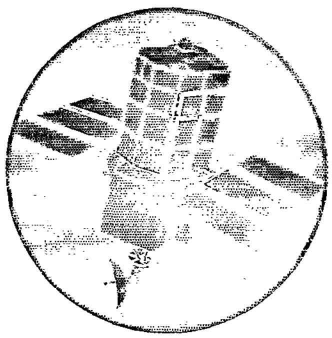
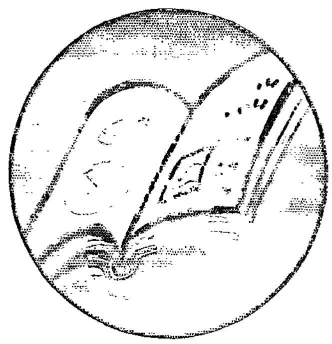
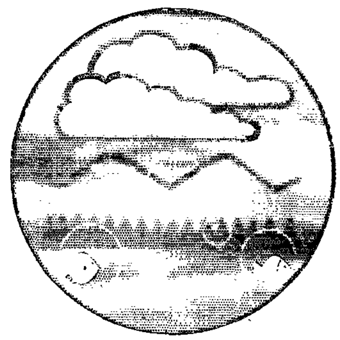
Overseas Approaches to Setting River Flow Objectives







Research and Development

Technical Report
W145

ENVIRONMENT AGENCY

Overseas Approaches to Setting River Flow Objectives

R&D Technical Report W145

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Research Contractor:

Institute of Hydrology

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Statement of use
This report details a study carried out by the Institute of Hydrology to review a wide range of methods, used to set benchmark flows for a purpose similar to that proposed for River Flow Objectives. Included are look-up approaches based on hydrological indices, hydrological simulation, biological data collection and analysis, discussion-based approaches and habitat simulation techniques. It has been compiled to assist the Agency in the development of their policy on River Flow Objectives

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EXECUTIVE SUMMARY

This study is a review of overseas approaches to setting River Flow Objectives. It has been compiled to enable the Environment Agency to learn from international operational experience in order to develop its policy on setting River Flow Objectives (RFOs), and ultimately, statutory Minimum Acceptable Flows (MAFs). Direct support has also been provided by the Institute of Hydrology, through part-funding from the Natural Environment Research Council.

A wide range of methods, used to set benchmark flows for a purpose similar to that proposed for River Flow Objectives, have been reviewed. These focus on managing river flow quantities as an environmental resource. The review follows Agency R&D Note 449 in categorising the methods into four levels: look up table, desktop analysis of historical data, collection and descriptive analysis of primary field data and flow-habitat-biological response simulation. There is a clear difference in the resources required to move from stage to stage. Drawing on documented experiences overseas, the potential advantages and disadvantages of River Flow Objectives have been briefly reviewed. Major issues are the processes used in their determination, resources required and their defensibility. Their role in moving towards sustainable development is highlighted. At the policy level, the characteristics that appear to relate to the success of such methods are also reviewed.

General findings

- Between countries, there is a wide difference in the application of these methods, and the terminology used. The term River Flow Objective is not used in other countries. The most common terms used abroad are 'minimum flow' (unspecific), 'environmental flow' and 'instream flow'.

- Of the countries reviewed, several have made considerable progress in the field of allocations of water to in-river functions, for environmental purposes. This issue is receiving a great deal of attention world-wide.

- No country has developed a definitive all-encompassing method. In some cases methods have been applied extensively. In others, methods have been proposed, but barely implemented.

Look-up techniques

World-wide, the most commonly applied methods are 'look up' techniques, based upon simple hydrological indices such as percentage of the natural mean flow or an exceedance percentile on a natural flow duration curve. This approach, also known as standard-setting, generally aims to determine some sort of minimum ecological discharge, sometimes with seasonal considerations, sometimes with other thresholds (desirable, optimum).

Such methods require considerable resources to set up initially; but once developed require a relatively low level of resources per site. These standards can play an important monitoring and strategic role and provide interim objectives, where further investigation is justified. Good examples of look-up techniques include the Tennant and Texas methods, and the Basque method.

Some of the standard setting methods reviewed would be applicable to England and Wales, although specific values for criteria would still need to be determined. This task should not be underestimated. Internationally, there has been over-expectation as to the transferability of the values of the indices between countries. Further debate will be required on the precise role of such indices. For example reconciling a look-up index with the concept that RFOs should relate to specific management objectives; furthermore, justification of an individual value is not generally possible under close scrutiny.

Discussion-based approaches and hydrological analysis

This review has highlighted the increasing use of methods where determinations of flow objectives are made using structured consideration of expert opinion in a highly structured fashion. It is believed that these methods offer significantly more than existing ad-hoc procedures that may have been used in the UK. The methods are able to consider broad ecological functioning, plus species requirements at an intermediate level of detail. They may include elements such as hydraulic modelling, but the key assessment is undertaken in a structured manner at an expert panel workshop. This would be of particular use for setting more specific interim flow objectives, especially in the absence of clear species-related management targets, and ensuring effective targeting of further study. Case studies provide a good example for the integration of flow requirements into catchment management planning. Within the context of the Environment Agency in England and Wales, these methods are of considerable interest.

In the context of setting River Flow Objectives, there is potential to learn from overseas experience in the use of hydrological time series analysis techniques. Key ecologically-relevant hydrological indices derived from comparison between historical, naturalised and other alternative time series are of considerable interest in their ease of use, generality and monitoring capability. Although it could be some time before there is clear operational evidence or justification for the use of these methods, they are thought to have some potential.

Biological response modelling

World-wide, the most consistently applied detailed methodology is the Instream Flow Incremental Methodology (IFIM), and variations. This type of approach is considered to be the most resource-intensive and defensible. Some countries have incorporated elements of the holistic approaches into their IFIM-equivalent framework, another common approach is to incorporate multivariate classification: of river sector types and their biotic communities.

The Agency is already using the PHABSIM (physical habitat simulation) method, which is still state-of-the-art internationally, and one element of the broader IFIM framework. There is currently considerable active research into the broadening of the techniques encompassed by IFIM in its entirety, many of which would be relevant to England and Wales. Of the more detailed approaches to setting flow objectives, there are few requirements that cannot be accommodated within a flexible IFIM-like framework.

Further findings

It is recommended that the various overseas approaches relating to expert panel-type approaches, and hydrological time series analysis be investigated in Phase II of this study. Some countries have already prepared publicly available frameworks, containing cross-functional guidelines for how to go about determining environmental river flow requirements. A document of this sort should be considered by the Agency for England and Wales.

It is recommended that the Agency discuss and clarify at what level or levels RFOs are to be used. For a major nationwide implementation of river flow objectives, consistent 'look-up' methods will be required. These methods should have ecological and seasonal relevance. For subsequent stages, or if river flow objectives are to be applied more selectively, a subset of river sectors will require further studies, of hydrology, ecology and geomorphology at an intermediate level of detail. Finally for the most important and contentious areas, detailed biological response simulation will also be required.

A reference list relating to overseas approaches is included.

KEY WORDS

River Flow Objectives,
benchmark flows,
hydrological indices,
hydrological simulation
biological data analysis,
habitat simulation,
water resources,
instream flows,
environmental flows.

1. INTRODUCTION

This report is a review of overseas approaches to setting River Flow Objectives. It has been compiled to enable the Environment Agency to learn from international operational experience in developing its policy on setting River Flow Objectives (RFOs), and ultimately, statutory Minimum Acceptable Flows (MAFs). Direct support has also been provided by the Institute of Hydrology, through part-funding from the Natural Environment Research Council. In this report, Section 2 outlines some background to the concepts, Section 3 details approaches used in different countries, Section 4 provides a comparative review of the most interesting methods, while Sections 5 and 6 detail conclusions and recommendations.

Many rivers in England and Wales are subject to significant regulation from human activities. These activities may include surface and groundwater abstraction (and return) for public, industrial and agricultural supply, impoundment for supply, hydro-power and compensation, and use of watercourses and resources for navigation. Kitson (1984) has reviewed hydrological aspects of river regulation. However, it is notable that even at that time, environmental issues, and their management through flow objectives received little attention from many hydrologists.

The Environment Agency has developed the concept of a River Flow Objective as a management tool for regulated rivers against the background of their legal responsibilities, and their ability to set statutory MAFs under Section 21 of the Water Resources Act 1991 (Evans, 1996).

In this document, a wide range of methods that have been used to set River Flow Objectives (or related tasks such as determination of instream flow needs or environmental flows) overseas, has been reviewed. These focus on the ecological requirements of rivers, and range from more traditional to state of the art. Included are simple hydrological indices (termed 'look-up' or 'standard setting' approaches), hydrological simulation, consensus and discussion-based approaches, historical data analysis and biological response (commonly 'habitat') simulation techniques. Between countries, there is a wide difference in the application of these methods. There are also considerable differences in the legal and institutional arrangements surrounding them.

In addition to protection of the ecology of a river, there may be a need to recommend flows to protect the rights of other abstractors, navigation, recreation, prevent saline intrusion, dilute effluent, prevent algal blooms, protect cultural features / visual amenity, and maintain channel diversity and flood carrying capacity. Clearly an 'instream flow' can potentially serve more than one function in the above list simultaneously. Methods for determining these criteria have been touched in less detail in this review. Methods for water quality modelling in setting flows for dilution are already relatively advanced.

It should be noted that few, if any of the techniques aim to provide the complete solution, and there is no reason why a range of approaches should not be appropriate. Furthermore, given the wide variety of river types and sizes in existence: including from baseflow to flashy and perennial to seasonal, and the ranges of perceived environmental importance and severity of different resource developments, it is unlikely that one method could be appropriate in all cases.

2. TERMINOLOGY AND SCOPE.

2.1 What is a River Flow Objective?

Petts *et al.* (1996), in a research commission from the NRA / Environment Agency (R&D Note 449), have proposed a system of River Flow Objectives. This is based upon the idea that:

'To achieve a balanced allocation of water, giving due regard to the interests of water abstraction, water quality, navigation, recreation, fisheries and conservation (both in-river and riparian needs), requires the objective setting of flow targets and their consistent application'.

The draft Environment Agency Water Resources Strategy (1996) has stated that in meeting its obligations the Agency will propose setting statutory minimum acceptable river flows where necessary.

'This Report [R&D 449] advocates that River Flow Objectives should be developed to guide decisions on abstraction licensing and / or flow augmentation which may properly be considered within Catchment Management Plans'

'These targets would clarify the Agency's permissive powers, given under Section 21 of the Water Resources Act 1991 to use Minimum Acceptable Flows as tools in water resource planning. Such objectives are closely linked to the abstraction licensing process, *and should be closely linked with specific management objectives.'*

Pre-empting this, Gustard *et al.* 1987 stated (when specifically considering compensation flow) in their conclusions "It is not possible or desirable to propose national standards for setting compensation flow. The requirements of the river below the dam will always be site specific and hence the compensation flow should vary from one site to another"

R&D 449 recommends that the RFO define a *flow regime*, using not only the magnitude of flows, but also information on desired timing, duration and frequency. An Ecologically Acceptable Flow Regime (EAFR) concept has been developed for baseflow-dominated rivers, specifying seasonally variable flows to meet ecological targets, including a minimum flow to sustain biota during extreme drought, seasonally desirable flows, and high flows to maintain physical habitat diversity.

At the heart of the RFO concept is a move away from the view that it is possible to determine a single year-round minimum flow to protect an ecosystem. Furthermore, the concept that too much water during natural low flow periods can lead to undesirable changes in an ecosystem has been extensively examined in countries with seasonal dryland rivers (such as Australia), but is also relevant in the UK (Everard, 1996).

R&D 449 recommends a pilot implementation programme, with a five year initial period where RFOs are applied to trial catchments with flow-related problems, or catchments where problems are expected to arise in the near future.

Finally, it should be noted that there is still not an equivocal definition of a River Flow Objective, as highlighted by these alternative definitions:

1. (Environment Agency Corporate Strategy) 'The flows which need to be protected to ensure the river can support the abstraction requirements placed upon it without compromising important ecosystems'.

2. (Petts *et al.* 1996) 'The flows which are needed to sustain the desired ecosystem, to meet abstraction requirements, and to support important in-river uses'.

2.2 Context: A multi-scale approach to setting River Flow Objectives

It is clear that the level of detail required will be case dependent. Each of the methods reviewed here will have a range of levels of detail at which it may be usefully used.

From this review, it is clear that many countries operate a two-tier system of a basin-wide and scoping method for 'level one' studies, and a more rigorous, defensible and detailed method for 'level two' studies. In addition, level two studies move away from 'standard setting' (i.e. a single minimum flow) and towards an incremental approach (i.e. quantification of varying instream requirements), enabling various management options to be assessed.

Petts *et al.* (1996) expand this to four approaches:

1. Look up table (hydrological indices);
2. Desktop analysis of historical data;
3. Collection of primary field data supported by descriptive analysis; and
4. Detailed flow-habitat-biological response simulation.

In this report, we have followed this terminology, although it should be noted that in such a framework, there will always be links between stages. The most notable link is integrated regional analysis of data collated as part of stages 2-4 in order to refine stage 1 procedures.

In considering the process of determining one or more River Flow Objectives, it is further important to outline the various stages that would be involved:

- Outlining of objectives;
- Data collection method;
- Modelling and analysis process, and the use of this information to set an objective or objectives in a rational manner;
- Use of tools in an active manner (e.g. reservoir releases); and
- Follow-up monitoring of success and revision of goals.

