Stage 1 Report **Project WFD48**

DEVELOPMENT OF ENVIRONMENTAL STANDARDS (WATER RESOURCES)

STAGE 1: IDENTIFICATION OF HYDRO-MORPHOLOGICAL PARAMETERS TO WHICH THE AQUATIC ECOSYSTEM IS SENSITIVE

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Use of this report

The development of UK-wide classification methods and environmental standards that aim to meet the requirements of the Water Framework Directive (WFD) is being sponsored by UK Technical Advisory Group (UKTAG) for WFD on behalf its member and partners.

This technical document has been developed through a collaborative project, managed and facilitated by Sniffer and has involved the members and partners of UKTAG. It provides background information to support the ongoing development of the standards and classification methods.

Whilst this document is considered to represent the best available scientific information and expert opinion available at the stage of completion of the report, it does not necessarily represent the final or policy positions of UKTAG or any of its partner agencies.

EXECUTIVE SUMMARY

WFD48 DEVELOPMENT OF ENVIRONMENTAL STANDARDS (WATER RESOURCES)

STAGE 1 REPORT: IDENTIFICATION OF HYDRO-MORPHOLOGICAL PARAMETERS TO WHICH THE AQUATIC ECOSYSTEM IS SENSITIVE

Background to research

This project arises as part of a coordinated effort by the UK environmental agencies to prepare for implementation of the Water Framework Directive – specifically in relation to water resources regulation. Its overall aim is to develop methods for the establishment of regulatory standards for rivers and lakes. The project excludes Heavily Modified Water Bodies.

Objectives of research

This is a Stage 1 report based on review of the international literature in order to identify all hydro-morphological parameters which affect aquatic ecosystems – either being used by water users/regulators around the world or identified within the research literature. It includes a gap analysis to report on parameters which have not been adopted in reported studies or practices, but which may merit consideration in the UK. It provides a focus for discussion between members of the project steering group and the contractors, and a sense of direction for future stages of the project.

Key findings and recommendations

- Most countries have various methods of determining environmental flows, each defined for a different purpose, *e.g.* strategic analysis, scoping or impact assessment.
- Licensing of reservoir releases and abstractions present quite different problems and different methods have been developed to deal with these issues. With reservoir releases, the whole flow regime (apart from very large floods that by-pass the dam) needs to be created. Abstractions, by and large, have no impact on high flows and so the focus is on low flow impacts.
- Where data are scarce, expert opinion is used, and increasingly a formal structured approach to getting consensus amongst a group of experts, including academics and practitioners is favoured.
- There is wide acceptance that all parts of the flow regime have some ecological importance. As a result, there is a growing move away from single low flow indices.
- Many methods determine environmental flows in relation to the natural flow regime of the river. Some methods define flow in terms of site characteristics, such as flow per unit width needed for salmon migration in Lancashire, but it has not been possible to examine the data or the basis of these derivations. Other methods define environmental requirements in terms of more direct hydromorphological elements, such as water depth and velocity.
- Small scale studies have shown that flow interacts with morphology to define physical habitat (such as width, depth, velocity and substrate) for specific organisms. These quality elements vary spatially; water is deep in pools and shallow on riffle; velocity is high in riffles

and slow in pools. Standards based on these quality elements at the broad water body scale cannot be readily defined. To implement standards at the reach scale, site data are essential.

- Implementation of the WFD will require that environmental standards are applied for all bodies regardless of hydrological and ecological data available. Consequently, standards are required that can be applied without having to visit the water body. This means that standards must be related to parameters than can be obtained from maps or digital databases, such as river flow, catchment area or geology. Any resulting standards will have less predictive power at a local scale and cannot be tested using site data.
- A hierarchical approach may be needed in which a broad scale approach, perhaps based on flow, is used as a screening tool to assess all water bodies. A more detailed approach, perhaps based on depth or velocity, may be applied to a smaller number of sites identified as requiring close attention.
- The flow regime is complex and is characterised by timing, magnitude, duration and frequency; all of which are important for different aspects of the river ecosystem. To produce operational standards, there is a need to identify a small number of parameters that capture its most significant characteristics. For example the number of high flow events greater than three times the median flow has been shown to be related to the structure of macrophyte and macro-invertebrate communities in New Zealand (Clausen, 1997).
- The equivalent for lakes is the water level regime. Water level is of direct ecological relevance since it determines the area of littoral zone exposed and, given its variability, the timing and duration of exposure. It is also directly related to water depth; it influences a range of system state variables including effective fetch, wave-base and re-suspension of fine-grained bed sediments; and it is linked to residence time. As for the river flow regime, there is a need to identify the most significant characteristics of the lake water level regime; for example annual or weekly ranges, seasonal maxima or minima, or rates of rise and fall.

The main outcome of Stage 1 was that the regulatory parameter for environmental standards for rivers at a broad scale should be flow, since data on potentially more ecological meaningful parameters such as depth and velocity are not widely monitored and cannot be determined with detailed surveys at all sites. Since flow varies greatly between water bodies, generic flow standards need to be expressed in dimensionless terms, such as proportions of natural flow or unit flow per drainage area or channel width. Nevertheless, UK agencies should develop a hierarchical approach to standards, where broad scales methods based on flow are used for screening, but detailed scale methods based on more directly ecologically meaningful parameters, such as depth and velocity, are used for site level impact assessment and license setting.

For lakes, water level is the key hydromorphological parameter because of its integrative role in relation to the volume and dynamics of flow (including residence time) and its relative simplicity of measurement. The relative ease of measurement however belies the paucity of existing long-term data in relation to natural regimes of lakes across the UK.

Key words: abstraction, flow release, hydrological regime, timing, magnitude, duration, frequency, hydro-morphology, parameters, standards, rivers, lakes

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1. BACKGROUND

1.1 Introduction

In order to deliver the ecological objectives of the Water Framework Directive (WFD), regulatory standards are needed that will allow the agencies to determine the ecological flow requirements of UK surface freshwaters. Transitional and coastal waters are outside the scope of this project.

These standards must provide sufficient protection for the water environment so as to restore and maintain the ecological status of waters and so meet the WFD and other environmental objectives. To promote the sustainable use of water and allow water users to continue to operate without unnecessary restrictions, these standards must be set in relation to the ecological sensitivity of waters to changes in hydro-morphology.

The measures and parameters that typically affect the relative ecological sensitivity of surface waters to changes in the flow regime, and the thresholds for these parameters that are important in maintaining the ecological status of surface waters need to be identified. As a minimum, this project must consider all those parameters that are covered by the ecological, continuity and hydro-morphological quality elements set out in the WFD. The best current scientific understanding of the links between hydromorphology and ecology must be applied in order to justify the selected parameters and thresholds.

Other issues not included in the WFD quality elements, such as land use, may also be important in protecting the ecological status of waters and so would also need to be considered as part of this project.

Particular consideration should also be given to the protection of ‘high status’ waters where the hydromorphological quality elements are given specific protection in addition to the role they play in delivering the ecological quality elements.

1.2 Project aims

The aim of this project is to carry out the work necessary to revise **water resource** regulatory standards covering abstraction and impoundments for rivers and lakes, throughout the UK based upon ecological status. This will be carried out in close liaison with the regulators. Closely linked to this work will be a separate project to develop new regulatory standards for groundwater in Scotland, Northern Ireland and potentially also for Wales. The development of morphological standards is being carried out as a separate suite of projects, however the consultants will be expected to ensure that they are aware of this work and that the two are complimentary.

The programme shall be structured as follows:

Stage 1: A review of existing UK and international regulatory standards and the identification of all relevant parameters.
Stage 2: The creation of a typology for rivers and lochs / lakes and the identification of the ecological sensitivity of each ‘type’ to changes of the parameters defined in stage 1.
Stage 3: To develop the regulatory standards (i.e. the thresholds for each of the parameters identified) by reference to the five categories of ecological status as defined in the WFD (High, Good, Moderate, Poor and Bad).

The project will be split into five main tasks for the purposes of project management (Table 1).

Table 1 Names of project tasks

Task	Project Stage and phase	Task Name
1	Stage 1, Phase 1a	Review of existing standards
2	Stage 1, Phase 1b	Identify all parameters
3	Stage 1, Phase 2	Regulatory standards and gap analysis
4	Stage 2	Create Typology
5	Stage 3	Develop regulatory standards

Other SNIFFER projects that will have close linkages with this work programme and that contractors will require to keep in close liaison with, include:

- WFD 53: A framework for setting abstraction limits from groundwater in Scotland and N. Ireland
- WFD 49: Development of decision making frameworks for managing alterations to the morphology of surface waters and
- WFD 44: Establishing the relationship between ecological and hydromorphological quality elements in rivers and lakes.

1.3 Project objectives

The UK agencies already employ a range of existing regulatory processes for controlling abstraction and impoundment of surface water. These are based primarily on the parameters of flow (in rivers) and level (in lakes). In addition, the parameters and thresholds that have been used to identify water bodies that are 'at risk' of failing to achieve WFD good status as part of the Characterisation process have been agreed by UKTAG and these can be viewed at the UKTAG website (http://wfduk.org/).

The agencies now require to augment these existing processes with a more comprehensive and ecologically driven set of parameters and thresholds that are needed to deliver the WFD and other ecological targets (e.g. Habitats Directive).

Stage 1 aims to identify those parameters to which aquatic ecology is sensitive. These will include hydrological parameters such as the flow (discharge), but also broader hydro-morphological parameters such as water velocity, water depth or level, channel form, or wetted area and may also include groundwater contribution (temperature, quality and/or quantity), seasonality etc. as appropriate.

The project aims to do this by carrying out a literature review to identify the full range of parameters for both rivers and lakes that may need to be controlled and the circumstances in which they are significant. Once identified, these parameters may, where appropriate, be grouped into generic sub-categories that allow those circumstances where they are of ecological importance to be defined. In tandem with this work, a review and appraisal of existing standards, both within the UK and internationally will be carried out to determine where there are any gaps – i.e. any parameters that have been identified as relevant but for which there are no existing UK or international standards available.

Stage 2 of the project aims to develop a meaningful typology to categorise the ecological sensitivity of rivers and lakes to the hydromorphological pressures that are created by abstraction and impoundment. This typology should then be used, along with the data collected as part of the literature review, to identify which specific parameters, from the full set identified in stage 1, are relevant to the ecological requirements for each of the types.

Stage 3 aims to determine the appropriate regulatory standards (i.e. the required thresholds) for those parameters included for each of the river and lake types identified in stage 2. The set of regulatory thresholds that are developed must be appropriate to deliver the WFD and other objectives and should relate to the boundaries for all five WFD classification bands.

2. REVIEW OF EXISTING STANDARDS (RIVERS)

2.1 Introduction

Abstraction and impoundment of water is required for many purposes to support the quality of life we enjoy, including public supply, hydro-power generation, industrial processing and irrigation. However, it is evident that taking too much water from rivers and lakes will degrade the water environment. Abstraction and impoundment of water are thus limited to ensure that rivers and lakes remain at given environmental standards. Because water users require permissible volumes of water that can be abstracted or impounded in a given period, standards are normally defined in terms of discharge rates in a source river or levels in a lake. However, the standards may actually relate to some more ecologically relevant measure. For example, the licence for abstraction from the River Kennet at Axford in Berkshire, defined the allowable abstraction rates for given river discharges, but these discharges were calculated such that there would not be more than a 10% loss in habitat for trout in the river.

Internationally, the river discharge (or discharge time series) required to maintain a given ecological condition in a river is called the environmental flow. Standards exist where an environmental flow has been adopted by a country as part of its water resources regulatory framework. Full standards only exist for a few countries. Nevertheless, many countries have developed a variety of environmental flow methods that might be used to set standards in the future. In addition, numerous scientists around the world have models of interaction between hydro-morphology and ecology. Whilst these may not be formal environmental flow methods, these models contain important concepts and ecologically relevant parameters. Consequently, the review of regulatory standards and parameters includes a wider review of environmental flow methods.

2.2 Regulatory standards used in different countries

Australia

Several environmental flow methods have been developed in Australia

(1) The 2/3rd rule
Australian scientists have suggested that in the Murray-Darling River basin the probability of having a healthy river falls from high to moderate when the hydrological regime is less than two-thirds natural (Jones, 2002). The Murray-Darling has been defined as a "working river" where significant abstraction is accepted as necessary for economic survival of farmers. The 2/3rd rule is a conceptual idea for a large dryland river system that has never been applied in practice; it has been superseded by MFAT (see 3 below) for environmental flow assessment.

(2) Holistic approaches (including expert panel methods)
This approach, described for Australian rivers, was developed in close association with the Building Block Method in South Africa. The procedure is to assess the complete river ecosystem, including the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary. A fundamental principle is that to maintain integrity, natural seasonality and variability of flows should be maintained.

Flood flows: initial - supply of nutrients, washout of particulates and sediment medium - redistribution of communities
large – if medium floods not managed correctly then large floods could cause more structural damage. Also floodplain issues

Low flows: maintenance of normal seasonal processes, including nutrient cycling, community dynamics, animal movement and reproductive development, influences on the survival of riparian seed banks and the establishment of plants, avoidance of fish kills in perennial rivers and avoidance of proliferation of pest species in periodic rivers.

Further key elements are:

- use of modelled historical and naturalised flow time series (using a daily time step where appropriate to identify key elements);
- interdisciplinary expert panels;
- field visits (viewing flow conditions and functional habitats);
- workshops, and publicly available reports; and
- involvement of all stakeholders.

Generally the holistic approach makes extensive use of a team of experts, including a hydrologist, hydrogeologist, geomorphologist, plus aquatic entomologist and botanist, and fish biologist. The expert panel will make judgements about the ecological consequences of various quantities and timings of water in the river. Where the river is affected by upstream impoundments, the panel may directly view the river at different flows, otherwise field visits will be accompanied by analysis of hydrological data.

Extensive use is made of cross-tabulated matrices (Table 2), indexed in three different ways, the fundamental elements, the categories within elements, and the ecosystem components.

Table 2 Example of cross tabulated matrix for flows and influences on invertebrates

Percentile	Physical features	Hydrological features	Flow regime
80	Meso-scale diversity	Flood duration	Flood frequency (large-scale 10-20 years)
50	Channel surface area	Rate of rise and fall, flood peak, flood and flow duration	Flood frequency, flow duration, sequence of events
25	Channel complexity, area, sub-reach features	Rate of rise and fall, flood peak, flood duration, freshets	Frequency of flow (1 yr return), flow duration, sequence of events
10	sub-reach features, snags, rock outcrops, macrophytes, litter	Flood ‘minimum’ – river falling below this level important, level variability	Frequency of floods (1 yr return), frequency of drought, flow duration, seasonality

(3) MFAT
The Murray Flow Assessment Tool (MFAT) was developed in 2003 for the Murray-Darling Basin Commission based on the Environmental Flows Decision Support System developed (Young *et al*., 1999). MFAT assesses habitat conditions for native fish, wetland vegetation, floodplain vegetation and water birds at selected key locations on the Murray-Darling River for each of a series of flow scenarios. Simple hydraulic rules are used to estimate variables such as rate of flow rise, duration of flow and extent, timing and duration of floodplain inundation. For each species and life stage, physical conditions are scored using habitat preference curves.

(4) Flow events method
The FEM (Stewardson and Gippel, 2003) provides generic methods for analyzing the frequency of individual hydraulically-relevant flow indices under alternate flow regimes. It is thus strongly

suited to scenario analysis, but not, so far, to objective setting. The authors suggest an expert panel for the selection of indices in any particular study.

(5) Wetted perimeter method
As river discharge increases, the bed area (wetted perimeter) is filled, but there comes a point, where for further equal increments in discharge, wetted perimeter increases less and less quickly. Thus it should be possible to identify a 'minimum discharge' from the point of maximum curvature on the wetted perimeter / discharge relationship. This 'technique', although rather vague, is very often quoted in reviews of instream flow methods, but has rarely been evaluated experimentally or critically. It has the advantage that it does not require detailed species / habitat relationship data. Gippel and Stewardson (1996), provide one such review, where they tested a clearly-defined wetted perimeter methodology. They noted firstly that evaluation of a breakpoint from a graph is highly error-prone, and demonstrate a technique for defining the point of maximum curvature mathematically. Secondly, they applied this technique to two headwater streams to define residual flows below diversions. They concluded that although the minimum discharges recommended by this approach were higher than those specified historically, invertebrate diversity and abundance were still significantly reduced. They thus suggest that although this is a useful analysis technique, it should only be used in conjunction with other methods. Reinfelds *et al.* (in press) refined the wetted perimeter breakpoint method for setting cease-to-pump limits (i.e. hands off flows) and minimum environmental flow in the Kangaroo River, Australia.

(6) Habitat modelling
PHABSIM has been applied in Australia (e.g. Gippel and Stewardson 1995), but it has not attracted wide appeal. In one particular study, Pusey and Arthington (1991) suggest that the major limits on fish populations are the variability of the flow regime, and the incidence of flooding. The Karim *et al.* 1995 paper should be read with caution, as it evaluates IFIM as a black box designed to produce a minimum recommended flow (which it is not). Rather it is a suite of techniques, in particular able to evaluate alternative management scenarios and incremental changes, and its role as a level playing field for negotiation.

Assessment
The 2/3rd rule is not well developed and may not be appropriate for UK rivers. The Holistic Approach and MFAT use a range of hydrological indices that influence the ecology of Australian rivers that are likely to be relevant to the UK. The concepts within the wetted perimeter method are covered in habitat modelling.

Austria

Standard procedures have been proposed: a holistic framework, combining expert opinion and a list of criteria (plus a seven-point naturalness scale), elements of IFIM (see USA section below), together with quantitative tools such as PHABSIM (see England and Wales section below).

Assessment
As far as we know, Austria has no novel standards or methods.

Canada

In Canada individual provinces undertake studies of Instream Flow Needs, under the auspices of the Fisheries Act (Canada). The Act only makes general prescriptions, and it rests with the Fish and Wildlife Divisions of each province to determine methods.

Atlantic Canada
Historically, 25% of the mean annual flow has been used as a minimum standard to maintain aquatic life for rivers in Atlantic Canada (Caissie, 1995), presumably implemented as a hands-off flow. Caissie compared this approach with 90th percentile, 7Q10 (low flow that is expected to occur for seven consecutive days once in ten years), Tennant (Tennant, 1976, Wesche and Reschard, 1985) and median monthly flow (MMF) (*c.f.* Matthews and Bao, 1991, New England methods). It should be noted that the rivers considered in this study would have had a snow-melt dominated flow regime. The MMF method was recommended for gauged catchments, while the 25% mean annual flow and Tennant methods recommended for ungauged catchments, with the mean flow regionalised using multiple regression. Scruton and LeDrew (1996), undertook a retrospective review of flows below the Upper Salmon Hydroelectric Development, and concluded that habitat methods such as PHABSIM were preferable to standard-setting approaches (e.g. Tennant) ‘where detailed analysis of habitat trade-offs as related to flow regulation are required.’

Alberta
In Alberta, there is a two level system, with the Tessman modification of the Tennant method (see USA section below) used for level one planning.

IFIM is used for level two studies. Models used under IFIM include physical habitat simulation and water quality. 16 IFIM type studies have been undertaken. The standard PHABSIM procedures are used, but the year is then divided into Biologically Significant Periods (BSPs) using knowledge about the life history of the target life stages. For each BSP, one composite physical habitat – discharge relationship is calculated mathematically and checked by fisheries scientists (denoted as a fish rule curve (FRC) (Locke, 1996)). Then, a minimum flow may be defined, either by considering obvious inflection points on the fish rule curve, or as the flow giving 80% habitat reduction from the optimum (although this figure is also varied depending on management objectives). An alternative approach is to select the flow giving the 80% habitat exceedance percentile.

Other provinces
Reiser *et al.* (1989) reported that the other provinces used a similar strategy, i.e. Tennant-type methods for level one studies, and IFIM for level two. Scientists at INRS-Eau in Quebec are developing a microhabitat modelling system called HABIOSIM which includes 2-dimensional physical habitat modelling.

Assessment
Canada has no novel standards or methods.

Czech Republic

IFIM-based procedures are being developed in association with the US National Biological Survey. Czech researchers have developed (micro) habitat suitability criteria for use with PHABSIM.

Assessment
The Czech Republic has no novel standards or methods.

Denmark

Advisory flow-based statistics were introduced into Danish legislation in the 1970s (Clausen and Rasmussen, 1988). They chose a simple low flow index, the median minimum, to use when considering allowable abstraction. The median minimum is defined as the median of the set of annual 1-day minima. Sensitivity of this figure to period of record has been examined. It is recognised that although easily calculated, other low flow indices such as the flow duration and flow frequency curves are more sophisticated.

Denmark is currently assessing the utility of physical habitat models such as PHABSIM.

Assessment
As far as we know, Denmark has no novel standards or methods.

England and Wales

The Environment Agency of England and Wales has developed four main approaches

(1) Flow rules
Although not strictly for environmental considerations, compensation flows have been established from reservoirs in the UK by Acts of Parliament (Gustard *et al.*, 1987). The rules often defined percentages of mean flow that need to be released constantly at an unchanging rate.

Many abstractions in England and Wales are managed according to an index of natural low flow; Q_{95} (ie. that flow which is equalled or exceeded for 95% of the time) is often used. However, in other cases, indices of rarer events (such as mean annual minimum flow) have been used. The figure of Q_{95} was chosen purely on hydrological grounds. However, the implementation of this approach (*e.g.* how much Q_{95} can be reduced) can include ecological information. Q_{95} has often been a hands-off flow; i.e. no abstraction is permitted when the flow is below this threshold (Barker & Kirmond, 1998).

In some cases, generic relationships have been established for specific elements of the river ecosystem. For example, Stewart (1973) found that salmon started their migration in rivers of northwest England when the flow reached 0.084 m^3s^{-1} per metre of channel width. Additionally, 0.03 m^3s^{-1} per metre of channel width is considered as a survival flow. It should be noted that the background data or rationale to these figures are not available, and no estimation of uncertainty is available. This approach has been recommended for implementation of the Habitat Directive as part of the LIFE in UK Rivers work (Hendry and Cragg-Hine, 2003).

