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SCOTLAND & NORTHERN IRELAND FORUM
FOR ENVIRONMENTAL RESEARCH

Anthropogenic impacts on the hydrology of rivers and lochs

Stage 1 Report:

Literature review and proposed methods

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EXECUTIVE SUMMARY

This report presents the preparatory elements of the SNIFFER R&D project A*nthropogenic impacts on the hydrology of rivers and lochs.* Its function is to present a review of all literature relevant to the project, and to make recommendations regarding the development of methods to be undertaken in the second (and most substantive) stage of the project.

The project fundamentally requires indicators of hydrological regime change, as a means of assessing the impact of change on aquatic ecosystems. A wealth of methods are available for describing regimes and, accordingly, there is also a large number of methods for describing regime change. Methods of so doing accurately provide a central challenge of this research.

The setting of targets for river management purposes is of key relevance. Where these activities have been undertaken for the protection of the river ecosystem, implicitly there is an indication of what aspect of the hydrological regime is thought to be of relevance to the well-being of ecosystems. Traditionally, the avoidance of low flows has been an important target, as effected through abstraction licensing schemes, but more recent research has illustrated a great diversity of aspects of the flow regime thought to relate to various elements of the aquatic biota. Flood flows have been particularly emphasised as important in relation to sediment movement and its relationship with habitat; flood frequency and season are also to be considered as well as magnitude. The report reviews the range of methods available for relating river management to ecological interests, focusing on the needs of this project relating to Scotland.

Outside the remit of studies focused on river management, an even wider literature exists regarding the relationships between flow regime and individual freshwater species. This literature is reviewed also, providing further background for the project. Most of the literature presented relates to rivers and streams. However, lakes also provide important elements of the freshwater resource, and the literature relevant to these is also reviewed.

Looking forward, the second function of the report is to recommend how the methods required in this research should be developed. Methods of characterising hydrological regime alteration developed by Richter and co-workers in the USA are recommended as a starting point, on the basis of the comprehensive treatment they offer of the hydrological regime, their flexibility, and their (apparently widely accepted and supported) stress on hydrological variability. Approaches to implementing these approaches in Scotland, including aspects of deriving synthetic data where required for the assessment of hydrological alteration, are outlined.

Perhaps the most difficult aspect of the research will be the calibration of new methods on ecological impact in Scotland. The report makes recommendations based on the use of 20 test catchments, with supporting hydrology, biology and chemistry data, in order to develop appropriate forms of model. Soft scoring methods are advocated, including the use of checklist-type data, in addition to direct measures of hydrological alteration, as a means of achieving reliable outputs. Comparable methods for lakes are outlined. Finally, preliminary suggestions are made regarding the relationship between the work of this stage of the research, and Phase II of the programme.

KEY WORDS

anthropogenic impact ; development of methods ;
freshwater ecology ; hydrological regime alteration ;
lakes ; rivers

1. INTRODUCTION

This literature review arises as the first of three stages of the SNIFFER project W(98)50: *Anthropogenic impacts on the hydrology of rivers and lochs*. Its aim is to inform the activity of the second and central stage of the project, which involves the development of new methods.

The research is concerned with developing methods for assessing the scale of anthropogenic impacts on the hydrology of rivers and lochs. The statement of requirements for the project requires that three discrete but related areas be addressed as a means of informing Stage 2 of the research:

- methods used to define the severity and extent of anthropogenic changes in the hydrological regime of rivers and lakes;
- standards, objectives and/or classification schemes used to define flow regimes or loch levels in a manner than protects aspects of ecological status; and
- the linkage between changes in flow regimes and ecological damage.

These three accordingly form a significant part of this review. However, a considerable amount of additional material is also provided, to assist in the contextualisation of the research. It is hoped that by providing this additional material at this stage, often amounting to assessments of factors which will constrain development of the research in certain directions, the research team and the SNIFFER Steering Group will be able to come more quickly to a consensus as to how the research should proceed.

The review is structured by the following sections:

1. Introduction – describes the processes of accessing the literature, the structure of the review, and background issues which will influence the utility of the literature, e.g. aspects of the forthcoming European Water Framework Directive.

2. Methods used to define hydrological changes – this section is based solely in the physical hydrology literature and includes a background to the measures used by hydrologists to describe hydrological regimes, changes to them, and why.
3. Standards, objectives and classification schemes – a review of the extensive international literature found on management approaches and tools used to protect aquatic ecology through hydrological regulation, including an overview of the tools used for estimating habitat sensitivity to hydrological change.
4. Linkage between changes in flow regimes and ecological damage – this section summarises the large number of papers addressing species, community and/or site-specific studies of the impacts of hydrological change.
5. Lake effects – the functions of the Sections 2-4 are dealt with in just one section in respect of lakes, reflecting the rather small literature available.
6. Discussion – drawing out points as a critical appraisal of the ideas of the review, leading to the recommendations.
7. Recommendations – outlining how the research should proceed in Stage 2, including a work plan, as a key point for discussion with the Steering Group.

1.1 Search facilities used

The following search facilities have been used to identify books, papers and reports relevant to the work of this project:

- BIDS (Bath ISI Data Service) – on-line catalogue of journals, books, reports
- GEOBASE – CD-Rom service offering similar functionality to the above; focused on geography/environmental sciences
- Custom bibliography created by Scottish Natural Heritage
- Reports/papers lent/recommended by colleagues at Scottish Natural Heritage, Institute of Hydrology, SEPA
- References known by members of the research team
- University of Dundee library

By far the most fruitful lines of enquiry were use of bibliographic databases and identification of references cited in other reports and papers. A particular advantage of these methods was their ability to provide details of literature very recently published – a feature of considerable advantage in a rapidly evolving area of environmental science and management. Various contacts were suggested by members of the Steering Group, but no new sources were found as a result of these enquiries. In all, 200-300 references were identified as being of possible relevance to the review, with access being made to more than 160 of these.

1.2 Constraints to the utility of the literature review

The forthcoming *European Water Framework Directive* is central to the need for a methodology to assess anthropogenic impacts on the hydrology of Scotland's rivers and lochs. Because SEPA will wish to ensure that its activities meet the requirements of the Directive, it is helpful to consider some of the literature relevant to this research against a background of assumed knowledge stemming from the Directive.

A key aspect of the forthcoming Directive is that anthropogenic changes are to be measured in a way which reflects ecological impact as a deviation from high ecological status. This may readily be interpreted as a worthy ideal, but one which may, in practice, present considerable difficulties in measurement or estimation. This, therefore, relates to a fundamental challenge inherent in the research. Two of the key difficulties are that:

- ecosystem response to imposed change is sensitive to many influences – not just flow regime, but also water quality considerations, the particular species in an aquatic community, and so on. Therefore the effects of change may not be perfectly transferable in space or in time.

- a stochastic (or 'chance') element may be involved in the response to some changes. In recognising this, the Steering Group has asked that the concept of

> ‘risk of change’ be used where possible, to accommodate the uncertainties which arise from stochastic behaviour.

A major task is therefore to evaluate the literature described in this review, and to assess its utility for the purposes of developing a methodology which can be applied in practice in Scotland. Sections 6 and 7 of the review move towards making recommendations for this purpose.

Practical constraints such as those concerned with field implementation, and ecological calibration of methods, are discussed in Sections 6 and 7.

2. METHODS USED TO DEFINE THE SEVERITY AND EXTENT OF ANTHROPOGENIC CHANGES IN THE HYDROLOGICAL REGIME OF RIVERS AND LAKES

This section of the review deals with purely hydrological measures, as reported in the formal hydrological literature of academic papers, books, etc and also in hydrologists' working tools as reflected by technical reports and manuals. The section begins with a consideration of the means by which hydrologists characterise river flow regimes, and then goes on to consider how change in the various indicators is expressed. Many of the concepts introduced in this section are developed further in Section 3, through their application to regime management and in relation to environmental objectives.

2.1 Indicators of river flow regime

Although rarely stated, it is often assumed in the UK that rivers are perennial and conform to the *simple regime* of Pardé's classic (1955) global classification of rivers, in this country having a single flow maximum in winter, and a single minimum in summer. While drought situations can occasionally lead to slight contraction of the contributing channel network, the simple regime classification can be uniformly accepted across the UK, as a result of climatic and catchment scale considerations.

Hydrological interest, in practice, is often directed to specific aspects of the flow regime rather than its totality, perhaps because of the uniformity of regime type, and can be divided into three categories:

- low flow characteristics
- flood flow characteristics
- overall or average characteristics

Flow characteristics for each of the three types are introduced and briefly evaluated as follows:

2.1.1 Low flow characteristics

***Q_{95}* (95% exceedance flow)** (m^3s^{-1}) is the most commonly used indicator of low flow rate in Great Britain, and has been widely adopted as a basis for the determination of licences to abstract (in England and Wales) and consents to discharge (Black *et al.*, 1999). Assuming that the flow is broadly natural before a proposed change is implemented, then the use of Q_{95} has been taken to indicate an acceptable flow to be maintained for river uses. In some recent instances, SEPA has used Q_{90} as an alternative, e.g. in setting consent requirements for new run-of-river small HEP schemes (SEPA, personal communication).

MAM7 (mean annual minimum 7-day average flow) (m^3s^{-1}) - this indicator tends to be used mostly for water resources applications, where a measure of the lowest sustained low flow period in an average year may be required (see Gustard *et al.*, 1992). However, bearing in mind that this may often relate to a period of high ecological stress, it may also be useful in habitat management terms. MAM7 may be given with a return period, to indicate the magnitude of a 7-day annual minimum to be expected once on average in every T years (e.g. MAM7(10) for the 10-year event), to indicate rare conditions.

2.1.2 Flood flow characteristics

Mean annual flood (m^3s^{-1}) is the most widely used basic indicator of the flood behaviour of British rivers. It is calculated as the arithmetic mean of the instantaneous flow maxima recorded over a series of years, with increasing record length providing increasing confidence in the sample mean; calendar or water years (the latter conventionally commencing 1 October) may be used. This measure has been adopted for flood study work as an index from which the magnitude of rarer events may be estimated (NERC, 1975), but the mean annual flood is also considered to be important in relation to channel-forming processes. The now classic work of Wolman & Miller (1960) indicates that in many rivers, over the long term, the most effective geomorphic work is done in floods of around the mean annual flood magnitude. Again, this links to habitat, representing a connection between hydrological regime and, ultimately, in-stream ecology. As with MAM7 above, values of Q_T representing flood magnitudes of some given return period of T years can be obtained by a range of accepted statistical procedures.

Peaks-over-threshold (POT) statistics - POT series were collected for the majority of British rivers gauged in the early 1970s in the work of the *Flood Studies Report* (NERC, 1975). Details of all floods were collected for events exceeding a threshold set for each gauging station, designed to give 4 to 5 peaks per year on average. These data can be used to calculate flood statistics indicating POT event frequency and magnitude. ***Annual POT frequency*** can be used to illustrate inter-annual frequencies, but is otherwise of little value because of its entire dependence on the value of the threshold set (the higher the threshold, the lower the annual average POT frequency). ***Mean POT exceedance*** indicates the average exceedance above the flow threshold set, and again has value in examining inter-annual variability, but can also be used in comparison with the threshold value to give a simple measure of flood variability (the standard deviation of an annual maximum series could equally be used).

Flood seasonality – Black &Werritty (1997) have studied the season of occurrence of POT flows in rivers across Scotland and related the patterns found to catchment and meteorological controls. The description of seasonality includes measures of mean time of year and the seasonal clustering of flood events. This work adds a useful extra dimension to the more standard flood descriptors above, and the seasonal methods used can be applied equally to low flows.

2.1.3 Overall or average characteristics

Annual flow (m^3s^{-1}) - arithmetic mean flow, often useful as a basic water resources indicator (see Marsh & Lees, 1998). Although rarely seen, a more useful alternative from an ecological perspective is the ***median flow*** which can be denoted as Q_{50}, the flow exceeded for 50% of all days.

Annual runoff (mm) - given as an average runoff depth over the contributing catchment, normally over a calendar year. However, monthly or even daily values can be produced from the daily flow record (e.g. see River Purification Board and SEPA annual reports).

Flow regime parameters - working in France, van der Wateren-de Hoog (1995) illustrates a method for reducing the flow duration curve to just two single parameters, indicating the maximum daily runoff value in the curve and the curvature of the entire line. Empirically obtained values of A and B can be used to obtain any percentile flow value Q_D from the flow duration curve from the equation

$$Q_D = A - B \ln(D)$$

where: A, B are model parameters, and
D is a percentage of time value.

From these two values, she indicates that the importance of catchment storage can be inferred, and that the flow duration curve can be reproduced to a high degree of representativeness. This offers a surprisingly simple method of condensing the information of a flow duration curve, but gives no sense of the annual regime or the seasonal characteristics of the flow. Indeed, for many purposes, it may achieve excessive generalisation.

A more common means of describing the annual flow of a river is through the separation of total runoff into quick and slow components. The ***Base Flow Index (BFI)*** became a common reference after publication of the Institute of Hydrology's (original) Low Flow Studies (IH, 1980), representing the overall fraction of total runoff derived from delayed rather than direct catchment sources. More recently, a ***Slow Flow Index (SFI)*** has been used in the Institute's IHACRES rainfall-streamflow model (Littlewood & Jakeman, 1994) which is now available in PC form, and other contemporary models feature other parameters with similar functions. In any of these cases, the available index indicates the fraction of runoff derived from storage, thus indicating regime flashiness. All other factors being equal, low values of these indices can therefore be taken to indicate more variable in-stream habitat than where high values occur.