2.3 Advantages and disadvantages of River Flow Objectives.

Advantages

Undoubtedly there has been a paradigm shift over the last 50 years in people's attitudes to water in the environment. For example in 1972, Law stated: (considering minimum residual flows close to tidal limits) 'The residual flow (*at the estuary*) should be zero ... unless there are reasoned arguments to the contrary' and 'water should only be left to pass to estuaries to assist the runs of sea trout and salmon when i) they are known to be approaching or waiting in the estuary and ii) natural spates are absent and fish kills may result from high temperatures in holding pools'.

Now in the 1990s, internationally, there is a genuine belief that the environment is a legitimate user of water. The United States has been in the forefront of developing ideas of instream and out of stream uses for water, and recognition of the rights of instream uses. Some countries have gone further, for example Australia: 'water belongs to the environment', although this is certainly disputed in the UK (Water Services Association, quoted in Petts *et al.* (1996)).

In this context, given historical management practices and resource exploitation and the commitment of the UK Government to Sustainable Development (e.g. specifically within Environment Act 1995 described by Gallagher, 1996), the development and implementation of River Flow Objectives would be an important management and monitoring tool. The House of Lords committee on Sustainable Development (Report, 1995) has recognised the importance of targets as a first step towards sustainable development. A further driving force will likely be the proposed EC Framework Directive on Water Policy (European Commission, 1996), which states that the Directive has three overall environmental objectives, which should be achieved by 2010:

- To achieve good surface water status in all surface waters;
- To achieve good groundwater status in all groundwaters; and
- To comply with all standards and objectives relating to areas requiring special protection, including waters for the abstraction of drinking water.

It is suggested that this could imply at least two ecological roles for River Flow Objectives. Firstly to assist in river management aimed at the fulfilment of the objective of good surface and ground water status (the importance of interim targets is implied), and secondly to assist in the management of rivers requiring special protection.

An analogy can also be drawn with (chemical) Water Quality Objectives (see NRA, 1991). Even a brief comparison would suggest that national implementation will involve considerable effort. The following quotation (Everard, 1994) in the context of WQOs, is equally applicable to River Flow Objectives.

'As a preliminary step on this journey [to sustainability], integration of economy and ecology through quality objectives provides a framework for negotiating upon an acceptable compromise between needs which have historically been viewed as conflicting'.

Furthermore, Petts *et al.* (1996) argue that when implemented at the statutory level, Minimum Acceptable Flows can be one of the most powerful ways to put instream water uses on a par with other statutory instruments, e.g. such as the development planning process.

Disadvantages

Despite the fact that rivers are complex changing hydrological and ecological ecosystems, River Flow Objectives will necessarily need to be made simple in order for them to be implemented. Unfortunately, the simplest objective is a single 'minimum flow'. Seasonal criteria and position within catchment must be included and natural hydrological variation must be considered. Furthermore there is a danger, if a minimum flow is defined, for it to become the goal.

Secondly one must recognise that for the foreseeable future, our knowledge of the environmental requirements of rivers will remain incomplete. In this case, there will always be a danger that the objective will be set too low, resulting in damage to a river, or too high, resulting in potential waste of resources, or exploitation of other more sensitive water resources.

2.4 Institutional perspectives.

It is important to view the findings of this study in the light of the legislative history under which the methods have developed and are operating. Not many countries have specific operational / legal frameworks for this type of assessment and planning. Even in the United States where assessments of this type have been undertaken for many years, there may be considerable disagreement even over the definition of terms such as 'protection' and 'minimum'. An example where there is a standard in law is France, where the Minimum Residual Flow must be at least 10% of the mean flow for new developments. More commonly, the environmental protection of instream flow is enshrined less specifically. For example in Austria, developments must not disturb ecological integrity 'significantly', while in New Zealand, the Resource Management Act prescribes that rivers are protected from adverse effects and their life-supporting capacity sustained or safeguarded.

In England and Wales, the 1963 Water Resources Act placed a duty to 'secure the proper use of water resources' on the appropriate authority (Owen 1991). Further duties have been prescribed by subsequent legislation, the Water Act 1973, the Wildlife and Countryside Act, 1981, the Water Resources Act 1991 and the Environment Act 1995. There have been further changes arising from European legislation, for example relating to the Habitats Directive, and undoubtedly will be others (e.g. EC Framework Directive on Water Policy) in the future.

Petts *et al.* (1996) reviewed the legislative history of the statutory Minimum Acceptable Flow in the UK, and highlighted where non-statutory flow objectives have been used.

3. THE METHODS

This section reviews and describes the approaches in use (and in some cases proposed) in different countries. The study consisted of an extensive literature review and personal communication with the people listed in the acknowledgements above. For some countries it was unfortunately not possible to make a personal contact, notably Japan.

Note: Many methods mentioned in the literature were developed on a state-by-state basis in the US in the 1970s. Since then there has been considerable rationalisation; if the methods have been superseded, they have been listed in Appendix A.

3.1 Australia

Background context

In Australia there is an extensive research programme to develop methods to determine 'Environmental Flows'. There are several nationally-managed projects aimed at method development, plus individual state programmes to establish environmental water requirements for particular rivers (Cullen *et al.* 1996). Two examples are given on the following pages. There are also close links with the National River Health Programme, a broad standardised biomonitoring method. State studies at the river basin level generally adopt the holistic approach (see below), aiming to consider the water requirements of the river and riparian areas.

The paper by Karim *et al.* (1995) reviews the problems faced in Australia, including:

- naturally seasonal rivers;
- high rainfall and runoff variability;
- lack of data (hydrological and ecological); and
- a requirement to act rapidly (and with precaution) to prevent further degradation.

Holistic approach (including expert panel methods)

This approach, described for Australian rivers, was developed in close association with the Building Block Method in South Africa. Several other countries (e.g. Austria, Spain, Switzerland) aim to combine IFIM with holistic elements.

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.

Results from a study will include interim flow recommendations and a programme of key monitoring and further study capable of clarifying outstanding issues, this could include further consideration of key habitat requirements.

Despite being developed specifically for Australian conditions, it is felt that many elements of the holistic method could be usefully applied to situations in England and Wales. Of particular relevance is the consideration of the whole river ecosystem, and the ability to act reasonably quickly to provide interim recommendations. The process then continues with recommendations on key monitoring, and further study, which may well include IFIM type analysis for key target species. We recommend that these approaches are investigated in more detail.

Generally the holistic approach described above 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.

Two examples of application of expert panel approaches are briefly described on the following pages.

Wetted Perimeter

Retention of wetted perimeter is often suggested as an expedient method for defining environmental flows. The logic is that as 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 'inflection point' 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.

IFIM / PHABSIM

Where deemed appropriate, IFIM has been applied in Australia (e.g. Gippel and Stewardson 1995). In one particular study (Pusey and Arthington, 1991) the authors 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.

Case study of the expert panel approach applied to headwaters of the Murray Darling

Swales and Harris (1995) describe the Expert Panel Method, and its application to flow requirements below headwater storage reservoirs on the upper stretches of the highly regulated Murray Darling Basin. Releases were made from reservoir storage, and an interdisciplinary panel viewed them and asked to make assessment of the appropriateness of the flow. There were two separate panels of three and deliberations were made within the panel. On the Murray Darling Basin, the current regime was the reverse of the natural, i.e. storage for irrigation led to low flows in winter and high flow releases in summer. Swales suggested undertaking a comparison between this method and physical habitat analysis.

Case study of the holistic approach, incorporating an expert panel, applied to the Barwon-Darling River (Thoms *et al.* 1996)

An expert panel / holistic study was undertaken by the New South Wales Department of Land and Water Conservation. The panel considered a series of sectors highly influenced by water abstraction for irrigation, although direct impoundment influences were low.

The following key stages were undertaken:

- Initial briefing for panel members, attended by range of agency staff, overview from a senior agency staff member, scoping of data requirements, criteria, sectors and sites;
- Field inspections and report of initial findings;
- Public meetings with key stakeholders in catchment;
- Interim workshop;
- Panel report, circulated widely; and
- Final workshop for panel and merit group (stakeholders).

Five major ecosystem components were identified: fish, trees, macrophytes, invertebrates geomorphology. Three fundamental habitat elements were considered, flow regime (longer-term hydrology), hydrograph (shorter-term hydrology), physical structure of the river.

Table 3.1. Examples of factors considered in holistic / expert panel 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		- Snags and tree roots, organic debris aquatic macrophytes, rock outcrops
Seasonality	Freshets	
Sequences of years		- Depths (stage for 80, 50, 25 and 10 percentile flow) at representative cross sections

Extensive use was made of cross-tabulated matrices, indexed in three different ways, the fundamental elements, the categories within elements, and the ecosystem components.

Table 3.2. 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

3.2 Austria

Background and context

In Austria, this field is governed by considerable legislation, starting with the Austrian Water Act, enacted in the mid-1980s. This has been added to by updates to the Water Act in 1985 and 1990 and the Austrian Environmental Impact Assessment Act (1993). The State of Austria has the responsibility for:

- protection of the **ecological integrity** of rivers;
- protection of groundwater;
- flood protection;
- technical maintenance (i.e. hydrometric stations etc.); and
- provision of recreation opportunities.

The use of water can be negotiated only if planned facilities do not disturb ecological integrity 'significantly'. All new projects must be built and maintained according to the state-of-the-art technology, and an ecologically acceptable minimum flow must be set at every abstraction area.

Official standards have been defined for ecological integrity. Specifically, "The maintenance of all internal and external processes and attributes interacting with their environment, in such a way that the biotic community corresponds to the natural state of the relevant aquatic habitat, and where the community is preserved by regulation, resilience and resistance to environmental stress".

Method

In Austria, standard procedures have been proposed: an 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).

- As necessary, assessment topics are defined :
- surface and groundwater hydrology;
- habitat structure;
- river continuum;
- physio-chemical parameters;
- riparian area; and
- flora and fauna.

Initially, factors are evaluated independently, either by using compliance values or an incremental system, and then combined for a complete assessment. The assessment of ecological integrity is maintained using a 7 point scale, from undisturbed to completely disrupted in comparison with the natural (reference) state.

The definition of the reference situation can be provided by assessing the ecological integrity of the river compared with the natural state of the river in question. This approach becomes increasingly difficult, since completely natural sites are rare.

Evaluations of fish and benthic fauna are undertaken qualitatively according to:

species inventory;
dominance structure;
abundance;
population structure (fish);
migration (fish); and
functional feeding yields (macroinvertebrates);
longitudinal distribution.

In addition, a quantitative fish habitat modelling approach is being developed. This is based on multivariate habitat preference functions, and research is currently incorporating the effects of flow changes, both in terms of direct habitat and longer-term effects (for example sediment dynamics, channel change).

3.3 Canada

Background and context

In Canada individual provinces undertake studies of Instream Flow Needs, under the auspices of the Fisheries Act (Canada). As with many other countries, the Act only makes general prescriptions, and it rests with the Fish and Wildlife Divisions of each province to determine methods. Many states operate a level 1 / 2 approach (see Section 2.2).

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 micro-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 (when a rapid decision is required or the value of the fishery is not great) (Locke, *pers. comm.*). 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 provincial government has funded the studies, however unlike the United Kingdom, the major water users in the state are all linked closely with the government. The University of Alberta has been active in developing two-dimensional hydraulic approaches for physical habitat modelling.

The standard PHABSIM procedures (analogous to Elliott *et al.* 1996) are used to generate physical habitat relationships with discharge for target species life stages. 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. A similar procedure is followed to define an 'average' flow, based on the 50% of optimum, or flow corresponding to 50% habitat exceedance percentile, and similarly for optimum conditions, using the starting figure of 20%. This procedure may be applied against the natural hydrograph in 'wet' 'natural' and 'dry' years.

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.

3.4 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.

3.5 Denmark

Advisory flow-based statistics were introduced into Danish legislation in the 1970's (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.

3.6 England, Wales and Scotland

Background and context

This has been reviewed in Section Two above. This section is intended to overview the methods used in England and Wales, concentrating on adoption of overseas methods. A small amount of information on Scotland is also reviewed.

Compared to other countries, England and Wales have a history of catchment-based management, relatively dense biological and hydrometric data collection, and a mature water licensing system. In some lowland areas, the Agency considers that water resources are fully utilised. Acreman and Adams (eds.) (1997) review issues relating to groundwater-dominated rivers, and Petts (1989) reviews issues relating to impoundment. Armitage *et al.* (1997) review the situation relating to collection of biological data.

Petts *et al.* (1996) describe the historical situation in England and Wales pertaining to the 'minimum acceptable flow'. Sheail in Gustard *et al.* (1987) reviewed this topic in relation to compensation flows. This highlighted the wide variation of compensation flow awards, and that they were based on 'local precedents, rules of thumb, and bargains struck by interested parties'.

Since 1989, physical habitat simulation has been developed for use in the setting of Ecologically Acceptable Flows in England and Wales. This is the most well-documented technique, other detailed site-specific investigations have been carried out relating to impacts on fisheries, for example Lawson *et al.* (1991) documented investigations for environmental management of the Roadford Reservoir Scheme. Identification of existing problem rivers initially centred around the ALF (Alleviation of Low Flows) review undertaken by the newly-formed NRA around 1990. Subsequently, the NRA developed standard procedures for assessing the severity of particular low flow problems. The issue of impacts of water abstractions continues to receive attention, and there is now the opportunity through the concept of River Flow Objectives, to review river water requirements at a more strategic level. The River Babingley technique (see below) has been suggested as a relatively high resource framework for application of the RFO concept to permeable catchments. This is described separately below. Compared to other countries reviewed here (Australia, Austria, Canada, New Zealand, USA), national standard guidance on application of techniques has otherwise been lacking.