(2) The RAM framework
The RAM framework is based on the idea that rivers vary in their sensitivity to abstraction. The first step to calculate the sensitivity to abstraction is to determine the “environmental weighting”. Four elements of the ecosystem are assessed: 1. Physical character; 2. Fisheries; 3. Macrophytes; 4. Macro-invertebrates. Each element is given a RAM score from 1 - 5 (1 being least sensitive to reductions in flow, 5 being most sensitive). In terms of physical characterisation, rivers with steep gradients and/or wide shallow cross sections score 5, since small reductions in flow result in a relatively large reduction in wetted perimeter. Lowland river reaches that are narrow and deep, are not considered to be so sensitive to flow reduction and score 1. Physical character is determined by comparing the river with photographs of typical river reaches in each class. Scoring for fisheries is generally determined by using expert opinion of Environment Agency fisheries staff to classify the river according to description of each of the RAM score classes. Scoring for macro-invertebrates and macrophytes uses flow-sensitive

metrics such as the LIFE score (described below).

Once a score for each of the four elements has been defined, the scores are combined to categorise the river into one of five Environmental Weighting Bands, where Band A (5) is the most sensitive (average score of 5) and Band E is the least sensitive (average score of 1). In a separate part of the RAM framework a flow duration curve (for natural flows) is produced. The RAM framework then specifies allowable abstractions at other different point (flow percentiles) of the curve for each weighting band. Table 3 shows the percentage of natural Q_{95} flow that can be abstracted.

Table 3 Percentages of natural Q_{95} flow that can be abstracted for different environmental weighting bands.

Environmental weighting band	% of Q_{95} that can be abstracted
A	0-5 %
B	5-10%
C	10-15%
D	15-25%
E	25-30%
Others	Special treatment

The RAM framework does not classify rivers according to use or broad objectives, as in South Africa (see below). This is broadly in line with the Water Framework Directive requirements to achieve “Good Status” (GS) in all surface waters. However, English Nature has produced supplementary standards for SSSIs and Habitats Directive sites for use within the RAM framework (English Nature, 2004).

(3) PHABSIM

For detailed studies of the impacts of abstractions and impoundments, the Environment Agency has used the Physical Habitat Simulation (PHABSIM) system. The PHABSIM method was developed in the United States and has been successfully applied in the United Kingdom for the past 15 years. PHABSIM is based on the principle that alterations in flow will change physical habitat in a river. PHABSIM modelling uses two data collection stages: field survey measurements of channel geometry, water level and stream velocity at transect sites on a river system (Elliott *et al.* 1996); and criteria on physical habitat conditions that life stages of aquatic species find suitable and unsuitable. The latter may be obtained by direct measurement, indirect measurement (e.g. expert opinion) or literature review. Hydraulic simulation of the river is combined with the habitat criteria using a habitat model. This expresses a relationship between a weighted index of potential physical habitat (termed Weighted Usable Area or WUA) and river discharge. This is undertaken for each species/life stage of interest.

PHABSIM is a widely applicable means by which biological information may be introduced into the water resources planning process, and utilised in an incremental fashion. It is not a population or biomass model nor is it required to rely on any direct link between populations and physical habitat alone. The reason for simulating physical habitat is that there are often no clear links between flow and population due to a multitude of confounding factors, both flow and non-flow related. However where habitat is limiting, populations will commonly be limited. Furthermore, Gore *et al.* (1998) found a significant correlation between habitat and actual benthic community diversity in the USA, Gallagher and Gard (1999) found that habitat correlated with spawning density of Chinook salmon, Gibbins and Acornley (2000) used PHABSIM to predict salmon spawning and Jowett (1992) related habitat to brown trout abundance.

Further advantages of such an approach lie in the successful matching of species physical requirements to flows, implicit incorporation of habitat structure formed by both channel form and flow, and not relying on extensive pre-scheme biological records.

PHABSIM is a relatively high resource approach, which will not be applicable for application to large numbers of sites or where impacts are clearly minor. Criticisms of the methodology have included:

- It has not been extensively developed for invertebrates and plant species;
- It does not predict biomass or population levels, but uses an index of habitat potential;
- Validation has been patchy;
- Procedures for integrating with other models (e.g. water quality) are less well developed;
- Many of the strengths and weaknesses of the model are not well documented;
- Consideration of sediment transport and channel change are not explicit;
- Its conceptual basis still disputed (but it is still more defendable that any other method); and
- It does not produce a single answer.

There has been an intermittent debate in the scientific literature over the last 20 years as to the validity of applying the PHABSIM model. This has been reviewed in Jowett (1997) and for the Agency by Bird (1996) for example. Hardy (1996) and O'Grady (1996) presented two opposing views in a UK context. Some of the original criticisms, dating from the mid 1980s, centred on deficiencies in the original PHABSIM I procedures (version II of the model was released in 1989). It is clear that the modelling and application procedures are still developing. A major current and future area of research is applying and using the model in a temporally relevant manner, particularly considering limiting events (physical habitat plus others) for key life stages.

(4) LIFE

The Lotic Invertebrate index for Flow Evaluation (LIFE) (Extence *et al*, 1999; Dunbar *et al*. 2004) is designed to be used with routine macro-invertebrate monitoring data. A metric of perceived sensitivity to water velocity scores all recorded UK taxa on a six- point scale. For a sample, the score for each observed taxon is modified based on its abundance, and mean score per taxon calculated. The system works with either species or family level data. The RIVPACS model can be used to calculate expected LIFE score for a site. For monitoring sites where historical time series of flows are known, the relationship between LIFE score and preceding river flow may be analysed. Moving averages of preceding flow have shown good relationships with LIFE scores over a range of sites, however there are statistical problems with this approach (Figure 1). Multiple regression analysis has shown consistent variation between family level LIFE observed / expected (O/E) score and flow across hundreds of sites; however the unexplained variation in LIFE is still high. Dunbar *et al.* (2004) found no evidence for anything other than a common LIFE-flow slope for all sites, providing evidence against differing sites having differing sensitivities to abstraction. However, sensitivity to abstraction was not the core analysis undertaken in that project, and the lack of variation in sensitivity across sites could well be due to the simple methods used to standardise LIFE score and flow across sites, or the use of family level data. More detailed analysis could well demonstrate such relationships.

The exact manner in which LIFE score variation can be used to manage river flows is still to be determined. Nevertheless, the principle is believed to be sound and LIFE has the major advantage of utilising the data collected by existing bio-monitoring programmes as required by the Water Framework Directive.

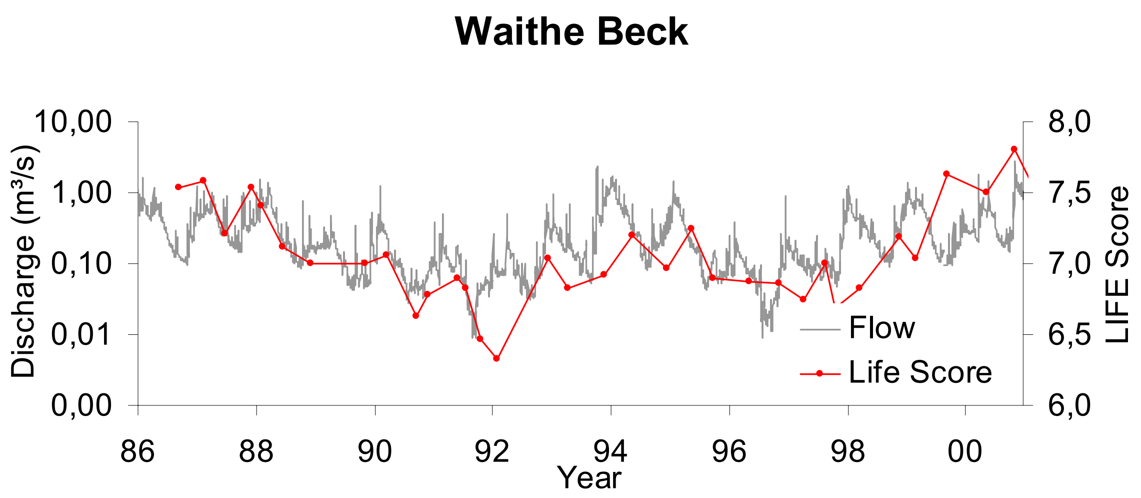


Figure 1 Flow and the LIFE score in the Waithe Beck in the UK (Extence *et al*., 1999)

Assessment:

(1) Fixed compensation flows do not constitute an environmental standard. Q_{95} is a useful measure of low flow, but its ecological relevance has not been tested. Flow per unit width of river may be a useful way of standardising environmental flow needs, however it requires width to be determined at the site of interest and map based estimates of width are normally poor.

(2) The underlying concept of RAM framework (linking 4 elements of the river ecosystem) seems intuitively reasonable. However, the percentages allowable takes in the RAM framework are not well supported by hydro-ecological studies and are only intended as a default method. More detailed methods, such as habitat modelling (PHABSIM), are recommended where environmental flows need to be defined in more detail. The RAM framework focuses on producing an ecologically acceptable flow duration curve. The flow duration curve retains some characteristics of the flow regime, such as the basic magnitude of flows. However, it does not retain other characteristics, including temporal sequencing, duration or timing of flows, which may be important for the river ecosystem (Poff *et al*, 1997). Many ecologists believe that ecosystems in flashy rivers are well adapted to flow change and so less impacted by abstraction. Cowx *et al.* (2004) concluded that flow statistics, such as mean flow, do not accurately reflect elements of the flow regime that influence fish. RAM uses an annual flow duration curve which does not allow for the ecological importance of flows at different times of the year, eg. for migration or spawning.

(3) PHABSIM provides a direct measure of impact of flow alteration on habitat for target species, but it is expensive to apply and is designed for scenario analysis (*i.e*. it does not define threshold levels of flow); it is therefore not suitable for WFD strategic level assessment (but see work by Lamouroux and Capra below).

(4) LIFE Graphs of LIFE score against flow indices provide indications of the sensitivity to abstraction of sites where invertebrate and flow data are available. In the time available for their project, Dunbar and Clarke (2004) were unable to demonstrate significant relationships between the slope of the LIFE-flow response and catchment / site characteristics such as catchment area, river width and RIVPACS ecological group. However, this is a fruitful line of inquiry as it allows the testing of sensitivity of macro-invertebrates to abstraction.

France

(1) Hydrological index rules
In 1984 the 'loi-peche' ('fish law') was passed, putting the requirements of aquatic biota on a par with other uses of water. Updated in 1992, the minimum flow is specified at not less than 1/40th of the mean flow for existing schemes, and 1/10th of the mean for new and renewed schemes.

(2) EVHA
More recently, the EVHA (EValuation of HAbitat) method has become the standard method (but not specifically prescribed in law) for re-licensing of impoundments and diversions. EVHA was developed by CEMAGREF Lyon in collaboration with EDF (Electricité de France). EVHA (a Windows package, Ginot, 1995), AGIRE (a multipurpose water GIS used internally by EDF) and PHABSIM used by ENSAT Toulouse all use similar physical microhabitat simulation.

(3) Rapid methods
Lamouroux *and Capra* (2002) found strong relationships between the form of the Weighted Usable Area v. discharge curve and hydraulic parameters Froude and Reynolds numbers. It was thus possible to predict the response of physical habitat to discharge given simple measurements of wetted width at two different flows: this work shows promise for the development of rapid assessment methods, but still requires some at-site data.

Assessment
The work of Lamouroux *et al.* is being explored using UK data by CEH within a collaborative project called Rapid Assessment of Physical Habitat Sensitivity to Abstraction (RAPHSA). No results are available yet.

Finland

Flow-related problems in Finland have centred around impacts of hydro-power schemes (Sinisalmi, 1997). There is consideration of ecological value of rivers if flow objectives are set, but no standard methods. The Finnish Water Act (1994) allows revisions to operating licenses if the regulations cause considerable adverse effects (Sinisalmi, 1997). Studies have generally centred around physical habitat for fish species, either using EVHA (Riihimaki *et al.* 1996), or detailed research-oriented approaches (e.g. Muotka *et al.* 1996).

Assessment
As far as we know, Finland has no novel standards or methods.

Germany

(1) Hydrological index rules
Historically, simple hydrological indices have been used to determine minimum flows, the majority related to hydro-power schemes. Once set, they were often legally-binding, but were determined entirely on a case-by-case basis. Over 100 flows have been determined using expert opinion or hydrological indices. Currently, many hydro-power licenses are due for renewal for the next 30-60 years. There is a major ongoing effort to develop newer, more ecologically valid methods. State government is the most common regulator. University departments conduct most studies, although in some cases it is the state regulatory agencies.

(2) CASIMIR
The Institute of Water Sciences, University of Stuttgart, has developed a microhabitat simulation model called CASIMIR (Computer Aided Simulation Model for Instream flow Requirements in regulated streams) (Jorde, 1996). It was developed for assessment of impacts of hydropower schemes, and includes three major habitat types, river bottom (benthic organisms, bottom dwelling fish), the aquatic zone (fish), and the riparian zone.

CASIMIR includes modules for the calibrated using Statzner's 'FST' hemispheres, alternative hydropower options, habitat modelling, time series analysis and economic analysis. New models are being incorporated for fish habitat, and riparian zones plant communities.

Assessment
As far as we know, Germany has no novel standards or methods.

Ireland

Activities so far in Ireland appear to have centred around requirements for migrating and spawning salmonids on rivers most affected by hydro-electric power development, the Shannon, Liffey, Erne and Lee. These have been undertaken using direct collection of fisheries data on population levels, spawning and migration.

Assessment
As far as we know, Ireland has no novel standards or methods.

Italy

(1) Minimum instream flow
In Italy, there are laws rationalising use of surface water between instream and abstraction functions, but they do not describe methods. The regulatory authorities (River Basin Authorities, Regions, Autonomous Provinces) and researchers have developed their own methods, commonly hydrological indices based on the concept of a Minimum Instream Flow (MIF) define as "the flow that must be maintained downstream water diversions in order to maintain vital conditions of ecosystem functionality and quality" (2002)

For the Po basin, a preliminary, regional standard was developed in 1992 as follows:

MIF= q. P.A.Q.N

Where:
q = 1.6 $ls^{-1}km^{-2}$
P = rainfall factor (1 at 1000mm, 1.8 at 1400mm)
A = altitude factor
Q = water quality factor (greater flows required if quality bad), also depends on local expectations
N = naturalness factor (1 for ordinary areas, 1.2 for national parks)

This is really a rapid empirical low flow hydrology method only applicable to the Po that has never been verified by ecological data.

Ubertini *et al.* (1996) considered basin-scale methods appropriate for the Tiber. These were the Tennant method (i.e. a method based upon field observation of fishery health in a wide range of streams of similar ecotype), the wetted perimeter method and IFIM / PHABSIM. The Singh, and Orth and Leonard methods were considered for regionalisation, along with a method for regionalisation of Q95 based on geology and catchment area.

(2) PHABSIM
Saccardo *et al.* (1994), undertook a pilot IFIM / PHABSIM study on the Arzino River, and compared with a suite of standard-setting methods, based on daily and annual mean flows, and flow percentiles. Maran (2003) used PHABSIM within Bayesian Belief Network (BBN)

framework to assess different water use options (hydropower, irrigation, habitat protection) on Vomano River.

Assessment
Italy has no novel standards or methods.

Japan

River conservation appears to come under the jurisdiction of the Ministry of Construction, who have a range of policies to promote systematically the preservation and creation of river environments. The term 'conservation flow' has been used. Studies to assess anthropogenic impact on river systems are ongoing, and have been conducted by university scientists. Emphasis has been on the development of techniques centred around physical habitat modelling, incorporating multi-dimensional hydraulic modelling, and multivariate habitat suitability criteria (Tamai *et al.* 1996).

Assessment
As far as we know, Japan has no novel standards or methods.

Lesotho

The Downstream Response to Imposed Flow Transformation (DRIFT) approach (King *et al.* 2003) was developed for determining environmental flow releases from dams in Lesotho (Lesotho Highlands Development Authority, 2002). It is a holistic approach that addresses all aspects of the river ecosystem. It is also scenario-based, providing river managers with a number of options (scenarios) of future flow regimes for a river of concern, together with the consequences for the condition of the river. Probably its most important and innovative feature is a strong socio-economic module, which describes the predicted impacts of each scenario on subsistence users of the resources of a river.

DRIFT has four modules:
(1) Biophysical. Within the constraints of the project, scientific studies are done of all aspects of the river ecosystem: hydrology, hydraulics, geomorphology, water quality, riparian trees and aquatic and fringing plants, aquatic invertebrates, fish, semi-aquatic mammals, herpetofauna, microbiota. All studies are linked to flow, with the objective of being able to predict how any part of the ecosystem will change in response to specified flow changes.
(2) Socio-economic. Social studies are done of all river resources used by common-property users for subsistence, and the river-related health profiles of these people and their livestock. The resources used are costed. All studies are linked to flow, with the objective of being able to predict how the people will be affected by specified river changes (last module).
(3) Scenario-building. For any future flow regime the client would like to consider, the predicted change in condition of the river ecosystem is described using the database created in modules 1 and 2. The predicted impact of each scenario on the common-property subsistence users is also described. DRIFT provides a routine for optimising the flow regime that gives maximum benefits for a given volume of water available. It indicates the uncertainty in the scenario impacts.
(4) Economics. The compensation costs of each scenario for common-property users are calculated.

Because of its multidisciplinary nature, a comprehensive DRIFT application could cost a million US$ or more for a large river system, and less for a smaller system. It is often an issue of trade-offs however and the greater the investment in investigative studies, the higher the confidence in the scenarios produced. To put this into perspective, even a comprehensive DRIFT study will probably still cost less than 1% of the total cost of many dams.

Assessment
DRIFT was developed for detailed studies of specific rivers systems and its expense precludes its use from assessment of large numbers of catchment. As DRIFT is scenario based, it is not so appropriate for achieving pre-defined objectives such as good ecological status under WFD. It was also developed for rivers with subsistence users in a developing country. Nevertheless, the socio-economic aspects could be applied to developed countries with some methodological changes. The DRIFT solver could be a useful tool for optimising reservoir releases given an agreed fixed volume.

The Netherlands

The Directorate General for Public Works and Water Management (Rijkswaterstaat) is responsible for the water management of national waters (including main rivers) in the Netherlands and for legislation. Regional Directorates take care of implementation. In addition to ecological effects, key issues are the maintenance of water levels for navigation and flows, for effluent dilution and to the sea to prevent saline intrusion. Furthermore, most water management is stage (i.e. level) rather than flow orientated, to maintain groundwater levels for water resources, and to satisfy the demands of agriculture. Target water levels may be determined using a complex hydrological model, the PAWN (Policy analysis Water Management of the Netherlands) system, first implemented in 1985.

Duel *et al.* (1996), elaborates this framework, describing the 'Aquatic Outlook' project '*to develop strategies to reinstate the ecological conditions and values of the inland and coastal waters, whilst improving the opportunities for functional use of these water systems'*. There appear to be strong potential synergies with Environment Agency strategy. The HEP (Habitat Evaluation Procedure) is the framework under which this is to be undertaken. This is a general habitat suitability scoring model, and appears similar to HEP as described under the USA section below.

Duel *et al.* (1996) describe a series of models / procedures that have been developed for ecotope classification, physical habitat modelling, habitat suitability and policy and alternatives analysis.

A report by Delft Hydraulics is quoted (in Dutch; Duel and de Vries 1996), outlining an HSI type model, used to examine alternative strategies in terms of areas of suitable habitat for many target species. It is implied that this includes the hydrodynamics of aquatic systems, but it is not known by what method.

The most important points to note are:

1. it is an official standard;
2. it considers a wide range of species;
3. it considers a wide range of habitats; and
4. it presents policy alternatives clearly.

However it might be argued that it is too simplistic.

Studies to determine minimum flows and required flood frequencies have been undertaken on the Meuse (see below), Rhine and Waal.

Microhabitat methods
Microhabitat models are in the process of being applied to certain rivers. For example Semmekrot *et al.* (1996) describe the development of a GIS (Geographical Information System) -based microhabitat model, also incorporating temperature and chemical quality, to the Grensmaas, a stretch of the River Meuse. The authors note greater spatial resolution compared to a standard PHABSIM application, but do not mention accuracy of hydraulic modelling of stage and velocity.

Assessment
The coupling of GIS to physical habitat models seems novel and interesting.

New Zealand

New Zealand rivers are managed under the Resource Management Act (1991), described in Gow (1996). The Act requires that rivers are protected from adverse effects and their life supporting capacity sustained or safeguarded (Jowett, pers. comm.). The Department of the Environment has issued guidelines on determination of Instream Flow requirements (Snelder *et al*. 1996). It considers Instream Flows for other functions, such as amenity and cultural values.

Habitat modelling
The main tool used in New Zealand is RYHABSIM (Jowett, 1989), a microhabitat method developed by Jowett at the National Institute of Water and Atmosphere (NIWA). RYHABSIM uses similar principles to PHABSIM, but has fewer options. This technique has been used on 25 rivers, more are ongoing and planned.

Research applying hydraulic and habitat methods to a range of river sizes has suggested that small rivers require a larger proportion of the average flow to maintain similar levels of environmental protection (Jowett, 1997).

Habitat versus flow curves have been generalised by Lamouroux and Jowett (unpublished work) and Jowett (1997) to produce a rapid assessment method.

Various papers by Clausen, Biggs and Riis have examined the role of hydrological variables in structuring macroinvertebrate and plant communities. In particular, the role of the FRE3 variable, the number of high flow events greater than three times the median flow has been noted. Separation of intercorrelated flow variables for ecological analysis has been studied.

Assessment
The work on generalised habitat-flow relationships is novel and useful. The work on relating flow variables to ecology has not led to regulatory standards but is definitely relevant to this project.

Northern Ireland

In Northern Ireland the Department of Environment (DOENI) has responsibility for promoting the conservation and cleanliness of water resources. Much of this responsibility is carried out by the Environment and Heritage Service (an agency within the DOENI). Regulatory control of Water Resources (e.g. abstraction/impoundments) may be exercised through planning legislation where e.g. the intended water abstraction or impoundment proposal constitutes development under the Planning (Northern Ireland) Order 2003. Control may also be exercised where an associated discharge results as a consequence of the abstraction. Conditions set within a discharge consent under the Water (Northern Ireland) Order 1999 could therefore control the amount of water abstracted.

The controls on abstraction and impoundment within existing legislation in Northern Ireland effect mainly large projects however provision does exist under the Water (Northern Ireland) Order 1999 to make Regulations controlling abstraction and impoundment activities but these powers have yet to be enacted and therefore no abstraction licensing system currently exists.