2.2 Indicators of regime change

The above summary of regime indicators illustrates that there are many measures of hydrological behaviour which are well established in UK hydrology and river management. Examination of the literature does not identify any coherent body of work to provide a nationally or internationally accepted method or set of methods for assessing change in these variables. Yet the detection, management or avoidance of such changes forms a critical focus in much of water and environmental management. Therefore it is not surprising that many of the research papers accessed refer to changes in one or more river flow variables. The object of this section is to review the means by which these changes are characterised.

2.2.1 Changes identified in relation to water management activities

Much of the literature on river flow regime is concerned with changes due to water management activities, such as impoundments, abstractions, transfers or regulation. This is unsurprising considering the global awareness of the environmental impact of human activities in general. While developed countries may lead the world in assessing and managing environmental impacts, the work of the World Bank (though its loan and development programmes) and other international organisations appears to have contributed to such global awareness.

While Sections 3 and 4 of this review deal in more detail with studies of environmental objective setting and the links between regimes and ecosystems, a helpful observation of many studies dealing with management objectives is that a small number of targets tend to be set in any one scheme for the sake of river interests. For example, Bickerton (1995) found it sufficient to refer only to April mean flow and summer low flows in a study of the River Glen in Lincolnshire, developing a model to predict macroinvertebrate community types. Because of this, assessments of change in river flow regime often tend to focus just on those targets which have been set, or on a limited number of other variables. No evidence has been found to suggest that annual average flows have any marked effect on aquatic ecosystems, so the focus of change assessment tends to be on low flows, flood flows or both.

Many geomorphology-based papers are concerned with changes in flood flows, and tend to present measures of change in the mean annual flood, e.g. a study by Rubin *et al.* (1998) concerned with scour of suspended sediments downstream of Glen Canyon Dam analyses change in relation to a post-impoundment reduction of mean annual flood from approximately 2600 m^3s^{-1} to 900 m^3s^{-1}. Such papers may be concerned with channel-forming processes for their own sake, or for the sake of studying the changes in habitat which result. In Scotland, channel capacity studies on rivers downstream of supply reservoirs in the Southern Uplands have been undertaken by Petts (1980), including the Camps Water and the Elvan Water.

However, it is only in the last few years that many of the research papers read have characterised changes in flow regime from a multi-dimension perspective. Petts, a well-respected figure in this field, argues in a paper concerning the future determination of ecologically acceptable flows in England and Wales (1996) that “floodplain flows, channel maintenance flows, minimum flows and optimum flows” all require identification and use. Biggs, working in New Zealand, also adopts this approach. A range of ecological indicators were related to some 34 hydrological indicators obtained from daily mean flow records, covering flow variability, floods, and low flow characteristics (Clausen and Biggs, 1997). Similarly, Richter and his co-workers take this very comprehensive view of describing the flow regime; an example of the calculation of their 32 parameters for a before-and-after comparison is shown overleaf (Richter *et al*., 1997).

Compared with the limited focus of some of the studies described above, these more complex systems offer important advantages:

- more detailed description of the regime;
- inclusion of temporal characteristics, e.g. season of maximum/minimum flows.

However, there are attendant dangers which must be borne in mind:

- changes in some of these many variables may not necessarily be significant;
- changes in river flow variables may be dependent on each other, posing possible statistical problems when interpreting changes indicated by multiple variables;
- information duplication may occur among the variables, leading to potentially cumbersome and unclear descriptions of change.

Richter *et al*. (1997) avoid over-complexity in their development of environmental management tools by focusing just on those variables which show unacceptable changes following a regime change. However, a large number of variables are computed in the first instance in order to gain a full picture as to what major changes have occurred.

The most fundamental issue which underlies all of these assessments of change is the extent to which indicators of hydrological change can be relied upon to indicate the extent and severity of ecological impact. It is important that ecological studies address overall ecosystem health although, in some studies, management targets concerning only single species are used as an environmental management tool, risking impact for other species. These issues are addressed in each of the following main sections of the report.

Table 2.1: Example of Range of Variability Approach application.

Source: Richter *et al.* (1997).

2.2.2 Changes identified in relation to climatic behaviour

The scientific literature indicates that great importance is presently attached to attempts being made to indicate the characteristics of river flow regime changes which might occur in response to climatic changes in the 21st century. Water resource and environmental management, and hazard management activities all require the best available information. Examination of some of this literature illustrates the regime descriptors being used for these purposes.

Arnell's (1996) book *Global Warming, River Flows and Water Resources* provides a comprehensive overview of the possible effects of climate change for UK water resources. In it, the hydrological measures most commonly used are:

- annual runoff
- seasonal runoff (based on four seasons)
- monthly runoff
- Q_{95}
- mean annual flood

In each case, changes are reported as percentage change relative to present average conditions. These are well recognised hydrological variables, although freedom to choose variables judged to be most useful by the author is illustrated by his inclusion of average annual aquifer recharge rate. A further original measure of change is given by Arnell (1999) in an European climate change impacts study, in which he measures deviation as changes in total deficit volume below Q_{95} on an annual basis. Something of this flexibility is evident in other studies, reported in Section 3 of the review.

2.2.3 Assessing regime stability

In contrast to the above sections on assessing change, some interesting papers by Krasovskaia (1995), working with Scandinavian rivers, address stability in flow regime. She identifies regime on the basis of the seasonality shown in monthly flow data, and expands the work in the context of climate change impacts. This allows the identification of those rivers most liable to show a change in regime, which is of value to environmental managers responsible for maintaining aquatic ecosystems. This approach does not offer the level of detail provided by many of the methods covered in section 2.2.2, but could be valuable where a broad overview of regional sensitivity is required.

2.3 Methods for estimating hydrological variables for ungauged sites

A final hydrological aspect of relevance to this research is the estimation of hydrological data for ungauged sites, i.e. points on rivers or lakes at which no river flow or water level records are kept. This is important, since such hydrological data are required both for:

(a) characterisation of hydrological regime as impacted by anthropogenic factors, and
(b) comparison of (a) with unimpacted conditions.

Much research has been devoted to the development of methods for estimating hydrological variables at ungauged sites, for a range of applications. These methods produce either:

(i) single variables, such as mean flow or a flood magnitude of some given return period, or
(ii) time series variables, such as daily mean flow or hourly mean flow values.

Methods of type (i) above are likely to be restrictive for the purposes of this project, since only a small range of descriptors of hydrological regime (and hence only a small number of indicators of change) can be produced – see Section 6.1. Therefore, the derivation of time series data, from which a wider range of indicators can be produced, appears desirable.

For river flow data, again, two approaches seem practicable:

(1) Where observed flow data are available upstream or downstream of a point of interest, i.e. within the same catchment, simple scaling of the available data can be done either by a ratio of catchment areas, or by a weighted average (e.g. weighted by annual average runoff estimate).

(2) Where observed flow data are not available in the same catchment, a flow duration curve for the ungauged site may be produced according to the methods of Gustard *et al.* (1992). A hydrologically similar neighbour (or reference) catchment is identified, as close as possible to the site of interest, and flow on each day is then found by obtaining daily positions on the flow duration curve for the gauged site, such that a flow can be obtained for the ungauged site by locating the equivalent point on its flow duration curve. This type of information transfer is recommended by Gustard *et al.*, but flow estimates may vary from actual if the hydrological behaviours of the two catchments differ (e.g. if one produces its lowest flows at the end of short, intense drought periods while the other does so in response to longer, less pronounced droughts).

Neither method is recommended for application to sub-daily data. Because the use of derived (or 'synthetic') data is likely to be a common feature of this research, it seems likely that the methods to be developed will therefore need to use data of no finer a time interval than daily. It is suggested that approaches (1) and (2) above will be appropriate to requirements (a) and (b), although this should be subject to testing. In practice, it may be possible (and operationally advantageous) to produce maps identifying the sources of reference gauging station data for all of the river network for which regime alteration assessment is to be carried out. It may also be possible to develop the Gustard *et al.* approach to allow more than one reference source of data to be used – this may improve confidence in the estimates produced.

These methods do not apply to lake level data, for which observations are limited in number. Sections 6 and 7 contain suggestions for assessing lake regime impacts.

2.4 Summary

This section of the report shows that a wide range of indicators are available for the characterisation of hydrological regimes, with choice being governed by purpose. Many are simple and well used, such as mean flow, mean annual flood and 95-percentile exceedance flow; but others may be more specific, referring to means, high or low flow indicators for specific times of year, or to the frequency with which defined events occur. This range extends to the measurement of regime change, choice again being governed by purpose. Some assessments of change are focused on single indicators which are thought to be important for single species or specific elements of an ecosystem. Others, more ambitiously, attempt to characterise change by reference to a comprehensive suite of indicators, which can be grouped according to type, or reduced in number according to an assessment of which appear to represent significant change. Inevitably, hydrological data are not always available at the point of interest to a user, so methods of deriving flow data are described. These are considered to be useful up to the point of generating daily mean flow data, but nothing at a finer time interval.

3. STANDARDS, OBJECTIVES AND CLASSIFICATION SCHEMES USED TO DEFINE FLOW REGIMES IN A MANNER THAT PROTECTS ASPECTS OF ECOLOGICAL STATUS

3.1 Introduction

Traditionally, hydrologists and ecologists work at different scales. Organisms occupy the "in-stream" habitat, where availability of food, living space and other resources necessary to complete their life cycles are related to the flow regime as measured by hydrologists at catchment scale, but are actually experienced as current and water depth at sub-reach scale. Moreover, organisms are influenced by factors such as water chemistry, nature of the substrate and the presence of other organisms, all of which are, in turn, influenced by the flow regime. Thus, application of the river hydrologist's tools to ecological problems requires some reconciliation between these two scales. A direct approach employing probability distribution models based on field measurements to quantify the relationship between discharge and water depth/velocity was developed by Singh (1989); and a method using statistical hydraulic models to express local hydraulic variables in a stream reach as a function of average characteristics of the reach is now under development in France (Lamouroux 1995). However, a number of pragmatic solutions have already emerged in the process of setting flow objectives and in classifying river systems.

3.2 Setting "environmental" flow objectives

Such a wide range of techniques is now available for setting instream flow objectives for particular purposes, including protection of the biota, that guides to their use are desirable. A recent example originates from New Zealand (Snelder *et al.* 1998). The principle involves setting and achieving an instream management objective[1], to which a flow regime requirement is attached. The latter requirement is expected to vary

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[1] The case study example for the Waitaki Catchment reports the "bottom line" objective, arrived at after discussion amongst all interested parties, of survival of the black stilt.

according to the objective defined, and an armoury of description techniques is offered to users (Table 3.1).

Table 3.1: Summary of New Zealand flow regime descriptors (Snelder *et al.* 1998).

Descriptor	Definition	Remarks
Yield	Total volume of flow over a set period	
Specific yield	Average discharge per unit area of catchment	
Flow duration curve	Relates each flow value to the proportion of time that flow is less than this value	Provides a useful summary of the flow record
Monthly flow histograms	Show average flow for each month	Indicate seasonal variation of the flow regime, but not extreme values
Mean flow (MF)	Total flow volume divided by record duration	Indicates average flow conditions
Median flow (Q_{50})	Flow which is exceeded 50% of the time	Indicates average flow conditions
Skewness coefficient (SK)	$= MF/Q_{50}$	Indicates flow variability
Coefficient of variation (CV)	Standard deviation of daily mean flow divided by mean flow	A measure of variability of the flow regime; < 1 in rivers with little flow variability, > 3 in rivers with relatively long periods of low flow and intermittent large floods
Base flow index (BFI)	Volume of base flow divided by total volume	Indicates flow variability; stable flow regimes give high BFI whilst low BFI indicates many floods, low base flow and high variability
FRE_3	Number of times per year that the flow exceeds three times the median flow	Indicates the frequency of disturbances generated by flood flows significant for habitat for benthic biota (periphyton and invertebrates)
Annual minimum flow distribution	Low flow frequency analysis	
Streamflow drought analysis	Probability of volume deficit below a given flow rate	Useful if abstraction is to stop below a certain flow
Flood flow statistics	Peak flow, volume of runoff, time to peak, annual exceedance probability (AEP; reciprocal of return period)	

The various approaches to setting flow objectives for aquatic biota presented at a conference of the American Fisheries Society in 1976 (Orsborn & Allman 1976 *op. cit*. Jowett 1997) concentrated on prescription of minimum and optimum requirements for maintenance of the aquatic ecosystem. Jowett (1997) groups such methods into three categories:

- *Historic flow methods* which rely solely on the recorded or estimated flow regime of the river;
- *Hydraulic methods* which relate discharge to surveyed channel geometry, expressing flow requirements in terms of wetted perimeter, width, depth or velocity of water;
- *Habitat methods*, which extend the hydraulic approach to express flow requirements in terms of specific biological needs.

Historic flow and hydraulic methods take into account the unimpacted size and character of the river and assume that lower-than-natural flows will degrade the stream ecosystem. Jowett considers these methods useful in cases where the ecosystem is poorly understood or where a high level of protection is required. Habitat methods make no *a priori* assumptions about the natural state of the river, and accept the possibility that conditions for specific in-stream uses or target species can be enhanced by other-than-natural flows.

More recently, the ecological relevance of flow variability has been recognised, and new techniques have been developed to incorporate this factor. Dunbar *et al*. (1998) review all types of methods presently in use worldwide, and provide a helpful summary table (Table 3.2). Some widely-used and potentially useful approaches are described in more detail below.