In Scotland, SEPA only has limited powers in controlling abstractions from surface and groundwaters (SEPA, 1997). SEPA is seeking to extend its powers in this area, and currently relies upon acting through persuasion and advice, except where a spray irrigation control order has been granted. 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.

Other techniques of potential future use are reviewed briefly below.

Various methods for relating flows to environmental requirements during summer low flow periods at the catchment level have been proposed, these are outlined briefly in Table 3.1. Within the Environment Agency, annual low flow indices for ungauged sites are generated using the Micro LOW FLOWS software (Young *et al.* 1996). This implements methods developed at the Institute of Hydrology to link mean flow with rainfall / evaporation and catchment area, and Q95 as a percentage of mean flow with catchment geology. Gustard *et al.* (1987) recommend the Q_{95} discharge as a minimum where more detailed studies are not justified.

Table 3.3. Catchment hydrology-based procedures for river (low) flow assessment

Name	Brief Description
Drake and Sherriff / Howard Humphreys & Partners	Catchment approach to establishing extractable volumes and minimum permissible flows, Environmentally Prescribed Flow (EPF) calculated as a proportion of MAM7, using six weighted categories.
Scott Wilson Kirkpatrick (SWK)	Scoring method for assessment of low flow conditions as above. Preliminary screening and full assessment Hydrological, ecological, landscape / amenity and public perception indices Uses historical data. Hydrological index relates to groundwater abstraction / recharge, surface water abstraction / Q95 and residual seasonal flow to minimum ecologically acceptable flow (MEAF) which may be seasonal Ecological index relates to ASPT (average score per taxon for invertebrates) and expert assessments
Welsh Water Authority	Identifies need to set minimum environmental flow (MEF) below which abstraction should cease. Procedure based around not allowing abstraction that would reduce flows below Q95.

SWALP

The development of the Surface Water Abstraction Licensing Policy (SWALP) was initiated by the NRA, with Sir William Halcrow and Partners contracted to assist with the work (Barker, 1997). The Agency are currently considering its implementation.

The aims of SWALP are to provide a consistent framework for the determination of surface water abstraction licenses. It builds upon the work of Howard Humphreys and Partners (HH) in the mid-1980's. It uses a scoring index system to assess the *sensitivity* of the watercourse, considering physical, fisheries and ecological character. The method protects low flows by setting a hands off flow (HoF), the procedure is not specified, but for the H-H method this was indexed to the Dry Weather Flow or Q95. Above the hands off flow, flow thresholds are set, tranches of water can be allocated for abstraction from the intervals between thresholds, following the concept of 'river flow banding' (Kitson, 1984). The size of the tranches is determined by the sensitivity index. In this way, it is hoped that critical flow variability is maintained. Flow requirements for downstream abstractions, water quality, navigation may be added.

Although the short description available does not make reference to Agency R&D Note 449, hands off flows and River Flow Objectives are closely linked. Clearly this procedure is a positive step in moving towards consistent evaluation of abstraction licenses on a day to day basis, and attempting to take into account biotic and physical sensitivity. It has not been possible to evaluate here the procedure for determining the sensitivity of the watercourse, and the values for the intervals. There may be potential to incorporate elements of the overseas procedures summarised here, in order to develop the framework for more detailed application of River Flow Objectives.

The River Babingley method

Petts *et al.* (1996) suggest the following steps in the preparation of an environmentally acceptable flow regime for a baseflow-dominated river in England or Wales:

1. Describe the river as a sequence of sectors

For each sector

2. Define ecological objectives and the flows / water level requirements to meet the ecological objectives
3. Define the water needs of in-river users
4. Quantify abstractions with reference to a secondary control point
5. Prescribe the RFO as a flow / water level regime
   specify any special requirements within a normal year
   describe contingency measures for exceptional circumstances
6. Define an implementation programme
7. Outline a programme of monitoring to ensure management objectives are met
8. Outline a programme for post-project appraisal to evaluate the success in achieving ecological objectives

For each catchment and each primary control point

9. Prescribe an RFO
10. Evaluate the benefits of promoting an RFO as a statutory MAF

The Babingley method has been developed for baseflow-dominated rivers, further research required for flashy catchments:

Quote: 'The determination of acceptable flow frequencies and durations to be attached to target flows remains a grey area. In the short term, it is recommended that the historic frequency and duration of the target flows based on naturalised data for low flows, and gauged records for high flows can be used.
However integrated analyses of existing hydrological and biological databases, no matter how incomplete would provide valuable information on the sensitivity of biota to hydrological variations to support decision-making. Ideally, long-term data on the response of biological populations to wet years, dry years and to sequences of wet and dry years, and to the timing of wet and dry periods within a year are required to provide the necessary information. Integrated biological and hydrological data collection within the NRA's routine programmes should be considered in order to provide this information in the future."

TEF: to sustain refuges
AEF: sustain habitat in at least one reach in each sector (under normal summer low flows)
DEF: sustain connectivity between usable habitat in all reaches
OEF: to maximise area of usable habitat
HMF: flushing sediment, % of CMF
CMF: maintain morphology / diversity

PHABSIM

The Physical Habitat Simulation system (PHABSIM) is a computer model which enables the assessment of impacts caused by changing flow regimes, on physical instream habitat for selected target species. It may also be used to assess impacts from changes in channel morphology, such as those arising from flood defence or habitat improvement schemes.

The PHABSIM method was developed in the United States and has been successfully applied in the United Kingdom for the past eight years. This section provides a review in the context of its use in England and Wales. In the USA, PHABSIM may be applied as part of the wider IFIM framework (see USA Section below).

As alterations in flow will change physical habitat in virtually any river, PHABSIM is a valuable tool in water resources investigations. However a study may also include models for water quality, water temperature or indeed any other model which simulates characteristic features which influence health of instream aquatic life, along with the analysis of historical hydrological and biological records, and ongoing biological survey and analysis.

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. Alternative habitat modelling approaches are available, for example oriented towards hydropower impact assessment or species with partially overlapping niches. Thus analysis of how physical habitat will vary on a spatial and temporal basis, can provide information to underpin future river management and water resources allocation.

The model is therefore 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 when physical habitat is limiting, populations will be commonly be limited.

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 everyday licensing use, 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 instead;
- 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 12 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 1980's, centred around 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.

Application of PHABSIM in England and Wales

The first UK use of PHABSIM involved studies at five sites on the rivers Blithe and Gwash, under a commission from the DoE (Bullock *et al.* 1991) by the Institute of Hydrology, Institute of Freshwater Ecology and Loughborough University. The study demonstrated the potential of PHABSIM as a practical tool for the generation of physical habitat vs discharge relationships for specific target species, notably salmonid and certain cyprinid fish, and particular invertebrates. Following this application, work has continued on its assessment and development for use in England and Wales. These studies include: the National Rivers Authority R&D project "Ecologically Acceptable Flows" a study examining the application of the towards the assessment of water resource issues, MAFF funded studies examining the application of the model to the assessment of river flood defence and habitat restoration/ improvement schemes, and the NERC science budget project "Faunal and floral response to reduced flows and habitat loss in rivers".

The first operation application of PHABSIM was carried out on two sites on the River Allen, Dorset, under a commission from the NRA (Johnson *et al.* 1993). The model has also been applied operationally to the Rivers Piddle, Vyrnwy, Cound Brook, several further studies are ongoing (Dunbar and Elliott, 1997). PHABSIM has also been applied to chalk streams in the Agency Anglian Region (Petts and Bickerton 1994, Petts *et al.* 1994), and was used as part of the evidence submitted by the Environment Agency to a public inquiry concerning a groundwater abstraction close to the River Kennet. It is also being used to evaluate impacts of hydropower operations on the River Tavy in South West England. To date the model has been applied to over 70 sites on 44 rivers in England, Wales, Scotland and Northern Ireland. A new Agency national R&D project aims to tackle key validation issues relating to site selection, hydraulic modelling, development and transfer of habitat suitability criteria, and linkage with longer-term population data.

Other techniques

This section outlines other approaches that have been used in England and Wales. These can be loosely grouped as follows:

1. Analysis of existing river / site biological data (including fishery catch data);
2. As above plus additional river /site data collected;
3. As above plus integration with data from other rivers (regional statistical models); and
4. Use of expert opinion.

Analysis of existing river and site biological data (including fishery catch data)

The Institute of Freshwater Ecology has undertaken two related studies, commissioned by the Agency, on 'Flow needs for fish', and 'Appraisal of the Use of Ecological Information in the Management of Low Flows in Rivers'. The former is focusing on flows required for fish migration and should enable flow objectives for fish movement to be quantified more accurately. The latter concentrates on developing a framework for incorporation of existing biological information, plus new more targeted data collection, in low flow management planning.

When looked at in detail, every river is different, yet there is clearly some room for standardisation of techniques of varying resource level, or at least guidance on which biological data analysis techniques are appropriate to achieve certain goals. Analysis of biological data, both historical and newly collected, already plays an important role within the Agency. Problems with this approach include ascribing cause of faunal changes to artificial flow influences with sufficient certainty, lack of or unsuitability of existing data, and the short time periods over which new data are collected.

There is considerable scope for the development of standard procedures for use of biological data in the setting of river flow objectives, and Armitage *et al.* (1997) suggest a move towards this. In the longer term, this could include development of techniques that integrate data at a regional level (see below).

A major element of the Roadford investigation (see below) involved an analysis of historical rod catch data. This was used to determine required flow levels in different river reaches for game fishing purposes.

Additional collection of river / site data

The biotopes approach (Padmore, 1997, outlined under South Africa below) and functional habitats (Harper, 1996) have all been suggested as being able to assist with the setting of River Flow Objectives. A potential approach would be to map biologically important functional habitats at a wide range of flows, and use this information to construct seasonal habitat discharge functions. However, this technique is still largely untested in the context of setting flow objectives.

In addition to analysis of historical data, detailed investigations of the flow regulation impacts of the Roadford Scheme (Lawson, 1991) centred around the following techniques:

- baseline fisheries and invertebrate surveys
- fish radio tracking (this has also been used to set flow objectives for fish movement on other rivers such as the Hampshire Avon)
- river corridor surveys
- ongoing post-scheme monitoring
- construction of a hydrological model

This investigation was a major new scheme, where the investigators concluded that routine monitoring data were not sufficient to make an assessment, but they were able to collect crucial further pre-scheme raw data. Although it was decided to set aside a portion of the reservoir storage for fisheries purposes, at the time of writing, it had not been decided how to allocate this water. Notable aspects of the assessment included varied flow level protection between the affected rivers, and a control system designed to protect small summer spates, of key importance for migration. In the future, there may be considerable potential to forge a greater link between hydrology and fisheries science in the process of developing fish-related river flow objectives.

Regional statistical analysis

Armitage *et al.* (1997) present a strong case for more active regional analysis of existing Agency-collected biological data, and the design of future sampling strategies so that data can best be utilised in the determination of biological community response to low flows. This is closely linked to the setting of threshold environmental flows (of greatest concern) but could also be extended to consider other targets such as desirable and optimum flow levels.

Analysis techniques such as RIVPACS (Wright *et al.* 1996) for invertebrates, and HABSCORE (Milner, 1985, 1991) for salmonid fish could be adapted for this purpose. Currently, RIVPACS is able to detect impacts arising from more severe droughts, but further development is required for it to achieve the same success in this area as it has in the analysis of chemical water quality. This could include incorporation of additional flow-related variables as outlined in Jones and Peters (1977), and incorporation of the significance of changes in abundance of key species, as well as their presence or absence.

Brown *et al.* (1991) used RIVPACS to define an ecologically acceptable flow regime for the River Darent. Invertebrate samples were taken at sites down the river. One site was identified with good ASPT (average score per taxon) and BMWP (biological monitoring working party) scores. The flow regime at this site was used to set the EAFR for the other sites, standardised by catchment area. Issues surrounding the sensitivity of RIVPACS indices to flow-induced stress as opposed to other forms of environmental stress were not examined in detail.

Jones and Peters (1977) undertook a desk investigation using routinely-collected flow and invertebrate data for 43 rivers. They characterised flow regime by five criteria (which have something in common with the more detailed criteria evaluated by Clausen (in press) and suggested by Richter (1996)):

- Average seasonal flow pattern: average timing of highest and lowest flows;
- Ratio of maximum to minimum flows for different seasons;
- Time by and quantity by which the mean daily flow is exceeded;
- Rate of change of flow with time; and
- Mean water velocity at the mean daily flow.

Some good relationships were obtained between these calculated variables and particular invertebrate communities. Recent unpublished work in Agency Anglian Region by Extence and Balbi, linking invertebrate community change to a moving average of the flow record, has re-iterated the potential use of this type of analysis. Given that twenty years have passed since the original Jones and Peters study, it would be highly beneficial to update and improve this work using more modern techniques and datasets.

Expert opinion

Historically, expert opinion has been a major factor used in determining environmental flow requirements. Existing Agency abstraction licensing procedures generally involve consultation with conservation staff in order to assess potential severity. It is not known what form these consultations take, or whether there are nationally-applied guidelines.

Some more detailed expert panel-type studies have also been undertaken by the Environment Agency, South West Region, relating flow to angling quality (e.g. Ibbotson 1996). Approaches such as stakeholder participation (e.g. Weston and Hodgson, 1991) are reviewed in the light of overseas experiences in Section 5 below.