The provision of public water supply is the responsibility of the Northern Ireland Water Service (an agency within the Department of Regional Development) under the Water and Sewerage Services (Northern Ireland) Order 1973. The main sources are reservoirs (47%) and loughs (41%) with rivers and groundwater accounting for only 12% of the public water supply (Water Resources Strategy 2002-2030). Proposals for future supplies will concentrate on water efficiency programmes, increasing abstractions from existing large sources (e.g. Lough Neagh) and through the rationalisation of smaller uneconomic sources.

In Northern Ireland abstraction issues are more localised and have focused on compensation flows from reservoirs and low head hydro-electric schemes. Major proposals for large public supply abstractions in the past have been subjected to public enquiry.

The abstraction of water in Northern Ireland will increasingly be governed by the Water Framework Directive and is currently under review within the Environmental Policy Group of DOENI. The Water Environment (Water Framework Directive) Regulations 2003 transposed the Directive into Northern Ireland law on 12th January 2004. The regulations provide the management structures within which river basin management planning will be conducted.

Assessment
No agreed standards or methodologies relating to water quantity have been developed in Northern Ireland.

Norway

The main issues in Norway are impoundment and hydro-power. A new law relating to ecologically acceptable flows is currently in the consultation stage (is this from EARFOs, if so probably out of date). This may define a simple hydrological formula to determine the flow objective, with no ecological input, although researchers in the field are lobbying against this. In the past, expert opinion has been used on a case-by-case basis.

River System Simulator
The Norwegians have developed a habitat-modelling framework as part of a sophisticated hydrological / limnological simulation system called RSS (River Simulation System) (Killingtviet and Fossdal, 1994). The system is primarily designed for modelling changes resulting from hydro-power. Target species are currently salmonid fish. There is the suggestion that optimising flows for salmon fishing would not lead to the best ecological flow regime overall.

Assessment
Norway has developed specific habitat models for considering hydropower dam management.

Scotland

Until recently, the regulation of water abstractions in Scotland lagged behind that in England and Wales in that no licensing regime was in operation. Water supply abstractions have compensation flows set on an individual basis, confirmed by the Secretary of State for Scotland (and now post-devolution by the Scottish Ministers). The same approach applies to the hydro power sector: individual acts of parliament were required for individual schemes put forward until 1943. Thereafter the Hydro-Electric Development (Scotland) Act 1943 provided for the Secretary of State to approve the detail of individual schemes, including compensation and freshet provisions, subject to a public inquiry if objections could not be resolved by the North of Scotland Hydro-Electric Board. Again, the approach taken to environmental provisions was on a case-by-case basis. This mechanism covered the development of most of Scotland's hydro schemes. Over the past decade or so, a new phase of hydro development has begun under various government-backed renewable energy programmes, with SEPA representing the aquatic environmental interest either through local planning authority or Scottish Executive decision-making, depending on scheme capacity.

The sole minor exception to the general position of private water abstractions being unregulated was provided by the Natural Heritage (Scotland) Act 1991, which introduced a mechanism of control orders for two small areas accepted by government as having particular abstraction problems caused by agricultural abstraction – the Ordie Burn catchment in Perthshire and the West Peffer Burn catchment in East Lothian. In these areas, the local River Purification Board (later SEPA) could apply for an order to be introduced when low flow conditions caused concern. The system was necessarily limited in effect.

The Water Framework Directive has been transposed into Scots law by the Water Environment and Water Services (Scotland) Act 2003. Primary legislation was considered necessary because of the fundamental need to introduce a widespread system of abstraction control, although the Act also introduces the powers to regulate impoundments and the other requirements of the Directive. In many senses it is a piece of enabling legislation since the detailed regulations will be introduced subsequently by the use of secondary legislation/regulations.

Current SEPA guidance for compensation flows is a figure between the 1-day Q_{90} and Q_{95} values, with consultation with developer, Scottish Natural Heritage (SNH) and District Fisheries Boards.

DHRAM (the Dundee Hydrological Regime Assessment Method) was developed in order to allow the severity and extent of hydrological regime alteration to be assessed and mapped (Black *et al*, 2000b). It has been developed in two forms, for rivers and lakes respectively, and in both cases using daily data (either for river flows or lake levels, respectively). Time series describing flows or levels in an (anthropogenically) altered situation are compared with un-impacted (reference) conditions, and deviations are obtained for 32 ecologically-relevant hydrological indicators defined by the Indicators of Hydrologic Alteration (IHA) methods of Richter *et al.* in the US Nature Conservancy. DHRAM uses IHA output to assess severity of regime alteration for any site in relation to a 5-fold classification. Iterative application allows results to be mapped. The method requires hydrological skill and judgement to be exercised when application to un-gauged sites is required – either for the un-impacted or impacted situation.

South Africa

The South African Water Law makes a specific requirement for an environmental flow (Rowlston and Palmer, 2002). It states that "the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems".

South Africa has two main environmental flow standards: (1) the Building Block Methodology, for setting environmental flows on specific individual rivers and (2) a desk-top model for strategic water resources assessment. Other methods being developed include (3) biotopes approach.

(1) The Building Block Methodology
The BBM (King *et al.,* 2000) is used to define the 'reserve' i.e. flow required to meet the management objectives. BBM divides the flow hydrograph into 4 components:

- low flows in maintenance years
- low flows in drought years
- high flows in maintenance years
- high flows in drought years.

The flows in each building block are defined in terms of percentage of natural annual flow. The BBM revolves around a team of experts that normally includes physical scientists, such as a hydrologist, hydrogeologist and geomorphologist and biological scientists, such as an aquatic entomologist, a botanist and a fish biologist. They follow a series of structured stages, assess available data and a wide range of model outputs, such as graphs of wetted perimeter v. discharge. The experts use their combined professional experience to come to a consensus on the building blocks of the flow regime. The BBM has a detailed manual for implementation (King *et al.* 2000), is presently routinely used in South Africa to comply with the 1998 Water Act (DWAF, 1999), has been applied in Australia (Arthington & Long 1997; Arthington & Lloyd, 1998)

(2) Desk-top method
To undertake strategic assessment of water resources, ie. scoping, Hughes and Hannart (2003) developed a Desk-top Model producing initial, rapid estimates of ecological flow requirements. They analysed the results of 97 applications of BBM and produced a set of generalised relationships between the percentage of natural annual flow allocated to each BBM component of the reserve and an index (CVB) of the hydrological variability of the natural flow regime. CVB is close to 1 for flow regimes with very low variability to over 50 for semi-arid regimes in South Africa.

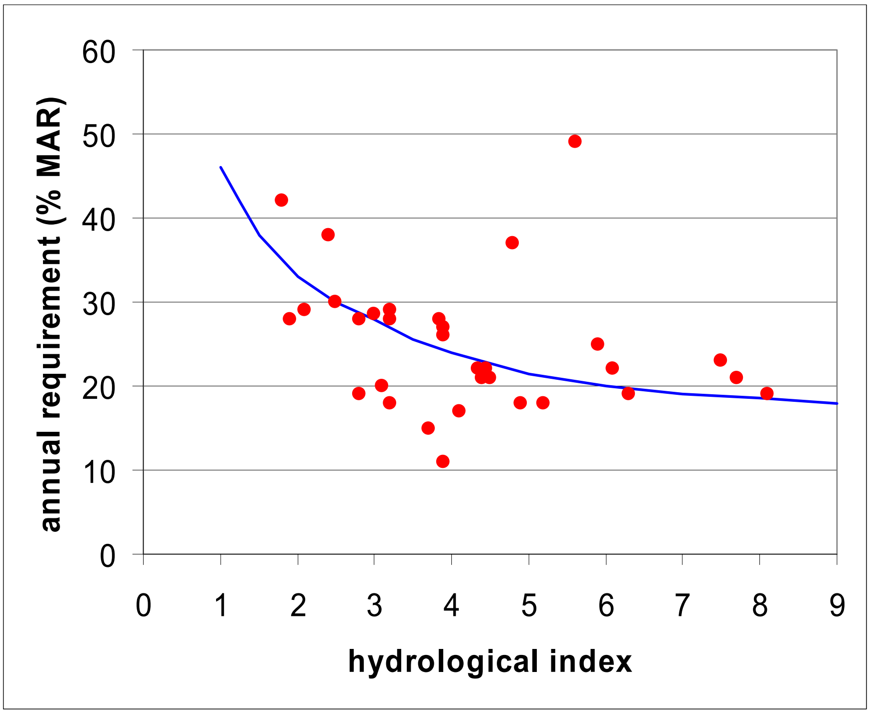


Figure 2 Relationship between the hydrological index (CVB) and annual total requirements for the maintenance low flows for B category rivers. The red dots show the results of individual BBM studies on B category rivers.

Figure 2 shows the index plotted against maintenance low flows for B category rivers. The red dots show the results of individual BBM studies on B category rivers. Clearly, there is a wide scatter, which suggests high uncertainty in the curves. Similar relationships were defined for high flows in maintenance years, although these increase with increasing hydrological index. In South Africa, drought high flows represent insignificant volumes, compared to the other requirements and explicit relationships with the hydrological index. Drought high flows are managed through assurance rules. It is noteworthy that in the Desktop Model, the higher the hydrological index (the more flashy the catchment) the lower the percentage of mean annual runoff needs to be allocated to maintenance low flows. This contrasts with RAM (see UK) where upland rivers tend to be considered more sensitive to abstraction (based on physical structure).

(3) Biotopes approach

This approach has been developed by Wadeson and Rowntree in South Africa (Rowntree and Wadeson, 1996). It has been investigated for application in the U.K. (Padmore, 1997). The procedure involves mapping surface flow types (e.g. rippled, smooth boundary turbulent, scarcely perceptible flow, unbroken standing wave) at representative sites. These flow types correspond to hydraulically distinct biotopes (e.g. cascade, riffle, run, glide, pool / marginal dead water). This data collection technique is also used as part of the procedure for the River Habitat Survey. Note that although a similar terminology exists, biotopes are not necessarily synonymous with meso-habitat types or morphological units used in physical habitat simulation.

Assessment

The BBM has two useful principles. First, the recognition that all parts of the flow regime may be ecologically important. Second, the use of structure expert consensus as opposed to expert opinion. Overall, BBM would be an excellent tool for standard setting on individual high priority/profile sites, but not for a large number of water bodies as required for the WFD.

The Desktop Model, with its relationships based on detailed hydro-ecological studies and hydrological index, has potential for the UK. RAM classes for CAMS assessment points could be used. The curves are very uncertain as the scatter of points in Figure 2 indicates. CVB may not be the best manner in which to characterise the variability in flow regimes of UK rivers. In addition, this type of relationship may or may not hold. For example, the flashiness of regime generally increases as one travels upstream as water depth decreases and width/depth ratio increases. If then, flashier channels are also wide and shallow, they may show greater physical sensitivity to abstraction (as is assumed in the RAM framework) rather than less sensitivity. This is still a subject of ongoing debate, resolution of which is central if sensitivity to flow changes is ever to be possible in a typology framework. Indeed Beecher (1990) suggests that in the USA it is small, lowland streams that are most sensitive to abstraction, not small upland streams.

The biotopes approach is still at the research stage and no formal method has been defined.

Spain

In Spain, there is a Water Law (1985) setting a broad basis for environmental protection, and regulations (1992) for minimum environmental flows, as with most other countries, specific standards and methods are not specified. There is a national framework for the production of Catchment Plans references to ecological flows are specifically included. In the absence of more details, the French criteria of 10% mean flow is used.

Habitat evaluation
Studies have integrated IFIM / PHABSIM with fish habitat classification using multivariate statistical models (Garcia de Jalon*, pers. comm.*). Habitat quality classification has been used as an initial survey method, for identification of potential factors limiting fishery biomass.

Cubillo (1992) described a method, used for the Madrid area, which is based upon a statistical analysis of naturalised flows, and ecological survey data from impacted and un-impacted reaches, indicating reference and target ecosystems. Flows required to reach target ecosystems are specified using hydraulic / microhabitat simulation of a range of target species.

Basic flow method
Palau (1996) developed an experimental approach that calculates an index from hydrological time series. A matrix is constructed of the mean annual 1,2...100 day minima for the series. The basic flow Qb is defined as the flow where there is the largest relative increase when considering the increase between 1&2 point, 2&3 point up to 99&100 point, presumably across all years (the description is rather abstruse). As well as Qb for a river, also calculated are Qb as a percentage of the mean flow, % of days where the flow is less than Qb, number of days when flow equalled or exceeded Qb, and the most frequent flow interval. The flow calculated is related to the flow ending the longest minimum flow series in an average year. The results in Table 4 were obtained for a study of 11 rivers.

The authors of the technique state that in rivers with the same annual mean flow, a river with short low flow periods will give a higher value of Qb than rivers with longer low flow periods. This is extended to claim that this gives the technique biological relevance, as the latter type of river, the biota will be more used to longer periods of low flow. The authors claim that the advantages of the technique are that it is easily calculated, not arbitrary, and more conservative when calculating Qb for small rivers, and finally, the Qb values generally agree with minimum ecological flow values obtained with other methods.

Table 4 Range of mean classified daily flow

River Type	Range of Qb as % of Qm
Seasonal groundwater	50%
Mediterranean rainfall	5.7-27
Snowmelt	15-16
Snowmelt and rainfall	17-37

The rationale behind this method seems to be an attempt to find a biologically more relevant (i.e. than a Q_{95}) low flow index. Whether it is relevant is certainly open to question, and from the description it does not appear to warrant further investigation. Unlike Q_{95}, the index is said to be a greater proportion of the mean flow for flashier rivers. More investigation on time series would be essential, as would its sensitivity to normal / impacted conditions (this is not mentioned in the description), and its utility as an analysis tool for physical habitat time series.

Basque method
Docampo and de Bikuna (1995) developed the Basque method for protection of invertebrate species diversity in unpolluted upper stretches of river and a hydraulic approach (protection of 60% of wetted perimeter) when lower reaches suffer from pollution problems. Flow is estimated at any point using multivariate regression techniques calibrated to individual river systems (similar to LOW FLOWS 2000).

The hydraulic method calibrates a model to estimate wetted perimeter variation based on discharge variation, using Manning's equation. It is calibrated using species diversity / wetted perimeter data taken from low flows on two rivers, but the detailed procedures are not documented in the material available.

The biotic method is based on river continuum concepts, i.e. in the upper / middle ranges of a river, species diversity increases with discharge (and thus drainage area). The optimum (whole-year desirable minimum) instream flow is calculated from the natural flow, as that which gives a reduction in species diversity of one unit. The absolute minimum instream flow is calculated as above, only considering summer-autumn conditions.

Assessment
The Basic Flow method does define a minimum flow but this is not based on ecological data. It does not appear to have advantages over other hydrological approaches such Richter. However, the Basque method warrants further investigation.

Sweden

Two instream flow studies have been completed using the River System Simulator (Harby, *pers. comm.*) (see Norway Section).

Assessment
As far as we know, Sweden has no novel standards or methods.

Switzerland

There is the requirement for an absolute minimum flow set by federal law (determined by a hydrological index), however each situation is also investigated individually at the Canton (administrative region) level, and further standards set using expert opinion. There are no other standard methods, but there are plans to investigate IFIM-type methods incorporating more flood plain ecological data (Peter, *pers. comm.*).

Assessment
As far as we know, Switzerland has no novel standards or methods.

United States of America

The USA has the most highly developed framework for assessing in-river water needs. Of relevance are both congressional and individual state laws. East of 100° longitude, the ultimate law is based upon riparian law, while west of 100° appropriation law (first in time is first in right) holds.

In some cases, the lead regulatory authorities are the state branches of the Fish and Wildlife Service. Often it is the resource developer who must undertake instream flow studies. However jurisdiction is varied, and the Forest Service, State Departments of Water Resources the Federal Bureaux of Land Management and Reclamation, and the US Army Corps of Engineers may manage resources, all have their own procedures. There will often also be a large number of interest groups and stakeholders all expressing their views.

Like most countries, the USA has methods appropriate for different objectives, including strategic/scoping exercises and detail environmental impact assessment.

(1) IFIM / PHABSIM
The Instream Flow Incremental Methodology (IFIM) (Bovee, 1995) (see Table 5) is a conceptual framework for presenting decision makers with a series of management options, and their expected consequences, in order that decisions can be made, or negotiations begun, from an informed position. Although hydrological analysis and physical habitat simulation are the most commonly applied component of IFIM, a study may also include water quality, temperature, legal / institutional analysis and negotiation study, time series analysis, channel and floodplain maintenance flows and effective habitat analysis and / or population modelling.

Table 5 IFIM (Bovee 1995)

IFIM Phase I: Problem Identification and Diagnosis
- Legal and Institutional Analysis
- Issues Analysis

IFIM Phase II: Study Planning
- Selection of the Appropriate Methods
- Study Objectives
- Bounding the Problem
- Definition and identification of Baselines
- Scope: Hydrology, Geomorphology, Temperature, Water Quality, Microhabitat

IFIM Phase III: Study Implementation
- The Hydrologic Component
- Water Temperature
- Water Quality
- Physical Microhabitat
- Integrating Macrohabitat and Microhabitat

IFIM Phase IV: Alternatives analysis
- Formulating Alternatives
- Testing Alternatives

IFIM Phase V: Problem Resolution
- Negotiation

Examples of comprehensive IFIM studies are illustrated in Nehring and Anderson (1993), and Railsback (1993). PHABSIM was developed by the Mid-continent Ecological Science Centre of the Fish and Wildlife Service. This research group is now part of the National Biological Service (NBS) of the Geological Survey. The NBS are currently undertaking research to develop PHABSIM, particularly improving spatial representation in two dimensions, this should lead to closer integration with current stream ecological theories.

(2) RCHARC
The Riverine Community Habitat Assessment and Restoration Concept (RCHARC - Nestler, 1996) is a recently developed hydraulic and physical habitat technique that has been designed to be applied to larger, more regulated rivers. It uses predictions of depths and velocities to contrast alternative water operation, or channel modification schemes. Rather than use habitat suitability indices for target species, it compares alternative options using the frequency distributions of depths and velocities present in the river.

(3) Tennant method
The Tennant method (Tennant, 1976) was developed to specify minimum flows to protect a healthy stream environment in the Midwestern US. It was also misleadingly christened the Montana method, the former name is used here as the method is not actually used in Montana. The method is widely applied, for scoping and strategic level studies.

Percentages of the mean annual flow (natural) are specified for various target life stage functions, e.g. 10% for survival, 30% for a satisfactory healthy ecosystem. It was developed using calibration data on hundreds of streams in the states north of the Mason-Dixon Line between the Atlantic Ocean and the Rocky Mountains. Other more detailed studies were undertaken on 100 reaches in Montana, Wyoming and Nebraska. On these rivers the year is divided into two 6-month periods, with high flows in summer from snowmelt. Since the methods were first developed, there have been some adjustments to take other regional flow regimes into account.

It was modified by Bayha (1978) for areas where spring runoffs felt important (see Wesche and Reschard (1985) for further details). Also a simple equation was introduced to take into account of existing flow modifications. Wesche and Reschard also recommend the Bayha report for procedures to take account of the unique flow characteristics of sub-basins within overall basin planning. It was further modified in 1980 (Tessmann) to incorporate monthly minimum flow limits. (S.A. Tessman, South Dakota Water Resources Research Institute, unpublished report). This procedure is also used in central Canada for level 1 studies (Locke, *pers. comm.*).

In the USA, it is widely used at the basin level, but not recommended for site-specific studies (Bureau of Land Management Instream Flow Guidelines, 1979, quoted in Wesche and Reschard 1985), and if negotiation is likely to be required. Where it is used, the following notes should be recognised:

- the basic method takes no account of flow fluctuations and seasonal effects;
- the method is more suitable to larger streams, which normally have less flow variability than do smaller streams;
- no account is taken of stream geometry; and
- recommendations should be compared to other flow statistics, e.g. mean 10 and 30 day natural low flows.

The CDM (1986) report claims that initial work was also done on eastern streams and that it was 'field tested' on 11 streams in Montana, Wyoming & Nebraska.

Although a Tennant-type method could provide a 'model' for development of similar guidelines for stream ecotypes in England and Wales, it should be remembered that it is underpinned by extensive fieldwork in the regions it was developed for. It is elegantly simple, and has other attractive features, such as the structured use of photographs at different flows. Further work would need to be undertaken to characterise flow regimes, which are generally skewed, for which the mean may not be a good descriptor, and relationships between catchment area, slope and river width (see the Texas method below).

Other similar methods have been proposed, many on a state-by state basis in the USA. For example the Northern Great Plains Resource Programme model, which recommended a minimum flow of the 90th percentile flow on a day-by-day basis, and the Hoppe method, which recommended the annual 80th percentile flow. The EA Engineering Science Report notes that many of these recommendations are mostly arbitrary, but not necessarily unreasonable.

(4) Texas Method

Matthews and Bao (1991) concluded that methods such as Tennant (recommendations based on mean) were not suitable for Texas, as stream flow frequency distribution is positively skewed – the method was thought to result in too high a flow. Similarly, methods based on annual exceedance percentiles e.g. Q_{95} gave too low a flow. This method uses variable percentages of the monthly median flow. The percentages are calibrated to regions with characteristic fauna, taking into account results from previous fish inventories and known life history requirements. This method appears to be a well thought-out example of a standard setting framework from which the UK environment agencies could develop its own procedures if required.

Note: the streams in Texas would be warm water, one further difference between US and UK streams is that their steeper gradient streams are relatively predictable, influenced by snowmelt, our steep streams are flashier (maritime vs continental climate).

Water resource managers in Texas are also in the process of developing Level 1 standards for compensation flows below dams. The compensation flow released from the dam is varied as a percentage of the inflow to the reservoir, this percentage is progressively reduced under drought and severe drought conditions in a pre-agreed manner.

(5) Habitat Quality Indicators
The 'Habitat Evaluation Procedure' is a general habitat-based evaluation method. It was created by the US Fish and Wildlife Service in the 1970s. It is a method which can be used to document the quality and quantity of available habitat for selected wildlife species. As such, it uses habitat suitability indices (HSIs), for 'cover types' deemed appropriate for the selected target species. Most often, all vertebrates in a study area will be considered, guided by activity type (e.g. carnivore feeding on invertebrates in tree canopy), in order to provide a baseline assessment of conditions or prediction of a particular habitat change.

