral metric for High Ecological Status; many of our regulated rivers (or at least reaches directly downstream from impoundments) have been separately classified as Heavily Modified Water Bodies, required to reach Good Ecological Potential (GEP) under the WFD.

1.5 Climate change

Climate change is a seriously challenging factor which directly affects most aspects of hydro-ecology, particularly river flow and temperature regimes as well as the distribution and species composition of fish communities. Its potential effects are still not fully understood, but they may require a rethink on flow management on many levels. Hence climate change, as a major confounding factor, is a subtext throughout these guidelines. For example, Fig 1.2 is based on an assumption that the historic natural flow represents a stable ideal state. This may still be the case for practical purposes, e.g. multi-decadal scales. However, future potential climate changes may mean that historical data are no longer applicable and it is not clear if normal selection processes act at rates that might cope with environmental change (Fleming and Jensen, 2002). This raises the potential for adaptation management (*cf* Wilby *et al.*, 2010) that might include actively altering flow regimes from what is "natural". Chapter 2 raises the beneficial effect of some artificially altered flows and Chapter 5 outlines the climate issues.

1.6 Terminology

Terminology can cause confusion due to different interpretation. Even the term "flow" can have different meanings to a hydrologist and an ecologist. In this report flow is used as a general term for discharge, the volume of water flow per unit time in channels (generally measured as cubic metres per second, $m^3\ s^{-1}$). As such it is synonymous with the term discharge. A change in river flow usually implies changes in the various hydraulic variables associated with it, such as velocity, depth, wetted width, turbulence etc, which are context specific. The fast-developing field of habitat hydraulics suggests that these are the more direct biotic influences, for which flow is a surrogate, demanding new techniques in computational hydraulics to get to the predictive capacity for environmental management.

The term "Flow Management" is used in the sense that the human activities affect flow and good practice requires some adjustment (management) of the activities to moderate environmental impacts. Flow "standard" is used as a general term for any specified level of flow, flow band or flow regime intended to offer protection to the target biotic group (fish mostly, in this account). "Threshold" is often used as a synonym for standard, when it actually means a level beyond which it is not desirable to go. Other special terms are defined when they first arise.

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CHAPTER 2 - RELATIONSHIPS BETWEEN RIVER FLOWS AND SALMONIDS

2.1 The importance of flow

An appropriate flow regime is essential for the maintenance of healthy and diverse river ecosystems. The natural flow paradigm (Poff *et al.* 1997; Richter *et al.*, 1997; Bunn and Arthington, 2002) states that river biota are adapted to natural changes in river flows, and that disruption to natural patterns will alter river ecosystems. Although animals may show specific adaptations to river discharge regimes, populations are nevertheless limited by the environmental conditions they experience. Alterations in river flow may be to the benefit or detriment of salmon and trout, and it is therefore important for fisheries managers to understand the flow requirements of these species in order to be able to predict the effects of activities that modify river discharge. River flow is the conveyor that delivers to salmon and trout their oxygen and much of their food; it can stimulate and assist both their upstream and downstream movements; it can provide cover from predators by creating depth, a rippled water surface and refuges in high velocities; and it is the medium by which many pheromones and other chemical cues that facilitate a range of crucial life functions are transmitted. It also has direct effects on other habitat features which are important to fish, ranging from channel structure to floral and faunal species composition. The flow regime will therefore have a major influence on the species that a river can support and their relative success; changing river flows can affect individual fish species, through impacts on particular life-stages, and may also affect the species composition of the fish community. This section summarises current knowledge about the effects of flows on migratory salmonids, as a basis for developing guidance on flow regulation.

2.2 Flows and other stimuli

Although it is flow (discharge, the total volume of water per unit time) that is regulated when water is abstracted or released, it is not flow *per se* that fish generally require, nor what they detect. Together, water flow and channel form provide a hydraulic template which river biota occupy (Rosenfeld *et al.* 2007). Hence, salmonid fish respond to hydraulic attributes such as water depth and velocity (Heggenes 1990; Scruton & Gibson 1993; Armstrong *et al.* 2003). These hydraulic attributes depend on topographical characteristics of the river channel, and vary among locations in the river across a range of spatial scales (Stewardson & McMahon 2002). This includes the well known repetition of alternating habitat types such as riffle-pool sequences, which constitute a finer-scale structure on the general clines (Leopold *et al.* 1964; Thompson 1986). Such hydraulic conditions also influence substrate composition, which in turn can affect habitats used by fish. In rivers with broadly natural morphology, mean water depth, velocity and width all tend to increase with distance downstream (Leopold & Maddock 1953; Rosenfeld *et al.* 2007; Booker & Dunbar 2008). With respect to water velocity, this may seem counterintuitive but although headwaters will contain areas of faster velocity, they also contain slow flowing areas. These hydraulic geometry relationships may be used to explain a number of the observations below, which indicate that various activities, including adult movement, spawning and selection of optimum habitats by juveniles, require higher flow percentiles in smaller channels than larger channels.

Fish respond to a range of other factors that are related to flow, including temperature, food availability, turbidity, dissolved oxygen and olfactory cues, as well as season and time of day. Local variations in relationships among these factors and channel hydraulic conditions may make it difficult to define general hydrological rules for ideal environmental flows for river biota (Beecher 1990; Acreman & Dunbar 2004) that apply to all rivers. The historical legacy of channel modification in many rivers adds additional complexity (Brookes *et al.* 1983; Raven *et al.* 1998). Nevertheless, clear general flow requirements of salmonid fish have been established and form a basis for river management. Water temperature is closely linked to flow and is an important variable that can confound the influence of flow *per se* on fish performance, particularly growth. The effects of temperature are not discussed here (see Chapter 6), but it should be noted that the discharge of water from reservoirs can have major effects on temperature regimes within rivers that in turn affect fish survival through processes such as growth, emergence and timing with natural production cycles (e.g. Crisp, 2000).

2.3 Salmonid flow requirements

2.3.1 Movements through estuaries

Information on the conditions favoured by adult salmonids, particularly salmon, on their spawning migration has been provided from radio and acoustic telemetry studies and the analysis of data from automatic fish counters. This information reveals migratory behaviour which appears strongly influenced by flow and temperature, and to a lesser extent by other factors such as levels of dissolved oxygen, although the mechanisms governing orientation and attraction are yet to be fully understood.

Movements of salmonids through estuaries and into freshwater are thought to be stimulated by olfactory cues, the availability of which is likely to be influenced by river discharge; for example studies on the River Tyne (Archer, in press; Bendall *et al*., in press) suggest that movement from estuary to freshwater may also be stimulated mainly by olfactory signals related to flow. Movements in the estuary are often influenced by tidal state (Potter 1988; Potter *et al*. 1992; Smith *et al*. 1994; Solomon *et al*. 1999), with upstream migration being more common on flood tides and fish sometimes dropping back downstream on ebb tides if conditions are not suitable for entry into fresh water. Many studies have shown that movements of salmonids from estuaries into fresh water are related to flow (Solomon *et al.* in press; Bendall & Moore, in press), although as flow and water temperature are often correlated it may be difficult to distinguish the effects of these parameters. Potter (1988) showed that most salmon on the River Fowey entered fresh water at night, and that these fish moved on lower flows than the smaller number of fish moving during daylight hours. This behaviour may reflect a predator avoidance strategy, with fish gaining protection by moving under hours of darkness or under turbid conditions.

Estuarial movements are strongly affected by the topography of the estuary and the availability of holding areas (Potter *et al.* 1992). Thus, in larger rivers salmon may migrate to the head of tide under all but the lowest flows, whereas in smaller rivers they may not even enter the estuary unless flows are above average levels. In larger estuaries, fish may also be able to find holding areas where they can wait for suitable conditions for upstream migration (Solomon *et al* in press), but in smaller rivers they may have to drop back out to sea (Potter 1988) or find refuge in larger rivers nearby (Clarke *et al.*,1991). In the southern part of Britain, salmon that are delayed for more than about ten days within the estuary tend not to migrate into the river until the autumn (Solomon *et al.* 1999). Fish thus delayed may suffer significant losses, and half the stock may fail to enter the river at all in hot dry summers (Solomon and Sambrook 2004). Further north there is less evidence of losses of salmon delayed in estuaries, suggesting perhaps that temperature is implicated in this phenomenon (Solomon *et al.* In press).

Fish exhibiting these different migratory behaviours are likely to face very different threats from marine predators, and there may therefore be marked differences in the survival through this phase of their spawning migration.

2.3.2 Adult migration in fresh water

The up–river spawning migrations of salmonids, generally comprise a number of phases, including an initial rapid movement into fresh water, a quiescent phase made up of long periods of holding interspersed with discontinuous movement, and a final spawning run (Milner, 1990). Solomon *et al.* (in press) suggest that the first of these phases may be regarded as a continuation of the migration which has brought the fish thousands of kilometres in the sea, although it is important to note that the fish's response to currents changes as it moves from the open sea through the estuary and into fresh water. This phase may continue for periods of several days (or even weeks in very large rivers), although upstream movements are often limited to the hours of darkness, with the fish resting in pools during the day.

The initial upstream migration stops when the fish experiences unfavourable conditions, often reduced flows, in the estuary or river. Initiation of a subsequent migratory phase, after a quiescent period, is generally associated with high flow events, although fish may then continue moving on the descending limb of a spate hydrograph, even when flows have reduced to relatively modest levels. Migratory phases also tend to be associated with relatively higher flows as salmonids progress upstream. For example, Solomon *et al.* (1999) showed that the flow required to initiate salmon movement on the River Exe increased from 97% of Q95 at the estuary to 516% of Q95 49km upstream. This appears to be associated with the changing hydraulic nature of the river, with clear step-changes in flow requirements where the river increases in gradient and passes from lowland to more upland topography, as well as at major confluences and barriers (Solomon *et al.* In press).

The final phase of the upstream migration determines the annual distribution of spawning in the river and may thus have a significant effect on recruitment of the next year class. Flow patterns during the year, and particularly in the autumn and early winter, will affect both their spawning location and spawning success. In low flow years, the distribution of spawning, and thus of subsequent parr production, may be severely truncated (Solomon *et al.* 1999).

2.3.3 Physical obstructions

Both natural and man-made obstructions may lead to a build up of upstream migrants in the areas downstream if the flows required to ascend are greater than those required to stimulate migration or to render the barrier passable. Note that flow-movement relationships based on data from electronic counters on weirs may have more to do with the passage of fish past the particular obstruction than with fundamental responses of fish to flow changes (Crisp, 2000) Congregations of fish may expose individuals to greater risks from such factors as predation, poaching and disease, and the right conditions must therefore be provided at the right time of year to aid migration past such obstructions. Fish may also be held up if water temperatures are too high or low as this will affect their ability to generate and sustain the necessary burst speeds to overcome the obstruction (Beach, 1984; Gowans *et al.*. 1999), and they may also be deterred by lights or other structures. Thus, determining the required conditions to aid fish passage is complex because it will depend on the precise nature of the obstruction as well as a range of other factors. However, managing flows to facilitate fish passage may be costly, and there are situations where providing better access past an obstruction, for example by providing a fish pass, may be more cost effective than increasing river discharge.

2.3.4 Spawning, eggs and embryos

The mating success of salmon, and distributions of offspring that they produce, can be expected to depend strongly on the availability of flows to permit adult fish access to suitable spawning areas during the spawning season (see above). Low flow conditions can delay entry to spawning tributaries and reduce upstream penetration (Moir *et al.* 1998). The choice of spawning areas by salmonids is generally considered to be strongly influenced by sedimentary characteristics which are in large part determined by the hydraulic conditions which transport and distribute sediments of different sizes (Moir *et al.* 1998, Moir *et al.* 2002). Thus patterns of flow even at times when fish are not present will be important in maintaining suitable spawning and nursery areas.

Flows utilised for spawning may vary through the catchment, with fish in upper reaches using higher relative minimum discharge than those in lower reaches, and fish in larger rivers spawning in deeper locations with higher velocities (Malcolm *et al.*, in press). Fish may also choose different areas to spawn on a riffle under different flows. There is some evidence that fish may avoid spawning during periods of rapidly changing discharge (Moir *et al.* 2006) which may have consequences for their spawning success. This has implications for reservoir releases above spawning areas.

Salmon and trout bury their eggs in 'redds' in the gravel, and for some time after hatching, the alevins remain in gravel, where they survive primarily on resources from their yolk sac. Flow affects the survival of eggs and alevins in the redd through a range of direct and indirect mechanisms. Although there are concerns that embryo survival can be adversely affected when redds are dried out by low flows or washed out by high flows, it appears that significant impacts probably only occur under extreme conditions (Malcolm *et al*. in press, Nislow and Armstrong, in press). Montgomery *et al.* (1996) suggest that salmonids bury their eggs preferentially at locations and depths where scour from high flows would be least likely to result in loss of ova.

Eggs are also able to withstand substantial periods of dewatering as long as relative humidity and temperature remain within tolerable limits, but oxygen demands increase dramatically post-hatching such that alevins are likely to suffer high mortalities after even relatively short periods of dewatering (Malcolm *et al.* in press). Intragravel survival is also highly dependent upon dissolved oxygen which is affected by the relative contributions of groundwater and surface water in the redds as well as by the deposition of fine sediments (Acornley & Sear 1999; Greig *et al*., 2005). In order to prevent silting in reduced discharges downstream of dams or abstractions the concept of 'flushing flows' is widespread in the setting of environmental flows in the USA.

2.3.5 Salmonid fry and parr

The quality of local habitat for fry and parr depends on how readily fish that occupy it can grow and survive. An increase in water velocity tends to result in an increase in delivery of drifting food, but also an increase in the costs of holding position and obtaining that food (Booker *et al*, 2004). The result of these two opposing relationships is an optimum velocity at which potential growth is maximised. This optimum growth velocity is higher in larger fish and lower in trout than salmon (Armstrong 2010). Survival prospects may also be influenced by flow, for example through provision of a rippled water surface that obscures the visual image of the fish to predators, and factors including water depth and abundance of rough river bed substratum. In principle, overall habitat quality across a range of water flows can be related to population level factors, such as fish number and growth rate, by an understanding of these local energy-gain and survival processes (Finstad *et al*., 2010). Such modelling is important because it links effects of water flow to parameters that are relevant to fishery managers. However, in reality, such modelling also requires incorporation of observations from empirical studies because the overall processes involved are so complex (Armstrong & Nislow, in press).

The timing of fry emergence from the gravel appears to be a compromise between advantages of early establishment of a territory and the increased risks associated with high flow events early in the season (Armstrong & Nislow 2006). Local velocity may be a key factor limiting distributions of fry, tending to constrain them to near-shore low-energy areas in larger rivers. Fluctuations in river height and discharge particularly affect this near-shore zone, and therefore maintaining stable flows at appropriate levels to maximise the marginal habitat zone in late spring and early summer can improve fry survival and growth (McKinney *et al.* 2001). Fry may also be highly susceptible to river bed movement and sediment disturbance caused by high flows.

As salmon parr grow, their size, swimming ability and energy stores increase and therefore reduce their vulnerability to the extensive short-term and seasonal changes in flow. However, on many systems, the effects of density-dependent regulation diminish as the parr increase in size, and there is less opportunity for losses of older parr to be compensated for by increased survival of the fish that remain. Changes in flow affect the landscape experienced by the fish, and local changes in water velocity affect availability of food, shelter and the metabolic costs of feeding and other activities. These factors all influence the growth and survival chances of each fish and hence the overall population strength.

Studies across a range of rivers and streams have recorded local velocities used by salmon and trout fry and parr (Armstrong *et al.*, 2003). Salmon fry (juveniles in their first year of post-emergent life) have been observed to use snout velocities (measured adjacent to the head of the fish) of 0.05-0.30ms^{-1} and mean water column velocities of 0.05-1ms^{-1} and salmon parr (juveniles >1yr old) observed to use snout velocities of 0-0.5m s^{-1} and mean water column velocities of 0.1-1.2ms^{-1}. Trout fry have been observed to use mean water column velocities of 0-0.5ms^{-1} and older trout use snout water velocities < 0.2ms^{-1} and mean water column velocities of 0-0.7ms^{-1}. These figures provide guidelines for the range of local current speeds that should be provided to allow occupation of river reaches by salmon and trout, however, they do not inform on ideal habitat, or indeed exclude fish that were losing condition in the station they were occupying. Numerous studies have shown preference for more restricted ranges of velocities at particular sites or in particular river systems (Heggenes 1990; Scruton & Gibson 1993; Armstrong *et al.* 2003; Dunbar *et al*, 2001). As noted above, factors such as temperature (hence metabolic rate) and food availability are known to affect habitat selection, however the complexity of the processes involved has mean that generic rules on deriving river or site-specific habitat preferences remain elusive.

River discharge affects water depth as well as velocity. Salmon parr tend to use water depths exceeding 0.2m whereas trout parr prefer depths greater than 0.5m (Armstrong *et al.*, 2003). However as depth and velocity correlate (Stewardson & McMahon 2002), separation of independent effects of the two factors on habitat selection is not straightforward. Salmon and trout fry are more typically found in shallower water but may overlap extensively with depths used by parr. It is not clear to what extent shallow water is preferred by fry or whether it is used because fry are excluded from deeper water. Some salmon parr respond to local abstraction by moving to deep areas whereas others become stranded and die (Armstrong *et al.*, 1998 and references therein). Salmon parr may coexist in pools with brown trout during temporary low flow events, but are then exposed to high stress from competitive interactions (Bremset and Heggenes, 2001;Stradmeyer *et al.*, 2008).

The effect of a change in discharge depends both on how the local habitat is populated by fish of different sizes, and how it changes local velocities and other habitat parameters in relation to optimum conditions. In addition, factors such as bed roughness are likely to be important in determining how the range and abundance of local velocities vary with river discharge. The optimum velocity for growth tends to be lower in fry than parr and in trout than salmon. However, there is extensive overlap in habitat use among these groups and there is potential for competition within and between year classes of salmon and trout and between the species. Therefore the effects of a specific change in discharge can affect each year-class both directly and indirectly through its effect on competitors.