3.7 France

Background and context

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 1/40 of the mean flow for existing schemes, and 1/10 of the mean for new and renewed schemes. More recently, the EVHA method (see below) has become the standard method (but not specifically prescribed in law) for re-licensing of impoundments and diversions.

EVHA

The EVHA (EValuation of HAbitat) method 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.

Differences between EHVA and PHABSIM include:

1. It functions entirely in metric units;

2. It uses a different method for calculating the substrate suitability index for a cell. The substrate for a cell is described by three numbers:

BIG: denoting the percentage coverage of the biggest substrate fraction
DOM1: cover of the dominant substrate
DOM2: cover of the sub-dominant category

Substrate suitability index is then calculated as:

$$0.2SI(BIG) + 0.4SI(DOM1) + 0.4SI(DOM2)$$

3. It uses a single hydraulic model and an alternative equation to describe channel hydraulics, the Limerinos equation. This was chosen as it was thought to more accurately represent the hydraulics of higher gradient streams.

$$S = V^2 / 33\ g\ R\ [\log(3.17R/D_{84}) - 0.314\log(R/Hm)]$$

S is the energy slope
V is average velocity
R is hydraulic radius
D_{84} is the maximum size of 84% of the elements of the substrate
Hm is the maximum depth of the cross section.

Aside from this equation, the model is similar to the techniques used in PHABSIM (discussed above). A major difference is that only one set of water surface levels need be taken. It is not believed that the velocity or habitat modelling procedures are significantly different.

EVHA has been validated for upland, trout-dominated rivers (Capra, *pers. comm.*), and is being extended to be useful in larger rivers with more diverse fish communities. Methods have been developed to identify critical periods where low flows limit fish populations, physical habitat was found to be a more suitable basis for analysis than flow alone (Capra *et al.* 1995). The number of variables modelled is being extended, and interactions between them characterised more fully. It has been applied in around 70 cases. As in the IFIM approach used in the USA, it does not specify a single minimum flow, but rather provides a quantitative method for including biological demands in the negotiation process.

EDF and CEMAGREF are conducting ongoing research into continuous fish population modelling based on mortality, growth, displacement, reproduction and carrying capacity, within the IFIM framework.

Statistical hydraulic and habitat models

A conceptual framework is presented by Lamouroux *et al.* (in press) for the coupling of statistical hydraulic models to similar habitat models. Previous work had shown that shear stress, depth and velocity distributions of river sectors could be modelled using simple shape functions. These statistical hydraulic habitat models could potentially then be linked to habitat models developed at the 'reach unit' scale: the latter relate fish community structure / biomass to point samples of physical characteristics. Although the procedures are clearly still at the research stage, they offer a promising method of deriving habitat / flow functions for multiple river sectors.

Models linking fish habitat to meso-scale features have started to incorporate Artificial Neural Network techniques (Baran *et al.* 1996) and in the future these too may be linked to hydrological / hydraulic models.

3.8 Finland

Flow-related problems in Finland have centred around impacts of hydro-power schemes (Sinisalmi, 1997). About 20% of Finland's energy comes from hydropower, with 60% of this generated on three rivers. 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).

3.9 Germany

Background and context

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.

A common index has been the mean of the values for the minimum daily flow for each year, or a fraction of this. Recently several microhabitat studies have been undertaken using CASIMIR (outlined below).

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.

The first model for benthic shear stress has been developed and is currently being validated. This works at a high spatial resolution, and is applied at the reach scale. It is calibrated using Statzner's 'FST' hemispheres. The principle is that greater shear stresses will cause denser hemispheres to move when they are placed in situ on a uniform flat plate. This may then be related to shear stress using a calibration function, although considerable experimental care must be taken.

Several discharges are used to calibrate the model, when considering hydropower it can be easier to 'specify' the discharges. Measurements are taken at randomly-selected points.

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

Results from an investigation using CASIMIR into invertebrate habitat below a hydro-electric scheme in Germany (Jorde 1996) reinforce the view of Petts *et al.* (1996) that a single minimum flow for a river reach can have negative consequences for the instream fauna.

3.10 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.

3.11 Italy

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. IFIM may be used for more resource-intensive applications. Studies have also been undertaken to relate fisheries standing crop to environmental variables, but these are not yet suitable for use in setting River Flow Objectives.

From the literature reviewed, considerable emphasis is placed on the 'minimum flow problem', that is determining absolute minimum values for river flows for environmental protection, that abstractions should not prejudice. The level of science supporting this does not appear to be as well developed as in other European countries such as France or the UK.

For the Po basin, a preliminary, regional standard has been developed as follows:

QMAF= 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 aims to produce a look-up method, based on a natural low flow statistic. It is not known how the q value was derived. Documentation recognises that this is an interim measure, that the regionalisation methodology must be improved, and that more detailed studies (IFIM) would be appropriate in particular individual cases. More comprehensive procedures for estimating low flow statistics have been developed for the UK.

Bagnati *et al.* (1994), outlined recent legislative developments, and illustrates a broad environmental impact assessment approach for evaluating hydropower impacts. This includes methods suggested for scoping (a matrix approach), and integration of hydro-ecological models with 'optimal sharing of water resources'.

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.

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.

3.12 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 IFIM / physical habitat, incorporating multi-dimensional hydraulic modelling, and multivariate habitat suitability criteria (Tamai *et al.* 1996). In this review, several attempts have been made to contact active researchers, but no replies were received.

3.13 Netherlands

Background and context

The particular situation of the Netherlands means that surface and ground water are highly managed. 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.

A more recent paper (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. Delft Hydraulics have also undertaken studies on the River Dniester (in Moldavia/Ukraine) to determine flow requirements for downstream wetlands, on the Danube (in Hungary) as part of habitat restoration, and on other international studies in a qualitative manner.

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 river has a mean summer flow of $100m^3/s$, so is huge compared to most rivers in England and Wales. Like PHABSIM the model uses suitability criteria, it also includes basic shear stress equations for the deposition of sediments at lower flows. An alternative 1-D hydraulic model is used, with simple hydraulics (no backwaters) it appears to model velocities on a similar scale to that in Dunbar *et al.* (1997), with the addition of bed particle size in calculating roughness. This could well be appropriate on such a large river if the morphology was relatively simple (e.g. negligible lateral flows). Spatial data on the river morphology over a 50km stretch were used, with transects every 50m. About 90 separate species / life stages were used.

The authors note the greater spatial resolution compared to a standard PHABSIM application, but do not mention accuracy of hydraulic modelling of stage and velocity for so many transects. Thus there is no evidence that this method would be better than fewer, more carefully-modelled transects.

This method is interesting in the sense that it seems to have made considerable use of existing data, and also for the ability to manipulate a GIS to undertake the same tasks as a custom-written physical habitat model.

3.14 New Zealand

Background and context

Unlike other Southern Hemisphere countries considered in this report, New Zealand has a more maritime climate. New Zealand rivers are managed under the Resource Management Act (1991), described in Gow (1996). As in other countries, the prescriptions of the Act are general, requiring that rivers are protected from adverse effects and their life supporting capacity sustained or safeguarded (Jowett, *pers. comm.*). The Department of the Environment has recently 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. This is an excellent document prepared by an interdisciplinary panel, it is recommended as highly relevant.

Methods

The assessment framework is as follows:

1. Assess the resource;
2. Define management goals;
3. Define level of protection; and
4. Select an appropriate method to determine instream flows: either based on historic (natural) flows or habitat analysis.

The main tool used in New Zealand is RYHABSIM (Jowett, 1989), a microhabitat method developed by Ian Jowett of the National Institute of Water and Atmosphere (NIWA), an organisation analogous to NERC, but in the private sector. 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).

3.15 Norway

Background and Context

The main issues in Norway are impoundment and hydro-power. A new law relating to ecologically acceptable flows is currently in the consultation stage. 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.

The RSS stores data in a common format database rather than ASCII files. Hydraulics are modelled using HEC-2, a standard step-backwater model developed by the US-Army Corps of Engineers. There are alternative habitat models called BIORIV I/II and HABITAT. Modelling may include temperature and physical habitat. Habitat 'preference' of target species is modelled on an index between -1 and 1.

Four studies have been completed using microhabitat modelling and RSS, another is ongoing (Harby, *pers. comm.*).

3.16 South Africa

Background and context

In many ways, the situation in South Africa is similar to Australia, with unpredictable rainfall and a continental climate.

Key issues include:

- rivers have a high degree of inter annual variability;
- some rivers are naturally seasonal;
- a high geomorphological diversity; and
- a lack of adequate streamflow data.

Over the last few years, South Africa has been a key player in the development of methods that assess flow needs using structured evaluation of expert opinion. The methods, including the building block method, are discussed below. Attempts have also been made to apply PHABSIM / IFIM, problems have been encountered relating to the key issues mentioned above. It is hoped that a major long term ecological / hydrological study of the rivers of the Kruger National Park will enable the development of appropriate techniques for application elsewhere in the country.

Building Block Method[1]

The method focuses on which parts of the flow regime are most important for the riverine ecosystem, accepting that part of the flow of the river will be taken for offstream use.

The South African Water Research Commission is funding research to identify the salient features of the **stable low flow** and indices for it, along with indices for freshes (mini floods), and habitat-structuring floods, and their ecological functioning.

The method is best described by quoting directly from King and Tharme (1994):

'Species associated with a river can cope with baseflow conditions that naturally occur in it often, and may be reliant on higher flow conditions that occur in it at certain times.'

'It is further assumed, though largely untested yet, that identifying such flow conditions and ensuring that they are incorporated as part of a modified flow regime will allow some semblance of the natural biota and associated functioning of the river to be maintained.'

'Finally it is also assumed that certain kinds of flow influence channel geomorphology more than others and that incorporating such flows into the modified flow regime will aid maintenance of the natural channel structure.'

The need to decide the long-term management objectives is stressed, recommendations will be based on this. Alternatively one may approach the problem from what is achievable or realistic, given current constraints.

The method is designed to be flexible in its application, and to be applied to data-rich and data-poor situations. The former might include studies where hydrological time series scenarios and qualitative species preferences are available, but this is not essential. Application may well include elements of an IFIM study, such as hydraulic simulation. The key distinction between the BBM and IFIM is that the BBM:

- does not use detailed habitat suitability criteria for target species / life stages
- aims to produce recommendations for a range of target flows and frequencies, arising from a workshop of experts

The method was developed to overcome the disadvantages outlined above, it has been discussed further along with the Holistic and Expert Panel methods in Section 4. below. It is recommended for further investigation.

[1] Note that the building block method is not the same as the research by the University of Leicester on 'Building Blocks for River Conservation, the latter relates to functional habitats, and has more in common with the biotope approach.

Multivariate statistical

Statistical techniques (cluster & discriminant analysis, correspondence analysis and covariance biplots) have been used to characterise flow regimes of rivers with different characteristic flora and fauna.

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 deadwater). 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 mesohabitat types or morphological units used in physical habitat simulation.

There are many potential uses for this information. Firstly, flow type diversity may be used for quantitative comparison of a river perceived to be impacted, with a database of similar un-impacted rivers. Secondly, the authors propose it as a method for quantification of impacts arising from alterations of flow regime, again in terms of changes in biotope diversity at different flows. Subject to a satisfactory method of specifying / transferring the flows to be mapped, this could lead to its use as a tool for the determination of River Flow Objectives, either at the scoping stage, or at a more thorough level, using an appropriate level of information.

One suggestion is that the method is that the method may be particularly suitable to high-diversity river environments, where it may be difficult to chose representative transects for a hydraulic / habitat simulation.

Geomorphological change

Heritage *et al.* (1996), present a conceptual model for the Sabie River, designed to predict changes in physical habitat resulting from channel change resulting from altered flow regime.

3.17 Spain

Background and context

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 (comparable with England and Wales Catchment Management Plans), references to ecological flows are specifically included. In the absence of more details, the French criteria of 10% mean flow is used. Methods are determined by agencies coming under the control of the regional governments. Individual regions have laws referring to more specific goals, terms (e.g. ecological) and methods.

'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)

This experimental approach 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 following results were obtained for a study of 11 rivers:

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

Range of mean classified daily flow was between Q_{60} and Q_{99}.

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.

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

This innovative (Docampo and de Bikuna, 1995) method considers 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 Micro LOW FLOWS (Young *et al.*, 1996).

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.

The method warrants further investigation.

3.18 Sweden

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

3.19 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 Kanton (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.*).

3.20 United States of America

Background and context

The United States 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. As described in the section on Canada, and in Section 2.2, a two level approach is often used.

The paper by Reiser *et al.* (1989) reviewed state-by-state application of various methods. The methods have been extensively reviewed (CDM 1986, EA Engineering Science and Technology 1986, Wesche and Rechard, 1985, Estes and Orsborn 1986, Hardy, 1996).

Flow evaluation for recreation has also achieved considerable attention. The review by Whittaker *et al.* (1996) provides a description of a variety of methods.

IFIM / PHABSIM

The Instream Flow Incremental Methodology (IFIM) (Bovee 1995) (see Table 3.2.) 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.

The main points of the PHABSIM method are considered above (Section on England and Wales). 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.

RCHARC

RCHARC (Riverine Community Habitat Assessment and Restoration Concept, (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.

Table 3.4: 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

Standard setting methods

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 Level one 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 United States, 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.

Texas Method

The authors (Matthews and Bao, 1991) concluded that methods such as Tennant (recommendations based on mean) were not suitable for Texas as streamflow 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. Q95 gave too low a flow. This method use 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 Environment Agency 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.