HEP is designed to be applied to the terrestrial or aquatic environment. For the target species a scoring process ranks the suitability of the cover types for different modes of feeding, and also reproduction. The area of the cover types weights these scores.

As a highly general method, it can be applied to target species in streams and rivers. Although the method has some interesting broad-level assessment procedures, in practice, there would be little to distinguish an application of HEP/HSI from one of IFIM.

Efforts to predict directly trout biomass from environmental variables have met with some success, in the United States initial development was undertaken by Binns and Eiserman (HQI) (1979) and Wesche (trout cover rating) (1980). The development of this type of model in the US has been reviewed by Bain *et al.* (1996), EPRI (1986) and Fausch (1989). The models aim to develop statistical relationships (most often using regression) between habitat features (most often cover features such as depth, overhanging and instream objects) and measured biomass.

As with many other types of model, precision has generally been achieved at the expense of generality (Fausch, 1989). Thus, the data collection effort required to achieve useful models should not be underestimated. In the context of a framework for setting river flow objectives, an overall habitat assessment of this type could play an important role. In a river perceived to be ecologically degraded flow regime will be only one of a number of factors implicated, thus this type of method could enable a more integrated assessment, targeting resources to enable the most easily achievable improvements.

(6) R2-Cross
The Colorado Water Conservation Board uses R2-Cross as its standard method for Instream Flow Determinations (Espegren and Merriman, 1995), although it does use other techniques as well. The method was originally developed by the US Forest Service (R2 is Region 2 of the Forest service; the other regions have / had different methods). It uses imperial units and field data from a single transect located on a riffle to calibrate a hydraulic model using Manning's equation. In theory an interdisciplinary team selects this transect as the shallowest riffle.

(7) Index of Hydrological Variation/Range of Variability Approach (IHA/RVA)
The Range of Variability Approach is a desk-top method developed by (Richter *et al.,* 1997). They developed a hydrological method intended for setting benchmark flows on rivers, where protection of the natural ecosystem is the primary objective. Development of the method concentrated on identification of the components of a natural flow regime, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency

(number of events), duration (indexed by moving average minima and maxima) and rate of change. The method used gauged or modelled daily flows and a set of 32 Indices of Hydrological Alteration (IHA; Richter *et al*, 1996). Each index was calculated on an annual basis for each year in the hydrological record, it thus concentrates on inter-annual variability in the indices. The question to be addresses is how much deviation from natural ranges of these parameters is too much? Where no ecological information is available to answer this question, a default range of variation of the indices may then be set, based +/- 1 standard deviation from the mean or between the 25th and 75th percentiles. This method is intended to define interim standards, which can be monitored and revised. Research to relate the flow statistics to river ecology at the species, community and ecosystem level is ongoing.

Assessment
The RVA method of Richter shows the most promise for application to the UK. Black *et al.* (2003) have applied the RVA method to Scotland for classifying river flow alterations (see Scotland). However there needs to be further research on how to set the limits for individual flow variables in RVA, the approach suggested by Richter *et al.* is rather arbitrary. Additionally, the current approach is more appropriate for retrospective assessment of how the statistics of the actual flow regime compare with the natural regime. This is not readily applicable to operational management of abstraction, although could be applied to reservoir releases.

2.3 Main findings from the review of regulatory standards used in different countries

The main environmental flow methods and their key attributes are summarised in Table 6.

Most countries have various methods of determining environmental flows, which each defined for a different purpose *e.g.* scoping or impact assessment. South Africa, for example, has used the Building Block Method for setting environmental flows on individual rivers and for impact assessment of dams. They have also developed a desk-top rapid method for screening and strategic water resources planning. Likewise, England and Wales has used PHABSIM for impact assessment of abstraction on individual river reaches, but has developed the RAM framework for catchment scale water resource assessment.

Licensing of reservoir releases and abstractions present quite different problems and different methods have been developed to deal with issues. With reservoir releases, the whole flow regime (apart from very large floods that by-pass the dam) needs to be created. Abstraction, by and large, have no impact on high flows and so the focus is on low flow impacts.

Most countries have some form of habitat modelling method that is used for impact assessment. At the detailed level for definition of abstraction licences and dam release options, there are few other methods available. However, this approach needs detailed site hydraulic and habitat suitability data.

Whilst rapid methods have the obvious advantage of speed, ease and cheapness to apply, the trade-off is reduced accuracy of predicted impacts at any specific site. Rapid methods would not in themselves be used to set individual licences or release patterns from dams as any results would not stand-up to scrutiny, such as in a public inquiry.

Some look-up tables, e.g. in France and RAM in England and Wales, are based on hydrological judgement and not verified by ecological data. Whilst the concepts underlying these methods might be transferred they cannot be relied upon to maintain any desired ecological character.

The Tennant method and the South African desk-top method are rapid methods that have been developed using extensive ecological data. However, they cannot be transferred without recalibration using data from the new region. This demonstrates the general principle that rapid methods can only be produced once considerable data have been collected and analysed.

Where data are scarce, expert opinion is used, but increasingly a formal structured approach to getting consensus amongst a group of experts, including academics and practitioners is widely favoured. This has the two advantages; first the results of a group of experts are less likely to be biased scientifically by the view of one expert and second that wider stakeholders have more confidence in an open multi-institutional process than one decided by a single agency.

There is wide acceptance that all parts of the flow regime have some ecological importance. As a result, there is a growing move away from single low flow indices for environmental flows. The IHA/RVA method uses a wide range of hydrological indices. Both the Building Block Method and the Holistic Approach link various elements of the flow regime to specific ecological functions.

Many methods determine environmental flows in relation to the natural flow regime of the river. Some methods define flow in terms of site characteristics, such as flow per unit width needed for salmon migration in Lancashire, but it has not been possible to examine the basis of these derivations.

Small scale studies have shown that flow interacts with morphology to define physical habitat (such as width, depth, velocity and substrate) for specific organisms. These quality elements vary spatially; water is deep in pools and shallow on riffle; velocity is high in riffles and slow in pools. Standards based on these quality elements at the broad water body scale cannot be readily defined. To implement standards at the reach scale, site data are essential.

Implementation of WFD will require that environmental standards are applied for all bodies regardless of hydrological and ecological data available. Consequently, standards are required that can be applied without having to visit the water body. This means that standards must be related to parameters than can be obtained from maps or digital databases, such as river flow, catchment area or geology. Any resulting standards will have less predictive power at a local scale and cannot be tested using site data.

A hierarchical approach may be needed where a broad scale approach, perhaps based on flow is used as a screening tool to assess all water bodies. A more detailed approach, perhaps based on depth or velocity, may be applied to a smaller number of sites selected as requiring close attention.

The flow regime is complex and is characterised by timing, magnitude, duration and frequency; all of which are important for different aspects of the river ecosystem. To produce operational standards, there is a need to identify a small number of parameters that capture its most significant characteristics. For example the number of high flow events greater than three times the median flow has been shown to be related to the structure of macrophyte and macro-invertebrate communities in New Zealand (Clausen, 1997).

Some recent environmental flow methods, such as DRIFT have been developed for situations where no ecological management objectives have been set in advance and are used to compare scenarios of river flow regimes. Such methods are less useful for defining standards for pre-defined ecological objectives, such as good ecological status of the WFD.

RAM is based on the concept of sensitivity to abstraction. This concept has not been tested using hydrological and ecological data.

The most promising methods for potential development in the UK for implementation of the

Water Framework Directive are: the IHA/RVA, the South African desk-top method.

A major gap in environmental flow methods is the ability to predict changes in sediment movement and morphology at local scale caused by changes to the flow regime. Habitat modelling methods assume that the substrate type and channel morphology are fixed and that changes in flow only change parameters such as depth and velocity

Table 6 Summary information on key environmental flow methods

Country	Method name	Basic concepts	Approach	Data used	Comments
Australia	2/3rd rule	Flow regime should 2/3rd natural	Use 2/3rd	Not defined, but probably elements of flow regime, e.g. low flow magnitude, no. floods	Rule of thumb not verified by ecological data. Precise method of use not defined.
	Holistic approach	Whole river ecosystem	Standards set by expert panel separately for each river/site	All available data; flow, hydraulic, morphology, sediment, biological	Integrated inter-disciplinary approach based on data and expert opinion
	MFAT	Habitat conditions for various flow scenarios compared	Developed for key conservation sites in the Murray-Darling basin	Many including flow magnitude, duration, inundation timing and extent	Produced for Murray-Darling basin. Similar concepts to PHABSIM applied at basin scale
	Flow events method	Frequency of flow events is important	Frequency of events (defined by expert panel) under different scenarios compared	Flow time series and at site hydraulic data	New method, currently appropriate for comparing scenarios
	Wetted perimeter	Wetted perimeter indexes river ecosystems	Standards set at inflection point in flow-wp curve	Flow and wetted perimeter	Define single flow value according to wetted perimeter. Not verified by ecological data
England and Wales	RAM	Sensitivity to abstraction	Look-up tables for flow duration curve to give permitted abstraction given sensitivity	channel structure, fish, invertebrates, macrophytes	Concept of sensitivity to abstraction limited not tested ecologically. Look up table based on expert opinion; not verified by ecological data.

Country	Method name	Basic concepts	Approach	Data used	Comments
	LIFE	Invertebrates index river ecosystem	Slope of flow v. invertebrate score graph indicates sensitivity to abstraction	Invertebrate samples and daily flow time series	Relationships between flow and invertebrate communities define for individual sites but not yet generalised
France	Hydrological rules	Minimum flow	1/10th or 1/40th of mean flow	Daily flow time series	Rule of thumb not verified by ecological data
Italy	Po basin standards	Minimum flow	Minimum flow is related to rainfall, altitude, water quality and conservation objectives	Rainfall, empirical factors	Rule of thumb not verified by ecological data
Lesotho	DRIFT	Combines hydrology, ecology, sociology and economics	Water allocations and ecological social and economic consequences of scenarios assessed	Many; including flow time series, hydraulics, water quality, geomorphology, vegetation, fish, mammals, invertebrates	Interdisciplinary method for high profile sites; very expensive to apply
Norway	River System Simulator	Impacts of hydro-power operation on salmonid fish	Salmonid habitat assessed for different dam release patterns	Flow time series, hydraulics, morphology	Physical habitat output, but tailored for releases from hydro-power dams
South Africa	Building Block Methodology	Components of the flow regime have different ecological function	Standards set by expert panel separately for each river/site	All available data; flow, hydraulic, morphology, sediment, biological	Integrated inter-disciplinary approach suitable for application to individual high priority sites based on data and expert opinion

Country	Method name	Basic concepts	Approach	Data used	Comments
	Desk-top method	Environmental flow need related to variability of the flow regime	% of mean annual runoff needed for river ecosystem defined	Many individual studies of BBM and flow time series	Concept is attractive, but needs results from many individual sites to calibrate
Spain	Basic flow method	Environmental flow linked to statistics of annual minimum series	Environmental flow based on mean flow and river type	Flow time series	Hydrological and ecological meaningfulness not tested.
	Basque method	Space-time substitution	Compares downstream increase in species richness to increase in flow	Macro-invertebrate data, downstream increase in drainage area / flow	Interesting concept, could be tested in the UK
USA	PHABSIM	Physical habitat model	Available physical habitat for any species/life stage and flow	Flow time series, hydraulic data from cross-sections, substrate data, habitat suitability curves	Used world-wide for impact assessment. Does not define critical levels of habitat, but indicates sensitivity to abstraction as flow varies
	RCHARC	Hydraulic model	Manage river flow to maintain hydraulic habitat diversity	Hydraulic model and river flow time series	Currently requires site-specific data. Useful when cannot define target species
	Tennant method	Minimum flows for healthy rivers	% natural mean annual flow presented for different life stage functions e.g. 10% for survival, 30% for healthy ecosystem	Flow time series, biological data	Calibrated with biological data from many rivers. Cannot be transferred without re-calibration. Mean flow is a simplistic statistic for use with ecological data

Country	Method name	Basic concepts	Approach	Data used	Comments
	Texas method	Minimum flows for healthy rivers	% flow duration curve	Flow time series, biological data	As for Tennant, but more flexible.
	IHA/RVA	All components of the flow regime have ecological function	All flow statistics should be within defined limits, e.g. 1 standard deviation of natural flow statistic	Many statistics of river flow time series, e.g. mean flow in each month, number of floods	Conceptually attractive, but not verified by ecological data and difficult to operationalise into a standard

3. REVIEW OF EXISTING STANDARDS (LAKES)

3.1 Introduction

The work reported in this section has been undertaken with a focus on lakes alone. It should be noted that the management of the hydrological regime of lakes cannot be done in isolation from the rivers that flow into and out of them, since there are inescapable links: management options for a lake (used as a reservoir say) are restricted by the inflows, while options for regulation of flow in the downstream river are constrained by the amount of water available in storage. Nevertheless, management objectives targeted at the aquatic ecology of a lake must normally be expected to be developed specifically for that lake, whether or not those objectives lead in turn to constraints for the achievement of other objectives in connected running waters. It is on this basis that this report focuses on regulation for lakes in a water resources context.

It is noted that the project brief explicitly excludes Heavily Modified Water Bodies (HMWBs). This is considered to be especially relevant in the sense that the regulations to be developed by UK regulatory agencies following this project may not apply to HMWBs. However, it is likely that a large proportion of the case studies drawn on in this study would, if located within Europe, be designated HMWB. The object of this report is to provide some insight into the basis on which regulatory standards have been developed for lakes around the world, according to available information, and it would be inappropriate to exclude such water bodies at this stage.

The report is based on a review of sources by internet and Web of Knowledge searches, the latter providing access to details of papers in all major scientific journals worldwide. Contacts have been approached in a number of European countries, but responses have not been forthcoming to date. However, through previous collaborations and a series of lakes-based WFD-related projects undertaken in recent years at Dundee, there is some cause to be optimistic about providing a reasonably comprehensive review of the relevant material available.

The first part of the report is made up of a review, country by country, of regulatory standards that have been identified from the sources, highlighting hydrological or other parameters used as the basis of regulation, and also links to morphology and ecology as noted in the sources. A distinction is made between regulations which have been developed for a specific reservoir or group of reservoirs, and more general standards which have been developed for national application or for application across a regional, e.g. in a devolved administration. It will be noted that the literature pertaining to lakes is considerably smaller than that available for rivers, reflecting the spatially-restricted distribution of lakes and the much greater engagement of the scientific community with the river flow and its ecological effects. Part of the context may arguably also be that the regulation of reservoir water levels for environmental purposes poses a greater challenge to reservoir operators than does the regulation of downstream flows. Restrictions on water levels amount to challenges to the amounts of water which can be stored at any time, and go to the heart of the purpose of constructing and operating reservoirs.

Following the review of sources, ecologically relevant parameters are extracted and evaluated. A gap analysis identifies gaps between the data availability and science-base available at present and the aspirations identified in relation to the establishment of ecologically relevant abstraction and water resource regulations for the UK. Throughout, links between hydrology, morphology and ecology will be identified in order that regulatory standards can be considered in an appropriate context.

3.2 International review of standards

This Section reviews the water resource standards that have been adopted for lakes in the UK and internationally. It aims to identify parameters that have been considered significant, and the associated circumstances; and the criteria that are taken into account when setting ecological objectives and abstraction ceilings. Most countries are still in the throes of developing procedures to meet WFD requirements, and there are generally few established standards for lakes.

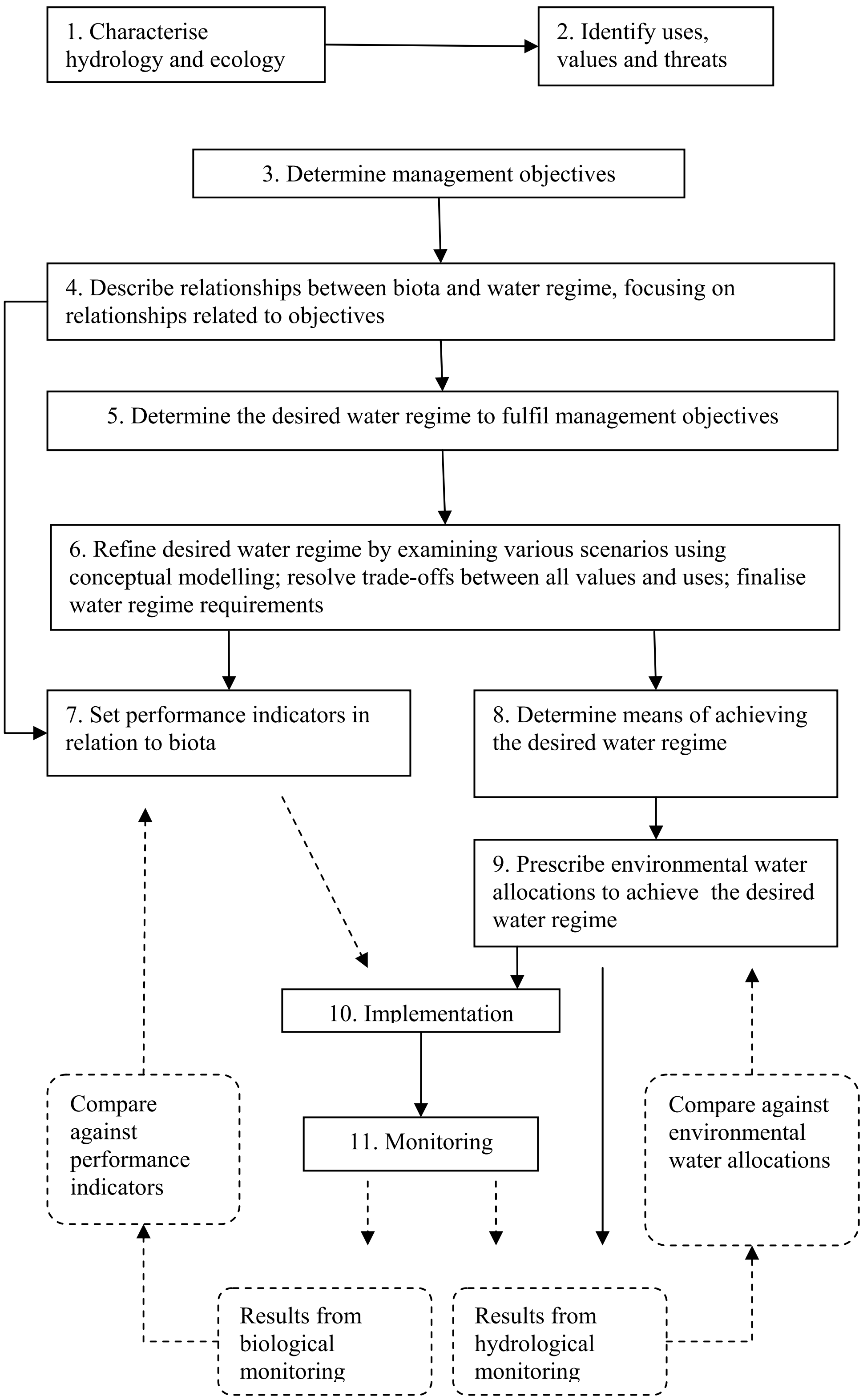
Australia
Davis *et al.* (2001) develop a framework for the determination of environmental flows that will protect Australian wetlands against decline in their ecological character and demonstrate its application to eight case study wetlands of international and national importance including lakes, marshes and swamps. They critically evaluate different approaches to water allocation, and the framework incorporates a combination of these approaches (Figure 3). They point out the need for management strategies for Australian wetlands to be sufficiently flexible to incorporate the temporal and spatial variability that is a major characteristic of these systems, driven by natural variations in climate resulting in variable water regimes both within and between years. As a consequence, the determination of environmental water allocations is likely to be an ongoing and largely site-by-site process requiring adaptive management, where actions are monitored and used to successively refine further management approaches. This will be a particularly important strategy for wetlands where changes need to be made when climatic conditions change.

The principal approaches distinguished are: hydrology-driven approaches, which are similar to historical discharge methods for rivers (e.g. Tennant Method, Flow Duration Curve Analysis, Holistic Approach) and involve description and reinstatement of the water regime that existed prior to development; and the ecology-driven approach which involves estimating the water regime requirements of species, communities and ecosystem processes and then meeting these requirements. Some methods developed for rivers were also assessed, as well as conceptual and ecological modelling.

The desired water regime may be characterised in terms of a variety of variables including:
- amount (area inundated);
- depth (minimum and maximum);
- seasonality (whether inundation is permanent, seasonal or ephemeral);
- season of maximum inundation;
- rate of rise and fall;
- size and frequency of floods / dry periods;
- duration of floods / dry periods; or
- variability

Finally, the environmental water allocations may be derived from relationships between stream flow and area inundated, or on water balance calculations. They are set in terms appropriate to the wetland type and available source - for example, frequencies of maximum and minimum depths of surface water (groundwater-fed systems); or regulators, dam releases or abstraction restrictions (surface water dominated systems).

The Lakes Sorrell and Crescent Rehabilitation Project was a large multi-disciplinary project carried out by the Australian Inland Fisheries Service in response to a significant decline in the trout fishery, water quality and ecological values of the two lakes. The key problem was identified as low water levels due primarily to drought conditions and competition for water by various users. It included ten sub-projects targeting key areas of physical and biological importance to the functioning and management of the lakes and the environmental requirements of their ecosystems, and four key technical studies which investigated the current status of fauna and flora (Inland Fisheries Service 2004). Various management targets were defined in terms of water level attributes necessary to maintain the important biological features of the system, namely wetlands, fish and invertebrates. These are summarised in Table 7. Some attributes of some of the targets, such as temporal scale, may not be appropriate to UK conditions because of the physical scale and ecological adaptation of these two Australian systems.



After Davis *et al.* (2001).

Figure 3 Framework for the determination of environmental water allocations. Feedback loops are indicated by dashed lines.