Table 3.2: Methods used for setting flow objectives, from Dunbar *et al*. (1998)

3.2.1 Methods which prescribe set flow rates

The most popular historical method is the **Montana method** (Tennant 1976 *op. cit.* Jowett 1997). A specified percentage of the (natural) mean flow is assumed necessary to maintain a healthy stream environment. It is based on data from 11 streams in Montana, Nebraska and Wyoming. For these streams, width, water velocity and depth all began to decline sharply at flows less than 10% of the mean flow. This formed the basis of Tennant's view that the habitat became degraded at <10% of mean flow; the associated average water velocity of 0.25 ms^{-1} and average depth of 0.3 m represented lower limits for aquatic life, providing for short-term survival only. He considered that satisfactory conditions (baseflow regime) occurred at 30% of mean flow, with average water velocity 0.45 - 0.6 ms^{-1} and average depth 0.45 - 0.6 m. The method has apparently now been modified to set monthly rather than annual standards, and is accessed through simple look-up tables. However, the calibration is liable to geographical variation.

Other methods are based on the natural flow duration curve. For example, in Denmark a proportion of the median of the annual minima has been recommended as a minimum flow whilst in New Zealand, a percentage (30-75%) of the 1 in 5 year low flow, and the flow equalled or exceeded 96% of the time (exceedance method) have been used (Jowett 1997, Snelder *et al.* 1998).

Hydraulic methods consider depth, velocity, wetted perimeter or cross sectional area, which increase with flow. Such variables can be derived from the discharge hydrograph, provided hydrometric field surveys are carried out for the reaches of interest (Gustard *et al.* 1987).

Variation in hydraulic geometry with discharge can be established by:

- measurements at different flows
- prediction from cross-section data and stage-discharge rating curves
- Manning's or Chezy's equations
- calculation of water surface profiles.

Two criteria have been used to specify minimum flow requirements using hydraulic methods:

- point of inflection in the relationship between flow and wetted perimeter
- percentage habitat retention, e.g. maximum allowable degradation is a 20% reduction in wetted perimeter from that at mean flow

Habitat methods extend the hydraulic approach to derive the area of suitable habitat for a target species associated with a particular flow. When this is done for a range of flows, it is possible to see how the area of suitable habitat changes with flow and ultimately to derive an optimum flow for the target species. The additional information required is habitat suitability data, derived from repeated observations of water velocity, depth and substrate type in areas used by the target species and usually presented as so-called habitat suitability curves. Several versions of this Instream Flow Incremental Methodology (IFIM) have been developed (see Table 3.2). Considerable success has been achieved in adapting and calibrating the U.S. Physical HABitat SIMulation (PHABSIM) system for use in Britain (e.g. Bullock *et al.* 1991).

The **Basque method** (Docampo & de Bikuña 1995) offers two equations appropriate to different parts of the river and/or levels of pollution. The biotic equation is derived from a diversity spectrum, which relates number of species to geometric mean discharge, calculated incrementally along the river. Assessment of minimum and optimum instream flow requirements is based on maintenance of biological diversity in the summer-autumn period. Distorted diversity spectra are obtained for rivers which are polluted or heavily modified, rendering the biotic approach inapplicable. In such cases, a hydraulic equation is used to calculate minimum acceptable discharge on the basis that the corresponding wetted perimeter is able to maintain 15 or more taxa.

3.2.2 Methods which incorporate flow variability

These methods are based on the principle that river ecology involves complex assemblages of species which constitute functional communities under natural conditions. The whole biota is adapted to the natural flow regime and all its ramifications, for example in relation to geomorphology and riparian habitats, with component species adopting diverse strategies to exploit the total range of habitat conditions offered by the river, in space and in time (see e.g. Power *et al.* 1996).

Such thinking led Australian and South African ecologists to propose the **holistic approach** to assessment of the environmental flow requirements of riverine ecosystems (Arthington & Pusey 1993). In this, the complete 'riverine ecosystem' (source area, river channel, riparian zone, floodplain, groundwater, wetlands and estuary) is considered, and the natural hydrological regime is used as a fundamental guide to the environmental conditions to be emulated through management. It is assumed that if the ecologically essential features of the natural flow regime can be identified and adequately incorporated into a modified flow regime, then the extant biota and functional integrity of the ecosystem should be maintained. The difficulty of distinguishing essential from redundant features of the natural regime must then be addressed. The Australian solution is the **expert panel approach**, in which specialists in all relevant aspects of ecology and geomorphology form a collaborative view of optimum flow regime.

The **Building Block Method**, under development in South Africa, focuses on identifying the most important parts of the natural flow regime for ecology. The philosophy of the method envisaged is to establish ecologically acceptable stable low flow conditions with superimposed mini- and habitat-structuring floods (King & Tharme 1994, *op. cit.* Dunbar *et al*. 1998).

A similar approach is adopted by Stanford *et al.* (1996) in the United States. Stream regulation reduces annual flow amplitude, increases baseflow variation and changes temperature, mass transport and other important biophysical patterns and attributes, potentially severing connectivity between reaches, channels, groundwater and floodplains. It is proposed that dam operation can be used inexpensively to restructure altered flow regimes; in particular restoring peak flows needed to reconnect and periodically reconfigure channel and floodplain habitats, and stabilising base flows to revitalise food webs in shallow water habitats.

Evans (1997), working on the Rivers Wissey and Babingley (England) proposed a method for deriving the full duration curve for the **Environmentally Acceptable Flow Regime** (**EAFR**) appropriate to a defined ecological target, in terms of five benchmark flows (Table 3.3). A value is assigned to each benchmark by field survey followed by modelling (PHABSIM). An acceptable frequency of occurrence is then assigned (largely subjectively) to each benchmark flow to yield the EAFR curve.

Table 3.3: Biologically significant benchmark flows (after Evans 1997).

TEF	Threshold Ecological Flow: that flow which sustains minimum habitat refuges to keep the target species alive
AEF	Adequate Ecological Flow: that flow which sustains low flow habitat for target species
DEF	Desirable Ecological Flow: that flow which sustains connectivity between, and usable habitat in, all reaches for target species
OEF	Optimum Ecological Flow: that flow which maximises usable habitat for the target species
CMF	Channel Maintenance Flow: bank full flow, which maintains and cleanses the channel

In America the idea that the natural, inherently dynamic, flow regime must be central to maintenance and restoration of biodiversity and ecosystem integrity was proposed as a new paradigm for river management by Poff *et al*. (1997). Five features of the natural flow regime (magnitude, frequency, duration, timing/predictability and rate of change/flashiness) are considered essential for ecology, on the basis of over 100 literature references[2] (Table 3.4).

On this basis, a comprehensive quantitative approach to assessing the degree of alteration of flow regime and setting flow targets has been developed by Richter and colleagues (1996, 1997, 1998). This is described in some detail in Section 3.2.2.1.

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[2] List available *via* Internet at http://lamar.colostate.edu/~poff/natflow.html.

Table 3.4: Importance of natural flow regime components in maintaining river habitats and biota, after Poff *et al*. (1997).

Component	Ecological influence
Magnitude and frequency	***Frequent, moderately high flows:*** sediment transport; export of organic resources e.g. detritus and attached algae; promote species with fast life cycles and good colonising ability ***High flows:*** remove fine sediments from interstitial spaces in gravel, providing habitat ***Floods:*** import wood to channel, offering new habitats ***High overbank flows:*** maintain floodplain wetlands; nursery grounds for fish; export organic matter and organisms back into main channel; scour soils promoting germination of some plant species; maintain high water table; maintain flood-resistant disturbance-adapted riparian communities ***Low flows:*** Recruitment opportunities for riparian plants where floodplain frequently inundated; promotes aquatic and riparian species with physiological or behavioural adaptations to drying-out
Duration	Often determines ecological significance of a specific flow condition acting through differences between species in tolerance to e.g. prolonged flooding in riparian plants, prolonged low flow in aquatic invertebrates and fish
Timing/predictability	Life cycles of many aquatic and riparian species are timed to either avoid or exploit flows of various magnitudes, e.g. fish spawning cues, egg hatching, access to floodplain, migration; forest emergency phenology and productivity. Can prevent invasion by non-native species.
Rate of change/flashiness	Behavioural adaptations in native fish, e.g. to avoid displacement by sudden floods; synchrony of root growth in riparian tree seedlings with flood recession.

Table 3.5: Hydrologic Alteration variables and ecological justification for their selection, after Richter *et al*. (1998).

Hydrological variables used	*Regime characteristics group* and Examples of ecosystem influences
Mean discharge for each calendar month	*Magnitude of monthly discharge conditions* Habitat availability for aquatic organisms Soil moisture availability for plants Availability and reliability of water supplies for terrestrial animals Availability of food/cover for fur-bearing mammals Access by predators to nesting sites Influences water temperature, oxygen levels, photosynthesis in water column
Annual maxima and minima: one-day, 3-day, 7-day, 30-day, 90-day means Number of zero-flow days 7-day minimum flow divided by mean flow for year ('base flow')	*Magnitude and duration of annual extreme discharge conditions* Balance of competitive, ruderal and stress-tolerant organisms Creation of sites for plant colonisation Structuring of aquatic ecosystems by abiotic vs. biotic factors Structuring of river channel morphology and physical habitat conditions Soil moisture and anaerobic stress in plants Dehydration in animals Volume of nutrient exchanges between rivers and floodplains Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments Distribution of plant communities in lakes, ponds, floodplains Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
Julian date of each annual one-day maximum and minimum discharge	*Timing of annual extreme discharge conditions* Compatibility with life cycles of organisms Predictability/avoidability of stress for organisms Access to special habitats during reproduction or to avoid predation Spawning cues for migratory fish Evolution of life history strategies, behavioural mechanisms
Number and mean duration of high and low pulses within each year	*Frequency and duration of high/low flow pulses* Frequency and magnitude of soil moisture stress for plants Frequency and duration of anaerobic stress for plants Availability of floodplain habitats for aquatic organisms Nutrient and organic matter exchanges between river and floodplain Soil mineral availability Access for waterbirds to feeding, resting, reproduction sites Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
Means of all positive and all negative differences between consecutive daily values Number of hydrograph rises, falls, flow reversals	*Rate/frequency of hydrograph changes* Drought stress on plants (falling levels) Entrapment of organisms on islands, floodplains (rising levels) Desiccation stress on low-mobility stream edge (varial zone) organisms

3.2.2.1 The Hydrologic Alteration approach

In this approach, 34 different hydrological variables are used to describe the ecologically significant aspects of the flow regime (Table 3.5).

The calculation procedure involves the following steps:

1. Derive a post-impact data series (Fig. 3.1b), for example a discharge record covering a period which post-dates construction of the dam or onset of other anthropogenic influence under investigation. Daily mean discharge values are usually used for rivers, but hourly or monthly means may be substituted.
2. Derive a reference data series (Fig. 3.1a) to represent unimpacted conditions. This may be a discharge record covering a period before perturbation, a synchronous record from an unimpacted reference system or derived from an gauge upstream of the source of impact (useful if climatic change is suspected), or an appropriate “repaired” or synthetic record.

3. From each data series, extract a value for each variable for each calendar year.

Two treatments of these data have been suggested, for different purposes.

<u>Indicators of Hydrologic Alteration (IHA)</u> (Richter *et al.* 1996)

1. Calculate inter-annual statistics for each data series. In this treatment, two statistics are chosen as measures of central tendency and dispersion; in practice the mean value and coefficient of variation (Fig. 3.2). These are calculated for 32 variables, yielding 64 statistics characterising each data series.

2. Calculate the percentage change in each statistic between post-impact and reference conditions, yielding 64 IHA values, presented in “scorecard” format (see Table 3.6).

Fig. 3.1: Two hydrographs for the same river before (left) and after (right) dam construction. From Richter *et al.* (1996).

Fig. 3.2: Comparisons of annual series of four flow variables for pre- and post-impact periods: (a) annual maximum 1-day values; (b) timing (Julian date) of annual minimum 1-day values; (c) annual low pulse counts; (d) annual average rates of hydrograph rise. Broken lines indicate values of the mean (dashes) and standard deviation (dots) for each period. From Richter *et al.* (1996).

Table 3.6: Example of results from Indicators of Hydrologic Alteration analysis. From Richter *et al.* (1996).

Range of Variability Analysis (RVA) (Richter *et al*. 1997, 1998)
This extension of methodology is designed for use in setting river management objectives. However, since the objectives are based on the unimpacted flow regime, the departure of the impacted regime from the natural state is regarded as a measure of hydrologic alteration. The method has been developed to the stage of defining classes of degree of alteration conducive to mapping. The data series are treated as follows.

1. An RVA target range is set for each variable derived from the reference data series. This is usually based upon selected percentile levels (e.g. 25th to 75th percentile) or a simple multiple of standard deviations. The associated management objective is that the impacted river should attain the targeted range at the same frequency as it would in its natural state.

2. Calculate the degree to which the RVA target range is not attained, as

$$((\text{Observed} - \text{Expected})/\text{Expected}) * 100)$$

where "Observed" is the count of years in which the observed value of the variable fell within the targeted range; "Expected" is the count of years for which the variable should fall within the targeted range under unimpacted conditions (Fig. 3.3).

3. Select those variables which are substantially affected by anthropogenic activity.

4. Compute the average of absolute values of hydrological alteration scores for these variables. In the case study reported, six variables were used to calculate mean values. These were drawn from four of the five categories of variables (Table 3.5) as follows:

- *Extreme discharge conditions:* annual maxima and 30-day low flows
- *Timing of extreme conditions:* date of annual maximum and minimum discharge
- *Frequency and duration of high/low pulses:* high pulse durations
- *Rate/frequency of hydrograph changes:* frequency of reversals.