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, guilded 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.

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.

Calculations are performed in a Lotus 123 macro, it should be noted that the same functionality is contained within the PHABSIM program suite. From this, it is a simple task to simulate the relationships between streamflow, mean depth, mean velocity and percentage wetted perimeter. The CWCB has tabulated standard values for these simulated variables for various widths of stream, in addition biological knowledge may be used to further define these standards. It quotes Nehring (1979) that the method produces similar results to more complicated procedures (i.e. full IFIM). However as the documentation is dated 1995, more evidence than one report conducted more than 16 year previously might be expected. Although it may be possible to characterise one transect on one riffle fairly easily from one set of data, collected at a medium flow, using this to make a recommendation for a whole river sector could be highly prone to error.

The method may be of relevance to more natural upland streams, in which case it could have particular applicability in Wales and Scotland. In order to gain fully from its simple nature, the method would have to be based upon standard tables of acceptable % wetted perimeter, mean depth and mean velocities, which is not unreasonable for rivers where a degree of detail between 'look-up' and full habitat simulation is required. The approach would need to be applied widely (within and between riffles on suitable streams), integrated with existing Agency hydrometry, and a national database maintained. It is not certain whether a halfway house such as this, requiring limited field data collection, would be of use in already artificially influenced streams in England and Wales.

Range of variability approach (RVA)

This relatively new method (Richter *et. al.* 1996, 1997), is intended for flow target setting on rivers where protection of the natural ecosystem is the primary objective. It has some analogy with the 'building block approach', in that it tries to identify the important components of a natural flow regime for the river / river ecotype. However, this approach uses gauged or modelled discharges, and a set of 32 statistics based upon them (mean annual 7,30, 60 day minima and maxima etc.). A range of variation of the statistics is then set, based on +/- 1 standard deviation from the mean or between the 25th and 75th percentile. It is intended to define interim standards, which can then be monitored and revised.

This type of technique is recommend for further investigation.

Regionalisation methods

There have been several attempts to produce regionalisation techniques for physical habitat models such as PHABSIM. These could be applied where guidelines need to be developed for the basin level, but a large multi-reach PHABSIM study would not be possible or appropriate. Singh (1989) has suggested the use of the principles of downstream drainage basin change (in depth, width, velocity) developed by Leopold and Maddock to model physical habitat over a wide area. The Singh (1993) paper suggests that this extrapolation method is being applied in Illinois and he provides a method for data collection and analysis.

Similarly, Orth and Leonard (1990) developed techniques based on PHABSIM sample reaches and aggregate habitat discharge relationships to produce simple power relationships between optimum, 80%, 60%, 40% of habitat and the mean flow. Jowett (New Zealand) has also used this latter approach. The 40% of habitat figure corresponded with Montana and 7Q10 predictions.

This study concludes that the percentage of the mean annual flow required to assure optimum habitat declines as drainage area increases. This is backed up by visual inspection of PHABSIM results, and again by physical habitat regionalisation work undertaken by Jowett in New Zealand and Beecher in the USA.

4. SUMMARY OF METHODS AND APPLICABILITY TO ENGLAND AND WALES.

4.1 Overview

It is clear that the issue of the environmental flow requirements of rivers is receiving considerable attention world-wide. A key finding of this study has been the vigour with which this concept is being pushed forward in many different countries. Some countries are already advanced in the process of developing detailed guidelines for national or (in countries with strong regional government responsibility) state-wide application. Within these guidelines, ideally there will be a suite of flexible methods, of different resource level. In addition, these countries have recognised the importance of linking ecological flow management with their equivalent of catchment management planning, and with their biological (and hydrological) monitoring programmes. It should be noted that although no country has developed a definitive all-encompassing method, there is much that could be learnt from overseas experiences.

This section aims to bring together key methods within the general 4-tier framework described by Petts *et al.* (1996) (See Section 2.2). Although this framework classifies the methods well, it should be noted that any classification will always be artificial to some extent. There is clear potential for feedback from the more detailed approaches to the more rapid approaches, and also to adjust an individual approach to give greater or lesser detail as required. This 4-tier framework can provide the underpinning for well-developed guidance for the application of River Flow Objectives.[2]

Figure 4.1 (over page). is an attempt to categorise the methods in another, two dimensional manner, not directly relating to the Petts classification. It distinguishes look-up approaches (requiring more resources in setting up the standards, and lower resources per site) from incremental approaches (i.e. biological response modelling), which apply standard methods in more detail to individual sites. A further distinction is between methods aimed at assessing the river ecosystem as a whole, and methods based around particular target species. This figure only summarises the examples considered to be of most interest to the Agency.

Good examples of guidance material relating to river channel from, conservation and engineering are contained in UK publications from Gardiner (1991) and Ward *et al.* (1994). Guidance material relating to river flow management in New Zealand is contained in Snelder *et al.* (1996), while examples of preliminary flow objective implementation in Australia are contained in Environmental Protection Authority (1997a&b).

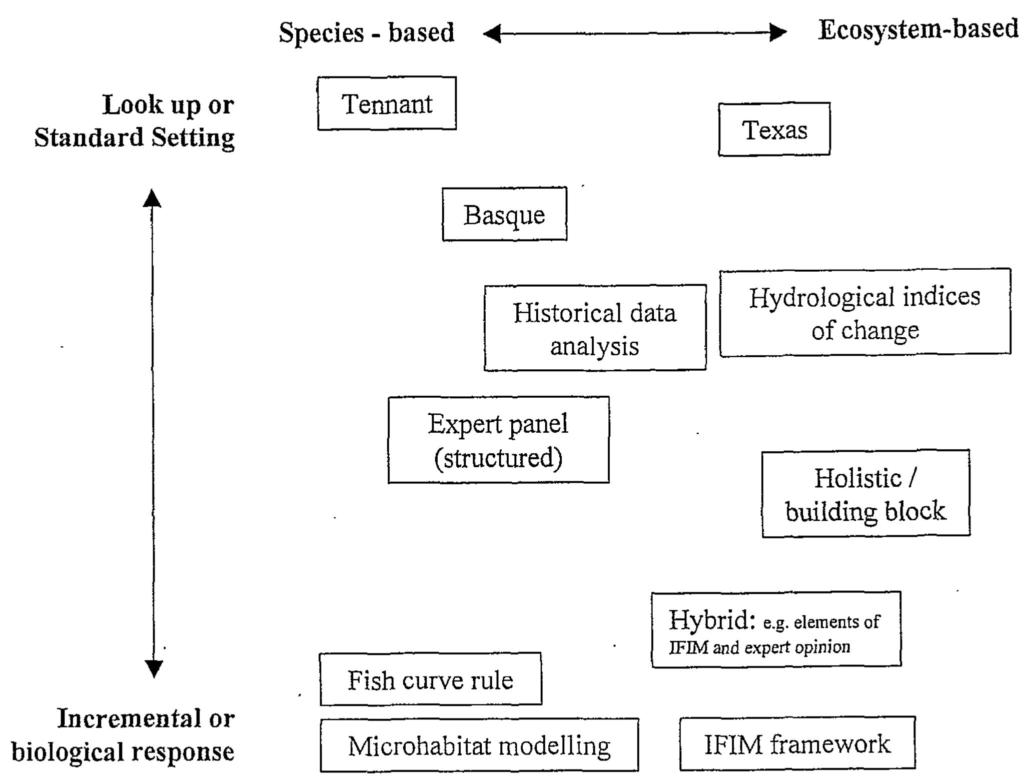

Figure 4.1. Summary diagram of selected key methods

Table 4.1. Summary table of key methods

Key method	Description
Tennant	Standardised regional relationships between percentage of mean flow and fishery quality, derived using a database of expert opinion
Texas	Variable proportions of the monthly flow duration curve, derived from existing studies
Historical data analysis	Evaluation of whatever existing hydrological and ecological data available
Hydrological simulation	Standard comparison of alternative regimes with ecological relevance of deviations from 'natural'
Expert Panel	Experts view river at various flows and comment on suitability
Holistic / building block	Decisions made at a workshop of experts from various disciplines, using whatever data available, including stage-discharge plots and alternative hydrological time series
Microhabitat simulation	Simulation of hydraulic preferences of target species
Fish Rule Curve	Standard methods for managing results of microhabitat simulation
IFIM	A framework for assessing incremental flow changes, incorporating a range of models
Hybrid	For example combination of IFIM and expert opinion

4.2 Look up table approach

This approach, superficially the most simple is termed 'look-up' (Petts, 1996) and aims to determine some sort of 'minimum' environmental discharge, which is vital to the ecological functioning of the river. Some methods go further to define other standards, such as desirable and optimum. These indices may then be used for monitoring the state of a river, or for abstraction licensing, where they could be implemented as Hands-off Flows (HoFs) or Maintained Flows (MFs). They will commonly be related either to a proportion of the mean or median discharge (e.g. 10%, 30% (Tennant, 1976)), or to an exceedance percentile on a flow duration curve. The methods may be indexed to annual, seasonal (90-day), monthly (Matthews and Bao, 1991), or special (e.g. months during which fish spawn) periods. Some effort may be made to correct for year-to-year variations in rainfall to a system, for example having alternate indices for normal, wet and dry years.

Other terms taken to mean the same basic strategy include standard-setting (the term used in the USA), use of a static index, or use of a 'rule of thumb'. Overall, they are the most commonly applied techniques world-wide. Some countries, such as France have been able to incorporate such an index as a legally defined minimum flow.

Such an approach, once the framework has been developed, requires a relatively low level of resources per site. However the resources required to develop a coherent framework should not be underestimated. This would be particularly true if it were decided to adapt a promising method to England and Wales.

This approach could be appropriate for setting preliminary targets in any situation, as part of a screening process, or for low controversy situations where a river was deemed not to be of critical ecological importance. Such methods are unlikely to be suitable if there is likely to be conflict between different interest groups, over the results of such determinations. Furthermore, such standards if set correctly could play a strategic monitoring role, and could provide advance warning (an amber alert?) of situations where further investigation was required, and give a national perspective on a par with the Water Quality Survey.

The indices are generally derived using one of two broad methods. Firstly, expert opinion, or secondly, more structured observations of the health of a group of rivers deemed to be of a similar type, combined with statistical analysis. Traditionally, the health of the river fishery has been taken to be the primary index in these cases, although invertebrate community analysis is becoming more common. Implicitly, these methods require that rivers, or river sectors be somehow categorised, using a combination of hydrological, biotic and geomorphological factors. Although such a characterisation will always be artificial to some extent, there is considerable potential for undertaking such work in England and Wales using existing data.

Within a group, the observations should ideally span impacted and unimpacted flow regimes, alternatively consider purely unimpacted rivers over a time period long enough to exhibit a range of natural stresses.

It should be noted that when calculating an index of this type, it is designed to be based on a natural or near-natural flow record. Internationally, this type of technique has been applied in situations where the river is either not subject to significant existing artificial influences, or good natural flow data exist. Statistical procedures have also been used to calculate average natural flow indices based upon values for effective rainfall and drainage area (O'Shea, 1993). Such procedures already exist for the whole UK, implemented in the Micro LOW FLOWS software (Young *et al.* 1996), although so far these have not been linked with similar broad ecological data sets.

Most promising methods

The Tennant method provides a model example of standards developed for rives with characteristic hydrology and ecology using expert opinion, although a more interdisciplinary approach would now be appropriate. The Texas method provides a more detailed, but still easy-to-use look-up procedure based around monthly flow duration curves rather than percentages of mean flow. The Institute of Hydrology has undertaken preliminary investigations into the regionalisation of seasonal flow duration curves (Gustard *et al.*, 1987, Bullock *et al.* 1994, Young *et al.* 1996). Models for regional standard-setting has been undertaken in New Zealand (Jowett, 1993 a&b), which used carefully-selected habitat modelling transects to produce general rules relating to salmonid and native fish in a range of similar rivers. Such procedures could be followed by the Agency if a national database of physical habitat studies were developed.

However careful consideration should be given to whether standard setting methods are **currently** appropriate for the determination of any type of River Flow Objective in England and Wales. National guidelines would need to be developed, their ecological relevance clearly examined. Furthermore the standards would also have to be reconciled with the concept that RFOs should relate to specific management objectives.

There is potential doubt over the relevance of the mean flow as a basis for a standard-setting index. While the mean flow, a reflection of conservation of mass, is of considerable use in some aspects of hydrology (for example hydropower estimation), it will be considerably influenced by extreme flow events, notably high flows. Use of indices derived from the flow duration curve may be more appropriate. Regional hydrological / ecological data analysis as suggested in Section 4.3 would clarify this issue, there may be benefit in introducing other techniques used in water resource management such as periods under threshold. Beecher (1990) highlighted the dangers of placing undue emphasis on flow statistics alone:

'Using flow as the unit of measurement in an instream flow standard does not ensure a consistent level of resource protection. Neither a flow nor an exceedance flow has a consistent relationship to habitat or production across a range of stream types or sizes.'

There is evidence from other countries (New Zealand, Germany) that a more realistic approach would be to introduce further scaling, giving small streams a greater degree of protection than larger rivers. Regionalisation methods for producing look-up indices from more detailed studies of a range of rivers of a particular ecotype, are detailed below.