Table 7 Water level management targets for Lakes Sorrell and Crescent

The key management recommendations for the lakes Sorell and Crescent wetlands are to: 1. Maintain or seek to restore an appropriate water regime for the wetlands under the following conditions: • Ensure wetlands are not kept permanently full – no longer than 5 consecutive years; • Ensure wetlands do not dry out for any longer than 5 consecutive years; • The wetlands are required to be inundated to a level of 300 mm (803.3 m AHD in Lake Crescent and 804.2 m AHD in Lake Sorell) at least once every 5 years; • Ensure a drying phase is included into the water regime with dry:wet cycles coinciding with climatic events; • Fluctuations of water levels should occur annually, on a seasonal basis (i.e. higher levels in spring, lower levels in late summer/early autumn); • Flooding should occur gradually to suit the germination and growth requirements of a variety of plant species; • Inundation should be at its maximum depth during spring/early summer; • Water should remain in the wetlands until late summer (above 803.0 m AHD in Lake Crescent and 803.9 m AHD in Lake Sorell); 2. Maintain the lake water level within Lake Sorell at an appropriate height to encourage improved levels in turbidity and reduce wind re-suspension of sediment and hence increase light availability and sediment stability and the growth of in-lake macrophytes.
The aquatic fauna of lakes Crescent and Sorell thought to be of particular importance, in terms of the health of the aquatic eco-systems and conservation value, were populations of the 'rare' and endemic freshwater fish, golden galaxias (*Galaxias auratus*), and the macroinvertebrate communities of both lakes. Key recommendations for their management include: 1. Historical seasonal cycles in the water level regimes of lakes Crescent and Sorell should be altered as little as possible. 2. Sudden decreases in water level, >600 mm, between May and September should not occur in either Lake Crescent or Lake Sorell, as this will de-water incubating *G. auratus* eggs. 3. Lakes Crescent and Sorell should be managed at mid to high water levels to protect habitat diversity and ensure good water quality. Water levels in Lake Crescent should be managed above 802.20 m AHD, the level above which rocky shore habitat becomes inundated and a critical level for *G. auratus* spawning during late autumn - winter. 4. The minimum frequency for Lake Crescent to have a water level below 802.20 m AHD during late autumn – winter, is 1 in every 3 years. This is however a high risk strategy which may have long term impacts on the structure and abundance of the *G. auratus* population. 5. The influence of higher water levels in lakes Crescent and Sorell on the abundance, distribution and life cycle of *G. auratus* populations should be examined as well as the relationship between the abundance of salmonid and *G. auratus* populations. 6. Replicate the in-lake invertebrate survey undertaken in the current study during an extended period of high water levels (possibly levels > 803.20 m AHD and 804.20 m AHD in Crescent and Sorell respectively). Sample in-lake macrophyte beds (if/when present) for invertebrates during the survey. Compare the diversity and abundance of the invertebrate communities to the results obtained for in-lake habitats during the current study to examine the effect of water level variation on invertebrate communities on in-lake habitats. 7. Replicate the wetland invertebrate survey undertaken in the current study in Kemps Marsh (Lake Sorell) and also conduct a survey in Interlaken Lakeside Reserve (Lake Crescent), during an extended period of high water levels. Compare diversity and abundance of invertebrate communities to the results obtained for Kemps Marsh during the current study to examine the effect of water level variation on invertebrate communities of the wetlands.

(Inland Fisheries Service 2004).

Canada
Jurisdiction for water resource management in Canada is shared between federal, provincial and local governments, resulting in a complex and large body of law and guidelines. For example, in Ontario the Lakes and Rivers Improvement Act seeks to ensure flow and water level characteristics of lakes and rivers are not altered to a point where other water users are disadvantaged and any work augmenting, impounding or diverting water must receive prior approval from the Ontario Ministry of Natural Resources (OMAF, 2004). The specific assessment methods are undertaken on an individual lake basis.

Finland
Taking into account the abundance of lakes in Finland, it is unsurprising that they have been well studied in the past, and so far have assumed somewhat greater priority in work towards implementation of the WFD than is the case in most other EU countries.

The established system of lake classification is based on water quality. Finnish surface waters are divided into five classes on the basis of oxygen content, colour, turbidity, transparency, nutrients, hygienic indicator bacteria, chlorophyll-a, algal blooms and toxic compounds. The most important hydromorphological pressure is alteration of the regime of water level fluctuations, and most morphological changes are primarily due to hydrological changes.

Various lake survey methods, models and tools are established, including:

- Detailed investigations of selected sites, recording species abundance and zonation.
- Macrophyte habitat assessment which involves mapping of 10-11 % of the shoreline from colour infra-red aerial images.
- Grayfish habitat model (under construction) uses exposure and gradient of shores to estimate suitable areas for grayfish, and can be extended to other species by addition of further habitat preference curves.
- Natural production of pike model calculates spawning potential for pike, expressed as number of fry per lake per year, on the basis of the area of suitable spawning habitat (*Carex* and *Equisetum* – stands).
- *VIRKI* models possible harmful effects and costs to recreational use of shores.
- REGCEL water level analysis tool. This incorporates largely empirically derived relationships between water level fluctuations and biota (Table 8). Values for seven different water level fluctuation indicators chosen for their relevance to e.g. aquatic macrophytes, littoral zoobenthos and fish reproduction are calculated. The procedure has been used, for example, in the WFD Heavily Modified Water Body designation process (Hellsten *et al.*, 2002).

(Antton Keto, *pers. comm.*)

Most directly relevant to the present discussion is the work in which Hellsten *et al*. (1996) outlined procedures for setting water level targets to favour biota in hydro-power regulated lakes. Ecologically based regulation practices (ERP) were based on underwater light climate and water level fluctuation data which made it possible to calculate the proportion of the frozen littoral to the total littoral area. Another procedure calculated biomass of benthic fauna from data on water level fluctuation and Secchi Disk depth.

Table 8 Main indicators and calculation principles in REGCEL analysis

	Indicator	Calculation principle
(A)	Annual water level fluctuation (m)	MHW - MNW
(B)	Water level decrease during ice-covered period (m)	W_IN – NW_ICP
(C)	Water level fluctuation during the summer (June-August) (m)	HW_(1.6.-30.8.) – NW_(1.6.-30.8.)
(D)	Maximum water depth in *Carex* zone during spawning of northern pike (m)	W_10_OWP – W_75_OWP
(E)	Minimum water depth in *Carex* zone during spawning of northern pike (m)	NW_(IO – IO + 1 month) – W_75_OWP
(F)	Difference between water level during ice-off and open water mean (m)	W_IO – MW_50_OWP
(G)	Water level rise during the nesting of birds (m)	HW_nesting – W_(IO + 2 weeks)
(H)	Number of dates from ice-off to maximum water level in spring (n)	HW, spring period – W_IO
(I)	Percentage of springs with low water level (%)	Years when, (W_75_OWP – W_IO > 0) / number of years * 100
(J)	Extent of frozen productive zone (%)	(W_50_growing season – W_6.2.) + (0.9 * ice thickness) / depth of productive zone * 100
(K)	Extent of disturbed productive zone (%)	(MHW – MNW) / productive zone * 100

OWP = open-water period, ICP = ice-covered period, IO = ice-off date, IN = ice-on date (from Hellsten *et al.,* 2002)

France
In France, a substantial protocol for the evaluation and classification of lake quality in terms of water, physical environment and biota known as Lake-SEQ, is at the development stage (Stephane Stroffek *pers. comm.*), but full details were yet to become available at the time of writing.

Ireland
Ireland is currently at the stage of developing new approaches for regulating lake water levels and residence times (Irvine *pers comm.*). Allot (1990) reported that washout became an important factor affecting phytoplankton when the residence time fell below 20 days at Lough Inchiquin.

Germany
Germany has two distinct scales of analysis with respect to lake systems. Two key areas of investigation are centred on Lake Constance and the northern German lake-land area of LUNG Mecklenburg-Vorpommern. Presently no systems are in place for the regulation of lake hydrological regimes and greater attention has been given to developing hydromorphological assessment tools (W. Ostendorp *pers comm.*). As an example of recent work in the area of groundwater connectivity, Dokulil and Teubner (2002) suggested phytoplankton communities were more resilient to perturbations in highly flushed lakes than systems with long retention times such as groundwater seepage lakes.

New Zealand

In New Zealand lakes are recognised as community assets that often need to be managed to cater for a variety of different users. Many lakes are used for electricity generation, yet also provide sports fisheries along with recreational and amenity value. The importance of lakes in habitat and biodiversity terms is also recognised. However, the demands from different users can sometimes be contradictory. A power authority, for example, may want to change the regulation practices, which could conflict with some ecosystem values or recreational users (NIWA, 2004).

The Resource Management Act 1991 (RMA) was a milestone in New Zealand legislation because it placed the concept of sustainable management of natural resources at the centre of government policy. The RMA instituted a series of consent agreements for the extensive hydro-power sector in New Zealand, which presently involves around 80% of New Zealand's natural lakes. Vertical water level can range from a few centimetres to several metres, with height changes varying over timescales of days, weeks, months or years in response to generation requirements (Riis and Hawes, 2002). Under the RMA consents were issued engaging operators to pursue their 'best endeavours' to comply with specified high and low operating ranges for lakes. The concept of best endeavours was considered more appropriate for lake-level management rather than 'inviolate rules', especially due to the high variability of the New Zealand climate.

In contrast to the situation in the UK, where there are very few records of natural lake water level regimes (Rowan *et al.* 2004), New Zealand has a rich tradition in lake monitoring, thus historical water level records can be used to examine the frequency distribution, extent (mean, maximum and minimum), seasonality and duration at different water levels (James *et al.* 2002). For some lakes, such as Lake Taupo, the record extends back to the early 1900s, and the alteration in regime resulting from regulation has been assessed by mass balance of inflows minus diversion inflows from other catchments in the Tongariro hydro-catchment system.

The National Institute of Water and Atmospheric Research (NIWA) is a stand alone, but largely government-funded research agency. It is routinely involved in cases where new water level regimes are proposed and the potential impacts on plants, invertebrates, wetlands and fisheries must be considered (NIWA, 2004). To tackle these issues, NIWA uses an ecosystem approach, which is based on an understanding of the range of interacting chemical, physical, and biological factors at play, and the way they affect resident communities (Table 9).

In 2003 NIWA completed a programme for Mighty River Power (MRP) to determine the effects of a new hydroelectric operating regime, which increased lake level fluctuations from about 0.7 to 3.5 m, on the ecology of Lake Waipapa in the Waikato catchment. A whole range of plant and animal life was monitored over a period of 18 months, including lake-side terrestrial plants, birds, aquatic plants, wetlands, and invertebrates and fish. The effects of increased water-level fluctuations on bank stability and sediment movement were also monitored. Prior to the new scheme the ecology of the lake reflected the relatively restricted regime, with riparian and littoral plant communities adapted to stable wet conditions. However, increased fluctuations in lake levels caused an immediate 95% reduction in macrophytes and a similar decline in invertebrate populations associated with the weed beds. Sediment slumping and shoreline modifications also meant to that many plants were destabilised and drowned out (NIWA, 2004). Following the cessation of the experiment, the macrophyte population rapidly re-established, but the effects on fish populations was inconclusive. This experimental work was required by MRP to develop new consent guidelines regarding future consent applications under the RMA.

Table 9 Checklist for assessment of lake water level modification

Effects of lake levels	
Lake level	Define natural extent, duration of different levels, ramping rate, periodicity for the lake
Extent	What is range proposed? What is the natural range, and how does the proposed range vary from this?
Duration	What the proposed period is at high and low levels compared with the natural regime?
Ramping rate	How quickly will the lake level rise or fall
Periodicity	Does the proposed regime have a different seasonal periodicity to that which would happen naturally? Are the changes to the natural periodicity on a daily, weekly, monthly or seasonal (winter/summer) basis?

(from James *et al.*, 2002)

Riis and Hawes (2002) undertook a study of the role of water level fluctuations on low-growing species-rich littoral plant communities in New Zealand. They presented a scheme for parameterising lake water level fluctuations in an ecologically relevant way that could capture spatial and temporal considerations. Three groups of statistics were identified:

1. The first was a quartile water level ranges (QWLRs), obtained from daily flow records over period of 10 years (Figure 4). The quartile range (25–75%) was selected to describe general conditions over the period prior to vegetation survey. QWLR measures for days, months and years were termed daily level ranges, monthly level ranges and annual level ranges. Whilst the importance of extreme events was recognised the authors indicated that timing was also important, e.g., the recovery time since a major and prolonged draw-down, thus this confounding effect led the authors to exclude extreme events for each lake.
2. The second group of statistics related to frequency and mean duration of events when the level fell below the median providing an indication of the potential magnitude of desiccation events. The frequency was determined as the mean number of events per year when the water level recessed through the median level. The average durations (days) of periods when the water level was below the median were calculated over the previous period of 10 years.
3. The third group of statistics related to levels on the shore where the mean dry period duration was 10, 30, 60, 120 and 180 days.

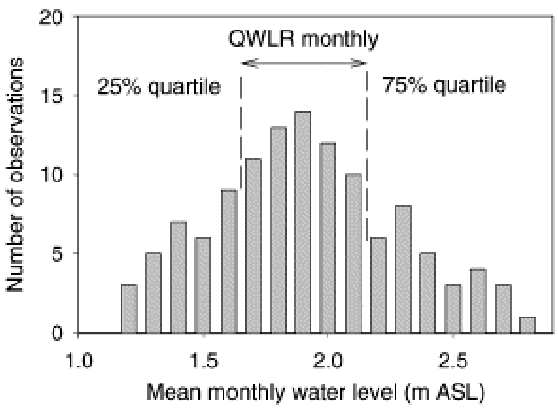


Figure 4 Illustrative frequency histogram showing how monthly QWLR was calculated for each lake. The same principle was used when calculating the quartile water level range for years and days (after Riis and Haws, 2002).

Understanding the key components of water level variation in structuring the composition of marginal plant communities is essential to understanding their vulnerability to artificial control of water level. The action of waves breaking on the lake-shore can be an important control on extent and composition of littoral macrophyte communities. Kirk and Henriques (1986) suggested that the breaking depth of waves is used as the basis for setting minimum water levels to minimise scour of littoral macrophytes. Fetch, wind-direction and wind speeds are used to estimate wave characteristics, and wave-breaking depth is taken as 1.33 times the 'significant wave' height (mean of the highest third of waves generated), e.g., on Lake Ohau 0.5 m waves broke in a depth of 0.65 m, thus the minimum water level recommended needed to take into account both the slope of the littoral zone and this depth of breaking waves.

Riis and Hawes (2003) used a wave model to assess wave exposure at each site along with records of shore slope and substrate composition for Lake Wanaka. Species richness, cover and depth limits of the low mixed community decreased with increasing disturbance on the sites, with the latter accounting for 62 % of the variance in species richness. Hawes *et al.* (2003) developed habitat requirements of key vegetation types in New Zealand lakes, demonstrating that the extent and diversity of shallow-growing species was related to a combination of the extent of water level fluctuation and wave exposure. Upper limits of many deeper-growing species could also be related to wave action exposure.

A summary of the range of impacts that water level modification can have across key component of a lake ecosystem are shown in Table 10.

Table 10 Summary of potential effects of extreme high and low lake levels in New Zealand lakes in different seasons

Regime	Terrestrial vegetation	Wetlands	Bird life	Macrophytes	Periphyton	Macro-invertebrates	Fish
1 Autumn/ winter low, Spring/ summer high	Freezing in some herbaceous species; mortality due to flooding	Minor, less chance of invasion by willow; lack of drainage in summer	Nests inundated	Freezing in upper macrophyte zone; reduced upper limit in autumn and winter	Little impact; freezing in autumn/winter	Freezing in some habitats	Maximise access to spawning streams; only minor impacts
2 Autumn/ winter high, Spring/ summer low	Desiccation in some herbaceous species; mortality due to flooding	Invasion by exotics in spring/summer	Increased risk of predators	Los of low-mixed communities; replacement by terrestrials	Lack of growth; exposure; strandings of filamentous spp.	Desiccation in spring; loss of some habitat for egg laying fish	Reduced access to streams for some spp; loss of lake spawning; loss of some feeding habitat in shallows
3 High for most of the year	Mortality of some species	Mortality of some spp.; lack of drainage; expansion of wetlands	Reduced feeding on macrophytes	Lack of flowering grassland spp.; change to distribution of vascular plants	Stable community; loss of a few spp.	Minor	Minor
4 Low for most of the year		Expansion of herbaceous plants and scrub; increased risk of invasion by willow and exotics	Increased predators; fragmentation of habitat	Shift in depth distribution of vascular plants; erosion of offshore face	Strandings of filamentous spp.; proliferation close to nutrient and groundwater inputs	Loss of some habitat e.g. cobble areas	Lack of access to stream; loss of lake spawning habitat; less feeding in cobble habitat; fewer terrestrial foods available.

Note the severity of most of the effects will depend on the duration at different levels and ability to recolonise or reach a new equilibrium
(After Smith *et al.*, 2002)

South Africa
MacKay (1999) describes the derivation of the Resource Directed Measure (RDM) for water quantity (lake water level requirements or LWR) required for ecological maintenance of the Mhlathuze Lakes in South Africa. This was derived within a project incorporating a planning meeting followed by specialist studies, and culminating in a specialist (expert) workshop to apply RDM methodology (Figure 5). The RDM consists of the Ecological Management Class (EMC) the Reserve (lake water level in the present context) and the Resource Quality Objectives (RQO).

The EMC is set in terms of classes A (unmodified) to D (largely modified) (Table 11). It is the average of subjectively-derived scores for human disturbance within the water body and the riparian/littoral zone attributes of the system (hydrology, water quality, hydraulic/geomorphic features and biota).

The Reserve is quantified first by setting water levels, in this case for:

- Drought levels – levels to be achieved during drought periods only, and not unnaturally maintained for extended periods of time
- Maintenance dry season levels - levels not be exceeded for lengthy periods during winter. If exceeded briefly during the dry season, maximum drawdown must never exceed drought levels.
- Management maximum levels - never exceeded for lengthy periods. Also reflect the maximum maintenance levels which would be experienced during summer.

The recommended lake water levels are provided in Table 12.

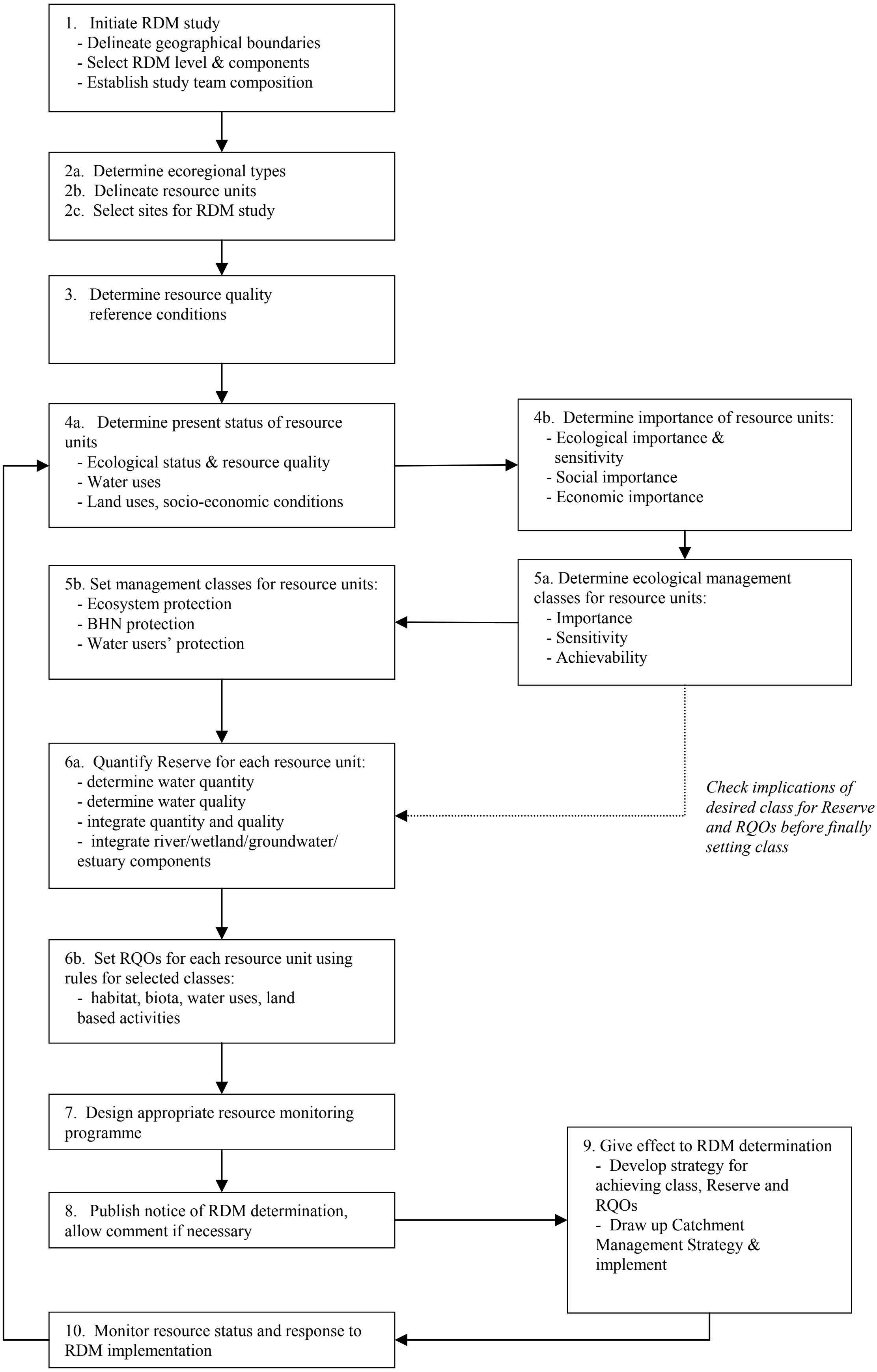


Figure 5 Schematic for determining LWR for ecological maintenance of the Mhlathuze Lakes in South Africa

Table 11 Interpretation of Mean* of Scores for all Attributes: Rating of Present Ecological Status Category (PES Category)

Category	WITHIN GENERALLY ACCEPTABLE RANGE
A	> 4; Unmodified, or approximates natural condition.
B	> 3 and ≤ 4; Largely natural with few modifications, but with some loss of natural habitats.
C	> 2 and ≤ 3; moderately modified, but with some loss of natural habitats.
D	= 2; largely modified. A large loss of natural habitats and basic ecosystem functions has occurred.
	OUTSIDE GENERAL ACCEPTABLE RANGE
E	> 0 and < 2; seriously modified. The losses of natural habitats and basic ecosystem functions are extensive.
F	0; critically modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat.

*: If any of the attributes are rated <2, then the lowest rating for the attribute should be taken as indicative of the PES category and not the mean.