5. Categorise the numerical measures of hydrologic alteration into a small number of qualitative classes. Whilst the authors acknowledge that the definitions of qualitative

classes should correspond to differing degrees of ecological impact, they consider that the range of appropriate ecological data normally available is much too limited to

Fig. 3.3: Examples of application of the RVA method in setting river flow objectives. From Richter *et al.* (1998).

form a meaningful basis for such classification. Therefore, they advocate arbitrary sub-division of the range of possible alteration values as the best practical description of relative degrees of hydrologic alteration at the river network scale. The set of classes used are highly altered (average score exceeds 67%), moderately altered (34-67%) and minimally altered (0-33%).

6. Mapping conventions are prescribed in order to characterise whole stream reaches on the basis of point-based hydrologic alteration data (which apply to the position of the streamgauge).

- High level of alteration (>67%) is assumed to apply from the streamgauge to the location of the first upstream dam; and to the first downstream confluence with a major tributary.
- Moderately and minimally altered (0-67%) conditions are assumed to extend upstream to the location of the first dam, to the location of the first dammed major tributary, or to a contact with a highly altered zone; and downstream to the first confluence with a major tributary.

7. The spatial distribution of averaged hydrologic alteration is then mapped (Fig. 3.4).

Limitations of the IHA/RVA approach

Puckridge *et al*. (1998) criticise the fact that no consideration is made of whether or not the flow variables selected are independent of one another. However, since the analysis tends to yield only a small number of significantly altered variables, perhaps such considerations could be deferred to the post-processing stage.

In the present context, the method is deficient in that calibration of degree of alteration of the flow regime in terms compatible with the European Water Framework Directive; for example the stage at which sensitive species are lost from the biota; has not been achieved.

Fig. 3.4: Map showing degree of hydrologic alteration (3 classes) within the Colorado River system. From Richter *et al.* (1998).

3.3 River classification systems

Within the U.K., several river classification systems have been developed in parallel over the last 20 years, each to serve a different interest (Raven *et al*. 1998). A number of these involve aquatic organisms, using their ecological requirements to indicate significant differences in river characteristics including flow, and so have some bearing on the problem in hand. Another possible reason for their relevance here is the Water Framework Directive requirement for establishment of unimpacted reference rivers as standards for assessment of degree of anthropogenic modification.

3.3.1 Classifications based on biota

Macrophytes: A classification of U.K. rivers based on their aquatic plant communities is described by Holmes, Boon & Rowell (1998); see also Holmes (1983). Between 1978 and 1991, a total of 1514 sites were surveyed on more than 200 river systems in England, Wales and Scotland, which were considered by nature conservation bodies to have reasonably intact macrophyte communities or to contain important plant communities in terms of rarity or species richness. A standard survey technique was employed, covering the entire channel and lower slopes of the banks of a 1 km stretch, recording abundance and cover on separate three-point scales. River flow type, substrate, width, depth, land use, geology, altitude and gradient were also recorded in the field or derived from maps. A three-level vegetation classification was derived using TWINSPAN; distinguishing four groups (A, B, C, D), ten River Community Types of which eight occur in Scotland, and 38 sub-types. The four Groups could be characterised on the basis of altitude of site, height at which river rises, gradient, underlying geology, sediment type and (subjective) flow velocity, and each had a small number of exclusive species. Flow type information is expressed in terms of percentage occurrence of pools, slacks, riffles, runs and rapids, and shows gradation across the ten types (Table 3.7).

Table 3.7 : Percentage occurrence of different flow types associated with each of the ten River Flow Types distinguished on the basis of aquatic plant communities, after Holmes *et al*. (1998)

Group	A				B		C		D	
River Community Type	I	II	III	IV	V	VI	VII	VIII	IX	X
Flow type										
Pool	3	8	4	4	10	8	8	5	27	8
Slack	94	93	90	77	86	83	57	70	62	40
Riffle	1	5	2	12	14	7	30	9	43	41
Run	29	32	56	49	65	71	59	74	40	53
Rapid	1	0	1	2	8	9	9	43	26	58

Invertebrates: A classification of British rivers based on invertebrate communities is available within RIVPACS (River InVertebrate Prediction And Classification System) (e.g. Wright *et al*. 1996, 1998). This system also incorporates a facility to assess the degree of stress for any river system, by predicting the target community for unstressed conditions from physical measurements, then comparing a score derived from faunal observation with that for the predicted community (Moss *et al*. 1999). However, this relies on the scoring system for 85 invertebrate families devised by the Biological Monitoring Working Party (BMWP), intended to reflect their tolerance to pollution (Armitage *et al*. 1983).

3.3.2 Classifications based on flow regime

Mader *et al.* (1997) developed a typology for Austrian rivers and streams based on calculation of a small number of characteristics of the flow regime: the ratio of mean monthly discharge to mean annual discharge and ratios involving two-monthly flow maxima and minima. Eleven classes were derived.

Puckridge *et al*. (1998) were able to characterise and distinguish the flow regimes of widely distributed large rivers on the basis of 23 hydrological measures based on facets of flow variability indicated by a literature review to be significant in relation to fish biology (Tables 3.8, 3.9).

Table 3.8: Biological responses of fish to facets of flow variability, after Puckridge *et al*. (1998)

LONG TERM PATTERNS (FLOW REGIME)	***Life-history responses***
Highly variable timing	Long breeding season, bet-hedging reproduction, flexible spawning strategies
Highly variable duration	Brief life-cycles, early maturity in floodplain species
Highly variable amplitude	Mobility, colonising ability
Long periods of zero flow	Wide physiological tolerances
High spatial variability	High mobility
Low predictability	Flexibility, variable breeding systems
RECENT HYDROLOGICAL EVENTS (FLOW HISTORY)	***Community and population responses***
Extensive surface drying	Local extinction
Protracted zero flows	More large carnivores, dominance of physiologically tolerant and small species, mortality from predation
Repeated low flows	Low abundance, more in-channel spawners
One extreme pulse	One dominant year-class and high population densities, particularly of floodplain-dependent species
High-amplitude variation	Increase in colonising species, irregular age-class strength, dominance of small omnivorous species, variable juvenile recruitment and assemblage composition
Sustained high water levels	High production, increased species richness and biomass, reduced abundance of small species
Highly variable duration	Variable production and recruitment
Rapid pulse recession	Less recruitment of floodplain spawners compared with channel spawners
Reduced pulse frequency	Reduced species richness
Series of increasing pulse peaks	Less proportional recruitment response
Highly variable amplitude of the falling limb	Variable migration intensity, variable mortality and year-class strength
Unpredictability	Assemblage instability, reduced community complexity
High multi-annual flow variation	Major variations in assemblage structure
Repeated high flows	High production
FEATURES OF PRESENT FLOW PULSE	***Behavioural and physiological responses***
Extreme pulse peak	Strong growth, high body condition, intense migration
Short-lived pulse	Weak growth
Steep rising limb	Fall in migration intensity of young fish
Steep falling limb	Weak growth, stranding of floodplain-spawning species
Extreme drawdown	High mortality, less feeding except in piscivores
Atypical pulse timing	No reproduction in seasonal spawners
Low pulse peak	Low incidence of floodplain spawning, weak growth
Extensive surface drying	Refuge-seeking, increased predation
Cessation of flow	Vertical redistribution of intolerant species in response to stratification, increased disease

Table 3.9: Flow variability measures employed by Puckridge *et al*. (1998).

‘Variability’ calculated as range/median (S100), interquartile range/median (S50) or 90th-10th percentile range/median (S80)

Code	*Flow variability measure*
ASKEW	((Mean-median)/median) of all annual flows
ANTF	Variability between years of each year’s variability between months
ATOT	Variability of all annual flows
FALA	Variability of amplitude of all falling limbs
FIVE	Variability of sums of every five years’ total annual flows
FLDR	Variability of the duration of all falling limbs (for zero flows duration calculated to end of continuous zero flows)
PSFR	Variability of number of pulses (peak to peak or trough to trough) in each year
FLRT	Variability of discharge fall per month for all falling limbs
LSEA	Inverse of variability between months of number of pulse troughs in each month
MDAN	Median between years of each year’s variability between months
MDMF	Median between months of each month’s variability between years
MSKEW	((Mean-median)/median) of all monthly flows
MNTF	Variability between months of each month’s variability between years
MTOT	Variability of all monthly flows
PEAK	Variability of all peak discharges
PSEA	Inverse of variability between months of number of pulse peaks in each month
RSA,	Variability of amplitude of all rising limbs
RSDR	Variability of duration of all rising limbs
RSRT	Variability of discharge rise per month for all rising limbs
SEVN	Variability of sums of every seven years’ total annual flows
THRE	Variability of sums of every three years’ total annual flows
TRGH	Variability of all minimum discharges
ZEROF	% of all months in record with zero flow

Poff (1996) classified relatively undisturbed streams in continental U.S.A. according to variation in ten hydrological characteristics which were deemed to be ecologically relevant. These included measures of flow variability and predictability for average conditions, as well as for low- and high- flow extremes. The classification was based on long term (15-58 year) records of daily flow data for 806 streams.

3.4 Some examples which combine methods in addressing specific ecological problems

3.4.1 The Barwon-Darling study (Thoms & Swirepik 1998)

This work addressed the problem of defining environmental flow requirements for the Barwon-Darling section of the Murray-Darling river system in Australia, whose annual discharge had been reduced to only 11% of its long-term median natural flow between 1970 and 1995 by industrial and agricultural water use. The holistic approach proved to be inadequate for assessing this large lowland river, and a "tailor-made" combined methodology was employed.

The steps involved were:

1. Establishment of a scientific panel.
2. Application of the Integrated Quantity and Quality Model (IQQM), a hydrological model capable of simulating stream flows on a daily time-step basis at a series of sites within each river zone to generate various flow and water resource development scenarios.
3. Assessment of modelled scenarios against simulated natural and present conditions by the scientific panel, producing a series of statements on the condition of the river system, a series of questions about the interactions between the river ecosystem and its flow regime, and a list of short term recommendations for quick implementation of suggested environmental flow strategies.
4. By this process, six major physical process zones and the dominant habitat templates (Resh *et al*. 1994) within each zone were identified. Each zone possessed a unique assemblage of river morphologies or physical habitat templates which differed in terms of hydrological regime; i.e. the primary ecological functioning varied between zones.
5. For each zone, river stage was surveyed to the nearest gauging station and discharge levels calculated from stage-discharge rating tables allowing construction of a series of flow bands and thus identifying parts of flow regime that were particularly important for ecosystem functioning.
6. Hydrological analyses were then conducted using the technique suggested by Richter *et al.* (1996), identifying the eight hydrological variables that may have

environmental significance for the river as: flow variability; magnitude; frequency of events in a range of flow bands; antecedent conditions; seasonality; duration of flow events; rate of fall in hydrograph; periods of no flow and drying periods (a natural flow regime feature for semi-arid lowland rivers in New South Wales).

Major recommendations arising from this work were for an adaptive management programme supported by long-term in-channel and floodplain monitoring at key sites; reinstatement of short-to-medium term flow variability with minimal extractions during floods with average return period up to 5 years; and total prohibition of water extraction during the falling limb of floods because the cohesive nature of the channel margins renders them prone to slumping with rapid falls in water level, and bank erosion reduces in-channel habitat availability along the river.

General conclusions relevant to the topic of the present review were:

- The results corroborate those of other studies, e.g. Petts (1996), which have concluded that environmental flow provisions must mimic the natural flow regime as closely as possible.
- It is possible to prioritise flow events according to their ecological importance, and thus to define environmental flow objectives throughout the basin and over the entire flow regime, using the natural flow as a benchmark.
- The basic unit for analysis of environmental flow strategies should be the river zone or reach.

3.4.2 Surface Water Abstraction Licensing Procedure (SWALP)

(Kirmond & Barker 1997)

This procedure, which is still under development, combines an interesting set of concepts to achieve environmentally acceptable flow regimes in conjunction with abstraction licensing in England. The elements of the procedure are:

1. A soft scoring system, incorporating assignment of scores for:

- river type, supported by a picture gallery
- ecology, supported by tables of macrophyte and invertebrate species ranked according to sensitivity to low-flow conditions
- importance for fish

2. Environmental weighting, based on scoring and a consensus of expert opinion
3. Flow naturalisation
4. Setting of a basic "hands-off" flow, at Q_{95} for sensitive and Q_{98} for less sensitive rivers, as indicated by environmental weighting
5. Setting of higher "hands-off" flows to divide the flow range into a series of slices or tranches
6. Licensing of 50% of the available flow within each tranche in order to retain flow variability
7. Integration of demands and returns along the river in order to ensure no double licensing.

3.4.3 Classification of New Zealand rivers (Biggs *et al.* 1990)

The New Zealand "100 Rivers Project" aimed

- to characterise, classify and model New Zealand rivers according to hydrological, water quality and biological properties;
- to provide the first national perspective on water quality and biology using a consistent methodology; and
- to take the first step in providing managers with robust models for predicting the effects on aquatic biota of changes in flow regimes and catchment land use.

It involved a comprehensive programme of data collection on catchment characteristics, flow regime, water chemistry, optical properties, periphyton, benthic invertebrates and trout. Separate classifications based on flow variability, water quality, periphyton, invertebrates and trout were then conducted, using correlative models, with the intention that these classifications would later be combined. However, since there were no clear similarities among classifications performed on separate biological groups, it was impossible to develop a unified classification scheme based solely on the biological character of the country's river systems. Discriminant analysis indicated that different environmental variables were important in each of the classifications (Table 3.10)

Table 3.10: Summary of variables identified as significant at primary and secondary level in each of the classifications of New Zealand rivers.