The combination of recruitment strength and the nature of the habitat structure is thought to determine the bottlenecks in the life-cycle at which the strengths of salmon and trout populations are determined (Armstrong & Nislow 2006). In some cases, the availability of suitable low velocity areas for the early fry stage is the limiting factor, whereas in others the availability of habitat suitable for larger fish constrains smolt output. For example, there is evidence from Spain of populations of trout being limited by flow conditions at the fry stage (Lobon Cervia, 2004) whereas Solomon and Lightfoot (in press) noted that while 0+ salmon parr performance in the Hampshire Avon was correlated with flows throughout the summer, the best fit was with August flow suggesting that habitat for relatively large fish was most limiting. Management of water provision requires awareness of the initial need to favour requirements of the limiting life stage over others, but also of the fact that manipulation of discharge, through its effect on habitat structure, can itself have the potential to change the life stages at which bottlenecks occur.

Despite this complexity, some general effects of variation in discharge are clear cut. For example, changes in flow often affect the wetted area of stream and water depth that are particularly important in providing cover. Extended periods of low flows may reduce the area of nursery habitat available for juvenile production in smaller streams, but may enhance production in larger rivers. Furthermore, it appears that parr do not migrate out of the rivers under these conditions (Riley *et al*. 2009), but tend to become aggregated and subject to increased intensity of competition (Stradmeyer *et al.* 2008). Empirical data from a relatively small stream suggest that production of Atlantic salmon and brook trout increases steadily with flow rates in spring, summer and autumn, but decreases with winter flow (Armstrong & Nislow, in review). However, it is predicted that these relationships for the spring, summer and autumn seasons would break down when considering large rivers in which much of the near-bed space is occupied by current velocities that exceed those favoured by salmon and trout fry.

2.3.6 Smolt emigration

Smolt emigration is a critical phase in the salmonid life-cycle. Smolts may be vulnerable to a wide range of factors and losses may be expected to have a directly proportionate effect on adult returns because subsequent mortality in the sea is not thought to be density dependent in most situations. Emigration depends upon the physiological and behavioural preparedness of the fish as well as the conditions in the river. Although emigration is often associated with increased flows (Nislow and Armstrong, in press), this may not be the main factor stimulating smolt movements since in many rivers, smolts appear to be affected more by the water reaching a threshold temperature. Nevertheless, low flows will generally delay smolt movements. Flows must therefore be of a sufficient magnitude to aid passage downstream and through the estuary, and may be critical in helping smolts pass particular barriers or negotiate lakes. Delays in emigration may result in smolts being more vulnerable to predators (Nislow and Armstrong, in press), missing the optimum time for entry into the sea (Solomon *et al.* in press) or losing their physiological and behavioural preparedness to migrate. Major delays in migration may increase the risk of coincidence with low summer discharge, low DO and higher pollution levels in estuaries (Cave, 1985: Crisp, 1987).

2.4 Effects of flows on ecosystems

In setting discharge regimes for salmonids, consideration should also be given to effects on other components of the broader aquatic community, including other fish species. Rather little is known about the specific flow requirements of other diadromous species and coarse fish. Some information has been obtained from population surveys which suggest that the cohort strength of coarse fish species such as roach and dace tends to be good when flows are stable during and after spawning but is reduced if major floods occur at this time. In contrast, some species require high flows to take advantage of marginal or flood plain spawning. The effects of flow at other life stages are less clear, and many fish species may be affected more by proximate factors such as temperature and dissolved oxygen (e.g. Mills & Mann 1985; Mann 1996), although these may be partly correlated with flow.

Other ecosystem components, on which salmonid fish depend, also respond to flow, including macrophytes (Suren & Riis 2010; Wilby *et al.* 1998; Franklin *et al.* 2008; Riis *et al.* 2008), macroinvertebrates (Extence *et al.* 1999; Gjerlov *et al.* 2003; Monk *et al.* 2006; Dunbar *et al.* 2010a; Dunbar *et al.* 2010b) and algae (Biggs & Close 1989). As a result any management of flows need to take account of the potential effects on all components of the ecosystem and the interactions between them.

Management of river flows in the context of the EU Water Framework Directive needs to take account of the natural variation in fish communities and the differences in their flow requirements. To this end a model has been developed (Cowx, pers comm.) based on fish survey data from notionally pristine reference sites in the national monitoring programmes in England and Wales. The model discriminated eight major fish community types that were characterised by different hydrological regimes, in addition to geomorphological conditions prevailing in the river reaches and broadly followed the classical zonation theory (e.g. Huet, 1959). This indicates that it should be possible to predict what the most likely fish community type is along a continuum from headwaters to lowland reaches. The results suggest that it is not only volume of flow but a combination of volume, rate, extremes and variability of flow that regulate fish community, and probably also population structure through habitat requirements at different life-stages (Poff *et al.*, 1997). Flow variability has been viewed by some as the primary factor in stream ecology (Resh *et al*, 1988), and in determining river ecosystem structure and function (Poff and Ward, 1989). Artificially induced flow variation, for example from hydropower generation, may create a regime of more frequent pulses which cause disturbance, or increased rates of change which result in more strandings of fish (Archer, 2004, Archer and Williams, 1995). Both flow variability and rates of change may require consideration as part of flow standards.

2.5 Implications for management

It is evident that there is no simple general relationship between river flows and population production of salmon and trout that is likely to inform assessments of required discharge regimes in all rivers. Rather, it is necessary to consider the size of the river or stream and the nature of the habitat within it to determine what life stages are likely to be limiting overall production and whether decrease or increase in discharge is likely to have a positive or negative effect. Furthermore, water flow should not be considered in isolation of other important factors, such as temperature, which affect the processes involved in population production. For example, such factors may mean that fish respond differently to the resulting discharge when a high flow is reduced by abstraction compared with the same discharge achieved by supplementing a low flow with a reservoir release.

There is abundant information on the biology of salmon and trout that can be used to inform management decisions on setting discharge regimes. However, we are some way from having appropriate models to use as tools for precise assessment across a broad range of river types (Armstrong & Nislow, in press). It is therefore appropriate to manage situations on a case-by-case basis and to adopt an adaptive management approach whereby flow regimes are set using initial predictions of salmonid population response and are then tested to determine whether further modification of discharge is appropriate in an iterative process.

In assessing a particular case, there are likely to be specific pinch-points in the lifecycle where flows are limiting, and these will vary among rivers and fish stocks depending upon co-existing species, and the range of habitat and environmental conditions available. Identifying the limiting life stage for the population as a whole and modifying discharge to increase survival at this stage is an important starting point.

However, ultimately, optimising discharge regimes to maximise numbers of adult salmon and trout requires integration across requirements of the life stages and may usefully employ some form of life cycle modelling. At some times of year, discharge requirements may be unambiguous. For example, during spring, the provision of fluctuating relatively high flows may be required to assist both with emigration of smolts and to attract early-running salmon into rivers. However, at other times there may be conflicts. For example, it would usually be favourable to maintain a steady, modest discharge during the period of emergence and early fry growth in June, but this strategy may reduce availability of spates to attract early running grilse into the river. Suitable protocols might be possible if it can be established that fry shelter provides adequate protection during transitory flow spikes targeted at attracting adults upstream. However, a degree of trade-off may be required in that high discharge and stability for fry may be at a cost of reduced movement and possibly survival of grilse. How this scenario would map onto conservation status of the population would depend on its overall strength in terms of sufficiency of spawning fish.

2.6 Principal knowledge gaps and recommendations for research

There is considerable understanding of the biology of the early life stages of salmon and trout in relation to habitat requirements, and numerous studies have demonstrated preferential habitat use of particular water depths and velocities by drift-feeding salmonid fry and parr (Heggenes 1990; Dunbar *et al*., 2001; Armstrong *et al*., 2003). These relationships are exploited in the development of physical habitat models which describe how physical habitat quality/quantity for chosen target species and developmental changes vary with flow. But the difficulties in translating measures based on empirically-defined habitat quality into more useful measures of production and long-term population viability have limited our ability to apply this knowledge to make predictions of discharge requirements.

Tracking studies have also revealed that salmon migration has broad common principles and, for example, that flow requirements for salmon vary systematically up rivers, but the particular flow regimes and physical features of different rivers can cause significant local variations. Since it is not practical to conduct studies on every river, methods to transfer information between (and within) river systems are vital for the sound management of river flows.

Coupling of process-based and empirical models across a range of river types has been advocated as one way forward (Armstrong 2010, Armstrong & Nislow, in press; Booker *et al*., 2004). This approach will require experimental manipulation and/or monitoring of discharge regimes of a range of rivers together with measurement of individual growth, survival and migration of fish. Information to assist in these studies might also be available in archives of national population monitoring programmes and tracking studies, and priority should be given to making best use of such existing data before initiating new targeted studies. This approach might ultimately overcome problems with transferring information across river systems through enabling the general modelling approach that is not feasible with existing understanding.

Integration of the effects of discharge across the salmonid life-cycle is also required to develop models that evaluate simultaneous impacts and benefits. For example, can the fry stages tolerate spikes in discharge for attracting grilse up river? Does abstraction of water in winter to improve survival of parr to smolts (Armstrong & Nislow, in press) interfere with spawning and survival of eggs? There is also a need for more consideration of the uncertainties in the modelling of fish-flow responses to enable the better assessment of risks and uncertainties in decision-making.

There is a large capacity for regulating water flows in areas of UK in which rivers regulated by impoundments. A priority action is to explore opportunities and develop research programmes using such heavily modifiable systems to develop a platform for the experiments and associated monitoring required to address key deficiencies in our current understanding.

2.7 Summary of recommendations:

1. Develop generalised models for transferring information on salmon flow requirements between river systems, likewise the flow requirements for critical habitat quantity and quality metrics.
2. Investigate the potential for coupling process-based and empirical models, based on experimental manipulation and/or monitoring of discharge regimes of a range of rivers together with measurement of individual growth, survival and migration of fish.
3. Give priority to making best use of existing information from archives of national population monitoring programmes and tracking studies to assist in developing models of salmon flow requirements before initiating new targeted studies.
4. Undertake modelling of the integrated effects of discharge across the salmonid life-cycle in order to evaluate the impacts and benefits of proposed actions at population level.
5. Explore opportunities for undertaking studies on the effects of flow regulation and manipulation through adaptive management and develop appropriate research programmes

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CHAPTER 3 - ASSESSMENT OF IMPACTS FROM ALTERED FLOWS

3.1 Introduction

It seems intuitive that fish and flows are inextricably linked. However, the relationships between fish and flows are often hard to demonstrate, inconsistent, highly variable and confounded by other factors, notably the influence of flow on physical habitat or hydromorphology. There are many reasons why establishing such relationships is problematic. For example, quantifying fish movements and identifying their impact on populations is extremely complex. Salmon are highly mobile and may simply move from one area to another to find flow-related conditions of their liking. In addition, impacts may not be as simple as changes in mere abundance; effects on lifetime fitness through survival, age structure and reproductive capacity involve subtle and still poorly understood genetic and phenotypic responses. Other impacts unrelated to flow such as other freshwater environmental factors, high seas survival or exploitation may also confound and confuse attempts to separate out the specific influence of flow parameters. The complexity and variability of these and other relationships mean that:

a) current models do not transfer well between systems
b) sophisticated approaches involving good design are needed to identify flow effects
c) inevitably, there is still a lot of uncertainty and therefore risk associated with decision-making
d) the understanding of biology and ecology is often too poor to model processes in ways that have widespread practicable application.

Whilst all of this may be confusing to the scientist and frustrating to the water resources manager, it does not mean that there is no direct and measureable link between salmon and their flow requirements. Indeed, progress has been made using a variety of approaches to inform policy (see Section 4.4) and with future improvement in understanding models and their application will improve. The purpose of this chapter is to:

A. Provide a range of evidence on artificial flow impacts from case studies
B. Define the relevant metrics which need to be measured in order to predict flow-driven effects, including the current wider regulatory brief of 'hydromorphology'
C. Summarise existing method/protocols to assess flow impacts
D. Evaluate impacts, problems of spatial scale, uncertainties and risks
E. Provide recommendations for future management of flows

3.2 Evidence of impacts from artificially altered flows

While it is easy to demonstrate that no water equals no fish, thereafter the complexity of the relationships and the other sources of natural variability make predictions of flow responses difficult and uncertain. Chapter 2 has outlined the influence of natural flow variation on salmonids, here the evidence of impacts from artificially altered flows is examined with a focus on direct flow alteration rather than flow modifications arising from changing land use and urbanisation.
There are two categories of flow modification to consider.

(1) Abstraction, in which water is removed from the system whether directly from the channel or via groundwater resulting in reduced flows. Management of these impacts is termed *restrictive,* because limits are imposed on volumes and regimes of water removal.

(2) Regulation, in which flow is controlled by a structure such as a dam or weir and may be increased above what might normally be expected as well as decreased. Hydropower, flood protection and indeed water supply schemes can all involve increases in flow, sometimes substantially above seasonal norms. While restrictive management may apply, flow regulation also requires *active* management, in which flows are augmented by compensation releases.

In contrast to hydropower generation, water supply reservoirs tend to reduce the variability in downstream flow leading to more stable flow regimes (Brooker, 1981). Hence, there is the potential for too much water to be damaging as well as too little. The evidence of impacts under these two categories is summarised below.

3.2.1 Abstracted Rivers

Referring back to the easy end of the spectrum, no water = no fish, there are several studies of heavily modified rivers below dams and weirs that are obviously excessively abstracted. Two intensively examined examples of this extreme situation are found in the upper reaches of the River Ribble in North West England on the rivers Brennand and Whitendale. The Victorian abstraction on these two rivers facilitates a full take of the entire flow below a certain fixed level, leaving the riverbed dry and fishless for several hundred metres downstream under normal dry weather flow summer conditions. Despite this extreme modification of the flow regime juvenile salmonids (trout) are found within a few metres of the emergence of the accreted 'new flow' in very shallow water, quite literally interconnected puddles between boulders. These fish are present in low densities year on year when surveyed during 'normal' dry weather flows, when the full flow is taken upstream by the abstraction (Hendry & Bellamy, 2003). Salmon only appear to colonise the lower reaches of these tributaries sporadically, with the higher winter flows (seemingly unaffected by the abstraction) being the key feature determining the extent of adult spawner penetration into the lower few hundred metres of the two rivers. So there is good evidence of flow related impact on trout in these tributaries. However, in this instance it appears to be relatively localised, of the order of several hundred square metres and would not appear to be a limiting factor on salmon juveniles for the catchment as a whole.

Similar examples can be found in Scotland where water has been diverted for the generation of hydro electricity. For instance, in the Tay catchment the total flow of the River Garry is diverted via the Garry intake into Loch Errochty, and in the Spey catchment the flow of the River Cuiach below Loch Cuaich is also captured for energy production leaving a section of river where the only flow is that which accretes from the catchment below the Loch. In each of these cases a man-made barrier blocks access by migratory salmonids to prevent stranding, but small populations of brown trout are known to be present in the sections immediately below the point where accreted flow first appears (Stephens *pers. comm.*).

Evidence for the effects of low flow on other fish species is available from a detailed study undertaken to examine the effect of groundwater abstraction on chalk streams of Southwest England. Bradley *et al*. 2003 demonstrated that statistically significant impacts on bullhead densities were apparent when groundwater abstraction resulted in a deviation of greater than 15% from modelled naturalised flows. The bullhead is a comparatively sedentary species, but was more significantly affected than the invertebrate community. While this study also demonstrated some potential for flows to impact (only significant at a limited number of sites) on stream carrying capacity of trout, no statistically significant effects were found on juvenile salmonids.

Abstraction can have an impact on adult migration. Substantial evidence of delays to adult salmon migration caused by low flows and implying impacts from abstraction was found by Solomon, Sambrook & Broad (1999), who undertook an extensive evaluation of long term radio telemetry studies on six rivers in South West England.

3.2.2 Regulated Rivers

There is also evidence to suggest that regulated rivers can have an impact on salmonids, where flows maintained at an excessively high level can reduce juvenile production. An example is the River Wolf, a tributary of the Tamar in South West England, which receives water from Roadford Reservoir destined for abstraction many kilometres downstream. Over a period of almost 20 years, detailed electric fishing investigations showed that in the Wolf downstream of the dam, the unseasonal high flow released during summer months appeared to reduced numbers of fry when compared to data from before dam construction and adjacent control rivers. This was thought to be attributed to increased depth and velocities rendering much of the habitat unsuitable for salmon fry. Conversely, salmon parr numbers (standing crop) increased compared with previous data and control rivers, the modified flow regime providing enhanced parr habitat (Sambrook, pers. comm.).

Similarly, on the River Tromie, a tributary of the Spey in Scotland, flows are maintained at an artificially high level (Q_{60}) and some sections of habitat which would otherwise be suitable for juvenile salmonids are currently unutilised, probably due to the excessively high velocities and depths experienced. This in turn is thought to have an impact on salmonid production (APEM, 2010).

Whilst abstraction impacts seldom occur at the higher flow extremes, geomorphological effectiveness (focused in high flows) is considerably impacted by regulation simply because 'dams store floods'. There is thus an extensive literature covering the downstream impacts of reduced formative flows created by regulation (see Petts, 1984 and the subsequent journal 'Regulated Rivers: Research and Management').

There is also evidence of impacts from too large a flow on fish populations from the Welsh Dee, one of the most significantly regulated rivers in the British Isles (Hendry & Cragg-Hine, 1998). The system is heavily modified with extensive reservoir systems in the headwaters used both for flood storage and for potable supply via releases to support abstraction in the lower reaches. Unnaturally high seasonal flows (augmented for abstraction) and the dampening of freshet flows were thought to be major factors negatively influencing both adult and juvenile salmon populations. Coarse fish populations were considered to be severely impacted by the higher augmented flows experienced, which negatively influenced early life stages during critical early summer periods.

3.3 Metrics

There is evidence from a number of studies in the British Isles that suggests the major impacts on fish populations arising from flow modifications by both abstraction or regulation are concentrated towards the extremes of the flow range. These may be both positive and negative impacts. Conceptually, any flow-dependent metric such as depth, velocity, wetted width, substrate size etc will provide an optimal range of conditions for fish, associated biota and their habitats. Outside this range suboptimal or even unacceptable conditions may exist with corresponding impacts on the biotic receptors.