Table 12 Lake Water levels for Lake Cubhu

Water level	**Lake Water level (mamsl)**
Current FSL (at time of assessment)	2.8
Drought minimum water level (12 months max)	1.8
Maintenance minimum dry season water level	2.3
Management maximum water level	2.8
Maximum draw-down rate	1 metre per month
Other recommendations	The construction of a fish ladder on the lake overflow point with the provision of appropriate overflows to enable the spawning and migration of estuarine fish and crustaceans from the estuary to the lake during maintenance wet months.

Notes: mamsl = metres above mean sea level; FSL = Full Supply Level

The relationships between water regime and wetland biota are described in general qualitative terms and tabulated, with selected examples presented as Table 13 and Table 14.

Table 13 Water depth requirements of emergent macrophytes

Species	Range of depths of occurrence (m) (Froend *et al.,* 1993)	Mean annual depth (m) (Chambers *et al*., 1995)
Bolboschoenus caldwelli		+0.3 to - 0.2
Baumea articulata	Minimum - 1.0 Maximum + 1.0	± 0.4
Typha orientalis	Minimum - 1.0 Maximum + 1.0	+0.1 to - 0.3
Baumea juncea		+0.2 to -0.3

Table 14 Water regime requirements of wetland vertebrate fauna

Type	Species	Water regime
Waterbirds	Long-toed Stint (*Calidris subminuta*)	Require exposed mudflats: only appear when these are present (Directory of Australian Wetlands web site)
	Waders (general)	Shallow water levels
	Australasian bittern (*Botaurus poiciloptilus*) and Little bittern (*Ixobrychus minutus*)	Require tall sedges
	Musk duck (*Biziura lobata*)	Require deep permanent water
	Blue-billed duck (*Oxyura australis*)	Require deep permanent water
Frogs	*Limnodynastes dorsalia* and *Litoria adelaidensis*	Survival of embryos within egg masses may require an absence of sudden increases/ decreases in water levels. Changes in depth which result in either the drying of the egg masses or their inundation (and subsequent de-oxygenation) may be detrimental
	Heleioporus eyrei	Water level increases between March and May may be detrimental to breeding success: this species lays eggs in burrows
Fish	None present (ANCA, 1996)	
Turtles	*Chelodina oblonga*	This species has two nesting periods (Sept.-Oct. and Dec.-Jan.). May require the presence of water in Dec. - Jan. for the second nesting period
Other reptiles	Insufficient data	
Mammals	Bandicoots	Dense fringing vegetation

Sweden

Although Sweden has more than 100,000 lakes larger than 1 ha, the only procedure for lake assessment so far available is a kind of lakeshore habitat assessment developed for the Jonkoping region of South Sweden (Lena Tranvik*, pers. comm.*).

UK England & Wales

Prior to 2003, the legislation governing water abstraction in England and Wales was the Water Resources Act 1991, as amended by the Environment Act 1995. The Water Act 2003 (HMSO 2003) was published on 29 November 2003 (Defra 2003). This combined the results of a review of water abstraction licensing prompted by the 1995 drought crisis, and the water company regulation reform initiated in 1998 (Wildlife Trusts 2001). The Act introduces amendments to previous legislation including the Water Resources Act 1991, establishing a new regulatory authority for the industry, to be known as the Water Services Regulatory Authority (WSRA), and a new independent Consumer Council for Water (CCW). Its principal focus is to promote the control of the water industry by market forces, specifically by extending opportunities for competition in the acquisition and distribution of water resources and in the trading of abstraction licenses. The Environment Agency's Catchment Abstraction Management Strategies (CAMS) and the Resource Assessment and Management (RAM) Framework are closely associated with the Act and are described in Section 2.2 (England & Wales). However, the methodology offers no procedure for lakes and so will not be considered further here.

UK Scotland

The Water Environment and Water Services (Scotland) Act 2003 (Scottish Parliament 2003) establishes a statutory system for water management planning based on natural river basins and comprehensive environmental and economic assessment and monitoring, and provides a framework for comprehensive controls over water abstraction, impoundment, engineering works affecting water courses and diffuse and point sources of pollution to water in order to achieve the best possible ecological status for all surface waters and to protect groundwaters from pollution and over- abstraction. It comprises three Parts:

> Part 1: Protection of the Water Environment. Makes provision for protection of the water environment (surface water, groundwater and wetlands) and implementation of the Water Framework Directive.
> Part 2: Water and Sewerage Services
> Part 3: General

Planning for the management of the water environment previously occurred on an *ad* hoc basis, but some statutory controls over the abstraction and impoundment of water have been long established. The most significant of these are the rights granted to Scottish Water to abstract water for the public supply through water orders made by Scottish Ministers, and the rights to use water granted to hydro-power generators by the Electricity Act 1989, the Hydro-Electric (Scotland) Act 1943 and several earlier scheme-specific Private Acts dating from construction of the large hydro-power schemes. Environmental conditions are factored into water orders and the hydro-electricity Acts and other permits, but they operate at a fairly local scale only. For example, the Tummel-Garry hydro-power scheme must operate to restrict summer water level fluctuations in Loch Tummel to a range of 0.6 m in order to maintain the amenity value of the Queen's View tourist viewing-platf orm (the full annual range is also restricted to 1.1 m). The consequent development of a population of pillwort (*Pilularia globulifera*)[1] led to the designation of Dalcroy Promontory SSSI for which maintenance of the loch's water level regime is critical, so that the water level regime of Loch Tummel is now also linked to the Wildlife and Countryside Act 1981. Similar conservation constraints apply to the hydro-power-related water level regime of the constant, shallow lake known as Dunalastair Water SSSI (Black *et al.* 2000b).

UK Northern Ireland

The Department of Agriculture and Rural Development (DARDNI) is responsible for maintaining the levels of Lough Neagh, Upper and Lower Lough Erne, the largest freshwater Loughs in

[1] A Habitats Directive Annex 1 species favoured by grazing and the particular water level fluctuations at this location, and highlighted in the Local Biodiversity Action Plan.

Northern Ireland. This is mainly for navigational and flood defence purposes.

The Rivers Agency (an agency within DARDNI) is required to regulate and control levels in Lough Neagh within a range specified in the Lough Neagh Levels Scheme (1955) (as amended) in so far as conditions of rainfall, wind and other natural influences permit. In Lough Erne, water level control is undertaken in conjunction with the Electricity Supply Board under the terms of the Erne drainage and Development Act 1950. Lake levels on both Lough Neagh and the Upper and Lower Erne are monitored continuously.

Rivers Agency are currently reviewing the operation and management of sluices in the Lough Neagh/Lower Bann as part of a new project to improve flood defence and navigational procedures.

United Kingdom
In the context of Water Framework Directive implementation, UKTAG (2003a) offers pragmatic, 'expert-opinion' based estimates of the degree of various types of hydromorphological change likely to impact the ecological status of lakes. However it is acknowledged that the links between specific morphological features and their associated biota are generally poorly understood (Rowan *et al*. 2003). Only two aspects of this guidance, relating to impounding and lowering, are directly relevant to water resources considerations[2] and these are summarised in Table 15.

[2] Morphological guidance will be considered explicitly in other SNIFFER projects such as WFD49.

Table 15 Guidance associating changes in lake water level with significant WFD ecological status thresholds developed by UK Technical Advisory Group on the WFD (2nd draft July 2003)

MEASURED ATTRIBUTE	MORPHOLOGICAL CRITERIA FOR HIGH/GOOD BOUNDARY	MORPHOLOGICAL CRITERIA FOR GOOD/MODERATE BOUNDARY
Specific pressure: L3 Impounding (severity: major)		
Height of impoundment	< Normal water level fluctuation	Greater than normal fluctuation by > 1 m
Regulatory capacity of impoundment (sluices etc.)	< Normal water level fluctuation	Natural range increased by > 1 m
Degree of seasonality of level change	Matches seasonality ± 0.5 month	Matches seasonality by ± 1 month
Proportion of littoral exposed at drawdown	< 5% exposed	< 10% exposed
Specific pressure: L4 Lowering/draining (severity: major)		
Reduction in surface area of lake	< 5% reduction	< 10% reduction
Reduction in depth	< 5% reduction	< 10% reduction
Relative changes in littoral / sub-littoral / profoundal areas	< 5% change in area	< 10% reduction

Various guidance notes have been developed for freshwater habitats and species in relation to the requirements of the EU Habitats Directive. Features that are important for the maintenance of *Natura 2000* interests are strictly defined, for the UK, on the basis of river habitats, although some of them might be considered relevant to the requirements of Annex 1 habitats and Annex II species where they are associated with standing waters (Rowan *et al*. 2003).

Smithers and Durie (1998) used hydrological simulation models to predict drawdown in Lakes Windermere and Ullswater resulting from abstraction under Drought Orders issued in 1995/6. The models were used to explore and define different mitigation conditions to protect the environment, particularly fisheries in rivers fed by the lakes, as the drought continued, and eventually to examine the impact of relaxing the Orders. However, it is suggested that such modelling could be extended to consider the impact on other biota, e.g. lake margin plant communities, and thus to clarify the trade-off between protecting lake and river habitats.

In Scotland, Smith *et al*. (1987) found that littoral macrophytes and zoobenthos communities were impoverished in lochs and reservoirs where regular water level changes occurred, even if their amplitude was quite small, as well as under conditions of large annual water level fluctuations. They concluded that rich littoral communities similar to those of lochs with natural water level regimes occurred in regulated lochs which had an annual water level range of less than 5 m and where weekly changes in water level were not greater than 0.5 m for 85-100% of the time. Impoverished communities occurred where either or both of these criteria were not met. This work was used as the principal basis for the Dundee Hydrological Regime Assessment Method (DHRAM) (Black *et al.* 2000a), designed for Scotland only, and relates specified characteristics of the water level fluctuation regime to risk of impact on ecological quality (Table 16). This is, however, based on extremely limited data, and calibration against the scale of ecological status remains tentative (Black *et al.* 2003). However, it represents an approach to a procedure for setting targets for water level fluctuations that can potentially be related at least to the GES/MES threshold.

Table 16 DHRAM: correspondence between annual water level ranges and ecological risk categories

Class	1	2	3	4	5
	Un-impacted	Low risk	Moderate risk	High risk	Severely impacted
Water level not affected by human activity	√				
Annual range 1.3 - 1.7 m		√			
Weekly fluctuations <0.5 m for 85% of the time		√			
At least 50 annual level reversals					
annual maximum level: 80% of dates fall between 01 October and 31 March					
annual minimum level: 80% of dates fall between 31 March and 01 October					
Mean of annual maximum daily rises 0.60 - 1.0 m					
Mean of annual maximum daily falls 0.20 - 0.55 m					
Mean annual range 1.3 – 3.7 m			Four criteria met	Three criteria met	> three criteria met

(source Black *et al.,* 2000a)

USA

No Federal legislation has been promulgated for the regulation of water levels in the standing waters of the USA, but several state legislatures where standing waters are widespread, e.g., Florida and Michigan, have enacted local legislation. In Florida State Law (Section 373.042, Florida Statutes) requires the Department of Environmental Protection to establish minimum flows and levels (MFLs) for lakes rivers, wetlands and aquifers (RCDD, 2004). This level is defined as

> "…the level of groundwater in the aquifer and the level of surface water at which further withdrawals would be significantly harmful to the water resources of the area".

Once established, this level guides protection, recovery and regulatory compliance. Guidance is provided in the Florida Water Resources Implementation Rule (Chapter 62-40.473, Florida Administrative Code [FAC]) which requires that:

> "consideration be given to the protection of water resources, natural seasonal fluctuations in water flows, and environmental values associated with coastal, estuarine, aquatic and wetland ecology"

In parts of the State, such as the Southwest Florida Water Management District, the Water Levels and Rates of Flow Rule (Chapter 40D-8 FAC) outlines methods for establishing minimum flows and lake levels. It distinguishes between three categories of lake (depending on size and presence of cypress-dominated fringing wetlands). Typically two Minimum Levels and three Guidance Levels are established for lakes. These are expressed in feet above National Geodetic Vertical Datum (Table 17).

Table 17 Lake water level definitions used for regulation in the State of Florida

Minimum and Guidance Levels	Definitions
Ten Year Flood Guidance Level	Provided as an advisory guideline for lake shore development. It is the level of flooding expected of not less than the 10 year recurrence interval.
High Guidance Level	Advisory guideline for the construction of lake shore development, water dependent structures and operation of water management structures. The HGL is the elevation that a lake's water level is expected to equal or exceed 10 percent (P10) on a long-term basis
Minimum Lake Level	Is the elevation that a lake's water level is required to equal or exceed 50 percent of the time (P50) on a long-term basis
Low Guidance Level	Is the elevation that a lake's water level is expected to equal or exceed 90 percent of the time (P90) on a long-term basis

(after RCDD, 2004)

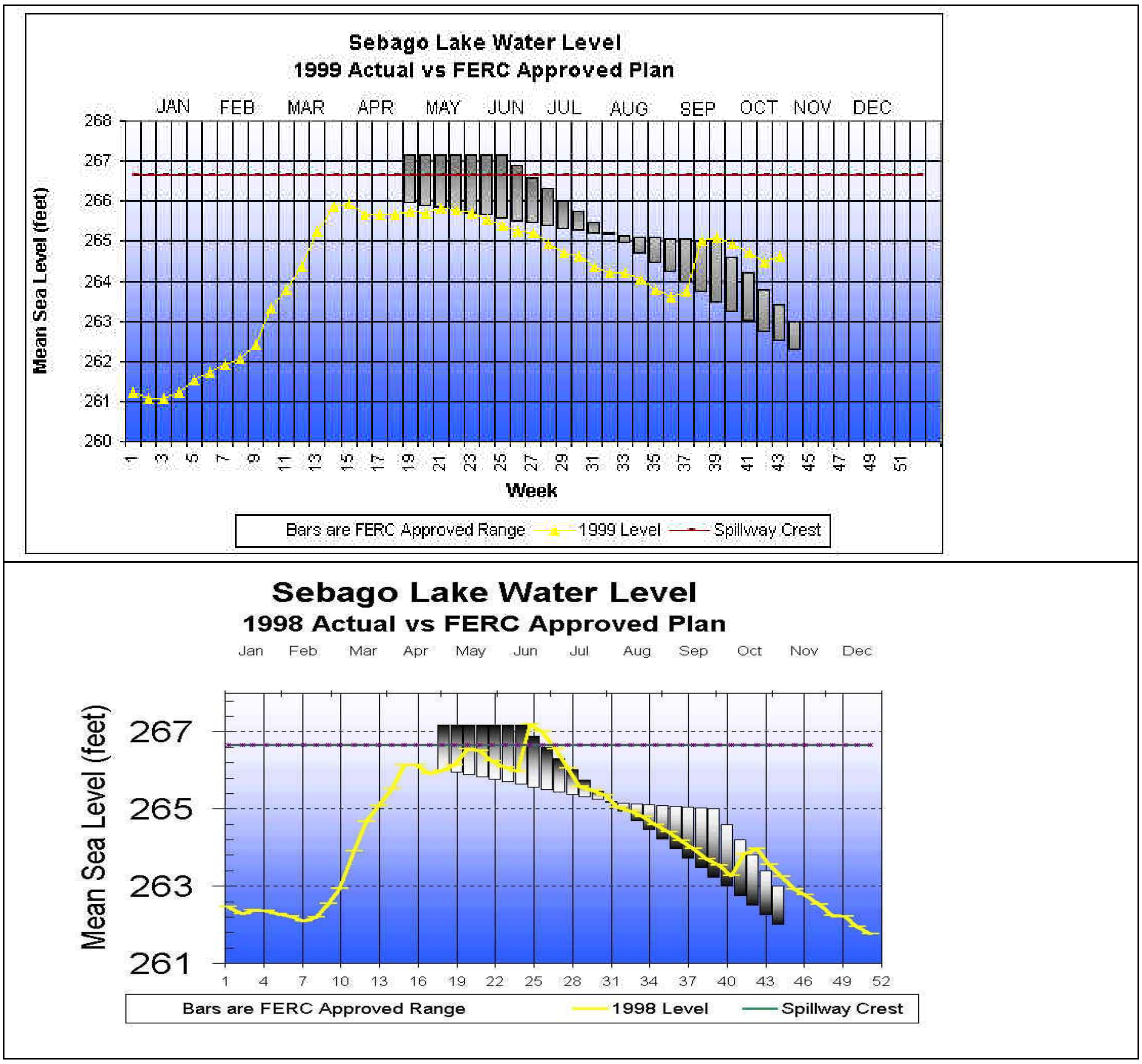
In Michigan, Act No. 59, the Inland Lake Levels Act of 1995, established a Drain Commissioner to oversee legal proceedings to maintain 'normal lake levels' for lakes within Oakland County. Part 307 of the Act defines a normal level as

> "…the level or levels of the water of an inland lake that provide the most benefit to the public; that best protect the public health, safety and welfare; that best preserve the natural resources of the state; and that best preserve and protect the value of the property around the lake"

The normal level is not defined as the highest possible level for lake, but is defined depending on local circumstances. The information used to define the legally binding normal level includes historical lake levels, seasonal fluctuations, the location of septic tanks, docks and other features, downstream impacts, fisheries and wildlife habitat protection and catchment hydrology. Most of the lakes in Oakland Country have outflow control structures (dams, weirs, sluices etc.,), but several are also controlled by pumping (augmenting and abstraction). Normal level thus specifies a legally-binding range of water levels and state engineers are tasked with maintaining levels within this specified range (Oakland County, 2004)

Beyond these examples where individual states have sought to regulate lake management practices across particular regions, much relevant science is conducted on individual lakes.

Sebago Lake, Maine was impounded in 1987, altering a water level regime that had been in place at least since 1832. This water level was raised and no water released until the water level reached 267.15 m a.s.l. (from 1993 266.65 masl), resulting in a 40% reduction in spring, summer and autumn outflows. The high, invariable water level obstructed progradation of beach materials and thus disturbed the sediment equilibrium of the shoreline, leading to erosion, loss of water clarity and proliferation of littoral macrophytes. On the basis of various studies, a water level regime was devised and applied in 1996. This mandates that two in nine years the water level will drop to 261.0 MSL or lower sometime between 01 November and 01 January. Also, water levels cannot remain at full pond 266.65 (spillway height) for more than 3 weeks from May 1 to June 15 (FOSL 1999). Former, target and actual water levels for 1998 and 1999 are shown in Figure 6.



Sebago Lake Association (2000)

Figure 6 Water level records for Sebago Lake, Maine 1998-1999

4. IDENTIFICATION OF ECOLOGICALLY IMPORTANT PARAMETERS (RIVERS)

4.1 General

Text books on river ecology (e.g. Hynes, 1970; Allen, 1995; Giller and Malmqvist, 1998) are consistent in identifying flow, oxygen, light, temperature, substrate and water chemistry as the most important factors influencing the river ecosystem. However, the literature is somewhat ambiguous about the precise meaning of flow, sometimes meaning discharge; sometimes velocity and often both. This project focuses on hydro-morphological variables; however it is important to consider how these impact indirectly on the ecosystem by altering oxygen, light and temperature as well as directly defining physical conditions.

Oxygen is a basic requirement of all life. Oxygen levels in rivers are controlled primarily by plant photosynthesis and respiration; many rivers show a diurnal variation with high oxygen levels during the day and low levels at night. To lesser extent oxygen may vary with temperature, flow velocity and turbulence. High organic matter loads may reduce oxygen levels as they create high biological oxygen demand (BOD). In general, groundwater tends to have lower oxygen levels, so groundwater-fed rivers will tend to be lower in oxygen than surface runoff-fed rivers.

Temperature influences the metabolic rate and life cycle timing of many species. Temperature is controlled by solar radiation and conduction from air and soil. Due to the lapse rate, streams at higher altitudes will have cooler water. Stream temperature tends to be constant where groundwater dominates the flow; e.g. water in British Chalk springs is constantly close to annual mean air temp 10-11^{o}C., In deep slow flowing streams there is often a water temperature difference between the surface and bed, but this does not occur in shallow turbulent (well mixed) rivers. Shading can reduce temperature.

Light is controlled by solar radiation and will thus be controlled by latitude and cloud cover. Within the river light levels tend to decline logarithmically with depth and will be mediated by shading from plants (both in and out of the river) and turbidity. Light levels have a direct impact on vision of fish and other species which is important for feeding, avoiding predators and navigation.

Substrate provides habit for a variety of activities such as resting, movement reproduction, rooting, and for refuge from predictors and flow. Substrate is quite a complex variable to measure as it includes the size of the particles and their relation to other particles of the same or different sizes. Embeddedness is an index of the degree to which larger particles (boulders and cobbles) are surrounded or covered by finer sediments

Water chemistry includes both natural water properties and anthropogenic influences. Key variables that influence the river ecosystem are pH (acidity of the water), hardness (concentrations of Ca 2+ and Mg2+ ions), conductivity (total ionic content) and alkalinity (concentration of carbonates). These can affect the physiology of river species including osmo-regulation and respiration. Changes in chemistry, associated with changes in discharge, have important impacts such as triggering fish migration.

River flow is considered in the next section.

Table 18 Broad relationships between variables influencing the river ecosystem and those that can be measured easily from maps

	Dependent variable					
Independent variable	**Temperature**	**Discharge**	**Light**	**Oxygen**	**Substrate**	**Water chemistry**
Altitude	Reduced temperature with altitude	Increased rainfall with altitude		Higher turbulence	Upland rivers tend to have coarser substrate than lowland rivers	
Area		Increased flow with larger catchments	Deeper rivers tend to have reduced light penetrat -ion	Wider diurnal variations if macro-phytes present		
Geology	Groundwater-fed rivers tend to have more stable water temperature	flashy runoff from impermeable rocks, damped runoff in groundwater-fed rivers		Ground-water-fed rivers tend to have lower oxygen levels		Natural groundwater-fed rivers tend to be higher in dissolved minerals and lower in nutrients

Under the Water Framework Directive, member states undertake a characterisation of water bodies. To implement this, a typology of natural rivers in Great Britain has been developed based on mean catchment altitude, catchment size and dominant geology (UKTAG, 2003b). This is consistent with System A of the Directive. Although the theoretical basis of this typology appears sound, in that it these three catchment variables provide surrogates for other parameters that are known to be important for the river ecosystem (Table 18), the results of the typology have not been tested ecologically.