Classification based on :				
Flow variability	**Water quality**	**Periphyton**	**Invertebrates**	**Trout**
Primary variables				
% flat land Northern steep soils Site elevation Water storage high Water storage med.	Catchment elevation % developed pasture % exotic forests % lime % schist % soft sediments % steep land % town % tussock grass % volcanic ash	Catchment elevation % developed pasture % hard sediments % southern alpine soils % yellow-grey soils	Catchment elevation % developed pasture	% alluvium % rolling % scrub % tussock % volcanic ash
Secondary variables				
Area % lakes	Inverse specific yield*	Conductivity Dissolved reactive-P Low-flow power Silica Specific yield* Temperature	Absorbance 270F Conductivity Mean annual temp. Mean / median flow Median flow Slope of river Visibility	% lakes Mean annual low / median flow Minimum annual temperature

* Specific yield calculated as (median flow ÷ catchment area)

Ecologically sensible groupings of rivers were achieved using an alternative approach, involving distinction of five "ecoregions" with boundaries positioned on the basis of rock type, flow and water quality characteristics (because biological communities had been shown to be primarily related to these physical factors):

1. Northern Ecoregion: low-moderate mean catchment elevations, moderate enrichment, and moderate-high mean annual water temperature.
2. Central Ecoregion: high mean elevations, high amounts of volcanic ash, low variability of flow and low-conductivity waters.

3. Eastern Ecoregion: moderate to high amounts of soft sedimentary rock, associated high conductivities and enrichment, and high flow variability.
4. South-western Ecoregion: small catchment sizes, low amounts of pasture, and low-conductivity waters.
5. Southern Ecoregion: high catchment elevations, low water temperatures, high amounts of hard sedimentary rock, low conductivity and enrichment.

ANOVA analysis indicated that primary variables distinguishing ecoregions were

- climate
- catchment elevation
- geology (% volcanic ash, hard and soft sediments)
- land use (% pasture, grassland, forest)

and secondary variables:

- hydrology (area, median flow, specific yield, flow variability)
- water quality (conductivity, dissolved reactive-P {DRP}, mean annual temperature, total inorganic-N {TIN}, TIN:DRP)

It was then possible to distinguish dominant biological communities for each of the ecoregions.

4. THE LINKAGE BETWEEN CHANGES IN FLOW REGIME AND ECOLOGICAL DAMAGE

4.1 Introduction

The purpose of this part of the literature review is to collect data for calibration of the boundaries of the proposed hydrological classification scheme. The literature which relates ecology to flow regimes is vast, but much of this is rather anecdotal or too limited in scope to be obviously relevant to calibration of catchment- or reach-level flow variables. Nonetheless, the information collated does indicate types of damage likely to result from different types of flow manipulation. Therefore, some literature which refers to each of the major groups of organisms is reviewed below.

4.2 Macrophytes

Macrophytes have been defined as aquatic plants visible with the naked eye and easily identifiable in the field. They are found submerged, emergent or floating or at the water's edge. Large algae, lichens, bryophytes (liverworts and mosses), ferns, horsetails and all higher plants which are aquatic or associated with the water's edge are included (RSPB, NRA & RSNC 1994). Snelder *et al.* (1998) distinguish macrophytes (large, vascular, rooted plants and bryophytes) from periphyton (non-vascular plants forming crusts, films or filamentous mats).

The U.K. National Vegetation Classification (NVC) (Rodwell 1995) describes vascular plant communities. 24 aquatic communities are distinguished, and are assigned to six categories:

1. Surface and sub-surface duckweed and frogbit vegetation (4 communities, of which one occurs in Scotland)
2. Free-floating or rooted and submerged pondweed vegetation (7 communities of which 5 occur in Scotland)
3. Rooted water-lily and pondweed vegetation with floating leaves (6 communities, all occurring in Scotland)
4. Crowfoot and starwort vegetation (3 communities, all occurring in Scotland)

5. Submerged swards of quillworts and hairgrass (2 communities, both occurring in Scotland)
6. Free-floating vegetation of impoverished base-poor standing waters (1 community which occurs in Scotland)

Communities occurring in Scotland and information on habitat are listed in Table 4.1. Rather broad flow tolerances are assigned to most communities, and nutrient status appears to be an important influence.

Robach *et al.* (1997) report differences in macrophyte communities between lateral side arms and a main channel within the Rhine river system. Vegetation in the latter habitat exhibits more complex structure and greater species richness and biomass, associated with flow regime but also with different quality of supply water and habitat variability.

Clarke & Wharton (1998) describe an ongoing project to examine relationships between physical habitat and sediment/macrophytes in combination. Submerged aquatic macrophytes rooted in the substrate potentially derive nutrients from both the sediment and the water, i.e. root and shoot uptake are important. Availability of sediment nutrients seems to be associated with river flow velocity amongst other factors.

Thus, the composition of lotic vegetation may be affected not only by flow regime but also by nutrient status and by the character of the sediment. It is important to note also that the presence of macrophytes may in turn influence the hydraulic geometry of the river channel (Huang & Nanson 1997), perhaps with a seasonal element (Hearne *et al*. 1996), and thus habitat conditions for animals; in particular by providing high food densities and refuge during periods of elevated flow (Garner, Bass & Collett 1996).

Table 4.1: Habitat preferences of aquatic plant communities occurring in Scotland, after Rodwell (1995).

Group and communities	Habitat
1. Duckweed and frogbit communities	
A2 *Lemna minor* community	Standing or very slow-moving, mesotrophic to eutrophic waters, circumneutral to slightly base-poor in reaction.
2. Free-floating and submerged pondweed communities	
A11 *Potamogeton pectinatus-Myriophyllum spicatum* community	Clear, standing to moderately fast-moving waters, generally mesotrophic to eutrophic and base-rich, sometimes marly or slightly saline. On finer mineral substrates.
A12 *Potamogeton pectinatus* community (sporadic records in the north)	Characteristic of still to quite fast-moving eutrophic waters, often with some artificial enrichment, frequently polluted and turbid.
A13 *Potamogeton perfoliatus-Myriophyllum alterniflorum* community	Typical of shallow to quite deep, mesotrophic and rather base-poor waters, still or usually only gently flowing, with fine to coarse mineral beds.
A14 *Myriophyllum alterniflorum* community	Characteristic of lime-poor and less fertile waters, standing to quite swiftly flowing or spatey, in lakes, pools and streams.
A15 *Elodea canadenisis* community	Still to sluggish, nutrient-rich waters, shallow to quite deep, generally with fine mineral beds.
A21 *Ranunculus baudotii* community (south of Solway-Forth line)	Shallows and margins of standing and slow-moving, usually brackish waters in streams, dykes and pools.
3. Water-lily and pondweed vegetation with floating leaves	
A7 *Nymphaea alba* community	Deeper vegetated zones of standing and slow-moving waters, most characteristic of oligotrophic and base-poor conditions; most developed in upland acidic, often peaty basins.
A8 *Nuphar lutea* community (scattered locations in Scotland)	Deeper, standing and slow-moving waters, mesotrophic and eutrophic, in some cases lime-rich.
A9 *Potamogeton natans* community	Mesotrophic to fairly nutrient-poor, standing to moderately fast-flowing waters, sometimes of considerable depth.
A10 *Polygonum amphibium* community	Characteristic of the surrounds and shallows of standing to generally slow moving, sometimes fluctuating, waters, often base-poor and usually only moderately nutrient-rich; periodically wet flood-plain hollows.
A19 *Ranunculus aquatilis* community	Typically found in and around the margins of mesotrophic to fairly nutrient-rich waters, sometimes quite fast-moving, in other cases standing or sluggish. Tolerates periodic or seasonal drying, will colonise disturbed or ephemeral water-margin habitats.

A20 *Ranunculus peltatus* community	Shallows and margins of mesotrophic to quite nutrient-rich waters, occasionally fairly fast-flowing, though usually sluggish or still. Withstands drying-out.
4. Crowfoot and starwort communities	
A16 *Callitriche stagnalis* community	Distinctive in quite fast to very swift, sometimes seasonal or spatey waters in streams with sandy or gravelly beds, base-rich or acidic and impoverished. Also occurs in shallow open water with sluggish flow.
A17 *Ranunculus penicillatus* ssp. *pseudofluitans* community (scattered in south Scotland)	Base-rich but generally moderately fertile waters, moderate to quite fast flow with sandy to gravelly beds
A18 *Ranunculus fluitans* community (just beyond the Scottish border)	Most characteristic of bigger moving waters, often with quite swift flow and stable, stony beds, moderately fertile and not very base-rich.
5. Hairgrass and quillwort communities	
A22 *Littorella uniflora-Lobelia dortmanna* community	Characteristic of the barren, stony shallows of clear and infertile standing waters.
A23 *Isoetes lacustris/setacea* community	Characteristic of barren, stony substrates in the clear, deep waters of less fertile lakes
6. Sphagnum-bladderwort vegetation	
A24 *Juncus bulbosus* community	Characteristic of shallow, base-poor, oligotrophic and often peaty standing waters.

Kirmond & Barker (1997) rank 50 macrophyte species and groups in order of sensitivity to reduction in flow (Table 4.2). Species considered to have greatest tolerance of rivers which are ponded, polluted and contain fine sediments include free-floating and floating-leaved macrophytes, whilst bryophytes are most demanding of rapid currents, clean water and rocky/open gravel conditions.

Snelder *et al*. (1998) employ information attributed to Biggs (1996) to illustrate how dominant vegetation varies with hydro-physical conditions. The order of importance given to physical factors is (1) flow variability, (2) substrate instability and (3) low flow velocity. However, an alternative interpretation is possible; namely that higher plants occur with periphyton on stable substrates so long as low-flow velocity and flow variability are small; bryophytes with periphyton are characteristic of stable substrates where flow variability is high and/or low-flow velocity is high; and periphyton occur alone on unstable substrates unless excluded by high low-flow velocity.

Observations of flow-related changes in macrophyte communities are broadly in line with the apparent ecological preferences of individual species. Wilby *et al*. (1998) report adverse effects of declining river flows on macrophytes in the Test and Itchen, where cover of *Ranunculus* species is positively correlated with flow velocity whilst the opposite applies for filamentous algae. Working on the Bow River in Alberta, Chambers *et al*. (1991) found that macrophytes declined as current velocity rose from 0.01 m s^{-1}, becoming rare in locations where velocity was above 0.1 m s^{-1}. Loss of the submerged species *Potamogeton alpinus*, *Nymphoides peltata* and *Ranunculus* spp. by scouring under abnormally high (but natural) flow conditions in the River Nene is reported by Brierley *et al*. (1989). During severe drought in 1989, dam operations on the Mississippi River created stable water levels, low current velocities and high water clarity throughout the year which promoted development of submerged and floating-leaved aquatic plants in channel borders and backwaters. Moderately high discharge during the two subsequent years reduced water clarity and, in combination with drawdowns, caused this vegetation to decline again (Theilling *et al*. 1996). Rorslett & Johansen (1996) report, on the one hand, absence of macrophytes from many regulated rivers in Norway, and on the other hand nuisance growth in low flow reaches with remedial weirs. Effective removal of macrophytes is achieved using sharply peaking flushing flows to scour sediments with the associated vegetation. Another technique involves halting hydroelectric generation in winter in order to drain the river and expose plants to frost.

Table 4.2 (next page): Ranking of aquatic macrophyte species according to sensitivity to impacts of abstraction. Class 1: rivers which are ponded and polluted with fine sediments; Class 16: rapid currents, clean water and rocky/open gravel conditions. Solid shading indicates normal range of occurrence, “whiskers” indicate occasional occurrence, for each species. Based on “best available information”; from Kirmond & Barker (1997).

4.3 Benthic biota

The benthic biota comprises generally small plants (periphyton) and (invertebrate) animals. They are considered together since similar influences are likely to affect their ecology.

The abundance of stream benthos is sensitive to changes in temperature (rate of growth and development), flow (physical state of substratum), substratum, vegetation, food supply and water quality (nutrient budget). Some species are capable of withstanding high flows, so that the composition of the benthos should be flow-sensitive. Invertebrates in particular are useful indicators of the general health of rivers, since they exhibit rapid responses to a wide range of environmental factors, and may be sampled quickly and easily (Gustard *et al*. 1987).

However, Duncan & Biggs (1998) indicate that the relationship between invertebrate abundance/diversity and flow regime is unlikely to be clear-cut since significant variation is introduced by differences in substrate stability.

In developing an adjunct to the U.S. incremental method for determining habitat suitability for sport fish species (PHABSIM), Gore & Judy (1981) derived habitat preferenda, in terms of current velocity, depth and substrate, for 19 aquatic invertebrates.

The RIVPACS technique (e.g. Wright *et al*. 1996, 1998; see Section 3.3.1) incorporates a scoring system for 85 invertebrate families devised by the Biological Monitoring Working Party (BMWP), intended to reflect their tolerance to pollution (Armitage *et al*. 1983). The SWALP guidance manual (Kirmond & Barker 1997) lists 48 invertebrate taxa in order of tolerance to reduction in flow (although sources of information are not attached). There appears to be little correspondence between BMWP and SWALP scores (Table 4.3).