Thus, both the lower and higher extremes of flow are likely to contain habitats which lie outside the useable range in the fish-flow relationship. Arguably it is the suboptimal and the associated response of fish to conditions around the suboptimal-useable boundaries that require detailed examination to assess the impact of flow change on fish populations.

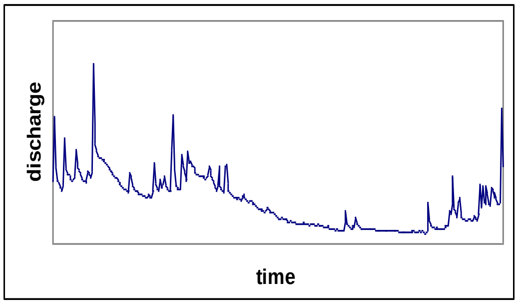
When attempting to understand the impacts of a particular change in flow on fish populations in a specific river, the key question is what should we measure? There are two main areas where metrics are required to establish cause and effect (see Chapter 1). These are:

- Hydrological and geomorphological metrics (i.e. the y-axis in Fig. 1.2) and
- Salmon population metrics (i.e. the x-axis in Fig.1.2)

3.3.1 Hydrological and Geomorphological Metrics

Rivers are characterised by the relatively rapid movement of water along a defined channel and this movement can be quantified in terms of a range of hydrological metrics. Water resource engineers have historically been involved in managing water volumes and their availability for public supply, irrigation or release through hydropower turbines. They have thus used volume per unit time as discharge (flow), usually in units such as cubic metres per second (m^3s^{-1}) or megalitres per day Ml/d (mgd is usually millions of gallons per day). Therefore, fish-flow impacts need to be scaled up from hydraulic detail to be expressed in terms of volume flow that have relevance to operational practice; even though aquatic organisms are known not to respond directly to available flow (discharge), but to the availability of suitable physical habitat arising from changes in depth, velocity and sediment deposition (Parasiewicz & Dunbar, 2001). Thus, in order to elucidate the ecological impacts of flow, practitioners must first be able to predict how changes in discharge translate to the quality and quantity of functional habitats required to fulfill the requirements of not only species, but also distinct life stages.

Variations in discharge with time define a discharge hydrograph (Fig 3.1). For water resources applications, flow hydrographs can be summarised as flow duration curves that relate flow to their probability of exceedance. This removes the temporal sequencing in flows because the process of producing a flow duration curve involves putting flows in rank order rather than historical order. Flow duration curves (Fig 3.2) provide a set of consistent metrics of flow, for example Q_{95} (the flow exceeded 95% of the time) provides an arbitrary but repeatable measure of low flow.



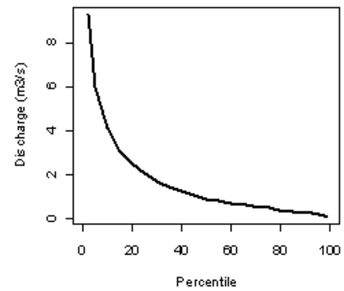
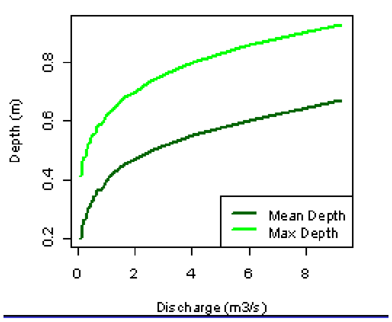


Fig 3.1 Discharge (flow) hydrograph **Fig 3.2 Flow duration curve**

Flow and its relationship to duration curve statistics are widely used to manage rivers through licensing, there being over 2000 gauging stations throughout the UK, since flow can be related to user volumetric abstractions. Flow is also recognised as being important to water quality as it provides a direct measure of dilution. However, it is less useful as a biological metric because species do not sense flow directly. Species respond to hydraulic variables, such as depth (Fig 3.3) and velocity (Fig 3.4) (See Chapter 2). Change in these variables with change in flow may be measured directly or predicted using hydraulic models calibrated to one or more flow observations. They also feature in a traditional research branch of geomorphology – hydraulic geometry, which relates dimensional characteristics of channels to flow both 'at-a-station' and downstream.



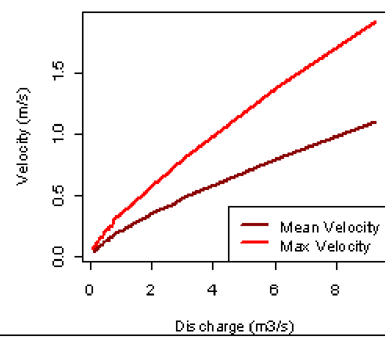


Fig 3.3 Changes in depth with discharge **Fig 3.4 Changes in velocity with discharge**

Some relationships between hydraulic variables are linear whereas others exhibit non-linear changes in slope, such as that between flow and river wetted width (Fig 3.5). The shape of such curves is controlled by the form of the river channel; where vertical banks are present there will be little change in width with change in flow, but when water is restricted to a shallow cross-section bed, there will be considerable change in width with change in flow. Analysis of a number of sites where physical habitat models for fish had been defined (Booker and Acreman, 2007) showed that the change in the relationship between flow and width varied, but was found at about Q_{95} for many (Acreman, 2010) (Fig 3.5). This point of change in the relationship might seem to reveal a simple feature of river channel shape but it does not necessarily represent a biological threshold because, for example, Q_{95} could be below the critical level of another metric (such as depth) for fish. There are many hydraulic-habitat models (of which PHABSIM – physical habitat simulation system is the most well known) which combine hydraulic predictions with information on the suitability of different hydraulic conditions for target species such as salmonids.

Assessing the full range of flow impacts must encompass the influence of discharge on (hydromorphological) habitat quantity –and quality i.e. hydraulic geometry. This relationship defines local flow diversity, assumed to be essential for the range of life stages and life functions of fishes and their food. It is partly captured in the recently defined and calibrated concept of hydraulic biotopes (Padmore, 1998; Newson and Newson, 2000). Hydraulic biotopes are a development of frequently-used descriptors of flow types, such as rapid, riffle, pool and glide; hydraulic measurements beneath these surface flow patterns have revealed significant differences between them. Using the metrics derived from for example biotope diversity, it is simple to conclude that, if fish and other biota 'prefer' habitat diversity, they are best served by flows at least Q_{60} or higher.

Nevertheless, the observations from hydraulic geometry are more easily transferable and, until greater details of fish preferences are revealed Q_{95} may in fact have a level of ecological significance and is not merely an arbitrary statistic derived from a flow duration curve.

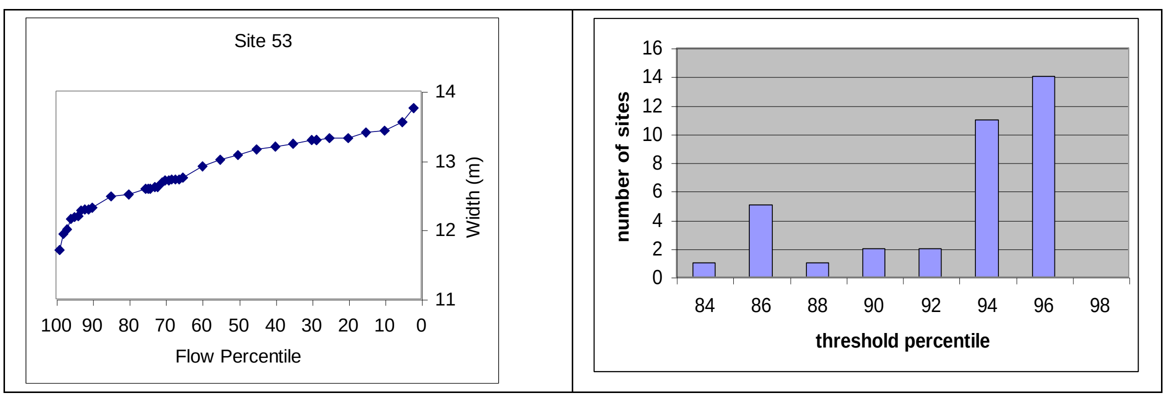


Fig 3.5 (Left) Typical relationship between flow and wetted perimeter at a single location. (Right) Frequency distribution of threshold flows at which the slope of the Q/wetted- perimeter line changes sharply, for 66 sites. From Booker and Acreman (2007).

The hydraulic variables referred to above are themselves determined by the interaction between flow and channel geometry. These variables include geomorphological parameters such as gradient, channel roughness (bed sediment size), width and shape. Data on river channel geometry, component features and the interaction of these elements with flows are scarce in the UK and there are no regular monitoring sites for the sediments transported. As a result, the information to predict physical habitat in UK rivers (and from which to set environmental flow regimes) is missing or uncertain. Under these conditions, applications

requiring geomorphological parameters have often had to accept rather coarse river channel typologies which no longer stand up to scrutiny (Newson *et al.*, 1998; Jeffers, 1998). These typologies may appear logical n that they combine channel gradient, size of the sediments on the bed and the condition of the banks but, where detailed research has been done on habitat processes, it has been shown that a much finer spatial approach is required. It was for this reason that river flow 'patches', identifying hydraulic biotopes were first developed. Meso-scale physical habitat models attempt to conceptualise these links (Parasiewicz and Dunbar 2001, Parasiewicz 2007).
Aside from developing an expensive and time-consuming geomorphological field survey for each environmental flow project (though this is becoming common – for Fluvial Audit techniques, see Sear *et al.*, 2010), there are two principal sources for *some* of the necessary data:

- The River Habitat (walkover) Surveys of the Environment Agency in England and Wales, recording for each 500m reach the major dimensions, features and flow types (surrogate hydraulic biotopes), both as a series of transects and as a 'sweep up' for the whole survey length;
- Available remote sensing and GIS resources at sufficient scale to show channel detail (for Ordnance Survey maps 1:10,000 or greater resolution) (Winterbottom and Gilvear, 1997; Hardy, 1998).

Neither of these two categories of survey sources provides hydromorphological interpretations available for a minority of river systems from Fluvial Audit (Sear *et al.*, 2010) but there is current progress to integrate them to provide a better information base for linking to biological data (Newson *et al.*, in press). Hydraulic biotopes, having been added to walkover surveys as 'flow types' in the River Habitat Survey technique, have now been used to predict habitat quality for a range of species. This approach is not limited by having to employ expensive walkover surveys: flow depth and bed sediment size can increasingly be derived from high-resolution aerial photography and, via hydraulic models the third major component variable, velocity, can be derived.

Another problem which frustrates incorporation of geomorphology in flow-setting procedures is that channel form and process both affect and are affected by flow discharge. This makes for highly nuanced and site-specific impacts but also relates to debates over higher flows (geomorphology a dependent variable) and lower flows (independent variable). Another developing field of geomorphological research is that relating to channel bed habitat damage from siltation and the resultant desire to modify channels or release patterns from reservoirs to effect 'flushing flows', cleansing the interstices of the substrate.

3.3.2 Metrics of salmonid populations:

Whilst many biological metrics have been used to good effect to measure the responses of individual fish or populations to changing flow regimes in research contexts, comparatively few are of routinely practical value. The attributes of useful metrics include:

- *Responsiveness*: having direct sensitivity to flow (or hydraulic) variables that can be related to the discharge metrics employed for regulatory management.

- *Significance*: having known impacts on the lifetime fitness of individuals (e.g. expressed through growth or survival), or fitness of populations (e.g. expressed through population growth rate, diversity and resilience).
- *Feasibility and Measurability*: capable of being measured, repeatedly, in diverse locations, with reasonable statistical power and at reasonable cost.

Table 3.1 Summary of common metrics having application to measuring flow impacts on salmonid fish. Code: NA – not applicable; Responsiveness (* low, ** medium, ***high); Significance (+ low, ++ medium, +++high); Feasibility (£ low, ££ medium, £££ high);? not sufficiently well understood to assess

	LIFE STAGE				
METRIC	**Eggs**	**Fry/parr**	**smolt**	**Adult (resident)**	**Adult (migrants)**
Population size	**/+/£	***/+++/£££	?/++/£	***/+++/££	NA
Run size	NA	NA	NA	NA	***/+++/£££
Survival	**/+/£	***/++/££	?/++/£	***/+++/£	**/+++/£
Growth/energetics (of individuals)	?/++/£	***/++/£	?/?/£	**/?/£	**/?/£
Behaviour (of individuals)	NA	***/++/£	?/?/£	***/?/£	***/++/££

These are demanding criteria for a discipline such as salmonid fish biology dealing with widely dispersed populations, species with high phenotypic plasticity (i.e. capacity to adapt life histories, morphologies and behaviours in response to pressures) and a high natural variability. Nevertheless, flow is one of many environmental and man-made pressures and in principle its assessment should be tractable, even if complicated by a wide variety of confounding factors and complex ecosystem pathways that may lead to indirect impacts on fish (see Fig 1.1).

Some of the likely candidate metrics are listed in Table 3.1 classified subjectively by responsiveness and feasibility. There are inconsistencies in such summaries that require more detailed explanation than is possible here. For example, eggs have great significance for the size of future populations, yet their patchy distribution around catchments makes the assessment of consequences of local impacts very difficult. Thus, while egg survival estimation is feasible, the significance of low egg survival at a site for the population as a whole is probably quite low. The same argument could apply to parr; but in their case it is more feasible, with good stratified survey design, to measure population level effects.

Also, a distinction should be made between early fry (within a few weeks post-emergence) and older parr. The former are likely to have any flow-mediated effects on abundance moderated through density dependent survival; while the latter are more likely to show proportional effects on the population, because most density-dependence regulation has happened by that stage.

Habitat measurements are essential for assessment of flow impacts on resident juvenile or adult populations for two reasons. First, flow has a direct and important effect on the physical habitat of channels through hydraulic variables, width, depth, velocity. Second, salmonids occupy different habitats during their life time and at any one time display complex dispersion patterns mediated by behaviour, which means that a wide variety of habitat types is needed to support populations, each of which may respond differently to flow change (see Chapter 2).

Any of the metrics in Table 3.1 might serve as potential indices of flow impact, normally with no translation to population effects. However, to fully describe and understand the effects, or to determine optimal flows in ways that might be used in cost-benefit analyses, requires extension of the effects to the consequences for populations and this can be difficult. The scale of assessment determines this difficulty and this is determined by the particular scheme. Scale may range from small, such as a small isolated tributary or a low head HEP scheme, to large, such as a major main stem impoundment or a catchment abstraction scheme.

In population terms the direct impact of flow manipulation can be measured in terms of egg deposition either directly in terms of the number of spawners or on egg survival, juvenile production (either as density / biomass of resident juveniles) and /or in terms of smolt output. The impact needs to be assessed in terms of:

1) the change in local population status and,
2) at the catchment scale on the river's breeding population.

This change must be evaluated against the ability of the population to persist at desired levels (e.g. salmon conservation limits). Scale of assessment is a constraint. In some cases, for example in relation to an abstraction on the river downstream of the main juvenile production area, the change in population can only be evaluated at the catchment level, either as smolt output and/or as returning adults.

The assessment of impacts will need to take into account how the change in flow will affect the salmonid population with regard to its current designation of ecological status under the Water Framework Directive and under the Habitats Directive (if the site is a designated feature). Any investigations must be sufficiently detailed to be able to detect impact change from flow modification from those changes in the population controlled by natural processes and/or other impacts such as fishing.

For abstractions impacting upon the quantity and/or quality of juvenile habitat (either in terms of depth, velocity or wetted area), the scale (surface area) of the impacted stretch and the current status of the population needs to be determined using appropriate and standardised sampling design protocols. In each case, the level of accuracy and precision of assessment needs to be defined and agreed between the developer and the regulator. For main river abstractions however, the scale of the impact needs be measured at the catchment level, due to the potential for the development to potentially impact upon salmonid production throughout the catchment.

3.4 Salmon production versus flow – a summary of existing method/protocols to assess flow driven impacts

While a detailed examination of the existing methodologies to determine 'environmental flows' lies beyond the scope of this report, several papers have previously addressed this subject and a useful review is provided by Acreman & Dunbar (2004). Of the range of methods available, each is acknowledged as having its own specific applications, resource and cost requirements and indeed limitations.

In the days before extensive flow gauging networks (ca. 1960's) and the flow predictions (floods, low flows) derived from the now extensive database on flows, either simple guesswork ('engineering judgment') was used to set flows or – as still prevails in the developing world – a consensus is approached about the flows desirable at pinch-points in the channel network. There has been a considerable breakthrough in our ability to model flows, hydraulics and hydraulic geometry, facilitating continual updates and improvements. Such models include software that provides a complete package of options for hydraulic-habitat modeling such as PHABSIM, RYHABSIM, and derivatives, and catchment hydraulic models coming from a flood risk background (HEC-RAS, MIKE 11, ISIS), which can provide some of the hydraulic predictions (e.g. water depth) which can be used to calculate physical habitat using external software (Dunbar *et al*. 1997; Booker *et al*. 2004).

With respect to salmon, hydraulic habitat models such as PHABSIM have been used extensively to predict changes in habitat quality and quantity in response to variables of discharge. These methods however focus on microhabitat. Some studies have modeled microhabitat at sub-catchment and catchment scales (e.g. Booker *et al*. 2004), and in other cases have linked to salmonid production models (Bartholow *et al*. 1993; Van Winkle *et al*. 1998; Capra *et al*. 2003; Goraud *et al*. 2004; Railsback *et al*. 2009; University of California Berkley & Stillwater Sciences 2009). However these studies tend to be expensive and the implications of microhabitat loss for production are not entirely clear (Anderson *et al*. 2006). Meso-scale habitat models have emerged as an alternative description of physical habitat preference (Borsányi 2004; Eisner 2005; Harby *et al*. 2007; Parasiewicz, 2007). These models use a broader description of physical habitat than microhabitat variables, their fundamental unit of habitat description being the mesohabitat (patch or biotope). Such methods have several potential advantages, although currently, because they are based on directly on mapping surveys rather than hydraulic model output, they are limited to prediction within the range of observed conditions.