4.2 River discharge

River flow is a widely used term, but is often ambiguously used to mean both river discharge (m^3s^{-1}) and velocity ($m\ s^{-1}$). River discharge does not impact directly on the river ecosystem, rather it works indirectly by, for example, diluting dissolved or suspended matter in the river, interacting with river channel morphology to define width, depth, velocity and associated hydraulic variables such as sheer stress. Nevertheless, river discharge is easy to measure and data are available at many locations, collected for water resources and flood management. Additionally, river abstraction is expressed in units of discharge (usually $ml\ day^{-1}$) so licences expressed as allowable volume related to river flow are both readily understandable by the abstractor and easy to implement in terms of threshold limits.

As discussed in section 2, early environmental standards were seen in terms of a single parameter, minimum flow, based on the concept that provided a critical amount of flow was left in the river, the ecosystem would be maintained. This idea is now largely rejected for two reasons.

(1) It is now widely recognised that all elements of a flow regime, including floods, medium and low flows are important, together with their timing, magnitude, frequency, duration and rate of change (Poff *et al*, 1997; Hill & Beschta, 1991). Thus any changes in the flow regime will influence the river ecosystem in some way. The idea is explicitly recognised in the development of the IHA/RVA method by Richter *et al*. Furthermore, the Building Block Methodology (and associated methods, such as the Holistic Approach) related the different elements of the flow regime to their ecological function. Consequently, standards should relate to medium and high flows as well as low flows. This has partly been addressed by relating flow to some probability of occurrence such as % of time exceeded as exhibited on a flow duration curve.
(2) Natural flow regimes vary on scales of minutes to years. The discharge in a river may naturally go below a single specified minimum flow. Indeed, too much flow in a river at the wrong time can be as damaging to the ecosystem as too little. For example, Everard (1996) has indicated that severe stress on the river ecosystem, such as droughts, may be beneficial in the long term. So standards must be set in the context of a variable regime. This has led to the practice of specifying standards in terms of, for example, percentage of the natural flow, rather than an absolute value. Use of the natural flow regime as a reference condition presents problems on rivers such as the Itchen, which have been managed for many centuries.

The natural flow regime of a river is complex as it varies continually (except in the cases of streams where the only source is a constant spring) and cannot be described by a few parameters. Richter *et al.* (1996) defined 32 hydrological Indices of Hydrological Alteration (IHA) to characterise statistical attributes of the flow regime relevant to the river ecosystem. These are presented in Table 19 and are calculated for every year in a time series, facilitating the computation of inter-annual statistics that describe the temporal variability of a flow regime. They claim that these parameters are related to the ecological functioning of a river; however this supposition has not been tested with biological data. They nevertheless, represent a comprehensive set of broadly independent flow statistics. Other statistics can be derived but are often correlated to the 32 defined in Table 19. Olden and Poff (2003) analysed 171 hydrological indices and concluded that IHAs represent almost all major components of the flow regime, although high flows were least well covered. They further suggested that selecting 4 indices with high information content could represent most of the flow regime.

Other flow statistics have been related to ecological data. Tennant (1976) analysed flow and biological data from hundreds of streams in the Midwestern USA and found that percentages of the mean annual flow (natural) are related to target life stage functions, e.g. 10% for survival, 30% for a satisfactory healthy ecosystem.

In some cases, flow is standardised for river scale. Stewart (1973) found that salmon start their migration in rivers of northwest England when the flow reached 0.084 m^3s^{-1} per metre of channel width and 0.03 m^3s^{-1} per metre of channel width could be considered as a survival flow.

In other examples, more complex flow statistics have been derived that relate to the river ecosystem. In South Africa, the hydrological index (CVB) has been related to percentage of mean annual runoff needed to maintain given ecosystem conditions. CVB combines a South African Base Flow Index (BFI_{SA}) and the coefficient of variation of flows (CV) where:

$$CVB = CV/BFI_{SA}$$

CVB is close to 1 for flow regimes with very low variability to over 50 for semi-arid regimes in South Africa. BFI_{SA} is estimated using monthly data as the ratio of base flows to total flows after a two parameter digital filtering separation method (Hughes *et al*., 2003) has been applied.

Table 19 Parameters used in IHA method of Richter et al. (1996)

IHA Statistics Group	Regime Characteristics	Hydrological Parameters
Group 1: Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and timing of annual extremes	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of annual extremes	Timing	Julian date of 1-day minimum flow Julian date of 1-day maximum flow
Group 4: Frequency and duration of high and low flow pulses[1.]	Magnitude Frequency Duration	No. of high pulses per year No. of low pulses per year Mean duration of high pulses in each year Mean duration of low pulses in each year
Group 5:Rate and frequency of changes in conditions	Frequency Rate of Change	Mean of all positive increases between successive daily values Mean of all negative increases between successive daily values Number of rises Number of falls

Notes
[1]High and Low pulses are defined as episodes of flow above Q_{25} and Q_{75} respectively

The Holistic Method developed in Australia uses primarily discharge parameters, but also some site and catchment factors (Table 20). The procedure aims to assess the complete river ecosystem, including the source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary. A fundamental principle is that to maintain integrity, natural seasonality and variability of flows should be maintained.

Table 20 Examples of parameters considered in the holistic approach

Flow Regime	Hydrograph	Physical structure
Total discharge	Rate of rise	Basin-scale:
Flood frequency	Rate of fall	Large scale reach features
General variability	Flood duration	Reach-scale
1, 7, 20 year return	Flood peak	Channel complexity, effluent creeks, wetlands
Overbank, General	Flood minimum	
Frequency of drought	Random short-term changes	Sub-reach scale
Frequency of flow duration	Freshets	- Snags and tree roots, organic debris aquatic macrophytes, rock outcrops
Seasonality		- Depths (stage for 80, 50, 25 and 10 percentile flow) at representative cross sections
Sequences of years		

In the development of the LIFE index (Lotic Invertebrate index for Flow Evaluation) Extence *et al*. (1999) used a range of flow indices to test whether it is possible to link changes in benthic invertebrate community structure with indices of historical river flow at a gauge close to the sample site. They found some correlations, but there were problems with the statistical methods used. Dunbar and Clarke (2004) used an improved statistical framework and demonstrated that there are generally consistent positive relationships between summer Q_{10} and Q_{95} and observed / expected LIFE score across a large number of sites (over 200). Relationships were much clearer for flashier catchments, it is thought that the flow indices chosen (simple seasonal percentiles) may not be appropriate for relating to LIFE on groundwater-dominated (high BFI) catchments.

The RAM framework incorporates a system, MTR, for examining macrophyte sensitivity to abstraction. While its typology framework is well-developed, the overall system has not been tested against flow data to the extent that LIFE has.

4.3 River hydraulics

Relationships between discharge and the river ecosystem arise because discharge is a surrogate variable for ecologically relevant parameters. Most importantly, the interaction of discharge with channel geometry (size, shape, slope, roughness) controls width, depth, velocity and associated hydraulic variables, such as sheer stress. For example, velocity controls anatomical and behaviour adaptations, sediment transport, movement of drifting species (invertebrates), respiration and food supply for drift feeders.

The European Commission's COST 626 network on hydro-ecology prepared a review of parameters used in habitat modelling used in member states of the European Union (Harby *et al,* 2004). The list is summarised in Table 21. Some specific hydraulic parameters such as Froude and Reynolds number are included within the term "turbulences".

Table 21 Key morphological and hydrological parameters considered in habitat models at different scales (Harby *et al*., 2004)

		Parameters		
Scope and scale		Morphologic	Hydraulic	Hydrological
"pico"-habitat ~ cm	"Nose position" of fish	▪ Substrate size, type, shape ▪ Substrate "quality" for biological purposes ▪ Motion/no motion ▪ k/d (roughness / depth)	▪ Shear stresses ▪ Laminar/turbulent near-bed boundary layer ▪ Local flow velocity (nose)	▪ Baseflow Q ▪ Maximum peak flow and duration ▪ Drought events
Micro-habitat ~ m	Section	▪ Substrate size/type distribution ▪ Substrate stability ▪ Local elevation along cross-section (geometry) ▪ Roughness ▪ Sediment porosity ▪ Bathymetry ▪ Roughness r (height of protruding rock) ▪ Embeddedness ▪ Porosity ▪ armour layer ▪ particle shape ▪ Wentworth scale (1..15), dominant/subdominant ▪ Macrophytes ▪ Overhanging braches ▪ Cover (Rocks) ▪ Percentage of fines	▪ Wetted perimeter (water width and depths) ▪ Local velocities ▪ Vertical hydraulic gradient ▪ Water transient storage zone ▪ Surface-subsurface lateral linkages ▪ Cover (pools) ▪ "Broken" water ▪ Turbulences ▪ Splashwater	▪ Temporal variation of discharge: daily, seasonal, inter-annual ▪ Flood and drought regime: frequency, magnitude, evenness
Meso-habitat ~100 m	Reach	▪ Topology ▪ Run/riffle/pool distribution ▪ Cross-section profiles ▪ Valley floor: constrained vs unconstrained ▪ Channel stability ▪ Bank stability ▪ Plan shape: meander v braided ▪ Description of morph. Patterns by shape and property ▪ Sinuosity ▪ Width/depth ratio ▪ Width/max. depth ratio ▪ Periphyton	▪ Mean cross-sectional velocity, water depths ▪ Spatial variance of velocity, shear stress, depth	▪ Mean annual flow ▪ Average duration of the floods and droughts ▪ Spatial variation of discharge

Macro-habitat ~1000 m	Catchment	▪ Drainage area: stream length ratio ▪ Frequency distribution of different stream orders ▪ Branching degree and distribution ▪ Longitudinal gradient ▪ Presence of barriers ▪ Land-use activity ▪ Number of pools/100m	▪ Mean water residence time ▪ Channel vs uphill position of water table (gaining or losing stream)	▪ Longitudinal variation of cumulative water yield ▪ Seasonal variability in runoff ▪ Surface or subsurface runoff ▪ Flow continuity
Ecoregion/Landscape		▪	▪	▪
Temporal Scale		▪ Disturbance frequency ▪ Disturbance duration (draughts, suspended sediments e.g.) ▪ Dry periods versus draught events (disaster events) ▪ Wet periods versus flood events		
Networking aspects		▪ Characteristic patch diversity ▪ Residual pool depths ▪ Availability and location of refugia (from different threads)		

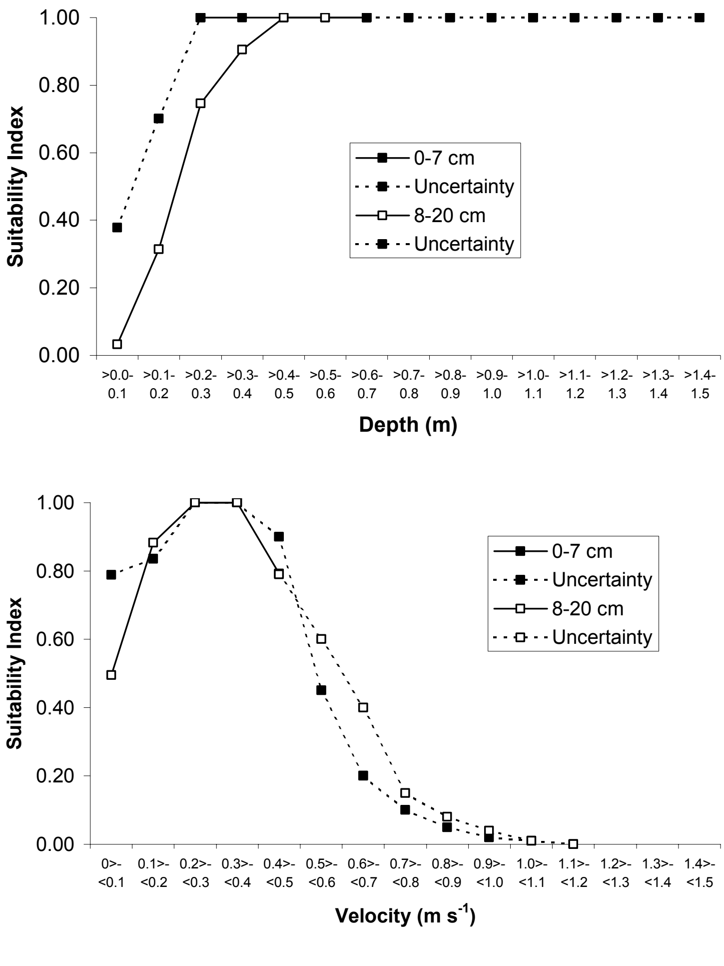


Figure 7 Habitat suitability indices (preference indices) for two size groups of juvenile trout (Dunbar *et al.*, 2001).

Most countries of the world that have experience of environmental flows use habitat modelling for impact assessment of abstractions or impoundments, even if the results are used within a broader framework of assessment. This reflects the success in relating hydraulic variables to preferences of river species. In particular the use of habitat suitability curves (HSIs) are widely used in models such as PHABSIM and its derivatives in France (EVHA; Ginot, 1995), Norway (RSS model; Killingtviet and Harby, 1994) New Zealand (RYHABSIM; Jowett, 1989) and Germany (CASIMIR; Jorde, 1996). Figure 7 shows 2 HSIs showing depth and velocity suitability for juvenile trout (0-7 cm and 8-20 cm). The steepness of the curve reflects sensitivity of the organism to changes in the parameter.

Collection of hydraulic data for a river reach requires site visits and detailed surveying. Parameters such as the topography of the river and bottom substrate characteristics can be defined during a single visit. However, other hydraulic parameters, including velocity, water surface slope and depth vary with discharge and thus several site visits are required at different discharges, to determine how these parameters change with discharge.

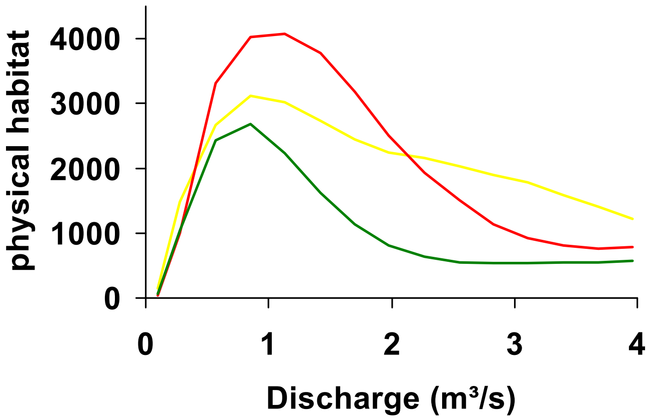


Figure 8 Physical habitat (weighted useable area m^2/1000m) v river discharge

Much current research effort is focused on finding generalised relationships between habitat and parameters than can be quantified more rapidly without the need for such detailed site investigation. Lamouroux and Capra (2002) found that differences in habitat versus discharge curves (Figure 8) for small to intermediate-size French streams could be explained using Froude and Reynolds numbers, which in turn could be predicted using simple measurements of river width at two flows and mean depth at Q50. However, the approach still requires estimation of these hydraulic values. This work is being followed-up for England and Wales as part of the Rapid Assessment of Physical Habitat Sensitivity to Abstraction (RAPHSA) project (Acreman *et al*, 2004a). The slope of the habitat-discharge curve provides a direct measure of sensitivity to abstraction.

Application of site-based hydraulic parameters means that environmental flows will be based on the channel characteristics as surveyed. For heavily engineered river channels, such as the River Tame in Birmingham, achieving the Water Framework Directive objectives may require morphological restoration as well as hydrological management (Booker, 2003). In such cases, there may be a mis-match between the environmental flow set and the eventual channel characteristics. For this reason, English Nature has argued that for designated rivers, standards should be set based on the river's characteristic form, ensuring a correct flow regime following physical restoration. Thus a designated river that has both un-natural channel structure and un-natural flows could present a practical, if not conceptual problem, in that management agencies are currently not joined up enough to address flow and physical restoration together (Acreman *et al*, 2004b).

4.4 River connectivity

Many papers refer to the importance of connectivity of river systems and in particular the river continuum and flood pulse concepts. The river continuum concept compasses the upstream and downstream linkages from a river's source to the coastal zone, as exemplified by migration of salmon from the sea to spawning grounds in the headwaters (Vannote *et al*, 1980). The flood pulse concept (Junk *et al*, 1989) is based on the importance of lateral connectivity between rivers and floodplains and sees the inundation of floodplains as the driving force behind river life. Connectivity has been recognised as important the Water Framework Directive.

Few environmental flow methods explicitly include connectivity, although flood parameter implicitly index floodplain inundation. On many large rivers in tropical Africa the area of floodplain flooded is a key indicator of ecosystem health (Acreman, 2000) and the release of water from reservoirs to inundate floodplain was a key recommendation of the World Commission on Dams (WCD, 2000). The MFAT model (Jones, 2000) used on the Murray-Darling river includes parameters of floodplain inundation

- Flood timing (FT)
- Inundation duration (FD)
- Annual drying period (ADP), and
- Flood memory (FM)

In the River Babingley method, Petts *et al*. (1996) suggest a series of steps to define an environmentally acceptable flow regime for a baseflow-dominated river in England or Wales. The "desired flow regime" (DEF) was explicitly designed to sustain connectivity between usable habitat in all reaches. However, no specific parameters were defined.

4.5 Catchment parameters

Many applications of environmental flow standards require a rapid assessment or application to many sites. This precludes detailed field visits, hydraulic site data collection or gather of long term river flow data. To overcome this problem some relationships have been established between parameters that can be measured remotely from digital data sets or maps and elements of the river ecosystem. Digital terrain models in particular are able to estimate such parameters as catchment area, slope, altitude and distance of sites from river source or mouth. Low Flows 2000 (Holmes *et al*, 2004) and the Flood Estimation Handbook (Institute of Hydrology, 1999) are examples of procedures that allow hydrological variable (flow duration statistics and flood statistics respectively) from catchment-based data including drainage area, rainfall and soil type.

In some cases ecological variables have been estimated from catchment characteristics. For example, Huet (1959) proposed a zonation scheme for temperate European rivers based on the dominant fish species. He used river gradient to develop 'slope rules to define brown trout, grayling, barbel and bream zones. Cowx *et al.* (2004) also found that river gradient was important for discriminating between 8 fish community types for England and Wales. However, they also found that flow characteristics and water chemistry (as measured by alkalinity) were major abiotic factors. Botosaneanu (1963) found changes in invertebrate fauna downstream. They identified three zones by their environmental conditions: crenon or headwater zones with constant cool temperatures, rhithron cool upland section and potamon constituting the warmer and less steep rivers in the lowlands. It is noteworthy that ecologists tend to use stream order as a measure of scale; it classifies a stream in relation to tributaries and age of water - residence time (Cole, 1994). This partly due to its ease of measurement by hand from maps.

The wide availability of digital maps, GIS and DTMs means that this is no longer a restriction. In contrast, hydrologist tend to use catchment area as

Most ecological models require at least some site variables. The River Invertebrate Prediction and Classification System (RIVPACS; Wright *et al*, 1984) defines macro-invertebrate communities from catchment and site data (Table 22). Original catchment data were those that could be derived manually from maps and so simple parameters were used such as distance from source. Methods to derive these automatically from GIS data have been developed (Dawson *et al*, 2002). However, the models have not been updated to employ other parameters that may be more ecologically relevant and can now be derived automatically, but which were too difficult to determine manually in the original study. HABSCORE (Milner *et al*, 1998) is a system for predicting the average fish population to be expected in a stream reach when fully recruited in the absence of artificial environmental impacts. It is based on salmonid stream habitat measurement and empirical models of fish density. Like RIVPACS, HABSCORE uses a combination of site and catchment predictors (Table 23).

Table 22 RIVPACS parameters

Site Registration Data
National Grid Reference
Altitude
Distance from Source
Slope 1
Discharge (mean) category
Mean air temperature 1
Air temperature range 1

Environmental Data (ideally measured several times over a year and averaged)
Stream width
Depth
Substrate characteristics
Water geochemistry (preferably alkalinity, but a surrogate: total hardness, calcium concentration or conductivity is acceptable) 1
Water velocity category (only required if discharge category not available)

1 These variables may optionally be used in the following combinations:

	Option				
Variable	1	2	3	4	5
Alkalinity	y	y		y	
Slope	y	y	y	y	
Mean air temperature	y	y	y		y
Annual air temperature range	y		y		y

Table 23 Parameters used in HABSCORE

Catchment parameters	Site parameters	Derived site parameters
Altitude (m) 1085 slope (m km^{-1}) Downstream link number Conductivity ($\mu S\ cm^{-1}$)	Date fished Mean depth (cm) Mean width (m) Shading Instream cover Substrate embeddedness Substrate diversity Substrate type (silt, sand, gravel …) Flow type (slack, glide, …) Discharge range (m^3s^{-1})	Surface area to volume ratio Boulder (%) x slack x flow (%) Cobble (%) + gravel (%) Cobble (%) x riffle (%)

4.6 Main findings of review of parameters

The literature presents a range of hydro-morphological parameters that can be related to the river ecosystem.

Small scale studies have shown that flow interacts with morphology to define physical habitat (such as width, depth, velocity and substrate) for specific organisms. To implement standards at this scale, site data are essential. Implementation of WFD will require that environmental standards are applied for all bodies regardless of hydrological and ecological data available. Consequently, standards are required that can be applied without having to visit the water body. This means that standards must be related to parameters than can be obtained from maps or digital databases, such as river flow, catchment area or geology. Any resulting standards will have less predictive accuracy at a local scale and cannot be tested using site data. Broad measures of ecology are needed to match broad hydro-morphological parameters. These are currently lacking but would need to be based on ecosystem functions, as much as ecosystem structure.

Many models (*e.g.* RIVPACS, HABSCORE) relating hydro-morphological parameters to the river ecosystem are compromises that employ data at various scales (at-site to catchment). They are normally design for purposes such as defining reference conditions and not for standard setting.

Hydro-morphological parameter data are available at a range of scales. There have been around 70 habitat modelling studies, which include detailed at site hydraulic data, River Habitat Survey for 17,000 500 m reaches across the UK. Catchment data are available in various GIS databases including rainfall, topography, geology and the river network. Few data are available at the water body scale that falls between the at-site and catchment scales. Some research has been undertaken to relate catchment to local scale parameters, primarily using RHS data, but few parameters are directly relevant for standard setting.

Catchment scale parameters (area, altitude, geology) are partly related to reach scale parameters (velocity, slope, alkalinity) and they control some higher scale aspects of the river ecosystem; though these have not been clearly defined.