4.3 Desktop analysis of historical data

Methods falling into this category are distinguished from look-up methods by one or both of the following two factors:

Generation and analysis of alternative hydrological time series

If a river flow regime is subject to significant existing artificial influences, naturalisation of the flow record may be necessary. This is not a trivial task, and the would negate the simplicity of applying a look-up approach. An exception would be if simple natural statistics were required and could be generated using a Micro LOW FLOWS type approach. The main techniques for naturalisation are by decomposition (Young and Sekulin, 1996); and catchment modelling (Watts, 1997). This subject is being taken forward by the Environment Agency National Hydrology Group. Once naturalisation has been undertaken, alternative water management regimes may be applied to generate a suite of alternate river flow scenarios.

A variety of techniques can be applied to the above scenarios in order to determine flow objectives. Commonly, they will either relate to specific benchmark flows determined using analysis of historical biological data, or simply aim to retain what are deemed the most important elements of the natural regime. As stated previously, the determination of such indices has perhaps not received sufficient attention (for example see Clausen, 1996), and they do not appear yet to have been applied operationally in any country. In part this may be due to lack of dialogue between ecologists and hydrologists, and partly due to the problems inherent in flow naturalisation. Furthermore in some cases, descriptions of some of these techniques in the literature tend to claim considerable ecological validity with little supporting evidence.

There is scope for the standard application of hydrological techniques for determination of interim flow objectives. In the absence of regional ('pooled') statistical studies, the type of analysis suggested by Richter *et al.* (1996, 1997) are of considerable relevance to England and Wales. Further examples of basic hydrological analysis for ecological needs are contained in the Australian expert panel / holistic studies. The application of such techniques in England and Wales could also be of considerable use in the development of the Babingley / Wissey methods to cover other river ecotypes. Knowledge of the ecological significance of high flows of various magnitudes and durations could also be improved.

Analysis of existing biological information and relation to historical flows

Countries such as the UK may have a historical record of routinely-collected biological data. Most commonly, these data have been used for the biological analysis of water quality, although there is clearly also a role for such data in the determination of river flow objectives.

World-wide, there is little information available on how such data could be applied for the setting of River Flow Objectives, although this may be contained in unpublished literature which was not available for this review. It is clear that there is still somewhat of a gulf between the effort that is expended in collecting these biological data, and their application to flow – related issues.

In theory, various data analysis techniques may be used to relate these data to historical flow records, and thus indicate flow levels required to maintain an acceptable level of population numbers or species diversity. Analysis of such historical data has much in common with analysis of newly collected, site-specific data, and is covered in the following section.

Commonly surveyed groups will be fish (particularly game fish), invertebrates (insects, crustacea, molluscs and other groups) and macrophytes (higher plants). Another potential source of biological data common in the UK may be records of rod-caught fish.

Problems with linking historical flows to ecological data may relate to lack of data or data suitability / quality, interactions between combinations of factors (complex life history strategies, migration, stocking, competition and predation, energy fluxes, historical river management), and problems relating to biotic population measurement. In short it is often difficult to establish causal links with sufficient confidence. Often, application of such analysis requires considerable experience, and decisions on acceptability rely on one or more experts using the data to make an informed decision as to what is acceptable. Pooled analysis of these data at a regional level could overcome some of these problems, as long as the data are compatible across a range of sites / rivers.

Multi-site databases, habitat quality and statistical analysis

Multivariate statistical techniques, such as regression, Twinspan and correspondence analysis may be used to relate primary biological variables, e.g. species biomass or diversity, to a whole range of environmental conditions, which may directly include flow, and other variables such as chemistry and temperature. Such techniques would generally require additional data collection in river sectors for which River Flow Objectives would be set, but given sufficient existing data, they may also be applied in the above category (analysis of historical data).

Examples of such models not solely flow-based are HABSCORE (Milner, 1985, 1993), RIVPACS (Wright *et al.* 1993, 1996), and habitat quality / trout cover models (reviewed in EPRI, 1986). Furthermore, 'biotopes' and 'mesohabitats' and their characteristic biotic assemblages are the subject of ongoing Environment Agency R&D research. These methods could fulfil several roles, from site survey and comparison with reference, development of look-up indices, and to biotope - flow simulation. Although these methods offer potential advantages over more established methods (for example a broader basis, potential cost savings), further development is clearly required before they can be applied under an operational setting in their own right. For national implementation and monitoring of river flow objectives, national databases of suitable field data would be required, it should be possible to integrate with existing data collection programmes. An exploration of the possible linkage of such meso-scale habitat models to varied flow has been undertaken in France (Lamouroux *et al.* 1996). Promising results have been obtained for habitat use by barbel and chub, although the techniques are still very much in the research domain.

Such techniques may play a number of different roles within a river flow objectives framework. Often, studies aimed at determining environmental instream flows have been criticised for too narrow a consideration of environmental variables and study locations. Broader databases should be able to provide a link between management of an artificial river flow regime, and management of other environmental characteristics that influence instream, floodplain and marginal habitat.

Key questions that such multivariate databases may enable us to answer include:

1. To what extent have the biotic communities of a river been altered?
   What are appropriate state measures: population numbers of important species, diversity of species, numbers of rare species, and where possible, appropriate physical surrogates?

2. What are the key factors controlling the health of a particular river sector ?
   What changes are most likely to lead to improvement ?
   What elements of the flow regime are most important in determining aquatic health?

3. Can typology of physical and biotic variables classify river ecotypes where particular appropriate management techniques are applicable ? Within a river type, how can appropriate river sectors, sampling sites be defined ?

Hybrid frameworks involving regression techniques have been suggested to integrate regional multivariate data analysis in the actual determination of environmental flows, although actual examples are relatively rare (Brown, 1991, Docampo and de Bikuna, 1995, Garcia de Jalón, 1994).

4.4 Data collection and primary analysis

In order to combat problems in establishing relationships between flow and river health from historical data alone, an additional data collection programme may be undertaken. Clearly factors as timing, frequency and extent of data collection will vary depending on external pressures (such as the need to make a decision by a certain date), and the perceived seriousness of an issue. Data collection may be used to increase the spatial and temporal resolution, or sampling intensity compared to existing routinely monitored data.

Holistic and professional judgement methods

In the last five years, there has been a considerable increase in the number of methods that aim to assess the flow requirements of a river through a cross-functional, multi-disciplinary appreciation of its ecology. Although hydrological simulations may be drawn upon (linking with hydrological analysis methods above), more detailed modelling is not generally used. The key recommendation as to an acceptable altered river flow regime is made following an interdisciplinary workshop. This may also lead to recommendations for further modelling (such as microhabitat, temperature, water quality) in key areas.

This review has highlighted the increasing use of methods such as the Holistic / Expert Panel approach (Australia) or Building Block Method (South Africa)[3]. Furthermore, of considerable interest is that these countries are placing a high priority in determining the environmental flow requirements of *relatively* large numbers of rivers and river sectors.

The ability of these methods to be used without requiring even historical hydrological data is not thought to be of particular relevance to England and Wales.

In England and Wales, where assessment of impacts of alternative water management regimes has been carried out, expert opinion in one form or another, has often played a significant role. However it is believed that current overseas developments are of considerable interest. These methods use multidisciplinary expert opinion in a highly structured fashion, and it is believed that they offer significantly more than existing ad-hoc procedures that may have been used in the UK. It is believed that adapting the techniques could enhance the capabilities of the Environment Agency in this area. The methods are able to consider broad ecological functioning, plus species requirements at an intermediate level of detail. This would be of particular use in the early stages of a study in the absence of clear species-related management objectives. Further requirements, such as consideration of recreational issues, landscape / amenity / cultural heritage can be considered by including the relevant experts.

Many tasks undertaken by the Environment Agency and their colleagues in other organisations are of relevance, such as LEAPS and catchment management planning, cross-functional committees, fisheries committees and biodiversity audits. Examples of consultations with stakeholders are almost certainly widespread within the Agency, but external documentation is limited (e.g. Weston and Hodgson, 1991, Goldsmith *et al.* 1993). Investigations have used a mixture of policy and ad hoc techniques rather than national guidelines and they have generally concentrated on summer low flows (driven by public concern).

The River Flow Objectives concept provides the framework for a more formal hierarchical method for such studies, the discussion-based approaches detailed here providing an example of what can be achieved using a truly cross-functional approach.

Of particular relevance is the:

- Use of multi-disciplinary teams and existing knowledge;
- Consideration of the river as an ecosystem;
- Ability to act relatively quickly;
- Ability to work at a range of scales;
- Ability to identify key issues and set preliminary targets where there is not the ability and or suitability criteria available to conduct a modelling study; and
- The considered success of the methods.

Simple hydraulic methods

These methods are in many ways a halfway house, although historically they have received some considerable use in parts of the United States. The simplest methods assume the integrity of the river is related to bed area of riffle habitat. They involve the identification of a point of 'diminishing returns' in the wetted perimeter / discharge relationship. This approach is discussed in more detail in the section on Australia above. Slightly more complex implementations (for example the R2-Cross method, (Espegren and Merriman, 1995)) aim to ensure suitable depths and velocities in riffle-type habitats.

However, channel hydraulics are considered to have a place in the expert panel-type approaches, and stage-discharge / velocity estimations provide a key element of workshop discussions in these methods.

4.5 Detailed biological responses model

These methods involve not only additional data collection, but also the use of those data in the calibration and application of time-varying mathematical models. Results of such models are then used to make decisions on values for river flow objectives.

Microhabitat methods

These are the most complicated models routinely applied in the determination of ecologically acceptable flow regimes. They attempt to model biological response of a river by combining modelled physical habitat (such as depths, velocities, bottom shear stress), with criteria on what conditions target organisms find suitable and unsuitable (Elliott *et al.*, 1996).

In the context of determining River Flow Objectives, they may be applied as one of a suite of modelling tools, which may also include models for instream water quality, temperature, or any other habitat variable that changes with flow.

Microhabitat models, of which there are a number of types, generally perform similar modular functions, hydraulic and habitat simulation, and time series analysis. They do not result in a single value for a 'minimum' flow, instead they attempt to provide decision makers with a numerical method by which biological values may be integrated into the water resources planning process (Bovee, 1995). Thus it is important that they be applied against a background of clear management goals.

World-wide, the most consistently applied detailed method is physical habitat simulation, within an assessment framework. Aside from PHABSIM, the methods appear in other guises, for example EVHA, RSS, RHABSIM, RYHABSIM, CASIMIR, HABIOSIM and others yet without a name. This type of method is considered to be the most resource-intensive and defensible. As outlined above, there are areas where physical habitat simulation may not be a suitable technique. An alternative high resource approach is collection and analysis of raw population data collected under alternative river management procedures. In reality, these approaches are somewhat complementary, but the need exists for better integration, the Agency being the natural body to take this forward.

One advantage of habitat simulation methods is their ability to be used within a water allocation framework (in the manner of Weston and Hodgson, 1991, Lawson *et al.* 1991). This has not been extensively developed in England and Wales. This means application of such simulations to surface water abstraction and impoundment issues, using the method in negotiation, and to set reservations of water for ecological purposes. Although elements of the IFIM have been used in England and Wales, there is still a need for the development of an overall framework for integrating physical habitat simulation with formulation River Flow Objectives where required.

Ultimately, the goal for higher-resource studies would be an integrated framework that considered all aspects of river ecology. Clearly, achieving this is a long way in the future, and may best be achieved by international co-operation and detailed study. Current international R&D programmes (IAMG, 1996), and European developments are of considerable relevance to England and Wales. It is important for those undertaking and applying such research in England and Wales to maintain awareness of and participate in international developments.

In the long term, the aim for detailed studies would be to target the following within an integrated framework:

- Issues as outlined in Section 1: prevention of algal blooms, water quality, navigation, recreation, visual amenity etc.;
- geomorphological and floodplain requirements;
- fish requirements, using habitat (hydraulic, statistical, water quality, temperature) models at an appropriate scale, for limiting periods (low and high flow);
- invertebrate requirements using multivariate techniques (perhaps developed along the lines of the Basque Method (perhaps using existing Agency monitoring data) or the Wissey method);
- plant communities (perhaps drawing on the development of the German CASIMIR model) or future Agency R&D (e.g. on Ranunculus)).

4.6 Relating potential methods to resources available

It is suggested that a modified four-tier strategy (Petts *et al.* 1996) consisting the following elements can also provide a clear framework, focusing in on key issues, and a clear progression, resulting in assessment of the need for increased resources necessary to progress from stage to stage:

1. In the first instance ecologically-relevant look-up indices (not just Q_{95} / Dry Weather Flow), combined with a simple water balance could be useful in setting flow objectives for relatively large numbers of river reaches. Indices should be seasonal and relate to river ecotype and perceived importance. In the manner of water quality objectives, compliance against the objectives can be monitored.

2. Desktop hydrological analysis and naturalisation, linkage with historical biological data where available, to characterise key elements of the natural and artificial hydrological regime.

3. Some combination of:
    - multi-disciplinary expert panel investigation to further refine key hydrological building blocks; and
    - targeted additional fieldwork.

4. Detailed biological response simulation using an appropriate modelling framework, and ongoing monitoring.

The following box emphasises this stepwise approach:

Stage 1 for all river reaches if required, Then:
either:
Stage 2 first. Then Stage 3. Then Stage 4.
or:
Stage 2 first. Then Stage 4. where appropriate
(e.g. clear species-related management objectives)

In reality, some individual approaches can be applied at a range of scales, and some are difficult to classify, however the methods listed earlier in this section generally fit into this framework well.

4.7 Transferability

The methods listed earlier are all general in their outlook, which is crucial for the regional and national implementation of River Flow Objectives, should this be required. Data requirements of the approaches vary, and this should be carefully considered when evaluating them for specific purposes.