The above methods require considerable data input. Approaches based on mapping can cover larger areas more quickly than those where data collection procedures are prescribed by the requirements of hydraulic models, although there are issues of subjectivity (Poole *et al*., 1997). Both microhabitat and mesohabitat approaches may benefit in future from the use of remotely sensed data on channel forms and hydraulic biotopes, for example using and multispectral aerial videography (Panja, 1994) or high resolution still photography (Clough *et al*., 2010) and LIDAR. There is a clear need to make available a broad toolbox of techniques for salmonid environmental flow assessment, and in the future, remotely-sensed data, providing it can be made sufficiently available, will clearly play a part.

The above techniques tend to assess the direct effects of changing flows on physical habitat. The focus of their application has tended to be on low rather than high flows, but there are examples both of the same models applied to investigate the negative effects of high flows (e.g. Booker 2003) and to provide flushing and channel maintenance flows (Hill and Beschta, 1991). Siltation of gravels during low flows and maintenance of an appropriate flow regime to mimic natural sediment transport are increasingly becoming important, requiring development of generic tools.

It should be noted that the PHABSIM-type approach, which has been widely advocated (see above), is contentious and has been subject to criticisms on scientific grounds,(most recently Finstad *et al.,*2011, but see also Marthur *et al.*; 1985; Railsback, 1999; Moir *et al.,* 2005 and many others). Some of these arguments are based on fundamental conceptual issues, others may reflect misunderstandings over the intended applications of the methods. In any event, this is an important continuing debate in the hydroecology arena, often sidestepped by managers, about which the workshop did not find a consensus or have time to follow through and does not attempt to offer a full account here.

3.5 What level of impact is acceptable? Evaluation of impacts, problems of spatial scale, uncertainties and risks

If changes in flow affect the conservation of salmon populations (e.g. by reducing spawning escapement) or the users of the resource (e.g. by reducing catches), regulators need to know what level of change is acceptable when determining the amount of water that they can take. A definition of acceptability is difficult to quantify. The decision on what is acceptable is often a societal decision, but scientific guidance is required to inform management about the risks of such decisions to fish populations. An important precursor to defining acceptability is to establish some quantified relationship between the management objective and the practical metrics for the target fish. An example of this is found in salmon fisheries, having become common practice in most salmon-producing countries. In the case of England and Wales For example, egg deposition is the salmon population metric or indicator; the management objective is predefined as "…to optimise recruitment"; and the Management Target represents the median egg deposition that should be achieved to meet the management objective (Potter *et al.*, 2003). That median egg deposition is related to a biological reference point (the Conservation Limit) determined from stock recruitment curves. There are undoubtedly technical and scientific challenges with such approaches and the detail is not relevant here (see EA, 2003); but the principle of objectives, standards which quantify the objectives and indicators introduces rigour in to the decision-making.

Examples of acceptability definitions for other species are rare, probably because the monitoring and assessment frameworks are not as advanced as for salmon. Nevertheless, decisions on acceptability can be made. A recent potable water abstraction/impingement study on the Welsh Dee involved a detailed assessment of likely fish losses for all life stages covering salmon, bullhead and lamprey species under a range of modified screening arrangements at five sites. New engineering solutions were implemented following agreement that an in combination loss of not more than 1% of each species/life stage was acceptable (O'Keefe et al 2007).

However, whilst in the case of the Welsh Dee agreement was reached on an acceptable level of loss between developer, regulator and conservation agency, this was against a backdrop of extensive long-term monitoring and modeling of fish populations including salmon (Clough *et al.,* 2008). In many cases, such detailed information may not be available and decisions on an acceptable level of impact must be determined by alternative means. Irrespective of the nature and extent of information available for a given catchment, it should be incumbent on river and fishery managers to seek scientific advice on issues such as the dynamics of the fish populations, the current stock status and additional existing pressures.

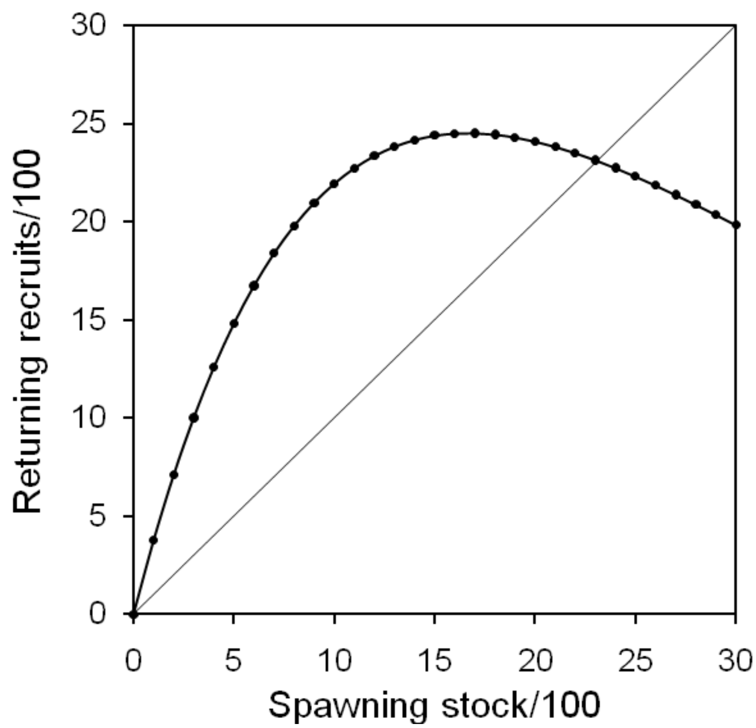


Figure 3.8. Stock Recruitment (SR) diagram showing effect of reduced 'stock' close to replacement and at a very low stock level.

Stock-recruitment relationships (Fig 3.8) come with substantial errors (Hilborn and Walters, 2001) and in salmon and sea trout studies the population variance explained by stock abundance alone may be as low as 20% in the case of full life cycle stock recruitment models (Milner *et al*., 2003). Much of the unexplained variance may be attributable to random environmental factors such as droughts (Elliott, *et al*., 1997) and so the uncertainties in predicting the consequences of a population are very high. Some means needs to be found to express this and the attendant risks.

In the absence of detailed readily available information on stock dynamics, a possible means of assessing an acceptable level of impact would be the establishment of risk analysis protocols. Such methodologies are used in countries outside of the British Isles and hence would maintain consistency of application amongst countries with the added advantage of removing any bias in scientific advice.

A risk analysis can build on the protocols developed for invasive species (Copp *et al.*, 2005) which are based on the likelihood of an event occurring and its consequential impact. For the impact of alterations of flows on salmonid species - this might be done using a suite of likelihood (Table 3.1) and consequence (Table 3.2) matrices to assess risk levels. Based, for example, on the critical point at which many flow and flow metric relationships change (e.g. Q_{95}), focusing in on sensitive areas of the hydrograph representing higher risk is feasible. Investigations can subsequently be targeted at these flows where hydrological metrics and fish populations are more vulnerable.

Where possible all assessments should be backed up by empirical data or existing studies - the greater the support information the less the uncertainty and therefore the more confidence in the likelihood of an event occurring. Acceptable levels of risk are assessed in relation to the measurable benefits to society. In addition to this analysis, risk mitigation procedures may be included to reduce the costs to society by eliminating or reducing the risks.

Table 3.1 Likelihood matrix, with *P* representing the probability of the event occurring (indicative only)

Level	Descriptor	Description	P
1	Rare	Event will only occur in exception circumstances	<5%
2	Unlikely	Event could occur but not expected	5-25%
3	Possible	Event could occur	26-50%
4	Likely	Event will probably occur in most circumstances	51-75%
5	Almost Certain	Event is expected to occur in most circumstances	76- >95%

Risk may be expressed as the likelihood of an event occurring multiplied by the consequence if it occurs. By way of example, uncontrolled abstraction leading to negligible flow, would be considered to have an 'Almost Certain' likelihood (i.e. level 5) of having adverse effects. The impact could be considered as 'Significant' if substantial spawning and juvenile rearing areas were affected and access to them denied. This would result in an 'Extreme' risk assessment. As a result, applications to abstract heavily would be discouraged. Possible risk mitigation could include a defined flow (e.g. Q95), established as a result of empirical studies, release of freshets to attract adult salmonids or construction of a fish pass that will maintain longitudinal connectivity under reduced flow scenarios and reduce the impact toward "insignificant" or "Minor".

Table 3.2. Example risk matrix: N = negligible; L = low, M = moderate; H = high; E = extreme

Likelihood	Consequence				
	Insignificant	Minor	Moderate	Major	Significant
Rare	N	L	L	M	M
Unlikely	N	L	M	H	H
Possible	N	L	H	H	E
Likely	N	M	H	E	E
Almost certain	N	M	E	E	E

The outcomes of such risk assessment exercises should be evaluated against the socio-economic and political imperatives of the target river system, national and regional objectives, and impact on other ecosystem services and species groups. Under such a scheme (indicative only here) extreme risk scenarios might be automatically rejected and high risk scenarios be rejected in all cases lacking an appropriate risk mitigation strategy, or strategies to minimise any potential damage caused by a scheme.

3.6 Summary

The assessment of flow related impacts on salmonids is very difficult because the underlying responses are highly variable and there are many confounding factors. However, it is thought likely that much information exists that could be used to inform our knowledge of flow impacts, particularly at the extreme ends of the flow spectrum. That knowledge can be used to build an effective science based approach that can provide confidence and assurance to protect salmonids from damage afforded by inappropriate river abstraction and regulation. This science agenda has not yet been comprehensively addressed and indeed the whole field of freshwater ecology has failed to integrate sufficiently with hydrology and with fluvial geomorphology (Vaughan *et al*., 2009; Rice *et al*., 2009. Understandably, flow-setting protocols are therefore derived from what is practicable from national data collection platforms. Much of the existing rivers science is highly uncertain (Newson and Clarke, 2008) and therefore cases of its implementation require monitoring under adaptive management strategies.

Formalised risk analysis provides a framework within which high risk impacts can be identified and categorised. In turn this allows a structured, evidence-based approach to investigation to be developed providing the information to identify the nature and extent of impacts. In many cases, investigations will need to be site specific, taking into account the wider implications for catchment scale interactions that may influence salmonid populations.

Over time, generic trends in terms of impact level and salmonid population response may be developed but such tools are not currently available and are unlikely to be developed without the appropriate science based investigative input. Hence for the foreseeable future, to allow water resource and river mangers to make informed decisions, adequate monitoring of hydrological, geomorphological and fish population metrics appropriate to the risk and scale of the impact, is essential.

3.7 Recommendations

1. Enhance the incorporation of hydrology and fluvial geomorphology with fish ecology in the understanding of flow impacts on fish populations.
2. Adopt formalised risk analysis into determination of flow impacts.
3. Focus on site-specific studies (rather than generic standards), taking advantage of adaptive management opportunities, but develop protocols to ensure that site-specific studies can be combined in meta-analyses in the future, so that the potential for generic standards can be re-assessed regularly.
4. Improve monitoring of schemes, including their statistical robustness, in an adaptive management context.

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CHAPTER 4 - SETTING FLOW STANDARDS AND MANAGING FLOWS

4.1 Introduction

The aim of this chapter is to present the principles of setting flow standards for salmonids, to describe the recent history of setting flow standards throughout Great Britain, and to draw attention to strengths and limitations of the approaches.

Throughout most of this chapter only the situation with respect to unsupported abstraction from natural river flow is being considered; the rather different scenarios associated with regulated rivers with artificial flow regimes are considered in a specific section at the end. For such unsupported abstraction there are no options for enhancement of very low flows, or generally for meaningful reduction in very high flows.

In an ideal world flow standards for each river, and each part of each river, would be based upon extensive local information on the biota and its relationship with flow, followed by monitoring of stock performance to allow adaptive management. Although in practice this is not realistic, it remains the ideal, and where such information is available it should be used either as a basis for rule-setting, or to validate, calibrate and modify any more general flow guidelines used. Reviewing global practice in setting environmental flows, Tharme (2003) drew attention to the growing popularity of 'holistic' strategies, employing a 'building block methodology' which combines each river management function and an appropriate inclusion of stakeholder views. It remains to be seen whether adaptive management can put these approaches centre-stage but, for this report, we are assuming a traditional, evidence-based, or rational, approach. Overall, there is considerable formal, scientific knowledge of the fundamental effects of flow on salmonids (see Chapter 2). However there are still key knowledge gaps:

- Transferring information from where we have knowledge to where we do not.
- Gaining a clear picture of the effects of existing abstractions on ecology, given the complexity of relationships with factors such as other river management practices and natural flow variation.
- Expressing our knowledge in a manner suitable for licensing of abstraction

Much of our knowledge is from chalk streams, because they have extended periods of low flow which makes flow-biota relationships easier to study. Care is needed in transferring lessons learned between river types.

The various attempts at setting flow standards (as discussed by Acreman and Dunbar 2004) have generally recognised the following principles.

- Low flows should be protected from further reduction to prevent damage to the ecosystem through, *inter alia*, drying out, reduced water velocity, width and depth, elevated temperatures, and deteriorating water quality, notably bed siltation.

- Variation in flow should be maintained and should be not too far removed from the natural flow regime of the river. Local biota have developed in response to the specific flow regime and we should preserve the critical elements of this as far as possible.

- There may be specific flow requirements of different life history stages for example upstream migration of adults, spawning and smolt migration, and different seasonal requirements.

- Finally, very high flow events are important in habitat formation and maintenance, and should be conserved to at least an extent, despite possible immediate adverse effects on salmonids. In practice this tends to happen by default as it is difficult to capture a significant proportion of very high flows by abstraction. Indeed, high suspended solids at such times may mean that the water is unsuitable for treatment and supply, and no abstraction may be taking place at all.

The following are suggested as first principles for developing flow standards for salmonid fisheries, based upon the biological relationships between flows, fish and wider ecosystems (Chapter 2).

- The standards for salmonid rivers should be conservative, with a greater level of deviation from the natural situation being permitted if, and only if, those who wish to promote the scheme can demonstrate that a greater take can be made without significant impact.

- Low flows should be fully protected from reduction – the Q95 is an often-used hands-off flow (HOF) for salmonid waters (see further discussion of this later). The fact that some abstractions (especially those operating under Licenses of Right and Licenses of Entitlement) breach these guidelines should be identified and either specifically condoned, or earmarked for review immediately or at some stage in the future, in an open and transparent manner. This approach will identify those abstractions that are or may be having an unacceptable impact, and more importantly will prevent new licenses from compounding the damage. It must be borne in mind that, for most river abstractions, protection of low flows can only be afforded to the extent that abstraction does not take place at such times. There is usually no scope for enhancement of low and very low flows.

- Above the HOF, only a certain percentage of the natural flow at the time should be abstracted. This preserves variability of flow, and allows substantial takes from high flows. This is one aspect of licensing that recent approaches to flow standards have incorporated

- For all migratory salmonid rivers the importance of residual flows to the estuary must be recognised.

- Location of abstraction is an important issue. For large abstractions in particular, taking water as low as possible in the catchment should be a strong principle, as it limits the geographical extent of any impact, and studies have demonstrated that the relative flow requirements for migration increase with distance upstream. It would also effect total protection to spawning and nursery areas.

- It would appear that the sensitivity of the ecosystem to changes in flow regime varies with river morphology. Small shallow streams of high gradient may be more vulnerable than larger deeper rivers with lower gradient. Recent approaches to deriving flow guidelines have generally incorporated an input for river morphology.

- Seasonality of abstraction is also an issue. It is likely that large volumes of water can be "mined" from high winter flows, especially low down in the catchment of many rivers without significant compromise to salmonids. With suitable storage facilities this can be used to protect more sensitive flows, locations and periods, and may greatly increase the drought-reliable yield of schemes. Although large-scale storage of water is expensive, and indeed may impose its own set of environmental impacts, it has been done successfully by some of the main water companies in England and Wales. For example, South West Water have developed winter pump-storage infrastructure for each of their three strategic reservoir schemes, though the current extent of deployment varies.

- The above principles must however be balanced by an acceptance of the needs of society for a reliable and affordable water resource infrastructure. Balancing these two is a fundamental challenge.

There have been a number of attempts to set flow standards for salmonids and other biota in the UK in recent years, and each appears to have been based upon an earlier one. The evolution of these approaches is important as many of the parameters such as hands-off flow and percentage takes have changed significantly, and the process highlights some of the strengths and weaknesses of generic flow standards. The steps in this evolution are described in the next sections.

4.2 Evolution of flow standards in England and Wales

The development of flow standards by the National Rivers Authority (NRA), and later by the Environment Agency, arose from concerns over how much water could be abstracted under various conditions without significant detrimental environmental effect. An abstraction license normally allows a take of a fixed daily quantity. This has a proportionately greater impact on residual flow at lower natural discharges, though the lowest flows are often protected by a prescribed flow rule or "Hands-off flow". Flow standards have been developed as a management tool for abstraction licensing, to assess the volumes of water that may be available for abstraction and to guide setting of operating rules.

4.2.1 Surface Water Abstraction Licensing Policy (SWALP)

One of the first of the recent developments was a project entitled Surface Water Abstraction Licensing Policy (SWALP) undertaken for the NRA by Halcrow (Halcrow 1995), though in fact this itself drew on an earlier Howard Humphries study for Yorkshire Region of the NRA. This came up with a matrix whereby the level of abstraction at different flow levels was determined by an environmental weighting (EW) score, which was in turn dependent upon the sensitivity in flow terms of its hydro-morphology, fish and ecology (which determines the environmental sensitivity band; for details see Halcrow, 1995). The table that appeared in the final report is reproduced here as Table 4.1. The "intervals" represent a series of successively higher hands-off flows. K is a flow statistic reflecting the relationship between median flow and low flow (K = $Q_n50 - Q_n95$), and is a measure of both the size and the "flashiness" of the river. One point to note is that no take at all was allowed from the lowest flows – i.e. below Q95 for rivers of high and medium sensitivity, and Q98 and Q99.5 from rivers of low sensitivity. However, the allowable take of 100% of successive intervals from rivers in the lower sensitivity classes is extreme – this effectively means that all water can be taken above Q99.5 from the lowest sensitivity rivers.