The flow regime is complex and is characterised by timing, magnitude, duration and frequency; all of which are important for different aspects of the river ecosystem. To produce operational standards, there is a need to identify a small number of parameters that capture its most significant characteristics. For example the number of high flow events greater than three times the median flow has been shown to be related to the structure of macrophyte and macro-invertebrate communities in New Zealand (Clausen 1997). Separation of inter-correlated flow variables for ecological analysis has been studied. Most standards focus only on flow magnitude, or flow percentile, which only partially capture the breadth of characteristics of the flow regime. Studies relating flow regime to river ecosystems have not been orientated towards defining environmental standards.

There is a growing recognition that rivers need natural flow regimes to maintain natural ecology. River management would be greatly facilitated if clear thresholds of hydro-morphological parameters exist at which distinct changes in the river ecosystem occur. Whilst some thresholds have been identified, many studies have relationships in the form of smooth curves or straight lines with no obvious critical points, suggesting a continuum of change in ecological communities with alteration in the parameter (Acreman, 2004).

5. IDENTIFICATION OF ECOLOGICALLY IMPORTANT PARAMETERS (LAKES)

Bragg *et al.* (SNIFFER WFD06, 2003) identified hydromorphological pressures and impacts for lakes with reference to the WFD hydromorphological quality elements, and attempted to link these to effects on biota, largely on the basis of work reported in the international literature. Tables 24 and 25 summarise the principal human pressures on lakes and their catchments that were identified, the resulting impacts on the WFD hydromorphological quality elements and, where available, on biota; the latter table focuses on damming and the associated changes in water levels, which are expected to be the principal focus of water resources regulation.

Table 24 Summary of human pressures on lakes, and the resulting impacts on hydromorphology and biota

PRESSURES	ACTIVITY	IMPACTS ON LAKE HYDROMORPHOLOGY	IMPACTS ON BIOTA
Agriculture	Clearing natural forest; increase in sheep stocks	Increase in sedimentation rate; change in composition of sediment load	Decrease in photosynthetic rates; degradation of lake bottom habitats
Forestry; timber harvesting	Ploughing, drainage, harvesting	Increase in suspended sediment production and lake sedimentation rate	Decrease in photosynthetic rates due to increased turbidity
Military activities	Army training using live ammunition	Disintegration of shoreline peat rafts	Loss of shoreline communities
Recreation	Hill walking, power boating, angling	Erosion of shoreline and paths; trampling of wetland	Loss of shoreline communities
Road building	Construction; culverting of lake outflow	Accelerated catchment erosion and lake sedimentation rates	Retreat of reed fringe; decrease in photosynthetic rates
Urbanization	Urban development	Increase in sedimentation rate and suspended sediments	Increase in algal growth rate
	Sewage discharge	Increase in sedimentation rate due to increased deposition of persistent algal remains	Emergent macrophytes (*Typha, Phragmites*) favoured
Mineral exploitation	Mining; gravel extraction from lake bed	Changes in sediment deposition and distribution patterns	Degradation of fish spawning grounds
Navigation	Dredging	Increase in water depth and turbidity	Siltation of fish spawning grounds
Upstream water use	Change in inflow rate	Change in water level	Phytoplankton favoured
		Increase in residence time	
Water supply	Direct water abstraction from lake		Changes in plankton populations; increases in frequency of algal blooms
	Groundwater abstraction	Change in rates of exchange between lake and groundwater; change in water quality (e.g. salinity)	
Hydro-power generation (water supply)	Water diversions	Reduction in residence time	Decline in frequency of algal blooms; changes in plankton populations
	Damming	See Table 25	See Table 25

Table 25 Summary of effects of damming on lake hydromorphology and biota

IMPACTS ON LAKE HYDROMORPHOLOGY	IMPACTS ON BIOTA
Increase in area and depth	Increased fish productivity
Change in outflow rate leading to change in water level	Phytoplankton favoured
Permanent changes in water level, maximum and mean depths	Succession in marginal plant communities
Rise in water level	Reduced growth of submerged macrophytes
Low water levels (reduced hypolimnion volume)	Changes in phytoplankton populations; cyanobacterial blooms.
Change in character and rate of water level fluctuations (leading to changes in relative sizes of littoral and pelagic zones and changes in sediment deposition patterns)	Changes in littoral macrophyte and zoobenthos populations; changes in invertebrate communities; changes in fish spawning success
Altered residence time	Changes in phytoplankton populations: <20 days flushed out; <1 year high biomass and populations resilient; >5 years low biomass

Pressures operating on the catchment land surface and involving use of the lake water affect hydromorphology by causing changes in the hydrological regime and sediment loads. Changes in individual WFD hydromorphological quality elements rarely occur in isolation, and some of the effects on biota operate indirectly by influencing other physical and chemical factors such as light levels (and thereby photosynthetic rates), temperature and water chemistry.

The current project focuses on water resources aspects only, and therefore is principally concerned with hydrological regime, viewed by the WFD as a combination of quantity and dynamics of flow, level, residence time and the resultant connection to groundwaters. Morphological issues are being dealt with in another SNIFFER project, but in view of the close relationships between hydrology and morphology – illustrated, for example, by the issues that arose at Sebago Lake (Section 2.4.2) – shoreline erosion can be initiated by raising and stabilising the water level.

5.1 Hydromorphological quality elements

The following sections provide further detail on the role of each of the hydromorphological quality elements for lakes, and some guidance on how values may be obtained for any lake. The elements contributing to hydromorphological quality are listed as:

Hydrological regime

- Quantity and dynamics of flow
- Water level
- Residence time
- Connection to groundwaters

Morphological conditions

- Lake depth variation
- Quantity and structure of the substrate
- Structure and condition of the shore zone

While the hydrological regime quality elements are of direct relevance to water resource regulation, in the sense that they may provide the basis of operating targets, morphological quality elements are also important since they provide a context for the hydrological elements and control the means by which hydrological quantities affect the ecology.

Hydrological regime

Quantity and dynamics of flow

Flow is a fundamental aspect of the lake environment, which controls, *inter alia*, lake level and residence time. It can be estimated at an annual time scale by water balance methods and at finer time resolutions, e.g. daily, by methods which combine the annual water balance with soils and other information which reflect the dynamic behaviour of a catchment. The latest UK standard for producing such information is Low Flows 2000 (Holmes *et al*., 2002a, 2002b), which will produce hydrological estimates for any point on the UK digital rivers network.

The overall rate of throughflow of a lake is susceptible to modification through alteration of the hydrology of the rivers or streams that feed it. The rivers component of the Dundee Hydrological Regime Assessment Method (DHRAM) provides one method to quantify the degree to which the flow regime of a river, expressed in terms of variables that are significant to ecology, departs from the natural condition (Black *et al.,* 2000a, b). The variables are drawn from the Indicators of Hydrologic Alteration method of Richter *et al*. (1996) and are shown in Table 26.

Table 26 List of 32 parameters of the Indicators of Hydrologic Alteration method (after Richter *et al*., 1996)

Group 1 - Magnitude of monthly water conditions
Mean January flow
Mean February flow
Mean March flow
Mean April flow
Mean May flow
Mean June flow
Mean July flow
Mean August flow
Mean September flow
Mean October flow
Mean November flow
Mean December flow
Group 2 - Magnitude and duration of annual extremes
1-day-minimum flow
1-day-maximum flow
3-day-minimum flow
3-day-maximum flow
7-day-minimum flow
7-day-maximum flow
30-day-minimum flow
30-day-maximum flow
90-day-minimum flow
90-day-maximum flow
Group 3 - Timing of annual extremes
Date of 1-day maximum flow
Date of 1-day-minimum flow
Group 4 - Frequency and duration of high and low pulses
Annual number of high pulses
Annual number of low pulses
Mean duration of high pulses (days)
Mean duration of low pulses (days)
Group 5 - Rate and frequency of change in conditions
Mean daily flow increase
Mean daily flow decrease
Number of rises
Number of falls

Water level

Water level is of direct ecological relevance since it affects the area of littoral zone exposed and, given the variability of water level, lengths of exposure and timing of exposure changes to the littoral zone. Similarly, it exercises a control on water depth. Given its variability, water level is used in many different ways, e.g. annual range, seasonally-defined maxima or minima (e.g. relevant to nesting periods) or the vertical extent of weekly changes in water level (e.g. Smith *et al*., 1987). Water level is measured and recorded daily for reservoirs covered in the UK by the

Reservoirs Act 1975 (those holding a capacity of 25,000m^3 or more), so this provides a valuable source of information. Some further recording of lake level information is undertaken by UK environmental and nature conservation agencies, but is thought to be limited in availability.

The lakes component of the DHRAM method (see Section 2.4.2) incorporates a method for calculating the degree of anthropogenic impact on the water level fluctuations in Scottish lochs, based on the degree of conformity to ecologically beneficial norms identified by Smith *et al*. (1987). For any site, it generates one of five classes, ranging from 'unimpacted condition' (Class 1) to 'severely impacted condition' (Class 5). Along with the RECGEL model, this method has been applied to analysis of the impact of water level fluctuation in regulated Lake Vaggatem, Finland (Hellsten *et al.*, 2002). Both methods provide a simple way to analyse environmental changes without the need for time-consuming fieldwork. The main difference between the REGCEL and DHRAM models is that the REGCEL model emphasises critical water levels which, according to empirical evidence or expert judgement, cause harmful impacts on littoral vegetation, zoobenthos and fish, for example. The REGCEL model also takes into account some site specific factors that affect the sensitivity of the system (this water level analysis model was developed by the Finnish Environment Institute between 1999 and 2000; it calculates more than 30 parameters of daily water level values, is coded by Visual Basic and uses an Excel program). The DHRAM model is based on the assumption that severity of departure from the norms identified by Smith *et al*. is always harmful, without estimating the adaptability of ecosystems to change (Hellsten *et al.*, 2002). The two methods provide comparable strategies for extracting ecologically relevant information from daily water level data.

Residence time

Residence time, T (also known as lake water retention time or turnover time) is a crucial concept in limnology. It is relevant to lake ecology principally because of its effect on water chemistry, affecting lake response to catchment nutrient budgets (Lyle and Smith, 1994), although seasonal differences in flushing rate must also be taken into account (Werritty *et al*., 1993). Residence times vary widely, e.g. contrast the 17 days for Loch Insh, a shallow kettle hole, with the 6.9 years for Loch Morar (Smith and Lyle, 1994). It is defined as the ratio of the lake volume, V (capacity), and the water discharge, Q (the latter is often expressed as the mean annual inflow, in which case T is the *theoretical* residence time).

In situations where the mean annual inflow to a lake is unknown, Q may be estimated using a water budget relationship:

$$E = P + I + U - R +/- S$$

Where: E = evapotranspiration
P = total precipitation
I = surface inflow
R = surface runoff
S = change in storage (both surface and sub-surface)

If surface inflow, underground outflow and storage changes are assumed to be negligible, thus:

$$R = P - E = Q$$

Thus Q may be estimated numerically from data readily obtainable from climatological maps. Lake volume, V, is often not known since, in many cases, bathymetric maps (and therefore hypsographic curves) are not available. In this event, to estimate residence time, it is necessary to predict lake volume. Håkanson (1997), following the rationale for a new approach to defining lake water retention rate (see Fig. 2.38 of Håkanson and Peters, 1995), has suggested the following predictive relationship between V (km^3) and variables that can be readily determined from topographic maps:

$$\log(1000*V) = 0.134 + 1.224*\log(A) + 0.332*\log(RDA)$$

where: A = lake area (km^2)
RDA = dh / ($\sqrt{ADA}$)

and: dh = altitudinal range of catchment area (m)
ADA = drainage area (km^2)

The above relationship would, however, require verification and validation within the context of UK standing waters. An early example of the development of predictive limnology was the work of Gorham (1958) who used the Murray and Pullar (1910) bathymetric data from a total survey of 562 Scottish lochs. Gorham (1958) examined the following inter-relationships between drainage area, lake surface area, length, mean breadth, mean depth and maximum depth for 262 rock basins and 137 basins lying in or dammed by glacial drift:

- Length and mean breadth
- Drainage area and lake area
- Mean depth and lake area
- Maximum depth and mean depth
- Replacement time (i.e. residence time) and lake area

For example, a good relationship ($r = 0.68$) was derived between mean depth and lake area for rock basin lakes but for drift basins the regression line was insignificant ($r = 0.24$). Outwith Scotland, it is suggested that collation and simple regression analysis of the available data should be undertaken so that predictive equations such as that for lake volume above (Håkanson, 1997) might be determined.

It should also be pointed out that whether or not a lake stratifies in the summer months will have a significant impact on residence time, since hypolimnetic waters will be essentially stagnant during such conditions whereas the waters of the epilimnion will be subject to exchange (see Fig. 2.38 of Håkanson and Peters, 1995). Allott (1990) undertook a simple ordination of 35 British and Irish lakes, plotting maximum depth (x) against length (y). He thereby discriminated stratifying from non-stratifying lakes, an approach that could well merit further consideration with respect to residence time calculation. A similar consideration arises in relation to lake plan-form: isolated embayments within some lakes may have locally much longer residence times than would be expected for the lake as a whole.

Connection to groundwaters

The degree of connectivity between lake and groundwaters is most strongly influenced by the permeability of the solid and/or drift geology in which the lake basin has developed, and to a lesser degree by basin form. An important characteristic is the ratio of groundwater inflow or outflow to total inflow or outflow, on the basis of which lakes can be divided into two groups; those that are groundwater dominated and those that are surface water dominated. Groundwater-lake relationships may be explored by direct measurements of the seepage flux through the bottom sediments, by tracer experiments, through study of the water balance (see above) or by using Darcy's Law. In general, the permeability characteristics of the soils surrounding a lake are much more important in determining the degree of hydraulic connection between lake and groundwater than are the thickness, permeability and distribution of sediment within the lake. Vanek (1985) has presented vertical section models to show the seepage pattern at the margin of a lake and it is suggested that this approach merits further investigation in the context of this hydromorphological quality element. As for residence time, connection to groundwaters is relevant to water chemistry and hence to ecology. It should be noted that groundwater connections in the UK are not restricted to lake margins, as evidenced e.g. by open-water patches amongst an otherwise frozen loch surface, thought to be a result of groundwater up-welling (Goody, *pers. comm.*).

Morphological conditions

Lake depth variation

Lake depth variation is an important control of habitat availability, e.g. in relation to the availability of light. In order to determine lake depth variation, information on the basin form must be known. Whist parameters such as mean depth and maximum depth might be predicted as described above, lake depth variation requires bathymetric data. Methods such as those due to Håkanson (1981) provide mechanisms for broadly predicting basin form for unsurveyed lakes using data readily available from maps.

Quantity and structure of the substrate

This quality element is also important as an aspect of habitat: the composition (e.g. particle size distribution, organic content) of the lake bed will act as a control on the aquatic communities found. It is a function of lake sedimentation rate, being controlled both by allochthonous (i.e. catchment derived) and autochthonous (i.e. within-lake derived) sediment supplies (Håkanson and Peters, 1995). Re-suspension is considered to be a function of lake size and form. Chapter 7 of Håkanson and Peters (1995) provides a basis for the modelling of quantity and structure of the substrate.

Structure and condition of the shore zone

Shoreline habitat measurement is important for identifying possible causes of ecological impact because many lakes are impacted by development on or near to the shore zone: immediate proximity provides no opportunity for attenuation of impacts. Shorezone development through pressures such as housing or industry can have a disproportionate impact on nutrient loadings compared to more distant parts of the catchment.

Measurement of parameter values

Ecologically relevant parameters can only realistically be used as the basis of regulation if their measurement already takes place, if they can be readily measured (without undue problems e.g. of cost), or if they can be estimated in an acceptably reliable manner. The preceding section has addressed each of the hydromorphological quality elements for lakes, indicated how data can be obtained or estimated as required. From this, one parameter stands out as being much more commonly monitored than any of the others, and of substantial relevance, namely water level.

Water level can be related to flow for an unimpounded lake by means of a rating equation, which could be built up over time by the repeated gauging of inflow streams and rivers and the relation of these measurements (after adjustment for ungauged areas) to lake level. The effects of winds, seiches (long-period waves) and hysteresis on water levels would also need to be accounted for. Some attempt could therefore be made to use level as a surrogate for lake inflow, but reliable output would not be possible without the use of considerable monitoring and modelling resources.

Residence time appears to be of fundamental importance to the ecology of lakes, but is demanding in terms of calculation and cannot be measured directly. However, the available methods of estimation could be used to generate one-off residence time values for individual lakes (indeed some tabulations have been published, e.g. Bragg *et al*. – SNIFFER WFD06, 2003) which could be used in conjunction with other characteristics based on level data.

Water level characteristics, expressing the temporal variability of water levels for any given lake, may be regarded as useful in identifying the values of parameters of ecological value. This will be explored in the following section.

6. GAPS ANALYSIS

6.1 Rivers

Implementation of the Water Framework Directive will require assessment of whether water bodies in the UK meet environmental standards that indicate good ecological status. The assessment will need to be made of thousands of water bodies within a short space of time on a limited budget, many of which will be in a semi-natural state without significant abstractions or impoundments. The level of assessment is best suited to a strategic planning/scoping level approach that is simple and quick to apply without the need for detailed site visits. A separate and more detailed method would be needed to assess impacts of specific abstractions or impoundments on particular water bodies and to determine licence conditions.

Four broad types of environmental flow methods are used around the world (Acreman and King, 2003; Acreman and Dunbar, 2004):

1. Look-up tables – e.g. the table of allowable takes used within the RAM framework
2. Desk-top methods – e.g. the LIFE method, IHA/RVA method and South African desk top method that require analysis of flow and biological data
3. Functional assessment – e.g. the Building Block Methodology and the Holistic Approach that use expert panels and analysis of a wide range of hydrological, hydraulic and biological data
4. Habitat modelling – e.g. PHABSIM and its derivatives that use detailed site survey data and hydraulic models

Both the Functional Assessment methods and the Habitat Modelling methods can be discounted as they require considerable detailed data collection at each site.

The IHA/RVA method has many attractions in that it considers a wide range of indices of the flow regime. It has two drawbacks (1) neither the indices nor the bounds on the indices have been verified ecologically (2) the method is not easy to implement directly to regulate abstractions; it is more focused on determining environmental flow releases from reservoirs. Issue (1) cannot be addressed within the scope of this project. Issue (2) could be addressed by developing a typology based on the flow indices, then selecting a reference catchment from each type. For each catchment, possible abstraction profiles could be assessed using standard flow times series. Allowable abstraction profiles would be those for which the IHAs remain within acceptable limits. However, given that most abstractions have limited impact on high flows, the many high flow indices may be redundant.

The South African Desk-top method is also attractive, but the UK does not have a dataset of studies where flow thresholds have been determined by detailed hydro-ecological studies. Some 80 PHABSIM studies have been undertaken in the UK, but the outputs from PHABSIM are smooth habitat v. discharge curves that do not define thresholds and so are used in scenario-based decision making that includes local negotiation and takes many additional factors into account. The only national dataset which is comparable is the set of environmental weightings defined for each CAMS assessment point. These could be used to test typologies and/or related to hydrological indices. These weightings do of course indicate sensitivity to abstraction and not standards (threshold of flow).

Perhaps the most useful data available are macro-invertebrate samples from which LIFE scores can be calculated. Research so far has identified broad relationships between the flow regime and LIFE scores (with steepness of slope relating to sensitivity to abstraction). They have, however, not defined thresholds that could be used as standards.

If UK datasets can at best define sensitivity to abstraction, then a further look-up table is required to define allowable changes to the flow regime for any given sensitivity, as presented in the RAM framework. Such a table could be developed to allow for different flow requirements of the river ecosystem at different times of year.

6.2 Lakes

The most fundamentally relevant gaps that arise in the preceding lakes sections are those that exist between the aspiration to have ecologically relevant regulatory standards for standing waters, which are scientifically well-founded and can be implemented in a rigorous, systematic and defensible way, and the means of delivering them. As a means of helping advance the development of regulatory standards for water resources, four main gaps have been identified which seem fundamental to the effective delivery of the WFD in the UK:

1. Water level data availability – it is clear that there is a paucity of lake water level data on which to characterise patterns of natural water level regimes and elucidate the linkages between water levels and ecology. Modern level-logging systems provide robust and cost-effective methods of gathering such data and, given the needs of reference condition description and for the protection of (relatively rare) natural lake systems, the case for a substantial expansion of lake monitoring activities seems increasingly persuasive.
2. Modelling – several aspects of lake-related modelling need further development. Given the general lack of lake water level data and the relatively coarse temporal resolution of those records that do exist, modelling the hydrological response of lakes based on inflows (e.g. using Low Flows 2000) would allow primary parameters such as water level to be obtained and would also permit derivation of secondary parameters such as lake residence time, which can be inclusive of issues such as seasonal stratification and seasonal differences in the connectivity of lakes to groundwater systems. Valuable progress could be made if systems for dependably modelling the attenuation of inflows through lakes could be developed and made readily accessible. Critically, improved modelling would allow such predictions to be given with known confidence intervals, allowing regulatory objectives to be defined in an appropriate context.
3. Bathymetry – there is a large body of work which demonstrates the importance of lake morphometry to ecological processes. However, with the exceptions of surveys for Scotland, the Lake District and Northern Ireland, there are major deficiencies regarding basic morphometric data such as mean and maximum depth, from which form factors (hypsographic curve), volume and variables such as the dynamic ratio which provide insights into the likelihood of sediment re-suspension. As an illustration of how morphometric indices could be used in a regulatory context, Bachman *et al*. (2000) reported that a simple change in water level can considerably affect mean depth which, in turn, can shift the dynamic ratio across the critical value of 0.8, resulting in significant changes in sediment re-suspension and attendant impacts on the ecology. Some analysis of existing data within the GBLakes database has been commenced by the Environment Agency for England & Wales (G. Phillips, pers. comm.), but success thus far has been limited. A key aspect in terms of improving modelling is having better bathymetric data, and this will also be essential in terms of developing type-specific regulations.
4. Analysis of existing hydrological regime data – while deficiencies exist in the availability of lake level data, valuable progress could still be achieved meantime by collation and analysis of those valuable records which have been collected by environmental and conservation agencies and organisations, and by analysis of modelled inflows or outflows (e.g. obtained using Low Flows 2000 and such routing algorithms as may be available), to develop an improved understanding of the hydrological regime of natural systems across the full range of UK conditions. One opportunity that requires further

exploration is the potential to use daily water level observations from reservoirs covered by the Reservoirs Act 1975, often extending back for several decades.

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