Table 4.2. Methods: description and ranking

Method / origin	Rank	Description
Look up' (hydrological)		
7Q10 (various)	☒	Low flow that is expected to occur for 7 consecutive days only once in 10 years. Has been used to set standards for dilution of wastewater: dilution at this flow would still maintain quality standard. However considered completely inappropriate for instream flow protection as it would grossly underestimate minimum ecological flows (disagreement on this though)
Q347 = 95 percentile (various, particularly UK)	in-use	Used in England and Wales as a low flow index. Annual statistic not generally considered suitable for setting flow objectives, seasonal considerations and durations important.
Tennant (US)	✔✔✔	Percentage of mean annual flow for various ecological functions, calibrated to Mid-Western US. Modified to consider monthly standards. Potential for development in UK (Texas method also highly relevant). Would require considerable resources, should await discussion as to whether 'standard setting' is appropriate in England and Wales. Variations for other US states.
ABF (US)	✔	August median flow, or lowest median monthly flow during spawning months
NGPRP (US)	✔✔	Group years into dry, normal and wet. Take 90 percentile flow from normal group. Of interest as it attempts to account for climatic conditions and acceptable frequencies.
Hoppe (US)	✔✔	Daily flow values for various trout life stage functions. Based on flow duration curve
Historical hydrological data analysis		
Texas (US)	✔✔✔	Variable percentages of the monthly median flow. Scope for further investigation on a river ecotype basis (see Tennant).
Basic Flow (Spain)	☒	Spanish. Characteristic Basic Flow for a river type. Not thought worthy of further investigation
Range of Hydrological Variability (US)	✔✔✔	Indices of hydrological change. Considerable potential for use in characterising hydrological variation. Method includes follow-up monitoring and review of standards. Recommended for further investigation in Phase 2.
Additional biological / hydraulic data collection and analysis		
Hydraulic methods		
Wetted perimeter (US, Australia)	✔	Identification of break point on graph of wetted perimeter versus discharge. This will be considerably influenced by channel shape. Depth /velocity not directly considered. Not generally seasonal. Potentially useful if correctly targeted with other methods
Singh (US)	✔✔	Estimates of hydraulic parameters at catchment scale. Of some interest, of considerable interest if easy to use and evidence for validation.
R2 Cross (US)	✔✔	Simulation of depth and water level over a shallow riffle using field data. For England and Wales, a simplified PHABSIM study would give same results. As above, may be useful if spawning habitat critically limiting
RCHARC (US)	✔✔	Riverine Community Habitat Assessment and Restoration Concept. Used to compare habitat hydraulics of a reference situation with alternative scenarios. Would be most useful where clear species-related management objectives not available
Biological / hydraulic methods		
RIVPACS (UK)		See Environment Agency R&D Report W72
Basque (Spain)	✔✔✔	Uses hydraulic for lowland reaches and data on invertebrate – flow relationships in uplands. A relatively coherent system for a

		relatively narrow range of river ecotypes. Potential for further investigation if a method of this type required.
HQI (US), HABSCORE (UK)	✔	Regression models. Used to predict biomass: site or ecotype specific. EPRI report documents HQI in detail.
Statistical hydraulics (France)	✔✔✔	Uses statistical models to predict frequency distributions of physical habitat. Not yet tested with biotic data, but considerable potential in the longer term.
'Habitat', professional judgement		
HEP/HSI (US, Netherlands)	✔	Standard guidelines for habitat – area analysis. Applied in the US, and to aquatic environments in the Netherlands.
Biotopes / functional habitats (UK, South Africa)	✔✔✔	Moves away from species to a habitat-based approach. Un-validated, needs more development. Would gain from field comparison with other methods. Existing Agency R&D.
Holistic approach (Australia) / Building Block Method (South Africa)	✔✔✔	Assess complete river ecosystem, river channel, riparian zone, floodplain, groundwater, wetlands, estuary. To maintain integrity, natural seasonality and variability of flows should be maintained. Field visits, hydraulic rating curves and any supporting information used to formulate flow regime at workshop. A potentially wide-ranging approach of great value. Recommended for more detailed investigation.
Expert Panel Assessment Method	✔✔✔	Field visits by interdisciplinary groups of experts to view specific flows, commonly downstream of impoundments. Again, worthy of evaluation for England and Wales.
Detailed biological response simulation		
IFIM (US)	✔✔✔, elements in-use	A conceptual framework for integration of ecological demands into the water resources planning process. National adaptations (e.g. Spain, Austria, Switzerland)
PHABSIM II (Physical habitat simulation system) (US)	in-use	A physical microhabitat simulation model. Freely available from the US National Biological Service. Environment Agency R&D Technical Report W20. Currently used in certain situations in England and Wales, world-wide, undoubtedly the most defensible method, although not without limitations.
RHABSIM (Riverine habitat simulation) (US)	n/a	from Thomas Payne Associates, is a commercial version of PHABSIM
Fish Rule Curve (FRC) (Canada)	✔✔	Canadian method for the use of PHABSIM / physical habitat time series to develop minimum, average and optimum flows for instream physical habitat.
RYHABSIM (NZ)	n/a	New Zealand microhabitat model
RSS (River System Simulator) (Norway)	n/a	Norwegian microhabitat model
EVHA (Evaluation of Habitat) (France)	n/a	French microhabitat model
HABIOSIM (Canada)	n/a	Canadian microhabitat model
CASIMIR (Germany)	✔✔✔	A reach-based shear-stress simulation model developed for hydropower impact assessment. Worth investigating these techniques at the research level for use in England and Wales.
Fleckinger method (Spain)	✔	Uses physical habitat simulation.
AGIRE (France)	✔✔	GIS system developed by EDF. Combines spatial and temporal data on a range of themes in the manner of WIS (Water Information System). Includes a model of fish-breeding habitat quality for brown trout

Note: shaded lines in Table 4.2 indicate methods mentioned in Section 4 text.

Table 4.3 Classification of methods

Method	Flow			Biological				Hydraulic	
	Look up index	Time Series Historic	Time Series Modelled	Historic biotic	New biotic	Historic biotic\ Habitat	New biotic\ Habitat	Current conditions	Historic conditions
7Q10	YY								
Q347 = 95 percentile	YY								
Tennant	YY								
	YY								
ABF (New England)	YY								
NGPRP	YY	Y							
Hoppe	YY	Y							
Texas	YY	Y		YY		O	O		
Basic Flow		YY							
Range of Hydrological Variability		YY		O					
Wetted perimeter						YY		YY	
Singh						YY		YY	
R2 Cross						YY		YY	
RIVPACS	YY			YY		O			
Basque	YY			YY					
HQI, HABSCORE						YY Me			
Statistical hydraulics			Y			Y Me	O	YY	Y
Biotopes / functional habitats	?					YY Me	Y Me	?	
Holistic approach / Building block		YY	Y/ YY	O	O	O	O	YY	O
Expert Panel Assessment Method					YY			YY	
IFIM + variations		YY	YY				YY Mi, Me, Ma		
Microhabitat simulation (PHABSIM etc)						1 – Mi	YY Mi	YY	
CASIMIR		YY	O				YY Mi	YY	
Wissey		YY					YYMi	YY	
RCHARC		YY	YY					YY	YY

Notation:
YY: major / key element
Y: secondary element
O: optional element

Scale of habitat methods (see glossary for definitions):
Mi: Micro Me: Meso Ma: Macro

5. CONCLUSIONS

This study has reviewed the techniques available worldwide that might be capable of being used in the setting of River Flow Objectives. Of the countries reviewed, several have made considerable progress in the field of determination of environmental allocations of water to rivers. A considerable amount of useful information has been collated, relating to policy development, overall framework, standard setting, use of expert opinion, and detailed simulation.

Drawing on documented experiences overseas, the potential advantages and disadvantages of River Flow Objectives have been briefly reviewed. Major issues are: the processes used in their determination, resources required, time taken, and their defensibility. Their role in achieving sustainable development is recognised.

From this review of methods, the following general points have emerged:

- The issue of the environmental flow requirements of rivers is receiving a great deal of attention world-wide;

- Studies to determine target flows for such requirements, the implementation of interim targets, their monitoring and refinement are very important for protecting river ecosystems, achieving sustainable development, and focusing public attention; and

- No country has developed a definitive all-encompassing method. In some cases methods have been applied extensively, in other cases, methods have been proposed, but barely implemented.

At the policy level there are several key characteristics that appear to relate to the success of methods:

- Clear guidelines and a hierarchy of techniques;
- Agreement of management objectives. These could either be target species or ecosystem-related, but must be stated clearly at the outset;
- Stakeholder participation;
- Close integration in the catchment management planning process;
- Consideration of other factors affecting ecosystem health;
- A phased approach with interim objectives;
- Integration with biological and hydrometric monitoring networks.

There is still not a standard terminology for this subject. The term River Flow Objective is not used in other countries. The most common terms used abroad are 'minimum flow' (unspecific), 'environmental flow' and 'instream flow'.

Methods for setting flows to protect instream resources may be based upon flow statistics alone, flow – habitat linkages or flow – population linkages. Some countries use a two level framework, Petts *et al.* 1996 have expanded this to 4 levels.

There are considerable operational attractions in the use of look-up methods (standard-setting) for preliminary objectives, and national, strategic monitoring. Good examples of standard setting which have actually been applied include methods used in the USA (Texas, Tennant), the Basque region of Spain and New Zealand. Seasonal considerations are crucial. In the future, current academic research could provide a firmer basis for desktop procedures suitable for setting seasonal benchmark standards. Development of such methods would require the collation and analysis of national databases of sampled biological and physical data (see 6.10).

Internationally, there has perhaps been over-expectation as to the ability of look-up methods to be used in a protective manner. There is generally not the supporting evidence for the use of these methods in setting individual River Flow Objectives, if they are to be attached to specific management objectives (Petts *et al.* 1996) and scientifically defensible.

Research has highlighted the use and development of hydrological time series analysis techniques in the setting of River Flow Objectives, whether this is at the desk study stage, combined with expert panels, or detailed biological response simulation. There is potential for the application and development of these ideas in England and Wales.

It could be some time before there is clear operational evidence or justification for the use of such hydrological methods. Nevertheless they are considered worthy of further investigation, their capabilities will only become apparent if they are put into practice to set interim standards. Key ecologically-relevant hydrological indices derived from comparison between historical, naturalised and other alternative time series are of considerable interest in their ease of use and generality, plus their attraction for monitoring of direct and indirect anthropogenic change.

This report has highlighted the international use of multidisciplinary discussion based techniques (expert panel, holistic, building block). The key elements of these techniques that appear relevant are reviewed in Section 5. Although more details are required on how these actually work in practice, there is much that could be learnt from overseas experiences.

Although some form of 'expert opinion' has often been used in England and Wales, these structured methods are considered to be of considerable interest to the Agency. It is believed that they offer significantly more than existing ad-hoc procedures that may have been used in the UK in the past. The methods are able to consider broad ecological functioning, plus species requirements at an intermediate level of detail. This would be of particular use for setting more specific interim objectives, especially in the absence of clear species-related management objectives, and ensuring effective targeting of further study. Case studies provide examples of the integration of flow requirements into catchment management planning.

Analysis of historical biological and physical data, is potentially of considerable use in the setting of River Flow Objectives in England and Wales due to our relative density of biological and hydrometric sampling. Few specific examples of overseas good practice have been found, although further examples must exist in unpublished literature. There needs to be greater discussion as to the role such data can play within an overall River Flow Objective Framework, and the extent to which regional biological data analysis should be pursued in the context both of standard setting and more detailed site investigations.

Internationally, an IFIM-type approach is considered the most defensible method in existence. It is a flexible framework which has been shown to be highly adaptable. Internationally, there is currently considerable active research into the broadening of the techniques encompassed by IFIM in its entirety, many of which would be relevant to England and Wales.

The Environment Agency is already using one key element of this, the PHABSIM methodology. A microhabitat approach such as this is still state-of-the-art internationally for in-depth studies of flow / instream biota interactions. As PHABSIM is such a flexible tool, there are few agreed standards as to how it should be applied, one good example is the Fish Curve Rule from Alberta.

In the USA and Canada, PHABSIM is part of the IFIM framework, elements of which have also been utilised by the Agency. It is the most commonly used technique where in-depth study of target species is required. Some elements of IFIM have evolved in response to technical and administrative demands in the USA. Thus several countries have taken IFIM and modified / adapted it for their own specific purposes. In particular, these countries are moving towards integration of IFIM with holistic and historical data analysis methods.

There is much that can be learned from the issues surrounding applications of IFIM-type approaches abroad, as well as the technical details. Current international developments aimed at integration of broader ecological criteria, improved consideration of scale, incorporation of multivariate statistical analysis of river sectors and mesohabitats, and consideration of plant communities, along with current Agency physical habitat validation R&D studies offer scope for continual improvement. Research organisations in the UK and abroad will continue to develop new high-resource / defensibility techniques (e.g. multidimensional hydraulic habitat modelling).

6. RECOMMENDATIONS

From this overseas review, the following recommendations relevant to England and Wales have been formulated. Issues surrounding these are all considered in more detail in the main report.

Phase II recommendations

It is considered that **discussion-based approaches** (holistic, building block, expert panel) are potentially of considerable use in England and Wales. It is recommended these be investigated in greater detail in Phase II of this project. They are used in combination with hydrological time series, when target species-related management objectives are not appropriate, or as part of a rapid, cross-functional cost-effective multi-stage approach. The opportunity should then be taken to adapt and test the methods, as part of the catchment management planning process.