Table 4.1. Hands-off flows (HOF), intervals (INT) and Takes allowed under the final SWALP methodology. From NRA R&D Note 438, Core report on SWALP project (Halcrow 1995).

Environmental sensitivity band	Hands-off flow	Intervals between successive thresholds			Licensable % of flow interval
		1st interval	2nd interval	3rd interval	
A	Qn_{95}	0.1K	0.3K	0.5K	25
B	Qn_{95}	0.1K	0.3K	0.6K	25
C	Qn_{95}	0.2K	0.4K	0.7K	50
D	Qn_{98}	0.2K	0.5K	0.8K	100
E	$Qn_{99.5}$	0.3K	0.6K	0.9K	100

SWALP was developed primarily in response to a large number of applications for irrigation licences in Yorkshire following the droughts in the early 1990's, and concerns over "death by a thousand cuts" on rivers extensively used for many small abstractions. SWALP was not adopted by all regions of the NRA, and experience showed a number of shortcomings.

4.2.2 Catchment Abstraction Management Strategy (CAMS)

The next development by the Environment Agency (successor to the NRA) was the Resource Assessment methodology (RAM) framework within the Catchment Abstraction Management Strategy (CAMS) initiative. CAMS was developed after receiving responses to the government consultation document "Using Water Wisely", issued following the drought of 1995 and aimed to make the decision process in abstraction licensing more transparent. It involves an assessment of the extent to which potentially allowable abstraction within a catchment is already utilised, and indicates the scope for further licenses and the operating conditions that should apply to them. It was based upon five sensitivity bands based on the fish, macrophyte, macro-invertebrates and physical typology, with abstraction availability of 5 to 30% of the flow in various flow bands. This methodology was subsequently modified to take account of the deliberations of the UK TAG (See below).

4.2.3 UK TAG and second round of CAMS

The UK Technical Advisory Group (UK TAG) was responsible for developing environmental standards for the purposes of the Water Framework Directive. For surface waters, environmental standards have been identified for the condition of bed and banks (morphological conditions), water flows and levels, toxic pollutants, general chemical and physicochemical condition and aquatic plants and animals indicative of the ecological quality. The Water Framework Directive only requires flow to be defined as part of classifying water bodies at High Ecological Status (HES). For all other classifications the flow is a supporting element to enable the achievement of the ecological status, and is not part of the status *per se*. However, UK TAG considered it would be helpful to indicate the flow that may be likely to “support” Good Ecological Status (GES), based upon expert judgement. The standards developed are shown in Table 4.2. (UK TAG 2008a).

The river classification used for this purpose was developed from earlier macrophyte community classification work by Holmes *et al.* (1998), and is shown in Table 4.3.

Table 4.2. Water resources standards for rivers of Good Status, from UK Environmental Standards and conditions (Phase I) Final report, April 2008. (UK TAG 2008a). See Table 4.3 for definitions of river type.

River Type	**Season**	**Flow > QN60**	**Flow > QN70**	**Flow > QN95**	**Flow< QN95**
	(% change allowed from the natural flow)				
Al	April —Oct	30	25	20	15
	Nov —March	35	30	25	20
A2 (downstream), BI, B2, Cl, DI	April —Oct	25	20	15	10
	Nov—March	30	25	20	15
A2 (headwaters), C2, D2.	April—Oct	20	15	10	7.5
	Nov —March	25	20	15	10
Salmonid spawning and nursery areas (not Chalk rivers)	April —Oct	25	20	15	10
	Nov —March	20	15	flow > QN8O 10	flow < QN8O 7.5

Table 4.3. Typology for water resources standards for rivers. From UK TAG (2008a)

		Type	Gradient (Metres per kilometre)	Altitude (metres)	Description
Type A	Clay and/or Chalk; low altitude; low slope Eutrophic; silt-gravel bed	AI	0.8 ± 0.4	36 ± 25	Predominantly clay. South East England, East Anglia and Cheshire Plain
		A2*	Slightly steeper 1.7 ± 0.8	low altitude 55 ± 38	Chalk catchments; predominantly gravel beds; base-rich
Type B	Hard limestone and sandstone; low-medium altitude; low-medium slope; typically mesotrophic with gravel-boulder or pebble-cobble) bed	B1	4.1 ± 9.9	93 ± 69	Hard sandstone, Calcareous shales; Predominantly South and South West England and South West Wales
		B2	Shallower than B1 2.7 ± 10.7	71 ± 58	Predominantly North West and East Scotland
Type C	Non-calcareous shales, hard limestone and sandstone; medium altitude; medium slope; oligomeso-trophic with pebble, cobble and/or boulder bed	CI	5.4 ± 6.5	101 ± 84	Hard limestone; more silt and sand than C2; mesotrophic
		C2	Steeper than C1 7.3 ± 10.8	130 ± 90	Non-calcareous shales; pebble bedrock; Oligomeso-trophic
Type D	Granites and other hard rocks; low and high altitudes; gentle to steep slopes; ultra-oligo Oligo-trophic, with cobble, boulder, bedrock, and/or pebble bed	DI	Medium gradient 11 .3 ± 15.6	Low altitude 93 ± 92	Oligotrophic, substrate finer than D2 (including silt and sand); more slow flow areas than D2
		D2	High gradient 25.5 ± 33	High Altitude 178 ± 131	Stream order 1 and 2 bed rock and boulder; ultra-oligo trophic torrential
	* To reflect the different sensitivities of the headwaters of chalk streams to the downstream reaches, type A2 was split into two — A2 (headwaters) and A2 (downstream)				

The second round of CAMS RAM guidelines take account of the recommended standards from WFD 48 for UK River types for achieving Good Ecological Status (Table 4.2), but there are significant differences. It was considered too complicated to incorporate seasonal variation in the 25,000+ existing abstraction licenses, so a single year-round figure is used. This results in lower protection of flows at the most sensitive times, especially when natural flows are at a level where a complete tranche of HOF-regulated takes are maximised (see below).

Based upon the values given in Table 4.2, for use in the RAM process the Environment Agency produced a set of environmental flow requirements for maintaining Good Ecological Status termed Environmental Flow Indicators (EFI); these are shown in Table 4.4 (Tanner 2010). These are the proportion of the natural flow of various levels that can be licensed for abstraction; for example, for a river within "abstraction sensitivity band 2 (ASB2)", 20% of a flow equivalent to Q70 may be taken. This is achieved by allowing a percentage take of different tranches of flow, as illustrated in Figure 4.1. For example, for an ASB2 river, 15% of the flow on the day can be taken when the flow is below Qn95 (unconstrained abstraction, "UNC"). When flows are above Qn95, 40% of the additional flow can be taken between each pair of fixed "Hands off Flow (HOF)" values of Qn95, Qn85, Qn75, Qn50 and Qn35. This equates to abstraction of 15% at Qn95, 20% at Qn70, 24% at Qn50, and 26% at Qn35, as indicated in Table 4.4 and figure 4.1. For compliance management all licences in each tranche have the same HOF. Licences with higher HOF's will be less reliable, and may be largely limited to winter takes which will require storage. In practice, few licences have so far been allocated with a HOF greater that Qn75. One result of this approach is that tranches of licences at a single HOF result in the residual flow duration curve "flat-lining"; such steps are clear in Figure 4.1, but cannot be detected in hydrometric flow monitoring. At the left hand end of each plateau the percentage is similar to the Nov–Mar values suggested in Table 4.2, but at the top of the tranche will be more similar to April-Oct values. The values in table 4.4 enable a comparison to be made between the CAMS/RAM flow standards and the UK TAG.

Table 4.4. Ecological flow indicators. ASB = abstraction sensitivity band.

Abstraction Sensitivity Band	Q30	Q50	Q70	Q95
ASB3	24%	20%	15%	10%
ASB2	26%	24%	20%	15%
ASB1	30%	26%	24%	20%

The abstraction sensitivity band (ASB) is derived from three indicators; physical typology (using the river types in Table 4.3), macro-invertebrate typology (using expected LIFE scores), and fish typology (using fish "guild" expected under particular physical parameters).

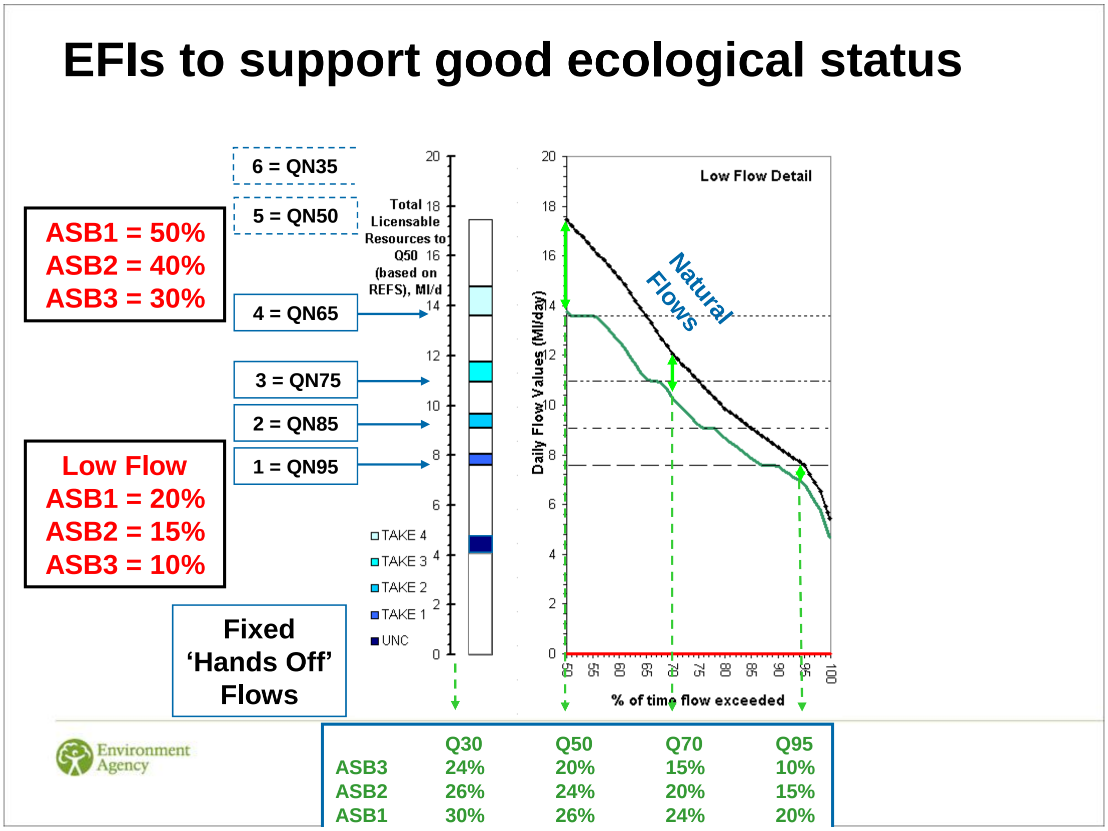


Figure 4.1. Illustration of the application of the current Environment Agency approach to abstraction licensing; a river of ASB 3 (most sensitive) is used here. The black line is the natural flow duration curve, and the green line is the resulting residual flow if all licensable abstractions are operated.

The TAG group Phase II report (UK TAG 2008b) dealt with transitional waters (estuaries), and they applied quite different rules for residual flows to estuaries; much greater takes were allowed compared to within rivers. They presented different figures for rivers of different status (Tables 4.5, 4.6 and 4.7).

Table 4.5 Maximum abstraction from transitional water likely to support good status, from UK TAG (2008b).

Type	Daily flows greater than or equal to Qn_{60}	Daily flows less than Qn_{60} but greater than or equal to Qn_{70}	Daily flows less than Qn_{70} but greater than or equal to Qn_{95}	Daily flows less than Qn_{95}
High sensitivity	40% of Daily Qn	35% of Daily Qn	30% of Daily Qn	25% of Qn95
Medium sensitivity	45% of Daily Qn	40% of Daily Qn	35% of Daily Qn	30% of Qn95
Low sensitivity	50% of Daily Qn	45% of Daily Qn	40% of Daily On	35% of Qn95
Inflows from areas adjacent to transitional waters that are not part of a defined water body are screened for net abstraction that are less than 30% of Qn95				

Table 4.6 Maximum abstraction from transitional water likely to support moderate status, from UK TAG (2008b).

Type	Daily flows greater than or equal to Qn_{60}	Daily flows less than Qn_{60} but greater than or equal to Qn_{70}	Daily flows less than Qn_{70} but greater than or equal to Qn_{95}	Daily flows less than Qn_{95}
High sensitivity	55% of Daily Qn	50% of Daily Qn	45% of Daily Qn	40% of Qn95
Medium sensitivity	60% of Daily On	55% of Daily Qn	50% of Daily Qn	45% of Qn95
Low sensitivity	65% of Daily Qn	60% of Daily Qn	55% of Daily Qn	50% of Qn95

Table 4.7. Maximum abstraction from transitional water likely to support poor status, from UK TAG (2008b).

Type	Daily flows greater than or equal to Qn_{60}	Daily flows less than Qn_{60} but greater than or equal to Qn_{70}	Daily flows less than Qn_{70} but greater than or equal to Qn_{95}	Daily flows less than Qn_{95}
High sensitivity	70% of Daily Qn	65% of Daily Qn	60% of Daily Qn	55% of Qn95
Medium sensitivity	75% of Daily Qn	70% of Daily Qn	65% of Daily Qn	60% of Qn95
Low sensitivity	80% of Daily Qn	75% of Daily Qn	70% of Daily Qn	65% of Qn95

These standards are designed for screening to identify areas that may be at risk of failing their WFD status rather than for setting rules for abstraction licensing.

New abstraction licences granted by the Environment Agency use the flows supporting Good status. Where existing abstraction impacts exceed flows supporting Good status, investigations will take place to assess whether the ecological status is impacted by the abstraction pressure.

4.2.4 Flow standards for conservation designated sites

In 2005, UK 'common standards' guidance on setting conservation objectives for SSSI and SAC rivers was established by the conservation agencies (Mainstone *et al*. In Press). This included a generic flow target of no more than 10% artificial deviation from daily naturalised flows throughout the flow regime for the river to be considered in 'favourable' condition. This guidance is currently under review, informed by a review of the evidence base (Mainstone 2010). In England, English Nature (now Natural England) has used a variation to UK common standards (Table 4.8), which were built into Environment Agency decision-making as the Habitats Directive Ecological River Flow (HD ERF). These SSSI/SAC standards are generally more conservative than the figures discussed so far, reflecting the way legislation underpinning SSSI/SAC designation is implemented. The Environment Agency has used the values for screening purposes and an increased level of environmental investigation to support levels of abstraction between the HD ERF and the standards supporting Good ecological status.

Table 4.8 Flow targets for SAC/SSSI rivers (Anon 2005).

RAM sensitivity band	Maximum % reduction from daily naturalised flow		
	< Qn50	Qn50-95	>Qn95
Very high	10	10	1-5
High	15	10	5-10
Moderate	20	15	10-15
Low	N/A	N/A	N/A
Very Low	20	20	15

NB. These percentages relate to the predicted naturalised flow on the day of observation.

An important question is:- if these flow targets are required to protect interests including salmon in SAC/SSSI rivers, is this tacit acceptance that lesser standards for other salmon rivers are having, or are likely to be having, an adverse impact? The answer appears to be that different policy drivers (e.g. WFD *vs* sites specially protected under conservation legislation) are being implemented using different levels of environmental precaution, based on an approach to uncertainty in the evidence base that is considered to be appropriate by the organization with principal responsibilities for implementing the legislation. However, the specific means by which uncertainty and precaution are addressed in the derivation of standards under these different policy drivers have not been transparent or auditable.

Overall, these varied sets of flow guidelines are rather confusing as there appears to be too little supporting evidence presented to justify the various parameters set. There is an urgent need for a review of past and current guidelines presenting all available evidence to support the approach and the values derived. There is a concern that many of the figures may have been derived to condone existing levels of abstraction; and indeed, there may be justification for the argument that in the absence of good evidence that current practices are having an adverse impact, then they are a good starting point for future management. The worry is that the absence of evidence, and the lack of attention to what evidence does exist, may allow compounding of potentially damaging practices.

4.3 Development of flow standards in Scotland

Prior to the introduction of the Water Framework Directive, which gave rise to the Water Environment (Controlled Activities)(Scotland) Regulations 2005 (CAR), the primary concern for the Scottish Environment Protection Agency (SEPA) when it came to regulating the water environment was the quality of the water. There were no legislative requirements or powers available for the regulation of engineering works, impounding works or abstractions. With the introduction of CAR came the introduction of these powers.

SEPA had detailed information on the water quality of Scotland's rivers and lochs in terms of chemical constituents and authorised discharges through the sampling and consenting regime, and this information has been maintained. However, this only represents one aspect of the overall ecological quality, and further environmental standards and information had to be devised and collated in order to build the full picture of the status of Scotland's water environment.

The UK TAG environmental standards for flows and morphological condition limits were adopted in Scotland and used in conjunction to determine the status of the water environment. Considering any water body now means that the overall ecological quality, or status, can be determined with a certain degree of confidence, and within that status the flow, morphological or quality standard can be identified.

In terms of regulation, SEPA uses Low Flows 2000 to generate the hydrological information necessary to calculate the required natural flow percentiles at un-gauged sites. The standards are then applied to this information. Through this, the potential of exceeding and therefore failing an environmental standard can be gauged.

For managed rivers flows (i.e. downstream of impoundments), SEPA would require some mitigation to protect high flows, provide for mid-range flow variation, and protect low flows for each application which is assessed. The reason for this is to minimise the impact of a proposal on the existing river flow regime. The assumption for a hydropower scheme, for example, would be to have the impounding works overtop at high flows, allow for flow augmentation, and provide a hands-off flow of Q95. However, this is true only for proposed schemes; existing schemes may not meet these criteria as they would have been designed and built prior to CAR. It is the case that some schemes exist which do not allow for the protection of low flows in Scotland; however, these may be reviewed where the environmental impact is considered significant and retrospective improvements would not be technically unfeasible or disproportionately expensive.