Table 4.3: Ranking of invertebrate species in terms of tolerance to low-flow conditions (see legend to Table 4.2 for further details) from Kirmond & Barker (1997). The BMWP score for each species (Armitage *et al.*1983) is also shown.

		scores:	SWALP flow type															
Taxon	Common name	BMWP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Acrolarus lacustris (Ancylidae)	Lake Limpet	-	X	X	-													
Corduliidae	Emerald Dragonfly	8	X	X	-													
Naucoridae	Saucer Bug	5	X	X	X	-	-											
Phrygancidae	Cased Caddisfly	10	X	X	X	-	-											
Molannidae	Cased Caddisfly	10	X	X	X	-	-	-										
Cyrinidae	Whirlygig Beetles	5	X	X	X	-	-	-										
Libellulidae	Dragonfly	8	X	X	X	-	-	-										
Psychomyiidae	Caseless Caddisfly	8	X	X	X	X	-	-										
Planorbidae	Ramshorn Snails	3	X	X	X	X	-	-	-									
Coenagrion spp. (Coenogriidae)	Damselfly	6	X	X	X	X	X	-	-	-								
Centroptilum spp. (Baetidae)	Mayfly	4	X	X	X	X	X	-	-	-								
Gerridae	Pond Skater	5	X	X	X	X	X	-	-	-								
Lymnaeidae	Pond Snails	3	X	X	X	X	X	X	-	-	-	-						
Notonectidae	Greater Water-boatman	5	X	X	X	X	X	X	-	-								
Corixidae	Lesser Water-boatman	5	X	X	X	X	X	X	-	-								
Asellidae	Water Hog-louse	3	X	X	X	X	X	X	X	X								
Caenidae	Mayfly	7	X	X	X	X	X	X	X	X	X							
Erpobdellidae	Leech	3	X	X	X	X	X	X	X	X	X	-	-	-				
Sialidae	Alderfly	4	X	X	X	X	X	X	X	X	X	-	-	-				
Gammarus spp. (Gammaridae)	Freshwater Shrimp	6	X	X	X	X	X	X	X	X	X	X	X	X				
Viviparidae	River Snail	6	-	X	X	X	-											
Corophiidae	Tube Building Shrimp	6	-	X	X	X	-	-										
Sphaeriidae	Pea/Orb Mussels	3	-	X	X	X	X	X	X	-	-	-						
Theodoxus fluviatilis (Neritidae)	Nettle Snail	6	-	-	X	X	X	X	X	X	-	-						
Potamopyrugus jenkinsii (Hydrobiidae)	Jenkins Spire Snail	3	-	-	-	-	X	X	X	X	X	X	-	-	-			
Ephemeridae	Mayfly	10				-	X	X	X	X	X	X	X	X	-			
leptophlebiidae	Mayfly	10			-	-	-	X	X	X	X	X	X	X	-	-		
Calopteryx splendens (Calopterygidae)	Banded Demoiselle (Damselfly)	-	-	-	-	-	-	-	X	X	X	-	-					
Simuliidae	Black-fly	5				-	-	-	X	X	X	X	X	X	X	-	-	
Hydropsychidae	Caseless Caddisfly	5				-	-	-	X	X	X	X	X	X	X	-	-	
Lepidostomatidae	Cased Caddisfly	10					-	-	X	X	X	X	X	X	X	-	-	
Plactycnemis pennipes	White-legged Damselfly	6			-	-	-	-	X	X	X	X	X	X	-	-		
Aphelocheiridae	Saucer Bug	10				-	-	-	X	X	X	X	X	X	X	-	-	
Astacidae	Crayfish	8		-	-	-	-	-	-	X	X	X	X	X	X	-		
Ancybus fluviatillis (Ancylidae)	River Limpet	-					-	-	-	X	X	X	X	X	X	-	-	
Ephemerellidae	Mayfly	10					-	-	-	X	X	X	X	X	X	-	-	
Glossoma (Rhyacophilidae)	Cased Caddisfly	7					-	-	-	X	X	X	X	X	X	-		
Goeridae	Cased Caddisfly	10						-	-	-	X	X	X	X	X	-		
Elmidae	Riffle Beetle	-						-	-	-	X	X	X	X	X	X	-	
Philopotamidae	Caseless Caddisfly	8						-	-	-	X	X	X	X	-	-		
Rhyacophila spp. (Rhyacophilidae)	Cased Caddisfly	7							-	-	-	X	X	X	X	-	-	
Leuctridae	Stonefly	10							-	-	-	X	X	X	X	X	-	
Perlidae	Stonefly	10								-	-	-	X	X	X	X	-	
Heptagenidae	Mayfly	10									-	-	X	X	X	X	X	X
Calopteryx virgo (Calopterygidae)	Beautiful Demoiselle (Damselfly)	-						-	-	-	-	-	-	X	X	-		
Perlodidae	Stonefly	10											-	-	X	X	X	X
Cordulegaster boltonii (Cordulegasteridae)	Golden-ringed Dragonfly	8												-	X	X	X	X
Plectrocnemia geniculata (Polycentropodidae)	Caseless Caddisfly	7												-	X	X	X	X

Relationships between occurrence of invertebrate species and flow conditions have been noted and partly developed into the so-called LIFE (Lotic Invertebrates for Flow Estimation) methodology by Extence (1999). This work is so far restricted to communities of chalk and limestone streams, but is claimed to show striking correspondence between occurrence of invertebrate species and flow history, and to have potential in assessment of habitat degradation. The basis of the LIFE system is, however, questioned by Hiley (1999) who found no relationships between invertebrate data and environmental factors in a 27-year record from the Yorkshire Ouse, and points out the immense potential for inconsistency in sampling. Both of these studies are currently unpublished.

Robinson and Minshall (1998) indicate that the influences of chemical status and flow regime on macroinvertebrate performance may be partly separable. Working on two Idaho streams with contrasting flow regimes, they conclude that attributes including density, biomass and production are structured by environmental factors regulating growth, e.g. water chemistry, thermal loading and periphyton, whilst other attributes (e.g. species richness, assemblage composition and life histories) are more closely related to thermal and flow regimes. The latter is underlined by an 11-year German study of aquatic dance flies (Wagner & Gathmann 1996), which indicates time and discharge pattern as the dominating influences, and water temperature regime as a subordinate factor in relation to the ecology of this species.

Clausen & Biggs (1997, 1998) set out to identify hydrological indices with relevance to periphyton and invertebrate ecology at 83 New Zealand stream and river sites. Thirty-four hydrological variables, reflecting flow variability and flood disturbance and showing a high degree of intercorrelation, were tested. Of these, four were significantly correlated with measures of periphyton biomass (chlorophyll *a* and ash free dry mass AFDM), 24 with periphyton biodiversity (Shannon Diversity Index), 31 with total invertebrate density and 4 with invertebrate diversity (Table 4.4). The most useful index in this context was judged to be FRE_3, defined as the frequency of flows higher than three times the median flow. Scatter plots of community measures against their best hydrological predictors, with regression lines, are also offered.

Table 4.4: Correlations between hydrological variables and measures of biomass (B) or density (D), number of species (N) and Shannon diversity index (S) for benthic biota, after Clausen & Biggs (1997). Asterisks indicate that correlation was demonstrated (significance level at least 95%).

Hydrological variables		Periphyton			Invertebrates		
Overall flow variables		B	N	S	D	N	S
Mean flow	Q_{MEAN}	*			*	*	
Median flow, exceeded 50% of the time	Q_{50}	*			*	*	
Skewness, Q_{MEAN} / Q_{50}	SK			*	*	*	
Coefficient of variation, standard deviation / Q_{MEAN}	CV			*	*	*	
Constancy, natural log of daily flow value / Q_{50}	CON				*		
Overall flood variables							
Flood flow index, flood volume / baseflow volume	FFI		*	*	*		
Flow exceeded 10% of the time / Q_{50}	Q_{10}		*	*	*	*	
Flow exceeded 20% of the time / Q_{50}	Q_{20}			*	*	*	
Flood frequency: mean number of floods per year using threshold:							
1 x median	FRE_1						*
3 x median	FRE_3	*	*	*	*		
5 x median	FRE_5		*	*	*		
7 x median	FRE_7		*	*	*	*	
9 x median	FRE_9			*	*	*	
Mean duration of floods, using threshold:							
1 x median	DUR_1						*
3 x median	DUR_3			*			
5 x median	DUR_5				*	*	
7 x median	DUR_7				*	*	
9 x median	DUR_9			*			
Mean number of days in a year in flood, FRE x DUR, using threshold:							
3 x median	TIM_3		*	*	*	*	
5 x median	TIM_5		*	*	*		
7 x median	TIM_7			*	*		
9 x median	TIM_9			*	*	*	
Mean volume of flood water / Q_{50},using threshold:							
1 x median	VOL_1				*	*	*
3 x median	VOL_3			*	*	*	*
5 x median	VOL_5			*	*	*	
7 x median	VOL_7			*	*	*	
9 x median	VOL_9			*	*		
Mean flood peak / Q_{50}, using threshold:							
1 x median	PEA_1		*	*	*	*	
3 x median	PEA_3			*	*	*	
5 x median	PEA_5			*	*	*	
7 x median	PEA_7		*	*	*	*	
9 x median	PEA_9		*	*	*	*	
Low-flow variables:							
Flow exceeded 90% of the time / Q_{50}	Q_{90}	*			*		
Mean annual minimum / Q_{50}	MAM				*		

Gustard *et al.* (1987) consider the effects of compensation flows on invertebrate populations, in largely qualitative terms. A constant compensation flow regime, in excess of natural low flows, results in enhanced numbers or biomass of macroinvertebrates even when short-term fluctuations are imposed; although periodic flushing is desirable to prevent settling of fines clogging interstitial spaces in the substratum. Constant flow below natural may result in severe reduction of wetted area and hence reduction in overall productivity. Complete drying up for even short periods can be catastrophic, although some species are able to survive in pools and under rocks for a short time. However, the accompanying study by the FBA indicates no detrimental effects at compensation flows of 4-60% ADF (average daily flow), using family level identification. Diptera, Chironomidae, Oligochaeta, Amphipoda and Gastropoda are favoured below dams, and microcrustaceans from reservoir water may also appear; Plecoptera are usually severely reduced, whilst Trichoptera and Ephemeroptera may be enhanced or reduced. The most detrimental flow regime is one with substantial and intermittent flow variations, periodically exposing large areas of channel and leaving species stranded. Variations in velocity may destroy pool/riffle relationships and create bank instability. Very high flows (in excess of 2 m s^{-1}) result in scouring of the bottom with a consequent decrease in aquatic vegetation and loss of fine organic food material. The conclusion is that the invertebrate fauna is remarkably resilient to change within the range of compensation flows experienced in the UK; although family composition and abundance does vary with flow regime.

Usseglio-Polatera & Bournaud (1989) found evidence for impoverishment of invertebrate assemblages in a 25-year record from the Rhone, which they attributed to environmental changes resulting from flow regulation. In particular, regular flushing of upstream reservoirs had released sediments which clogged interstitial spaces over long periods, reducing diversity of the substratum and possible food sources; this effect was aggravated by a new dam just downstream of sampling point. Conversely, DeBrey & Lockwood (1990) reported little effect of sediment deposition on aquatic insects in a high elevation Rocky Mountain stream, even though they were most abundant on gravel and rubble substrates. A high discharge in spring severely reduced abundance and diversity but the populations recovered rapidly. The only group which showed little recovery was Diptera.

Cereghino & Lavandier (1998) studied the effect of an intermittently-operating hydroelectric power plant on distribution and larval development of the Plecoptera of a Pyrenean stream. The principal modifications in lotic environment during power generation involved flow and temperature. Upstream of the plant, larvae drifted due to accidental dislodgement whereas downstream of the plant the flushing action of peaking flows caused catastrophic drift. Since Plecopteran life cycles are completed during warm summers when the impact of artificial thermal fluctuations is low, the main influence of this type of river regulation was considered to act through hydrological disturbances. Working in the same geographical area, Lauters *et al*. (1996) report that hydropeaking from hydroelectric plant influences invertebrates and, consequently, fish feeding habits.

Casado *et al*. (1989) studied the effect of flow regulation downstream of the Cernadilla reservoir on the River Tera in northwest Spain. The reservoir is managed for hydroelectric generation and water supply, so that the regulated flow pattern is characterised by higher summer flows, higher daytime than night-time flows, and lower weekend flows. The overall effect on downstream communities was described as adverse, with reduction of macrophytes, fish and invertebrates. However, within this overall pattern, an interesting seasonal effect on invertebrates was identified. Elimination of damaging spring floods was beneficial, whereas elimination of extreme low flows and cooler water in summer was not. This was attributed to the more damaging effect of short-term flow fluctuations in summer. High benthic biomass indicated that lack of food could be eliminated as a possible cause of deterioration of fish populations, which were nonetheless more affected by stream regulation than were the macroinvertebrates.

4.4 Planktonic biota

Ruse & Love (1997) describe responses of phytoplankton taxa to discharge in the Thames, whilst Vieira *et al*. (1998) use mathematical modelling to study eutrophication vulnerability under the artificial flow regime of the River Cavado, Portugal.

Donnelly *et al*. (1997) report development of a cyanobacterial bloom in the Darling-Barwon River during a period of low river flow and hot, still conditions in 1991. This is attributed to a chain of events following influx of sulphate-rich saline groundwater to the river, enabled by prolonged low-flow conditions. The management implication is that sufficient river flow should be maintained to prevent significant groundwater influx.

Kobayashi *et al*. (1998) studied zooplankton in the Hawkesbury-Nepean river, New South Wales (Australia). Results indicated a characteristic increase in protists (*Vorticella* spp) towards the downstream reaches of the river. Community density was significantly negatively correlated with river flow rate, and positively correlated with temperature, turbidity, conductivity, total P and chlorophyll a.