Desktop analysis of alternative hydrological time series data, leading to key ecologically-relevant indices, should also be investigated in more detail. There is little in the formal scientific literature on this subject but some individual cases in unpublished literature. As part of Phase II, we recommend further evaluation of hydrological analysis as a tool to set ecologically-relevant River Flow Objectives. This could include identification of seasonal hydrological characteristics using historical / naturalised flow data and biological (fisheries, invertebrate) data already available to the Agency. A desk-based study could use a standard set of flow data and alternative scenarios from a set of representative catchments. This could form the first step towards a guidance manual for application of hydrological analysis to ecological flow requirements in England and Wales.

Recommendations for the Agency to consider further

Overseas experience suggests that an **overall national framework** for the determination of River Flow Objectives, will be critical for successful implementation. The existing catchment management planning procedures provide an encompassing framework for this. However, as a considerable portion of this process is reactive, it is felt that it could gain from linking closely with a structure for determining River Flow Objectives.

This should be based around a **hierarchy of techniques**, and should be updated as new knowledge is gained; one method cannot cover all river types and resource levels. It should provide guidance, be developed by a cross-functional operational team and experts from a range of disciplines, be widely available and consulted upon. Within the Agency, it should be formulated at the highest level possible, making use of the expertise of researchers, river users and other agencies as required. It should be closely integrated with the catchment management planning process.

Thus we recommend the Agency should strongly consider developing its own framework, specifically tailored to the situations and institutions in England and Wales. Within this should be sub-frameworks for lower and higher-resource studies in England and Wales, well-integrated within overall procedural guidance. The forthcoming R&D report on 'Low Flows, Groundwater and Wetlands' (Acreman and Adams, 1998) and R&D report W72 (Armitage *et* *al.* 1997) are important moves towards this. Examples of relevant overseas frameworks include the New Zealand Instream Flow guidelines, IFIM guidelines (and variants such as those applied in Spain, Austria) and the Building Block Method guidelines.

Considering look-up indices (also known as standard setting), their implementation is tied to the extent to which River Flow Objectives are to be applied. **If RFOs are to be applied at a strategic, national scale, look up indices will have a clear role.** The Environment Agency must discuss this further. For standards to be successful, clear guidelines must be formed, based on key seasonal indices. Overseas examples are the Texas, Basque and Tennant methods. There should be further discussion as to the appropriate form of the index, such as flow percentiles or percentages of the mean, plus ways of expressing acceptable frequencies. The indices should arise from a combination of statistical analysis of existing species abundance data, expert opinion and target species simulation at critical habitat points. There is potentially considerable scope for integration with existing tools and datasets such as MICRO-LOW FLOWS, River Habitat Survey and routine monitoring data.

If required, the Agency should initiate a pilot study for standard setting, focusing on a small number of river types, not those badly impacted or of critical ecological importance, building on the development of the SWALP and SWK procedures.

If River Flow Objectives are to be reserved for selected cases, only more in-depth methods will be appropriate.

Physical habitat simulation (currently using PHABSIM) will continue to be a key analysis technique used in the determination of River Flow Objectives. The Agency is already tacking key validation issues of this approach. It should be well integrated with overall Agency guidelines. This may lead to the development of a more country-specific adaptation of IFIM, with its own unique identity, probably building on the ideas of the Babingley method.

It is clear that learning from both method development and technique application is an ongoing process. The Agency and their collaborators should maintain close links with overseas researchers and practitioners. Particularly within Europe, this should allow individual countries to achieve considerable savings of time and financial resources.

Two further separate investigations are suggested:

- Comparison of the different field-based approaches, including physical habitat, biotopes, and the Expert Panel Method; and
- The role that national biological and physical databases could play in the development of look-up indices and assessment techniques.

7. GLOSSARY

7Q10 flow
Flow which on average occurs for 7 consecutive days once every 10 years. Commonly used in design outflow of effluent treatment plants.

APST / BMWP
Average Score Per Taxon and Biological Monitoring Working Party Score. Invertebrate scoring systems.

Biotope
An area of river with particular flow attributes created by combination of discharge and channel form.

Channel maintenance flow
A flow higher than the flushing flow, required to allow the river to maintain an interaction with its floodplain.

Compensation flow
Denotes a flow that is required to remain in a river when a dam is constructed.

Dynamic hydrological technique
Defining a flow objective using information gained from analysis of alternative simulated flow time series, but without habitat simulation

Ecologically Acceptable Flow Regime (EAFR)
See Section 2.1.

Environmental flow requirement
A flow that achieves the protection (or a degree of protection) of the wildlife of a river channel. May include flushing flow requirements. This term is most often derived from Australian usage.

Flow duration curve / exceedance percentile
A duration curve, whether for flow, habitat or another instream variable, displays the relationship between the variable and the percentage of time it is exceeded. It is constructed by sorting the data (time series of flows or habitat values) from highest to lowest, and expressing each data point as a percentage of the total number of values.

Flushing flow
A higher than average flow required to clear out silt and other debris from a river system.

Habitat simulation / Biological response simulation
Defining an objective by linking flow time series to simulated habitat available to target species / life stages.

Instream flow / Instream flow needs
A flow required to remain in the river, to maintain a function of the river. Most commonly used to refer to an instream flow for wildlife, it may refer to any function.

Level 1 / Level 2 approach
A common distinction between a method appropriate for initial screening of potential impacts, or for setting flow objectives where there is low controversy or agreement (Level 1), and a method appropriate for examining the impacts of a particular scheme in more detail, where there must be greater certainty.

Look up table approach
Defining a flow using a static hydrological technique

Mesohabitat
Refers to areas within a river at a scale between tens of centimetres up to a few tens of metres.

Microhabitat
Refers to areas within a river at a scale between a few centimetres and a few tens of centimetres.

Minimum Acceptable Flow (MAF)
A term used in the 1963 Water Resources Act. Not recommended that this term be used except where referring to flows specified under the act

Minimum Flow / Minimum Residual Flow
Never clearly defined, it implies that water may be taken out of a river without causing significant damage, until the minimum flow is reached. It is not recommended that this term be used.

MMF / median monthly flow
For each month, the median value of all flow data for that month.

Q95, Q80 etc
Corresponds to flow taken from reading an exceedance percentile from a flow duration curve. E.g. the Q95 is the 95% exceedance percentile, or the flow that is exceeded for 95% of the time.

Regional method
A method designed to make predictions about unobserved locations by reference to a large database of observed conditions.

River Flow Objective (RFO)
See Section 2.1.

Standard setting
Defining a flow objective using a static hydrological technique.

Static hydrological technique
Defines a flow index derived from natural or near-natural flow data, using a proportion of the mean or a percentile. May be seasonal. May be particular to a type of river.

Sustainable Development
Development that meets the needs of the present, without compromising the needs of future generations to meet their own needs.

Time series
A sequence of events, arranged in order of occurrence.

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APPENDIX A SUPERSEDED METHODS

Connecticut river basin method
One flow method
Washington base flow, spawning, rearing methods
West Virginia method
Oregon usable width method
WRRI cover method
USFS Region 4 method (similar to PHABSIM)
USFS Region 6 method halfway between R2 and R4 - uses >1 transect
Waters method
Indicator species - overriding consideration method
Idaho method - uses single low flow calibration of WSP hydraulic model plus key species requirements

APPENDIX B PROPOSALS FOR STAGE II

Environment Agency R&D project W6B(96)04[4]
Overseas Approaches to Setting River Flow Objectives
Draft Stage II framework *The role of discussion-based, natural-hydrology and field survey methods in the setting of River Flow Objectives*

Introduction

Stage 1 of the Environment Agency / Institute of Hydrology R&D Project 'Overseas Approaches to Setting River Flow Objectives' is now complete. This study made an extensive review of overseas methods, their strengths and weaknesses, and their applicability to England and Wales. The study made a number of recommendations for more detailed examination of certain methods.

There are several overseas developments that the project has reviewed. These generally fit into the framework for RFOs originally described by Petts *et al.* 1996. We recommend that Stage II of the project investigate techniques acting at an intermediate level of detail, i.e. requiring greater resources than a simple 'look-up' approach, but lower resources than a full IFIM / PHABSIM application.

[Another recommendation, for the Agency to consider independently, is to assess whether there is a role for the development and application of look-up indices to set preliminary river flow objectives.This review has included some ideas on how such indices could be developed]

There are various approaches that could be investigated, we suggest that the one single method that most could be gained from investigation is the building block method (BBM) developed in South Africa. The BBM is able to stand in its own right, however in the context of England and Wales, we believe that a similar technique could provide more formal bridging between hydrological indices and detailed biological response simulation. It has been fully applied in at least 11 cases, and is perceived to be very successful.

The BBM makes use of alternative simulated hydrological time series, and biological / hydraulic / geomorphic data where available. This leads into assessment of alternate regimes by an interdisciplinary panel of experts, in freshwater biology and fisheries, hydrology / hydrogeology and fluvial geomorphology. Emphasis is placed on field visits and consultation with stakeholders, and as such there are some elements common with the Agency's LEAP process. An ongoing monitoring programme against the specific objectives is provided for, as are techniques for altering objectives during drought and severe drought conditions.

We feel that there is a considerable amount that can be learned from the practitioners of these approaches, and case studies of where they have been applied. These approaches have been shown to be particularly appropriate when target species-related management objectives are not appropriate, or as part of a rapid, cross-functional cost-effective multi-stage approach.

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[4] part funding provided by Institute of Hydrology / NERC Science Budget

Such techniques:

- provide an 'inclusive' solution
- provide recommendations for a flow regime (including magnitudes, timings, frequencies and durations (Petts *et al.* 1996)
- consider alternate climate scenarios
- do not require detailed species / microhabitat preferences
- aim to consider all aspects of a river's requirements
- are able to develop recommendations relatively rapidly
- provide targeting of future research

The project has been particularly successful in developing contacts with overseas researchers, with which it is hoped that the Agency can establish long-term co-operation.

Study visit

We propose a study exchange is the best way to take this research forward. Two countries have pioneered the approach, Australia and South Africa. We have developed good contacts with Australia during the course of this study, and have excellent existing contacts in South Africa through previous IH work. We recently discussed the idea of a visit with Dr Nick Schofield, who is Water Resources Manager for the Land and Water Resources Research and Development Corporation, and he offered to host us and provide guidance for us during a visit. Dr Jackie King showed a similar enthusiasm for assisting us with a visit to S. Africa.

We suggest that Stage II comprise the following elements:

- Visit of a South African scientist to the UK
- Meetings with IH and Agency: presentations on the BBM, discussions on applicability to England and Wales.

- Visit of IH / Agency staff to South Africa to observe the BBM being used for instream flow determinations. Such an application is planned for late 1998.
  This will enable us to see how the method works in practice, to review recent developments, and to meet and discuss with other researchers undertaking discussion-based instream flow studies, including:

- The management authorities responsible for water management decisions who have commissioned and acted upon such studies

- Stakeholders who have had involvement in such studies – including perceived success, and implementation of post-project recommendations and monitoring. Through our contacts we will also take the opportunity to discuss the development of the method and its strengths and weaknesses with policy makers (DWAF) and R&D managers (WRC)

- Other desk-based studies: further investigation of hydrological indices. As hydrological time series analysis / modelling plays a crucial role in such applications, it is proposed to develop ideas as to how existing techniques could best contribute to the setting of River Flow Objectives.

- Reporting and presentation. As well as detailed documentation of the study visit, the project will include a review of the potential of the methods for application in England and Wales, recommendations for a possible trial study, if deemed sufficiently applicable.

Naturally there are many differences between such Northern and Southern hemisphere countries: such as in climate, public attitudes, regulatory regime and freshwater flora and fauna. However from a fundamental consideration of what these techniques could be capable of achieving, it is clear that basic problems, such as protection of river and floodplain ecosystems, consideration of the different elements of the flow regime, and integration of hydrology and ecology are common. Other approaches such as 'Landcare' that have been developed in Australia have been successfully applied in the UK.

Follow up

As a separate project, we aim to organise an international workshop on River Flow Objectives / Instream Flow Requirements in Winter 1998, to be held in either the UK or South Africa. Funding options are still being addressed. See below for workshop details.

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Workshop

Title: The role of expert opinion and hydrological analysis in setting River Flow Objectives

- Introduction: Environmental Flows in the Northern and Southern Hemispheres
  - Overview of UK situation: hydrology; types of flow modification; main players; historical development;
  - Overview of S. Africa: hydrology; types of flow modification; main players; historical development;
  - England and Wales: River Flow Objectives;
  - SA Water law developments.

- Top level methods
  - Identification of the problem (broad survey and scoring).
  - Monitoring programmes
  - (Brief outline)

- Natural hydrology and expert opinion
    - Background of the BBM
    - Relationship to other similar methods (EPAM etc)
    - Application and success
    - Discussions

- Mechanistic / biological response modelling present and future directions
    - Case Studies (England: Kennet, SA)
    - Multivariate factors: sediments, channel shape, water quality
    - Discussions

- Building an integrated framework
    - Multi scale
    - Regionalisation
    - Economic analysis
    - Follow-up monitoring (incl case studies)
    - Application to licensing
    - Discussions

Attendees

UK: Mike Dunbar, Mike Acreman, Agency representatives.
S.Africa: Jackie King, Rebecca Tharme, hydrologists, managers.
Australia: Nick Schofield to recommend.