4.4. Depleted reaches

So far, the scenario considered has been of a consumptive abstraction removing water from the river leaving a reduced flow from the abstraction point to the sea. In many situations flow may be removed temporarily before being returned to the river; examples include run-of-river hydropower schemes and fish farms. Although the impact may be limited in geographical terms, such abstractions may represent a high proportion of the river flow and have a dramatic impact upon local conditions. Further, depleted reaches may be of considerable length, up to several kilometres and a series of such reaches may occur within a single river. Impacts may include direct effects of reduced flow/depth/wetted area upon juvenile fish in the depleted reach, upstream migrants being attracted to the flow return at the downstream end of the depleted reach, unattractive or impossible conditions for migration within the depleted reach, and downstream migrants being diverted with the abstracted flow (Thorstad *et al* (2008). Historically, in England and Wales, licensing of fish farm abstraction has been subject only to a maximum take with little protection of low flows; fish farms require a constant take of water and stopping abstraction at times of low flow would be unrealistic. With the current interest in HEP throughout the UK there is an urgent need for guidelines on management of flow in depleted reaches, as the takes being contemplated are often prodigious, for example equivalent to Q50 flow (Environment Agency 2009).

4.5. Strengths and limitations of flow standards

The great strength of a common set of flow standards is consistency and fairness in developing operating rules for new abstractions and for any Review of Consents (RoC) procedure. If the guidelines have been developed by a group comprising the most knowledgeable experts in the field, the scope for damage to fisheries interests should be minimal, while allowing responsible and appropriate development of water resources. Perhaps the best way of summing this up is that a good set of guidelines is better than nothing, if indeed nothing is the alternative.

There are three main concerns about the guidelines in current use in England and Wales. First, some take is allowed from very low natural flows. Until about 15 years ago almost all new surface-water abstractions were subject to a hands-off flow of Q95, and this principle was incorporated into the SWALP methodology; the more sensitive waters (including those containing salmonids) having a HOF of Q95, though the protected flow was lower in less sensitive waters. However, a level of take from the lowest flows (between Q95 and Q100) has crept into the more recent flow standards. This appears to have been done on the basis of pragmatism, to allow for existing licensed abstractions which are allowed take from lowest flows. However, deviation from the protective standards should be by assessment on a case-by-case basis rather than by reduction in the generic standards.

Second, there is very little information available about how the various parameters in Tables 4.2, 4.3, 4.5, 4.6, and 4.7 were derived. There is concern that they were not supported by rigorous scientific assessment.

A third major concern is the format and extent of the allowed take used in the UK TAG standards for transitional waters, already discussed, in which the take from flows below Q95 is given as a proportion of Q95, not of the flow on the day. The prodigious takes allowed from somewhat higher flows are also a cause for significant concern on all salmon rivers. The standards appear to have been set without regard for the extensive studies of salmon migration through estuaries funded by the Environment Agency and its predecessors.

4.6 Why Q95 for HOF?

If the likelihood that low flows represent some level of stress to aquatic ecosystems is accepted, along with the desirability of not exacerbating the situation, the principle of a HOF must be recognized, even if its value will, for most rivers, incorporate the uncertainty of extrapolating from or interpolating between our relatively sparse network of flow gauging stations. Equally, if we any particular flow level for HOF is to be promoted and accepted, we need to be able to justify the choice. Why Q95? Why not Q90, Q97 or indeed the lowest natural flow on record?

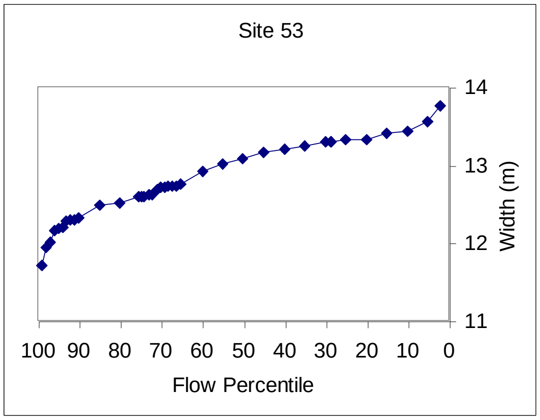
At the York symposium and Workshop, adoption of the Q95 as a hands-off flow was challenged by both the industry and regulators. Although in widespread use for such purposes there is a lack of clear scientific justification. Therefore the case for its retention and more widespread application needs to be considered, recognising that, even in the absence of scientific information, some limits have to be in place.

The Q95 statistic has the advantage of having been used for a long time as an indicator of low flow; for example it is the only low-flow measure given in the "Concise Register of Gauging Stations" in the National River Flow Archive (CEH website). It is used for setting discharge consents, and many abstraction licences have used it as a HOF. It thus has widespread acceptance as a standard with licensing authorities and with water companies.

The widely accepted view is that Q95 feels about right. It means that conditions are not worsened during the lowest 5% of the hydrograph. It is a level that occurs naturally and below which the flows naturally fall for on average about 18 days a year. It is likely that a somewhat higher HOF is justified in some streams at some times, for example small salmonid nursery streams (see Chapter 2). However, given that flows this low occur naturally for 5% of the time, it may be that better conditions will be maintained by restricting the proportion of the flow above the HOF that can be taken than by increasing the HOF as such.

It is stressed that Q95 is not being promoted as a maintained low flow, just that no take should be made to worsen the already natural impact of flows below that level. The volumes of water involved are relatively small in water resource terms, though of course any HOF will mean that alternative sources, probably involving reservoirs or other conjunctive sources, will be required to cover supplies for such times. A higher flow such as Q90 would afford a greater level of protection but it may be hard to justify given the impact it would have on drought-reliable yields.

There is evidence that a flow of around Q95 does represent some sort of threshold in terms of river morphology. One of the most obvious physical dimension that can be changed by altered flow regimes is the wetted perimeter (area of river bed submerged) of the channel. Graphs of discharge and wetted perimeter provide a basic tool for environmental flow evaluation (Figure 4.2, left). Analysis by visual inspection of the flow at which there is a change in slope of flow-width curves from 66 habitat modeling studies (Booker and Acreman, 2007), many from chalk streams, suggested that many thresholds occur at around Q_{95} (Figure 4.2, right), giving support to this flow percentile as a trigger point for flow setting.



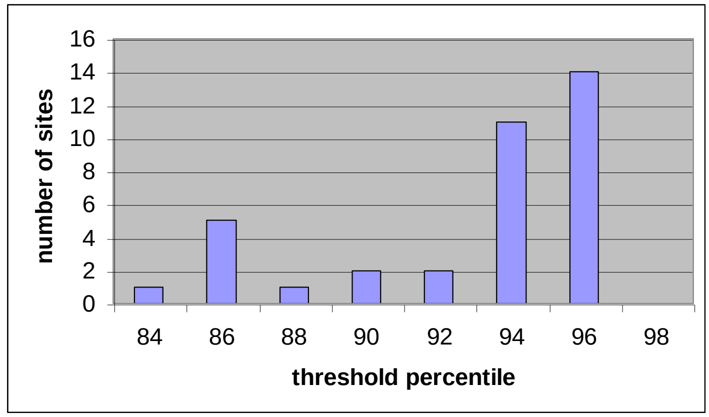


Figure 4.2. (Left) Typical relationship between flow and wetted perimeter at a single location. (Right) Frequency distribution of threshold flows at which the slope of the Q/wetted- perimeter line changes sharply, for 66 sites. From Booker and Acreman (2007).

As seen in the successive E&W flow standards reviewed above, there has been erosion in recent years of the principle of protection of low flows in general and Q95 in particular. While Q95 remains as a common threshold, the lack of scientific evidence for any particular low-flow threshold is undoubtedly a weakness. There is an urgent requirement to gather and present all available evidence to establish an appropriate approach to protection of low flows. The erosion of low-flow standards in the absence of firm guidance will increase the fisheries conservation risk. Once licences lacking in low flow protection are granted, recovery of the situation may be impossible in the short to medium term. All new abstraction licenses granted by the Environment Agency are time-limited, but most of the 25,000 plus existing licenses are not.

4.7 Regulated rivers

So far in this chapter, the discussion has centred upon abstraction from free-flowing rivers, and management of reduction in flow. Rivers and tributaries with on-line impounding reservoirs present a rather different set of issues. The flow regime immediately downstream of such a reservoir is dependent entirely upon releases (e.g. compensation flow, HEP generating flow and regulation releases), and on spill when the impoundment is full. The flow at any time may be significantly lower or higher than that which would have occurred naturally. Further downstream, natural runoff from the catchment and tributaries renders the hydrograph increasingly natural in form.

The downstream hydrological impact of reservoirs varies markedly between schemes for different purposes, with flow regimes that are as different from one another as each is from the natural situation. This is best illustrated by example.

Reservoirs used for direct water supply or for diverting flow outside the catchment will cause an overall reduction in mean flow. Low flows are often protected by a constant compensation flow release, with the only discharge at higher levels occurring when the reservoir is full and it spills. Even then, flow peaks will be attenuated in magnitude and extended in time compared to any high-flow events entering the reservoir. Examples of such schemes are Derwent Reservoir on a Tyne tributary, and Burrator reservoir on the Meavy (Plym tributary).

River regulating reservoirs generally return all impounded water to the channel downstream but under a highly modified flow regime. The usual function of such reservoirs is to provide water for abstraction downstream. Thus at times of naturally high flow only minimal releases may be made (there is usually a compensation flow provision), and maximum releases may be taking place during droughts when the water resource scheme may be totally dependent upon releases. An example of such an impoundment is Cow Green Reservoir on the River Tees. This inversion of the natural flow pattern may be even more extreme in pumped-storage schemes, where water from downstream or from other rivers is pumped to aid reservoir refill. In such situations the mean flow downstream is higher than natural, and with a very highly modified seasonal pattern. Examples of such schemes are Roadford in the Tamar catchment, and Colliford Reservoir in the Fowey catchment.

The third main type of reservoir scheme is impoundment for HEP; there are of course many examples of such schemes in Scotland, including at Pitlochry on the Tummel (a River Tay tributary). Here the releases are likely to vary markedly on an hour by hour basis, as electricity is generated to meet fluctuating demands. Because they can respond quickly to demand they are often used to satisfy peaks in support of conventional power stations that are more suited to supplying baseline demand, exaggerating further the diurnal pattern of power generation and thus release of water. There is usually a compensation flow requirement, but this is generally used for power generation as well.

Reservoirs are also used for other purposes, for example for attenuation of flood peaks, and many impoundments are used for more than one purpose. Some schemes incorporate a fisheries water bank, an allocation of storage that can be released specifically for fisheries purposes, and which is protected from abstraction downstream; for example there is such a provision equivalent to about 300 Ml/year, in the Colliford scheme on the Fowey in Cornwall. This is sufficient to allow a release of one cubic metre per second for a total of 84 hours per year. Fishery bank allocations at a range of locations have been used to create artificial freshets or extend/amplify natural freshets to stimulate migration or good angling, and to attempt to ameliorate for adverse effects of low flows, high temperatures or poor water quality. Generally, however, the effectiveness of such releases has been poorly evaluated and there is a need to review the situation to ensure the optimal use of these resources. Alternatively, if the value of fisheries water banks is doubtful it may be possible to negotiate some alternative compensatory action with the operator of the reservoir. Reservoir storage is valuable in cash terms and redeployment of under-utilised fishery allocations could increase scheme yield and efficiency, allowing alternative mitigation measures to be adopted.

There appears to be even less consistency in flow guidelines and operating rules for reservoir releases than there is for run of river abstraction schemes. UK TAG guidance (UK TAG, 2007) on environmental flow releases from impoundments outlines broad advice on designing site specific flow release regimes based on Building Block Methodology (BBM) and intend to achieve Good Ecological Potential (GEP), the appropriate target for water bodies classified as Heavily Modified Water Bodies under the WFD. Thresholds of hydrological alteration were developed to assess degrees of change that would still permit achievement of Good Ecological Status. (Table 4.9)

Table 4.9 Thresholds of hydrological alteration to meet GES (From UK TAG, 2007)

Low Flows 2000 statistics: mean January flow (m^3s^{-1}) mean April flow (m^3s^{-1}) mean July flow (m^3s^{-1}) Mean October flow (m^3s^{-1}) Q95 (m^3s^{-1}) Q5 (m^3s^{-1}) Base Flow Index (BFI)	**Low risk of failing GES if alteration<40% in all statistics**	**Medium risk of failing GES if alteration >40% <80% in any statistic**	**High risk of failing GES if alteration >80% in any statistic**

However, that guidance is provisional and offered in the knowledge that the scientific understanding of such modified flows impacts requires improvement.

Compensation flows equivalent to Q95 are common, but much lower and higher values exist. In some cases there is no compensation flow requirement at all and the river bed may often be dry between the dam and the next tributary confluence downstream. Operating rules may define the timing and maximum extent of releases, and maximum rates of change in flow as releases are increased and decreased. Patterns of spill will depend upon the underlying hydrometry, the reservoir size and the pattern of deployment of stored water. Burrator Reservoir in the Plym catchment spills reliably each autumn, whereas Colliford reservoir on the Fowey system, 30 miles to the west, did not spill for a seven-year period between 2001 and 2008. At Roadford Reservoir on the Tamar system a regime of enhanced winter flows has been adopted to attempt to provide suitable conditions for salmonid migration and spawning (Sambrook and Gilkes 1994).

With regard to flow guidelines, similar principles appear to apply to rivers downstream of impoundments as do for abstraction regimes, with creation of adequate low flows, variation of flow, and provision of adequate flows for migration, spawning and habitat maintenance (see Table 4.9 and text above). It is worthy of note that some of the highest densities of juvenile salmon and trout recorded in England and Wales have occurred downstream of Burrator reservoir, on the River Meavy in Devon (Source; Environment Agency electric fishing surveys). This is a direct-supply reservoir, with no regulation releases being made. Critical factors may be the more stable than natural flow regime throughout the summer for optimisation of nursery areas, and reliable spill in the autumn for adults to enter this tributary from the main River Plym and to spawn. However, while the flow regime appears to favour production of juvenile salmonids it is nevertheless far from natural and is likely to be to the detriment of other biota which may be dependent upon other features of the flow regime (Poff *et al* 1997), and the overall effects of the changes remain uncertain. And while there are such examples of salmonid populations being maintained or even enhanced downstream of reservoirs, there are many situations where production appears to have declined. Overall, the picture is far from clear and there has been no authoritative assessment of the wide range of schemes for which information is available. There is an urgent requirement for a review of the impact of operation of on-line reservoirs on salmonid populations, and indeed other biota, throughout the UK. From this, firm guidelines for future management should then be derived.

4.8 Summary of conclusions and recommendations for further work

1. There is an urgent need for a review of past and current flow guidelines presenting all available evidence to support the approach and the values derived.

2. There is an urgent requirement to gather and present all available evidence to establish an appropriate approach to protection of low flows, including the use of hands-off flows such as Q95.

3. With the current surging interest in small-scale HEP in the UK there is an urgent need to develop appropriate guidelines for management of flow in depleted reaches.

4. There is a need for a review of deployment of fishery water bank allocations in reservoirs to aid effective deployment and to inform review of such provisions.

5. There is an urgent requirement for a review of the impact of operation of on-line reservoirs on salmonid populations throughout the UK. From this, firm guidelines for future management should be derived.

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CHAPTER 5 - EFFECTS OF CLIMATE CHANGE

5.1 Introduction

Climate change is expected to modify water supply and demand in the UK, as well as exert additional pressures in aquatic ecosystems, including migratory salmonids. Thus discussion of the impacts of river flow on fish needs to be informed by an appreciation of climate impacts.
The principal aim of this chapter is to describe the most recent UK climate change projections within the context of their potential impacts on salmonids as the result of modifications to the general temperature and precipitation patterns. A general description of the UK Climate Projections (UKCP09) is provided together with a description of how climate change is likely to impact on salmonid populations both in the freshwater and the marine environments.

5.2 UK Climate Projections (UKCP09)

There are five scientific reports covered by the UK Climate Projections (UKCP09). These include recent trends in the UK climate (Jenkins *et al.,* 2008), climate change projections (Murphy *et al.,* 2009), projections of future daily climate from the Weather Generator (Jones *et al.,* 2009), marine and coastal projections (Lowe *et al.*, 2009) and a briefing report (Jenkins *et al.,* 2009). Copies of all five reports are available to order or download from:
http://ukclimateprojections.defra.gov.uk.

The UKCP09 Projections provide a basis for studies of impacts and vulnerability
and decisions on adaptation to climate change in the UK over the 21st century. The reports provide information on the following:

1. Change in mean temperature, winter and summer means, (25 km resolution and marine regions).

2. Change in mean daily maximum temperature, summer, (25 km resolution and administrative regions).

3. Change in precipitation, annual, winter and summer means (25 km resolution).

4. Change in annual mean precipitation (river basins)

Some examples of projected seasonal and annual changes in temperature and precipitation are provided below (Murphy *et al.*, 2009). The projections are for the summer, winter and annual mean changes by the 2080s (relative to a 1961–1990 baseline) under the Medium emissions scenario. Central estimates of change (those at the 50% probability level) are followed, in brackets, by changes which are very likely to be exceeded, and very likely not to be exceeded (10 and 90% probability levels, respectively).

- All areas of the UK warm, more so in summer than in winter. Changes in summer **mean temperatures** are greatest in parts of southern England (up to 4.2ºC (2.2 to 6.8ºC)) and least in the Scottish islands (just over 2.5ºC (1.2 to 4.1ºC)).

- **Mean daily maximum temperatures** increase everywhere. Increases in the summer average are up to 5.4ºC (2.2 to 9.5ºC) in parts of southern England and 2.8ºC (1 to 5ºC) in parts of northern Britain. Increases in winter are 1.5ºC (0.7 to 2.7ºC) to 2.5ºC (1.3 to 4.4ºC) across the country.