4.5 Fish

Hendry & Cragg-Hine (1996) review habitat requirements for salmon. Preferred spawning sites are in the transitional area between pool and riffle where flow is accelerating and depth decreasing, and gravel of suitable coarseness is present. Suitable flow velocities range from 25 to 90 cm s^{-1}, and depths from 15 to 76 cm. Juvenile salmon occupy shallow, fast-flowing water with a moderately coarse substrate and with overhead cover provided by surface turbulence. Suitable velocities are 20-80 cm s^{-1}. Depths occupied in summer increase from 20 to 60 cm with age, but deeper areas with cobble and boulder substrate are used in winter. Low flows represent an immediate threat to salmon due to elevated water temperature and deoxygenation, and to their redds through stranding, dewatering and freezing. Under prolonged low flow conditions, loss of spawning areas, juvenile rearing habitat and ‘living room’; and failure of adult fish to enter the river or to gain unobstructed passage to spawning areas pose additional threats to successful life cycle completion. High flows and sudden discharge fluctuations associated with flow regulation may result in erosion and coarsening of spawning beds, and promote bank erosion with associated input of undesirable fine material.

A similar study for trout was undertaken by Summers *et al*. (1996), and a review of environmental requirements for trout, salmon and grayling is presented by Crisp (1996).

A substantial amount of recent literature indicates effects of anthropogenic flow modification on individual fish species and life stages; an indication of the types of studies reported follows.

Particularly for juvenile fish, anthropogenically-induced high current velocities may exceed swimming ability, and thus restrict the range of such individuals to areas of shallow water or thick weed (Lightfoot & Jones 1996; Mann & Bass 1997; Flore & Keckeis 1998). Baras *et al* (1995) demonstrated similar habitat preferences between cyprinid species, distinguishing running water fish (*Barbus barbus*, *Leuciscus leuciscus*) from more phytophilous species preferring smooth substratum (*Leuciscus cephalus*, *Condrostoma nasus*). At low flows, the risk of stranding of juvenile salmonids in side channels is increased during rapid flow decreases associated with river regulation (Bradford 1997), and also enhanced by a tendency for individuals which have never sampled pool habitat to remain in riffles during drought (Armstrong *et al*. 1998); although those remaining may bury themselves in the gravel under critical conditions (Debowski & Beall 1995).

The flow regime also influences migration. For cyprinids, within-river foraging may involve movements of 2 to 20 km with marked diurnal and seasonal rhythm, likely to be disrupted by physical obstructions and alterations to the flow regime (Lucas & Batley 1996). Drifting goby larvae are likely to survive to begin feeding in the sea only in above-normal flow conditions (Moriyama *et al.* 1998). Early arrival and rearing of first-year chinook salmon in the Klamath River estuary is associated with poor up-river conditions in low-flow years by Wallace & Collins (1997); whilst Zabel *et al.* (1998) report a tendency in the Snake River for this species to spend more time in regions of high flow velocity, thus enhancing downstream migration speed, as the season progresses. Murphy *et al* (1997) conclude that juvenile Pacific salmon can remain in the lower Taku River for up to two years instead of migrating to sea, implying prolonged dependency on flow conditions outwith their spawning areas.

Patterns of salmonid movement at hydropower dams are associated with water velocity and with turbine operation by Steig & Iverson (1998). Spawning migrations of Canadian tomcod are reported to be influenced by restricted access to the river mouth at high flow (Bergeron *et al*. 1998). Schaffter (1997) observes that upstream movement of sturgeon in the Sacramento River is stimulated by small increases in river flow; whereas Gustard *et al.* (1987) consider that there is little firm evidence that freshet release aids migration of salmon in the U.K., and reduction of travel times of sockeye salmon in the Columbia River between 1955 and 1994 is associated with flow decline and temperature increase by Quinn *et al.* (1997).

Various effects of modification of the flow regime on spawning are also reported. McKinley *et al*. (1998) associate enhancement of lake sturgeon reproductive development with altered river flow below a hydroelectric works in northern Ontario, whereas Auer (1996) reports a positive spawning response in the same species following a change in operation of a Michigan hydroelectric facility to yield near-run-of-river as opposed to peaking flows. Keckeis *et al*. (1997) consider that the predominant factor governing selection of spawning sites by Danube nase is low water current. However, New Zealand koaro are reported to have died of old age whilst waiting for alleviation of low-flow conditions unsuitable for spawning (Duffy 1996). For Atlantic salmon in the Girnock Burn, Scotland, river flow during the spawning period appears to have significant influence on accessibility and subsequent distribution of redds, although bed slope controls the distribution of spawning-calibre sediment (Moir *et al*. 1998). Riffle reconstruction to improve spawning habitat for chinook salmon in three Californian rivers was confounded by scouring of spawning-sized gravel from the river bed at a flow with a return period of 18 months (Kondolf *et al*. 1996). Pinder (1997) points out the potential importance of marinas and gravel pits in maintaining habitat diversity for cyprinid species in the regulated Great Ouse, where suitable natural habitat for spawning and young fish is depleted due to isolation of the main channel from the floodplain. Similar importance is attached to engineered dike fields in the lower Rhone (Nicolas & Pont 1997).

Klingeman *et al*. (1998) report drastic modification of the flow-duration curves for three reaches of the Rhone bypassed in construction of hydropower schemes, reducing annual mean and low flow discharges to small fractions of their former values. In addition to changes in sediment dynamics and channel morphology, the fish fauna has been reduced to a small set of resistant species, placed in the following decreasing order of resistance: roach (*Rutilus rutilus*), bream (*Abramis brama*), white bream (*Blicca bjoerkna*), chub (*Leuciscus cephalus*), bleak (*Alburnus alburnus*), perch (*Perca fluviatilis*), eel (*Anguilla anguilla*) and pike-perch (*Stizostedion lucioperca*).

Bowen *et al.* (1998) investigated the relationships between structure of fish assemblages and availability / temporal persistence of key habitats under natural and regulated flow conditions, using a combination of field sampling and PHABSIM modelling. Hydropeaking dam operation reduced the average length of time that shallow-water habitats persisted and also reduced year-to-year variation in their persistence. Mean fish density was positively correlated with the persistence of shallow and slow water habitats, whilst the proportion of catostomids was positively correlated with persistence of such habitats only during spring. The proportions of cyprinids and percids were respectively positively and inversely related to median availability of deep-fast habitat.

HABSCORE is an empirically derived system for measuring and evaluating salmonid stream habitat features. Catchment and site variables, including mean width, depth, flow type and discharge range, are measured and related to occurrence of fish (Milner *et al.* 1998).

4.6 Habitat quality

The term "habitat quality" is interpreted here in the sense of the U.K. River Habitat Survey (RHS) (Raven *et al*. 1997). RHS was developed in response to the need for a nationally applicable classification of rivers based on their habitat quality. Four related outputs are envisaged:

a) standard field survey method (Fox *et al*. 1998)
b) computer database of national reference network of UK sites
c) classification of river types based on a predictive model of physical structure
d) a scheme for assessing habitat quality

RHS is used to inform the U.K. System for Evaluating Rivers for Conservation (SERCON), which aims to provide a consistent basis for identification of rivers worthy of conservation status on the basis of physical diversity, naturalness, representativeness, rarity, species richness and special features (Boon *et al*. 1997, 1998); other potential applications are in assessment of environmental opportunities for riverine species (Brewin *et al*. 1998; Naura & Robinson 1998). A classification scheme based on more than 5000 surveys remains under development (Jeffers 1998).

The standard survey covers a 500m length of river corridor, 100 m wide. Within this stretch, 10 spot checks and a 'sweep-up' survey are conducted. The full set of features recorded is summarised in Table 4.5. From this, it appears that the aspects of in-channel habitat quality most likely to be influenced by flow regime are those affected by transport of both debris and sediments, e.g. geomorphological attributes such as channel form and stability, and flow type.

Petts (1988) showed elevated concentrations of (sub-2 mm) fines in gravel substrates below dams and for about 2.5 km below the first downstream confluence from each dam, on both the Derwent (England) and the Daer (Scotland). Although considered local, such deposition had implications for the benthic invertebrate communities and, where the proportion of fines exceeded 20-26%, for survival of embryos of some salmonids. Conversely, Ibanez *et al*. (1996) conclude that sediment transport in the lower Ebro River, Spain, has declined by 99% (from 1.0×10^7 Mt year^{-1} to $0.1\text{-}0.2 \times 10^6$ Mt year^{-1}) since construction of large dams at the end of the 1960s. This is attributed to suppression of seasonal and storm-related peaks in sediment transport associated with river regulation and hydropower generation.

Gippell *et al*. (1996) report general depletion of the volume of large woody debris in rivers, through direct removal and clearance of riparian vegetation. In view of the important environmental role of debris and long timescale of natural replacement, artificial re-introduction is being considered. With this end in mind, debris hydraulics are modelled to predict effects of various manipulations.

Table 4.5: Summary of RHS survey data (after Fox *et al*. 1998)

BACKGROUND AND MAP-DERIVED DATA

General information

- Date of survey
- River name
- Catchment name
- OS six-figure grid reference
- Altitude
- Valley slope
- Solid geology code
- Drift geology code
- Mean annual flow
- Distance from source
- Height of source
- Site planform

FIELD SURVEY

Spot check

Channel data

- Predominant substrate:
  - Bedrock / Boulders / Cobbles / Gravel or pebbles / Sand / Silt / Clay / Artificial / Not visible
- Deposition features
- Vegetation types and extent
- Predominant flow type:
  - Free fall / Chute / Broken standing wave / Chaotic / Rippled / Upwelling / Smooth boundary turbulent / No perceptible flow / No flow (dry)
- Modifications

Bank data

- Substrate
- Erosion and deposition features
- Modifications
- Bank face vegetation structure
- Banktop land use

Sweep-up

Channel data

- Braiding/side channels
- Shading of channel
- Trees:
  - boughs overhanging channel / underwater roots / fallen trees
- Debris:
  - dams / coarse woody / leafy
- Extent of:
  - waterfalls / cascades / rapids / riffles / runs / boils / glides / pools / marginal deadwater
- Waterfalls > 5 m high
- Number of riffles / pools
- Artificial features:
  - culverts / weirs / foot bridges / road bridges / outfalls / fords

Bank data

- Shape
- Modifications
- Flood embankments
- Extent of bankside trees
- Exposed bankside roots
- Number of point bars
- Extent of side bars

Other site data

- Valley shape
- Adjacent land uses:
  - broadleaved woodland / coniferous plantation / orchard / moorland or heath / scrub/ tall herb or rank vegetation / rough pasture / improved or semi-improved grassland / tilled land / wetland / open water / suburban or urban development
- Site dimensions:
  - bank-top height and width / water width and depth / embankment heights
- Special floodplain features:
  - artificial or natural open water . water meadow / fen / bog/ carr / marsh / flush
- Notable nuisance species:
  - Giant hogweed / Himalayan balsam / Japanese knotweed

4.7 Riparian zone

In prairie wetlands in Canada, phytoplankton production rose and productivity of non-planktonic algae declined when water depth was increased to 60 cm. Also, density of emergent macrophytes was reduced by flooding (Robinson *et al.* 1997a, b). In similar vein, the Weaver Bottoms, a 4000 acre backwater marsh on the Mississippi in southeastern Minnesota has suffered loss of aquatic vegetation and associated habitat degradation since the 1960s, largely due to persistent high water, sedimentation, and associated re-suspension of sediments and poor light penetration (Woltemade 1997).

Alpine stream corridors have been affected by diking/channelization cutting off large areas of flood plain, and infilling of by-pass channels since the early 19th century. Areas which remain uncultivated have become silted and flooded, initiating establishment of fens which, at 150 years old, exhibit a higher plant diversity than unsilted areas. Flooding/silting operations promoted rapid reinstatement of biological richness in alluvial wetlands (Girel & Manneville 1998).

Stabilization of a newly-repaired embankment section on the Grand Canal in Ireland was unsuccessful when a layer of moss peat seeded with grasses was applied, since the grass roots failed to bind the peat to the sub-layer of Puddle clay and erosion ensued. Transplantation of reeds (*Schoenoplectus lacustris*, *Glyceria maxima* and *Phragmites australis*) was attempted as a potentially more successful technique (Caffrey & Beglin 1996).

Tremolieres *et al.* (1998) report that restoration of floods in the upper Rhine alluvial hardwood forest (*Querco-Ulmetum minoris*) contributes to the preservation of alluvial vegetational structure and composition, the stimulation of biological processes and improved plant mineral nutrition and water supply.

The Platte River in central Nebraska responded to water development by rapid channel narrowing and expansion of native riparian woodland during the 1930s and 1950s, but had stabilised by the 1960s. On most reaches, relatively low flows and infrequent peak flows during the last decade have been sufficient to maintain the open channel area, which may even have increased because floodplain erodability increased as vertical banks developed and woodland aged. However, one section underwent a 10% loss of channel area downstream of an area where vegetation clearing had liberated excess sediment (Johnson 1997).

The apparent variability in responses of riparian tree communities to flow alteration was clarified by Scott *et al.* (1996), who found that the relation between streamflow and establishment of trees is conditioned by fluvial processes. Successful establishment of cottonwoods, poplars and willows occurs on bare, moist surfaces protected from disturbance. During channel narrowing, these requirements are met on portions of the bed abandoned by the stream and establishment is associated with a period of low flow lasting for one or more years. During channel meandering, favourable sites occur on point bars following moderate or higher peak flows, whilst after flood deposition they arise on new deposits high above the channel bed.