- Changes in the **warmest day of summer** range from +2.4ºC (–2.4 to +6.8ºC) to +4.8ºC (+0.2 to +12.3ºC), depending on location, but with no simple geographical pattern.

- **Mean daily minimum temperature** increases on average in winter by about 2.1ºC (0.6 to 3.7ºC) to 3.5ºC (1.5 to 5.9ºC) depending on location. In summer it increases by 2.7ºC (1.3 to 4.5ºC) to 4.1ºC (2.0 to 7.1ºC), with the biggest increases in southern Britain and the smallest in northern Scotland.

- Central estimates of **annual precipitation** amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.

- The biggest changes in **precipitation in winter**, increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.

- The biggest changes in **precipitation in summer**, down to about –40% (–65 to –6%), are seen in parts of the far south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.

- Changes in the **wettest day of the winter** range from zero (–12 to +13%) in parts of Scotland to +25% (+7 to +56%) in parts of England.

- Changes in the **wettest day of the summer** range from –12% (–38 to +9%) in parts of southern England to +12% (–1 to +51%) in parts of Scotland.

- **Relative humidity** decreases by around –9% (–20 to 0%) in summer in parts of southern England — by less elsewhere. In winter changes are a few percent or less everywhere.

- **Summer-mean cloud amount** decreases, by up to –18% (–33 to –2%) in parts of southern England (giving up to an extra +20 Wm-2 (–1% to +45 Wm-2) of downward shortwave radiation) but increase by up to +5% (zero to +11%) in parts of northern Scotland. Changes in cloud amount are small (–10 to +10%) in winter.

However, it is accepted that there may be a wide variations in the predicted climate change scenarios as a result of the different models.

5.3 Impact of climate change on the aquatic environment

A description of the potential impact of climate change on river flows across England and Wales by the 2050s is outlined in an Environment Agency Report (Environment Agency 2008). The study used catchment-level models to look at river flows across the whole of England and Wales. Its principal finding was that total annual river flow could drop by as much as 10–15 per cent by the 2050s as the result of lower summer and autumn river flows and higher winter river flows. The work was carried out using the Continuous Estimation of River Flows (CERF) model, which is a regionalised rainfall-runoff model developed by the Centre for Ecology and Hydrology (CEH) for the Environment Agency. The model uses time series data of precipitation and potential evaporation demand to model time series of daily river flows. The baseline daily climate data was then perturbed with the UK Climate Change Impacts Programme 2002 (UKCIP02) to produce the 2050s scenario river flows across England and Wales.

Changes in mean monthly river flow suggest that nowhere in England and Wales is likely to escape the effects of reduced river flow. Wales and the north and west of England are predicted to see significant reductions in river flow throughout the summer months (June, July and August). The south and east of England see the same percentage reduction but not until later in the year (September and October), with even river flows in November dropping to almost half their current volume. This delayed reaction is due to the predominance of underground aquifers in the south and east, which help to support river flows until later in the year.

These results show a possible decrease in mean monthly river flows during the summer and autumn months of around 50 per cent, with a fall of up to 80 per cent in some areas. They also show a corresponding increase in mean monthly river flows during the winter months of up to 15 per cent. Even though the absolute change in flow will be much less when flows are lower, these changes are still very significant. The study suggests that the number of months where river flow increases will be less than the number of months where river flow decreases. When combined with increased temperatures – and hence increased evaporation – this pattern is likely to affect the total annual river flow. However, the study does not provide sufficient information to predict the frequency of droughts and extreme flood events and in particular Q95 in catchments supporting spawning salmonids.

An updated study ('Future Flows') funded by Defra, Environment Agency and NERC will provide revised river flow estimates both back and forward in time, delivering in late 2011.

5.4 Effects of climate change on salmonids - Atlantic salmon (Salmo salar) and trout (Salmo trutta).

The impact of climate change on salmonid populations will principally operate through changes to the river temperature and flow/discharge. The impacts of temperature and flow on salmonid populations have recently been reviewed by Jonsson & Jonsson (2009) with additional works by Solomon & Lightfoot (2008) and Solomon and Lightfoot (in press). Overall, the impact of climate change on salmonids is likely to impact populations both in freshwater and the marine environments. It is possible that in certain circumstances there will be independent effects on salmonid populations arising from changes to water temperature and river flow, although the relationship at this time has not been fully described. However, temperature and flow may also interact to increase the impact on salmonids. For instance at reduced flows and higher temperatures certain contaminants will be concentrated and the toxicological effects enhanced. The potential impact of climate change on specific life-history stages of salmonids are provided in more detail below for both the freshwater and marine environments.

5.4.1 Freshwater environment

There is considerable uncertainty as to the potential impacts of climate change on river flows at regional and smaller spatial and temporal scales (Kundzewicz *et al.,* 2008). However, based on best predictions the expected increases in winter temperature and precipitation will be greatest in NW England and in Wales; the highest increase in summer temperatures will occur in SE England where there will be a corresponding reduction in summer and annual rainfall. The frequency of extreme events such as droughts and floods will also increase. An increase in the water temperature will accelerate embryonic and alevin development during the winter, and lead to earlier emergence of fry from the gravels.

The consequential effects on survival and growth of later stages will depend on a synchronous phenological advancement of food organisms, plant growth and other requirements. Survival of eggs and alevins in upland rivers could be reduced should expected higher winter rainfall generate more frequent river spates resulting in wash-out of the embryos. Growth rates of salmonid parr will increase significantly as the result of an increase in temperature providing that there is a commensurate increase in their food resources. The faster growth could lower the mean age at which parr reach the smolt stage by about 1 year, increasing smolt production for a particular year-class. However, density-dependent regulation would regulate overall smolt production.

Reduced river flows as a result of decreasing precipitation would inhibit or delay the emigration of smolts and their entry into coastal waters. Reduced flows and increased river/estuary temperatures will inhibit and delay the movement of adult spawning salmon into the freshwater environment. Increased temperatures will reduce the amount of suitable thermal habitat for returning salmon. Reproductive success and fecundity may be reduced at higher water temperatures.

However, increases in river flow may facilitate upstream spawning migration and assist the movement around obstacles such as weirs and barrages. There is also reason to expect a northward movement of the thermal niche of anadromous salmonids with decreased production and population extinction in the southern part of the distribution areas.

Finally, increased temperature may also result in migrations earlier in the season, later spawning, younger age at sexual maturity and increased disease susceptibility and mortality.

5.4.2 Marine environment

There are major uncertainties regarding the impact of changes in climate within the marine environment. The various models and predictions indicate either small gradual rises in sea surface temperature, no significant changes, or even slight cooling in those regions occupied by salmon Changes to sea surface temperature and oceanographic features such as currents may modify the distribution and abundance of key prey items of the post-smolts and adult salmon. A mis-match in prey availability during entry into the marine environment may reduce post-smolt survival and growth. Changes in sea surface temperatures (SST) may also reduce the amount of suitable thermal habitat required for the suitable growth and development of salmon in the sea. Additional changes to oceanographic features such as shelf edge currents may compromise the bioenergetic requirements of the migrating fish and lower survival both at the post-smolt and returning adult stages.

Finally, variations between the coastal water and freshwater/estuarine temperatures may reduce survival of emigrating smolts and modify the timing of adult returns to freshwater.

5.5 Conclusions

The climate change scenarios predicted for the UK suggest that there will be a rapid change to the freshwater environment. The extent of the change will differ in different parts of the country and with season. In particular, the reduction in precipitation in the southeast coupled with the increasing temperature may combine to impact resident salmonid populations to the greatest extent. Depending on the actual changes on the flows and discharges of particular rivers there may need to be a reassessment of present-day protective flow standards. This will need to be assessed on a river by river basis and will also need to take into account additional pressures on river flows resulting from abstraction and any future modifications to the morphology of the river itself. In the southeast of England for instance, demographic changes to the population may also increase the requirement to manage water resource allocation. At present, it is difficult to interpret the predicted changes to our river systems in a quantitative way especially in relation to existing Q95. However, climate change is already considered to be operating to modify our rivers and streams and serious consideration should be given to reassessing the impact of flows on salmonids and other fish populations.

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CHAPTER 6 - FOLLOWING THROUGH: MONITORING AND ADAPTIVE MANAGEMENT

6.1 Introduction

A recurring theme during the York Symposium (Atlantic Salmon Trust, 2010), reinforced at the Workshop, was the shortage of data and information about the impacts of flow regime changes on fish alone or, even more rarely, on fish together with other ecosystem components. Although much river flow alteration occurs as part of routine water resource management and renewable energy supply, lessons from this are rarely learnt because effective monitoring and investigations are not carried out. There are several possible reasons for this:

- lack of awareness of the long term benefits of monitoring,
- lack of allocated responsibility for such work (e.g. amongst industry, government, regulators, others),
- lack of opportunities where monitoring is compatible with operational constraints,
- the technical difficulty of designing and implementing a monitoring programme that has clear and tractable aims, coupled with lack of clear objectives,
- the costs involved, coupled with staff skills and resource limitations.

A distinction should be made between monitoring just to record environmental responses (e.g. changes in fish abundance or passage rate past a barrier) and scientific studies needed to evaluate and understand impacts sufficiently to modify and optimise a scheme. The latter introduces adaptive management (AM), which is a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs. It has an established history in marine fisheries (e.g. Hilborn and Walters, 2001), forms an integral part of the Ecosystem Approach to environmental management (www.jncc.gov.uk) and is recommended in the UKTAG Guidance (WFD82). However, to date in the UK formal AM has been uncommon in the freshwater context. This may be for the same reasons noted above for monitoring, coupled with the constraints of restrictive licensing regimes, the irreversibility of major consented engineering works and conflicts with third parties. It should be noted that abstraction licence charges include a contribution towards environmental monitoring, but the cost-effectiveness of this may be questionable.

The iterative process of AM means adjusting policies and operational regimes and monitoring the outcomes in a structured way that is analogous to any other scientific experiment (Hilborn and Mangel, 1997). By doing this at operational scales the results have relevance and acceptability that may be harder to achieve in detailed experimental studies. The downside of AM is that the detail of resolution and process understanding, that are precisely the benefits of scientific experimental studies, may be lacking. However, these aspects should be manageable through objective setting and careful design of AM projects (Hilborn and Mangel, 1997). It is contended here that the whole range of studies, scientific experimental, monitoring and adaptive management, have value and that if properly integrated offer complementary approaches to improving the understanding and practice in flow management. This is not a new plea. Souchon *et al*. (2008), reviewing a 2006 flows regulation conference, concluded that although there had been significant advances in analytical capabilities there had been little validation monitoring of actual outcomes or research relating to the response of aquatic-dependent species to new flow regimes.

In this section the potentials for practical monitoring and adaptive management are reviewed and the main topics that might benefit from this work are outlined. Sampling protocols, design and costs are generic issues across all fish and habitat field studies and here we give only sources of the methods and note aspects that are specific to the flow context.

6.2 Monitoring

Monitoring is required to increase our understanding of the flow impacts on salmonid populations, to pick up trends and to support the investigation of site specific flow responses. Routine fisheries monitoring is carried out by the government regulators (SEPA and EA) and increasingly by River Trusts, which may provide a resource for flow studies. Historical fisheries data might register retrospectively temporal responses to seasonal flow patterns. However, the proximate causal factors, such as temperature or hydraulic variables, or confounding factors such as water quality, are rarely measured simultaneously. Routine monitoring and investigative studies may occasionally be useful in their own right in retrospective identification of flow impacts; but depending on the conjunction of locations, they might also complement data collected in adaptive management projects (Fig 6.1).

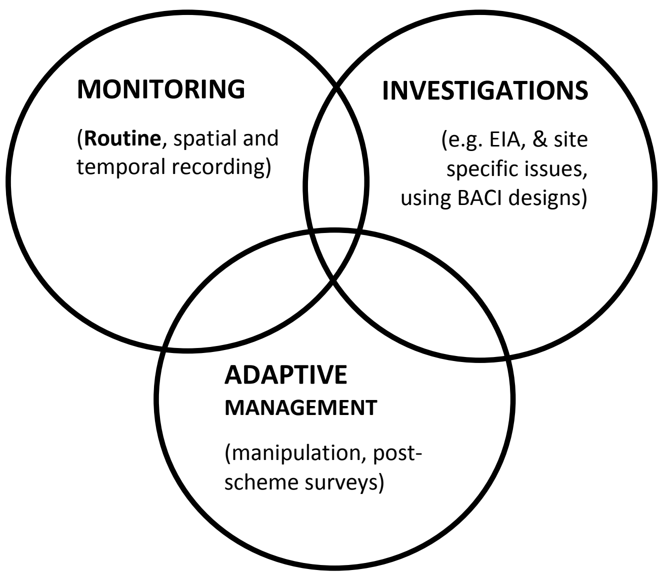

Fig 6.1 Showing intersections of different monitoring activities

What is missing is a repository and catalogue of such studies nationally, but this is a resolvable shortcoming that could offer considerable cost savings in future work.

There is a major need for an overview of existing monitoring data, much of which is unpublished and lies with operators and regulators, to assess if it offers opportunities for studying temporal and spatial patterns of flow response in fish populations.

Fisheries monitoring practises such as sampling methodology, survey design and statistical analysis are well-established and good practice would adopt CEN standards wherever possible (e.g. CEN, 2003; 2005 a, b; CFB 2008a,b,). It is not necessary to repeat this technical guidance here (a list of useful references is given in Appendix 6.I), but some issues are worth highlighting.

Scale of assessment. The effects of scale are relevant to all monitoring designs because natural river habitats are spatially heterogeneous and temporally variable, migratory fish access is variable and population distributions vary correspondingly (Foldvik *et al.*, 2010). Habitat surveys should always precede and be used to stratify fish surveys.

In theory any disruption of river habitat connectivity, including from flow modification, might have some repercussions on fish populations by changing for example physical carrying capacity, reproductive capacity or trophic and predation interactions.

Complementary environmental data. Harmonisation of fisheries monitoring with other flow-related environmental variables is highly desirable. While a large range of variables could be listed, the important ones are flow and temperature. Extrapolation and interpolation methods, which can be acceptable, are almost always required and need to be considered in the design stage. Unfortunately, flow is gauged in only a small proportion of river reaches but there are ways to estimate flows in ungauged reaches (e.g. http://www.hydrosolutions.co.uk/products.asp?categoryID=4780; Bragg *et al*. 2005). Similarly, temperature data is often rare, but there are ways to estimate temperature regimes from physical features (e.g. Webb and Walsh, 2004).

Linking monitoring to management units and objectives. Fisheries and conservation management planning is normally applied to self-sustaining stocks (a stock is an assemblage of populations together forming the managed exploited unit), whereas most monitoring is at smaller site scales (e.g. <100m). In monitoring planning, decisions need to be made about what Evolutionary Significant Units (ESU) (Waples, 1995) are relevant and how these might be matched with Operational Conservation Units (OCU) (Dodson *et al.*, 1998). Failure to do this can result in the common difficulty that monitoring data does not meet retrospective management questions. A related issue is the type of data collected. Reporting of fish numbers (N) as 0+ and > 0+ densities (N/Area) is an increasingly common practice; but this is of limited value in population terms, in which at least age structure is required, preferably on a quantitative basis.

The use of semi-quantitative or qualitative data is increasingly employed in large monitoring programmes on grounds of cost (it is quicker, allowing more sites per day to be surveyed). While such data can be of value for routine stock assessment, they are of limited value for impact assessment which demands some form of quantitative modelling, which in rigorous, modern applications can also incorporate age- or size-specific data in life cycle frameworks. This boils down to clearly setting the objectives of monitoring at the start and accepting that cost-cutting in the data collection stage is rarely, in the long run, cost-effective.

6.3 Adaptive management

6.3.1 Practices amenable to adaptive management

Adaptive management is unlikely to be cost effective or feasible where large scale capital development or complex permissions are required and there are uncertain outcomes. It may be limited by water availability in public water supply. It is likely to be more appropriate for operational practices in the following areas, where highly modified flow regimes may be required to meet human needs:

- High head (major dams) HEP regimes
- Low head HEP schemes
- Abstraction and licensing agreements; trialling different regimes and augmentation under S32 consents
- Mitigation for adaptation to climate change such as for rising river temperature

Examples of recent or current studies that are true adaptive management (i.e. demonstrating iteration between monitoring and operational practice) were hard to find, but some examples which approximate the definition are shown in Table 1. These are typically funded by operators where there are potential operational or environmental benefits, or where there is a failure to meet legislative standards, such as GEP in Heavily Modified Water Bodies.

Table 6.1 Examples of trials in adaptive management

Flow management regime	Issue	Location and trial
Hydroelectric power generation.	Adult fish passage	River Cassley, Sutherland, reallocation of freshets with fish counter to measure effects. River Tyne northeast England, restructuring of HEP releases to limit salmonid mortality in the estuary.
	Smolt passage	River Conon, Experiment with smolt curtain, machine running and fresh*et al*location amalgamated into high overshot flow in Borland lift. Tor Cahility, Aigas, Kilmorack, Pitlochry, Lairg Dams, trial survival rate under different turbine rates (using balloon tagging)
HEP	Stranding of fish after freshet flow	Meig and Luichart dams; redesign of freshet delivery.
Low head hydropower	Improving fish passage	Tadnoll brook- improvement of fish pass and restocking u/s to restore salmon population (CEH)
Public water supply abstraction- Ground water	Restoring Q95 flows	Chitterne, Piddle rivers. Trial of 2 reduced abstraction rates and GW augmentation (see Wessex Water web link) tested on juvenile trout (electro-fishing) and invertebrates
Public water supply abstraction- reservoir	Inappropriate baseflow	Rivelin & Loxley reservoirs. Rebalancing of compensation flows, brown trout population monitoring and invertebrates.
	Insufficient baseflow and inappropriate seasonality of flow and spate flows	Digley and Brownhill reservoir, River Holme, and Holmesties reservoir, River Ribble. Trialled seasonal flows and spate flow in October with brown trout population monitoring and invertebrates.
	Sporadic dry reaches limiting spawning	Walshaw Dean, Widdop & Gorple reservoirs, Hebden Water. Trialled seasonal flows with brown trout population monitoring and invertebrates.
	Trout spawning under pump storage	Wimbleball. Monitoring of juvenile brown trout under winter increased abstraction for pump storage. (WW)

The subsequent benefits of adaptive management will depend upon how the results of post-scheme monitoring are taken up. Because this has not been recorded systematically it is not clear if benefits have been realised, but this remains a need in future practice.

6.3.2 Fish responses amenable to monitoring and adaptive management

Chapter 2 outlined the ways in which fish respond to flow regime changes. Virtually all aspects of fish population dynamics and ecology might be affected; but not all are amenable to cost-effective monitoring or yield information of equal value for management purposes (see Ch 3).

The regulatory drivers for the monitoring will establish the objectives which should set the information needs. Thus statutory instruments may set specific features of fish populations that are to be protected and these will determine the data to be gathered. A rare example of relating policy objectives to assessment and monitoring lies in the specification of egg deposition levels as Conservation Limits in Salmon Action Plans for England and Wales (Environment Agency 2003). Under such circumstances a reasonably clear pathway of monitoring and assessment has to be followed to generate the required metrics to evaluate the management outcomes. More usually the policy aims are described in less prescriptive ways that give flexibility but also leave considerable ambiguity in monitoring aims and options. Thus the Water Framework Directive specifies that the "water body" should be the unit of assessment and the standard is the EQR (Environmental Quality Ratio, See Box 1), which is the composite probability that fish abundance (23 species) is less than expected in a river of the reference type. This may be acceptable for the WFD purposes, which are to protect necessarily (because of the national scale of application) broad notions of ecological condition; but it rules out interpretation of site monitoring data in catchment or even sub-catchment population terms and offers no features that are readily incorporated into flow impact studies or flow optimisation.

Ideally all vulnerable life stages would be sampled, but that this is prohibitively expensive and impractical. The key target stages relevant to the likely impacts are usually identifiable. Pragmatically, the most generally applicable basic metrics for migratory salmonid monitoring are:

1) Fish habitat features. Habitat data are always essential to 1) stratify sampling and 2) qualify and interpret the final population data. They normally comprise various combinations of in-channel and bankside physical structure and vegetation, sometimes coupled with fluvial audit of the catchment as a whole.

2) Abundance and distribution of juvenile stages in rearing (i.e. 0+ to 3yrs old). Measured as density (by age, see above), or in special circumstances by timed survey (normally for fry only). Spatial and seasonal effects will need to be considered in survey design. The scale of assessment should be relevant to the problem. Issues to consider are the scale of any predetermined standards (e.g. water body, whole catchment, or some other specified protected area such as SAC); the connectivity of habitats and relationships with adjacent populations and the availability of control sites. The general principles of good experimental design (e.g. BACI and other designs) should apply (e.g. Sedgwick, 2006).

3) Fish passage at critical locations, e.g. into the target impact area or past obstacles likely to be compromising to passage if natural flow patterns are changed.

4) Adult fish runs, which may be measured directly using counters or traps, or indirectly using partial traps or catches, possibly combined with marking exercises. Rod catches are also indices of fisheries performance and thus offer additional information benefits, providing that adequate relationships with run size exist and can be established (Milner *et al*. 2001; Shields *et al*., 2006).
The methods for these are well-described and some key references and examples are given in Appendix I.

Other ecosystem components and functions may be very important and decisions on this would be made on the basis of the anticipated problems and in the knowledge of flow-sensitive features. They might include:

- other fish species,
- food availability,
- energy cycling, growth performance and
- responses of other taxa to flow change that alter fish-related ecosystem function and structure e.g. algae, biofilms, macrophytes, invertebrates, predators.

6.3.3 Partnerships and funding

Adaptive management is potentially complex, because it involves activities in the operational context, with tight resource constraints, and often applies to river catchment scale, with many competing interests. Further complications arise through accountability and responsibility for planning, coordination and delivery.

Potential partners potentially include Rivers Trusts, District Salmon Fisheries boards, SEPA, EA, Natural England, CCW, water users such as hydroelectric operators, water companies, fish farms and agriculture, NGOs, private, etc in collaborative integrated projects.

Given the high national economic value of water supply and increasingly hydropower, it seems logical to expect that funding to develop and enhance the related environmental protection should follow these widespread pressures. So far, this has not been the case.

6.4 Recommendations

The following steps are recommended to maximise the benefits to the industry and the environment of past and future flow-related monitoring.

- All monitoring programmes should have clearly defined objectives and statistical robustness
- A review of adaptive management examples should be carried out to investigate their strengths and weaknesses, management value (take-up and benefits), factors limiting their completion or application and making recommendation for good practice.

- Monitoring data (routine and investigative) relevant to fish-flow interactions should be reviewed against specified objectives. This will identify data mining opportunities, show if monitoring is capable of answering the questions posed and how it might be improved if necessary.
- Adaptive Management should be actively promoted across the water industry as a way of achieving best outcomes for flow management.
- A national collaborative (between industry and regulators) plan for adaptive management to maximise knowledge generation and exchange should be developed and coordinated.

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CHAPTER 7 - KEY DISCUSSION POINTS

Shortfalls in flow standards

A consensus view from the Workshop was that the improving scientific evidence base, as currently presented, is not yet sufficient to justify substantive revision of the standards supporting management of river flows. Equally, present day generic standards were regarded as unsuitable for their purpose in many circumstances and were vulnerable to criticisms because of a weak evidence base, being derived largely from expert opinion and remaining untested. Therefore, while the current standards are necessary to provide a basis for management, to keep them unmodified was considered to be unsatisfactory. There were a number of actions agreed as necessary to advance this situation (see Recommendations).

Restrictive and active management

A distinction was repeatedly made between the development and application of standards for <u>restrictive</u> management (i.e. the control of water abstraction to ensure that natural flows are not unduly reduced) and those for <u>active</u> management (i.e. the increase in flows by release of water from impoundments for HEP, water supply or flood risk management). Restrictive management has been the main focus for the development (through UK TAG) of generic standards for flow to support implementation of the Water Framework Directive. However, attempts to do this for active management have been less developed or successful (Acreman and Ferguson, 2010) and this is a key area for development.

Generic vs specific flow standards

Generic flow standards for river flows, in the sense of those applied to water quality, for example, may in reality be unachievable (Poff and Zimmerman, 2010). The trend seen in the evolving towards life-stage, seasonal and location or river type-specific standards is clearly more realistic, scientifically. However, as detail and specificity increase so do the technical resources and scientific knowledge demands, presenting trade-offs between effectiveness, practicality and costs. Finding and negotiating this balance is a challenge for the many parties involved in river management.

Two contrasting perspectives emerged from the Workshop. One acknowledged that the same fish species appear to live satisfactorily in many different hydrological environments, that standards set for one will not necessarily apply in others and that generic rules can be wasteful and inefficient. The other pragmatically sought patterns to which generic rules (standards) might apply; with a concession to natural complexity by acknowledging categories of rivers (*cf* WFD river types) for which different standards should apply. The positions have defensible arguments, but different priorities.

In practice the viewpoints may not be mutually exclusive if a means for deriving standards can be devised that takes the generic aspects of fish flow needs, but applies them, in a consistent and auditable way to different rivers and applications with appropriate stakeholder involvement in defining the local objectives. Some moves are now being made in this direction (e.g. Poff *et al.*, 2010; Acreman and Ferguson 2010), although such flexibility is at odds with the imposition of WFD-type generic standards. Formally developing this approach, which might require a conjunction between process-based and empirical modelling methods, in the UK is recommended.

Remaining technical questions and how to deal with them
However, the lack of assembled knowledge, information and data that influence how flows should be managed remains disconcerting. This is in spite of the significant expansion of the fish ecology and behaviour understanding over the last twenty years, including process-based studies into flow-related effects. Furthermore, the lack of coordination and collaboration mostly prevailing across the sectors to address common question remains a failure in national research planning and monitoring design.

During the Workshop several questions arose across the scientific, technical and implementation domains of flow standards under five related categories and, while there was not always total agreement, the broad consensus on these is summarised in Table 8.1. A significant issue, not resolved, was the different views over the scientific basis of the PHABSIM family of protocols that combine hydraulic and biological models. This longstanding dispute is still topical and unresolved, surprisingly so because such approaches have become widely adopted in aquatic assessment.

The beneficial effects of unnatural flow regimes
The focus of the Workshop was on the presumed deleterious, negative, impacts of alterations to natural flow regime, because that is what protective standards set out to avoid. The assumption in Fig 1.2 was that deviation from natural flow regimes beyond some point impairs fish or fishery performance. This seems reasonable for the purpose of setting protective standards, which is the common requirement of restrictive flow management. However, some examples were reported where changed flow regimes, such as enhanced low flows from impoundments, elimination of flood peaks and more stable flow regimes, may lead to increased fish standing crop, production and, in the case of migratory species, increased smolt production.

This raised interesting and challenging questions about the nature of "natural flows" and the environmental aims of flow management and regulation. Ecosystem protection must consider other components as well as fish, such as the maintenance of geomorphological processes, sediment transport and channel forming. However if the benefits of modified flows are corroborated as genuine enhancements of lifetime fitness to the fish populations without detrimental effects on ecosystem function, this may be a fruitful area for exploring new ways to manage flows. Such trials would lend themselves to adaptive management and collaboration between industry, researchers and the regulators.

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Poff, N.L. *et al*. (2010) The ecological limits of hydrological alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshwater Biology **55**, 147-170.

Table 7.1 Recurring thematic issues and questions arising during the Workshop.

Thematic issue	Questions	Answers
1. The nature of the perceived science shortfall	Are there true gaps in knowledge because the appropriate studies have not been done?	Yes, there are gaps, see this table
	Are the data and knowledge actually there, but not pulled together effectively?	Partly, there are thought to be significant source of information in grey literature
2. The nature of the required science (questions and methods)	Is the current collective research effort directed at the appropriate questions using appropriate approaches?	Don't know, because no unified statement of the questions, or inventory of the research. No clear specification of tolls needed for management.
	Is the current research effort coordinated and funded effectively?	No
	Is any more research going to enhance the evidence base to a level that will make a difference to the practice and effectiveness of regulation? – or – "have we gone as far as we can reasonably go?"	Yes, certainly; but up to a point yet to be explored or identified.
3. Effectiveness of present day regulatory processes	Is the evidence base of regulation rational, consistent and transparent across regulatory frameworks (i.e. amongst activities and across regulatory bodies)?	No
	What evidence is there about the ability of current regulatory practice to protect adequately natural fisheries and related ecosystems?	None, because not yet scientifically tested
	What evidence is there that current regulatory practice is too risk averse leading to inefficiencies and wastage in water use (this point arose primarily from hydroelectric power applications).	Yes, qualitative accounts in some cases, from industry,
	Is it acceptable to manage for migratory	Often, yes. But not always, NB fish pass design and

	fisheries purposes as surrogate for ecosystems?	between taxa evaluation has not been systematically reviewed.
4. Effectiveness of present day standards	Is the use of Q95 as generic "hands off flow" defensible?	Remains an arguable and important point. Scientifically it is unvalidated, but it has great practical value in absence of alternative.
	Is the assumption that natural flow regimes are "best" always safe?	Mostly yes, for restrictive management purposes; but in impounded rivers there are examples where artificially enhanced flows may be beneficial. Also, climate adaptation may require e.g. augmented or stabilised flows. This issue raises questions about environmental objectives.
	Are uncertainty and risks adequately allowed for in current regulation?	Some risk aversion is implicit in some standards, but no formal risk evaluation or estimation of uncertainties was discovered
5. Clarification of objectives	What are we trying to protect and to what level?	Biological resources are partly specified through e.g. WFD, SAC, SSSI and Conservation Limit standards; but these remain general.

CHAPTER 8 - RECOMMENDATIONS

8.1 Specific chapter recommendations

Chapter 2 Relationships between river flows and salmonids

1. Develop generalised models for transferring information on salmon flow requirements between river systems, likewise the flow requirements for critical habitat quantity and quality metrics.

2. Investigate the potential for coupling process-based and empirical models, based on experimental manipulation and/or monitoring of discharge regimes of a range of rivers together with measurement of individual growth, survival and migration of fish.

3. Give priority to making best use of existing information from archives of national population monitoring programmes and tracking studies to assist in developing models of salmon flow requirements before initiating new targeted studies.

4. Undertake modelling [to integration?] of the effects of discharge across the salmonid life-cycle in order to evaluate the impacts and benefits of proposed actions at population level.

5. Explore opportunities for undertaking studies on the effects of flow regulation and manipulation through adaptive management and develop appropriate research programmes.

Chapter 3 Assessment of impacts from altered flows

6. Enhance the incorporation of hydrology and fluvial geomorphology with fish ecology in the understanding of flow impacts on fish populations.

7. Adopt formalised risk analysis into determination of flow impacts.

8. Focus on site-specific studies (rather than generic standards), taking advantage of adaptive management opportunities, but develop protocols to ensure that sites-specific studies can be combined in meta-analysis in the future, so that the potential for generic standards can be re-assessed regularly.

9. Improve monitoring of schemes, in adaptive management context.

Chapter 4 Setting flow standards and managing flows.

10. Conduct a review of past and current flow guidelines presenting all available evidence to support the approaches, the values derived and to demonstrate their effectiveness.

11. Gather and present all available evidence to establish an appropriate approach to protection of low flows, including the use of hands-off flows such as Q95.

12. Review the use of fishery water bank allocations in reservoirs to aid effective deployment and to inform review of such provisions.

13. Review the impact of on-line reservoir operation on salmonid populations in the UK, in order to develop guidelines for future management.

Chapter 5 Effects of Climate Change

14. Recognising the difficulties in quantifying future climate scenarios, there is still a need to evaluate the impacts of scenarios on the effectiveness of current to emerging flow standards in key river types and geographical locations in the UK.

Chapter 6 Following through: monitoring and adaptive management

15. Set clearly defined objectives and statistical standards (e.g. CEN standards) for all monitoring programmes.

16. Review examples of adaptive management to investigate their strengths and weaknesses, management value (take-up and benefits) and factors limiting their completion or application, in order to make recommendation for good practice.

17. Monitoring data (routine and investigative) relevant to fish-flow interactions should be reviewed against specified objectives. This will identify data mining opportunities, show if monitoring is capable of answering the questions posed and how it might be improved if necessary.

18. Adaptive management should be actively promoted across the water industry as a way of achieving best outcomes for flow management.

19. A national collaborative (between industry and regulators) plan for adaptive management to maximise knowledge generation and exchange should be developed and coordinated.

8.2 Overall recommendations

The individual chapters gave rise to nineteen specific recommendations listed above, the priorities amongst which are captured in the three overall recommendations shown below.

1. Review the evidence

There is believed to be a lot more information and knowledge in the grey and peer-reviewed literature than was available to the Workshop, which might help to answer some key questions. These questions are not always tightly specified and priorities vary between sectors, but there needs to be an agreed balance between the views of regulators and industry on what tools they need taking account of scientific realities. There was broad agreement that a review of this information should be undertaken, focussing on the following subjects:

- Explore the effectiveness of WFD flow standards for protecting salmonid fisheries (as e.g. abundance, structure, production, fitness) and the consequences of their use for lost water supply and power generation, through case studies across a range of river types. A particular issue lies in the use of Q95 as a low flow standard and what alternatives might be proposed.

- Investigate the uncertainties and decision risks implicit in the variability of fish-flow and flow-habitat relationships and means to incorporate them in to decision making.

2. Review and improve the mechanisms for coordination and funding fish-ecosystem-flow-related sciences.

There are major inconsistencies in objectives, practices and standards across the water use sectors and the regulators in the British Isles. The supporting science is also uncoordinated, leading to gaps, divergent approaches and failure to act on potential synergies. Coordination of research, the applied sciences (e.g. impact assessments, standards development) and monitoring is not being achieved under the current arrangements for aquatic environmental management. A discrete working group to take this forward is recommended, given the varied infrastructures and legislation across the regions and participating sectors (the sciences, operators and regulators). Current national economic constraints should not be taken as a reason to avoid setting out detailed needs and options for delivering this coordination and funding.

3. Promote adaptive management as a vehicle for collaboration

True adaptive management is still rare in the UK, but offers a potential route for some of the studies that are otherwise too expensive to pursue in conventional experimental formats. There is a clear precedent in the way uncertainties in the initial water body assessments for WFD are being followed up by 'investigations' to refine 'measures'. The lack of objective evaluation of the effects of changing flow regimes, imposed licenses and standards remains a major omission, which is wasteful of national resources. Also required are procedures for reporting results of locally applied flow regimes and their incorporation in to more general developments of flow standards. However, adaptive management is a significant planning and financial burden that should be shared amongst industry and the regulators. This recommendation requires a national working group or similar that can explore funding, planning, implementation and reporting.

APPENDIX I Sources of information for sampling design and practice

Sampling design

(NB there are very many accounts of this subject, these are just a selection)

Downes B.J., Barmuta L.A., Fairweather P.G., Faith D.P., Keough M.J., Lake P.S., Mapstone B.D. & Quinn G.P. (2002) Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters, Cambridge: Cambridge University Press. 446 pp.

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Ricker, W.E. (1975) Computation and Interpretation of Biological Statistics of Fish Populations. Bulletin of the Fisheries Research Board of Canada. Number 191. 382pp.

Wyatt, R.J. and Lacy, R.F. (1994) Guidance Notes on the Design and Analysis of River fishery Surveys. R&D Note 292, National Rivers Authority. Internal Report.

Sampling methods (Electro- fishing and habitat)

Cowx, I.G. & Lamarque, P. (eds) (1990) *Fishing with Electricity*. Oxford: Fishing News Books, Blackwell Scientific Publications, 245 pp.

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Hendry, K. and Cragg-Hine, D. (1996) Restoration of Riverine Salmon Habitats; A Guidance Manual. Environment Agency R&D Technical Report W44. Environment Agency, Bristol.
Environment Agency (2003) River Habitat Survey. Field Survey Guidance Manual: 2003 Version.

Scottish Fisheries Coordination Centre. See link below for habitat and electro-fishing protocols. http://www.scotland.gov.uk/Topics/marine/science/sfcc/Protocols