5. LAKES

5.1 Introduction

Friedman and Sanders (1978) defined a lake as, ".... a landlocked body of water occupying some kind of basin". A lake may be thought of as a receiving basin, downstream of a receiving catchment area from which water and sediments enter the basin. Lakes modify the discharge from their catchments, acting as both filters and buffers. As a filter, a lake retains a proportion (sometimes 100%) of the sediment being transported into it from the catchment area. As a buffer, a lake modifies both water and sediment quality responses to chemical and biochemical processes operating within its waters. Also, by integrating the inflow from different drainage basins, lakes dampen the extremes of river discharge.

Those lakes that receive drainage of surface waters may, in simple terms, be considered as wider and deeper sections of river systems. As such, the consequences for habitat are characteristically low water velocity and near-constant water depth. However, it should be recognised that some lakes do not receive runoff from rivers and are replenished entirely by groundwater discharge.

There have been several attempts to classify lake systems but the most useful and comprehensive is that of Hutchinson (1957) which is based on mode of formation. Hutchinson lists eleven major processes responsible for building, excavation and damming (Table 5.1) which produce 76 different types of lake basin.

Estimates based on 1: 250 000 scale Ordnance Survey maps, which include standing waters with surface areas of 4 ha and greater, reveal that the total number of freshwater lakes and reservoirs in Great Britain is 5505, of which 3788 (69%) are in Scotland (Smith & Lyle 1979). The vast majority of the Scottish lochs were formed by glacial activity and, as such, fall into Hutchinson's categories 4b, 4c and 4d; although lochs formed due to fluviatile action and associated with shore lines are also present. Thus, within Scotland there are lochs with a wide variety of sizes and shapes, from those occupying long, narrow and very deep rock basins to shallow kettle hollows containing lochans within fluvioglacial deposits. Moreover, since the size and shape of a lake are of great importance in determining its biological characteristics, the Scottish lochs collectively present an equally wide variety of ecosystems.

Table 5.1: Classification of lakes (after Hutchinson, 1957).

1. Tectonic basins
2. Lakes associated with volcanic activity
3. Lakes formed by landslides
4. Lakes formed by glacial activity:
    (a) Lakes held by ice or by moraine in contact with existing ice
    (b) Glacial rock basins
    (c) Moraine and outwash basins
    (d) Drift basins
5. Solution basins
6. Lakes due to fluviatile action:
    (a) Plunge-pool lakes
    (b) Fluviatile dams
    (c) Lakes of mature flood plains
7. Lake basins formed by wind
8. Lakes associated with shore lines
9. Lakes formed by organic accumulation
10. Lakes produced by the complex behaviour of higher organisms
11. Lakes produced by meteorite impact

At the turn of the last century the Scottish freshwater lochs provided the basis for major pioneering limnological studies. These commenced with bathymetric surveys of the chief Perthshire lochs (Earn, Rannoch, Tay and Tummel) being undertaken by Grant Wilson (1888). Perhaps stimulated by Grant Wilson's work (Duck, 1990) but conclusively overshadowing it, an enormous total of 562 lochs, including all the major water bodies of the country, were surveyed between 1897 and 1909 under the direction of Sir John Murray (Murray & Pullar 1910). In conjunction with these surveys, an extensive programme of geological, chemical, botanical and zoological research was carried out. The suite of bathymetric charts, all of which report the water level above OD at the time of survey, and allied data, thus form an important baseline with which to compare contemporary observations. Indeed, even 90 years on, few countries can boast such comprehensive exploration of their freshwater lakes.

Using the Murray & Pullar (1910) data, Gorham (1958) examined interrelationships between drainage area, lake surface area, length, mean breadth, mean depth and maximum depth for 262 rock basins and 137 basins lying in or dammed by glacial drift. In terms of hydrobiology, water temperature is of prime importance. In general the lochs begin to develop thermal stratification by April, with the smallest and shallowest lochans reaching temperatures of 7-10ºC, while the largest and deepest lochs remain at *circa* 5ºC. By May, stratification is usually well advanced in all lochs, with the smallest lochans reaching *circa* 13ºC at the surface while the largest lochs are still cold at about 6ºC. From June to August, surface temperatures of small lochans tend to remain near to 13ºC while the large lochs heat up gradually to this temperature. In shallow lochans (mean depth <2 m) the bottom water temperatures are only a fraction of a degree cooler than those at the surface, while in the deep lochs (mean depth >80 m) they remain at 4-5ºC. By September the small lochs have usually begun to cool down, and by October surface water temperatures are falling in all lochs, while lochs up to about 130 ha in area and 15 m mean depth are nearly isothermal. At this time the large lochs are slightly warmer than the small ones, and remain distinctly stratified (N.B. in the case of Loch Ness, the largest loch, stratification does not break down completely until the end of November). From April to October, average surface and bottom temperatures in the smallest lochans are *circa* 13ºC and 12ºC, respectively, while in the largest lochs the range is from 10ºC at the surface to *circa* 5-6ºC at the bottom (Gorham 1958; Lyle & Smith 1994).

Some insight into lake hydrology arises from Jaani's (1996) description of Lake Peipsi, Estonia. This is large (area 3558 km^2) but relatively shallow (up to 15.3 m deep). Surface discharge by rivers accounts for more than 80% of its water balance, and the average residence time of water is approximately two years. The mean amplitude of annual water level fluctuations is 1.15 m with highest levels occurring in spring.

Virtually all of the major lochs in Scotland are now integrated within the networks of hydro-electric schemes. Many receive water diverted from neighbouring catchment areas and/or have their outflows controlled, for both operational and aesthetic purposes, by weirs or dams. Thus, the water level fluctuations observed today are generally different from those which would have occurred in the natural regime. Indeed, there are few, if any, completely natural major lochs in the country.

A rather small quantity of information on athropogenic modification of lake hydrology was identified, but indicates the types of disturbance to be anticipated.

5.2 Methods used to define the severity and extent of anthropogenic changes in the hydrological regime of lakes

Muzik (1998) studied the effect of river flow regulation on water levels in the adjacent Lake Athabasca in Canada. Maximum water level in the lake normally occurred in July. The change in lake water level regime associated with commencement of flow regulation in 1970 was illustrated by plotting a series of July levels from 1960 to 1999. The change was quantified by comparing the mean and standard deviation of July levels recorded in 19 years before 1970 with the same statistics calculated for 15 post-regulation years.

Hill *et al*. (1998) estimated the variability of the water level regimes of lakes and reservoirs, showing that some modified regimes were hypo- and other hyper-variable by comparison with natural conditions.

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

5.3 Standards, objectives and/or classification schemes used to define lake levels in a manner that protects aspects of ecological status

Hellsten *et al*. (1996) outline procedures for setting water level targets in lakes regulated for hydropower production in Finland. Ecologically based regulation practices (ERP) are based on under water light climate and water level fluctuation data which make it possible to calculate the proportion of the frozen littoral to the total littoral area. Another procedure calculates biomass of benthic fauna from data on water level fluctuation and Secchi depth.

In Scotland, Smith *et al*. (1987) found that littoral macrophytes and zoobenthos communities were impoverished in lochs and reservoirs where regular water level changes occurred, even if their amplitude was quite small, as well as under conditions of large annual water level fluctuations. They concluded that rich littoral communities similar to those of lochs with natural water level regimes occurred in regulated lochs which had an annual water level range of less than 5 m <u>and</u> where weekly changes in water level were not greater than 0.5 m for 85-100% of the time. Impoverished communities occurred where either or both of these criteria was not met.

5.4 The linkage between changes in lake water level regime and ecological damage

<u>5.4.1 Macrophytes and algae</u>

Fraisse *et al.* (1997) evaluated macrophyte species for their suitability for revegetation of the margins of reservoirs with fluctuating water level. In general, tested species were able to survive both drought and immersion. Growth was more sensitive to substrate type than to water stress conditions, and immersion was a more severe constraint than drought. Eight suitable species were identified.

Major changes in vegetation in lakes of west Connemara, Ireland were associated with fluctuations in water level coinciding with periods of drier and wetter climate, which seemed to have much greater influence than phosphorus inputs from surrounding agricultural land (van Groenendael *et al.* 1996).

Isoetes lacustris declined rapidly below 3 m depth in Norway due to low levels of daily insolation (Rorslett & Johansen 1995). In Lake Baciver, Spain, this species survived between depths of 5.8 and 6.1 m ten months after the water level had been raised by 5.5 m, responding to declining irradiance by producing fewer, longer leaves. The following spring, no new growth occurred and this was attributed to low oxygen levels at depth beneath winter ice (Gacia & Ballesteros 1996).

Camargo & Esteves (1996) recorded increase in biomass of the macrophyte *Eichhornia azurea* growing in a tropical oxbow lake in response to a flood pulse which imposed substantial increases in nitrogen and phosphorus levels. Nogueira *et al.* (1996) found that floating stands of *Eichhornia azurea* and *Scirpus cubensis* were enriched by nutrients washed from flooded areas adjacent to the lake at high water levels, and thereafter derived nutrients released by decomposition of old plants directly from the water. By this means, maintenance of high biomass of the stands during the entire hydrological cycle was possible in a closed system with episodic flooding.

Expansion of the Flowering Rush *Butomus umbellatus* to form continuous stands in reservoirs with fluctuating water level is promoted by low water levels (shallow water) following summer drainage (Hroudova *et al.* 1996); whereas the ratio of root to shoot mass of the bulrush *Scirpus ancistrochaetus* was shown in laboratory experiments to decline as water level rose from 0 to 10 cm above the soil surface (Lentz & Dunson 1998).

The Myrkdalem lake in western Norway was permanently drawn down by 1.4 m in 1987, and artificial islands were constructed on the dewatered ground. During the subsequent eight years, major changes in island vegetation were observed. Initial colonisers including acrocarpous mosses were replaced after three years by wetland communities including *Carex rostrata*, *Carex vesicaria*, *Phalaris arundinacea* and *Salix nigricans* which resembled marginal communities present before drawdown (Odland 1997).

Nilsson *et al*. (1997) assessed the long term effect of water level regulation on riparian plant communities of storage reservoirs and run-of-river impoundments in Sweden. Soon after the onset of regulation, there were few species and sparse vegetation cover, regardless of whether the new water level intersected former upland or riparian vegetation. In the longer term, an impoverished vegetation was maintained by storage reservoirs, whereas in run of river impoundments, some community characteristics deteriorated and others recovered compared to adjacent free-flowing rivers. In Norway, revegetation of the shores of reservoirs and impoundments was promoted by light fertiliser dressing but observation highlighted the need for nearby seed banks or refugia. Reducing the designated fluctuation range from 7 m to 1.6 m enabled recolonisation by submerged macrophytes (Rorslett & Johansen 1996). Changes in the Peace River / Lake Athabasca delta (Canada) were studied using digital Landsat data by Wickware & Howarth (1981).

Hill *et al*. (1998) compared shoreline vegetation of regulated and unregulated lakes in Nova Scotia. Regulation rendered the hydrological regimes of different lakes either hypovariable or hypervariable in comparison to unregulated systems for both within-year and among-year fluctuations in water level. In consequence, plant communities of dammed systems were less diverse, contained more exotic species and were generally devoid of rare shoreline herbs. The desired water level regime was defined as one which allowed manipulation of within-year water level variation by 1-2 m whilst ensuring that among-year variation (standard deviation of summer levels) was less than 25% of within-year variation. A similar comparison carried out in Finland indicated slightly higher diversity in littoral vegetation at unregulated Lake Lentua than at regulated Lake Ontojarvi, but that the difference was statistically insignificant. The authors conclude that the vegetation at Ontojarvi is well adapted to the ecological disturbance caused by water level fluctuations (Hellsten & Riihimake 1996).

Lake Saint-Pierre in the St Lawrence River has experienced natural cyclic variations in average seasonal water levels with amplitude of 2 m over the last 80 years. A simultaneous decline in the vertical range of seasonal water levels from 2.2 to 1.5 m is attributed to discharge regulation. A strong negative relationship was observed between seasonal water level and the percentage of emergent plant cover. The lake changed from an open water body at high water levels to a large marshland in dry periods, and these changes were considered to affect aquatic plant biomass allocation and species diversity (Hudon 1997).

De Emiliani (1997) compared aspects of phytoplankton community organisation in river and lake habitats in the Parana River system in Argentina. Whilst water level was the main factor controlling phytoplankton biomass in the river, the lake displayed an autogenic successional sequence during the isolation phase and responses to disturbance during flood. Following damming of the outlet of Lake Kinneret (Israel), water level fluctuations were routinely stretched beyond the limits possible under the natural flow regime of the feeding river. Evidence available in the 1970s and supported by a further 15 years' data indicate that low water levels tend to initiate a chain of physical, chemical and biological changes, involving reduction of hypolimnion volume, consequent increase in concentrations of end products of organic decomposition, and fundamental changes in phytoplankton composition and biomass after fall turnover (Hambright *et al*. 1997).

5.4.2 Invertebrates

White (1999) attempted to apply RIVPACS methodology (see Section 4.3) to invertebrate communities of lake shorelines in Ireland. He found that, despite variation in the type of substrate sampled, each lake had a distinctive invertebrate fauna. He attributed this to the dominance of water chemistry over substrate type in determining community composition.

Hofmann (1998) points out that water level fluctuations affect the size of the pelagic zone relative to the size of littoral habitats, and thus may influence the relative abundance of planktonic and littoral cladocerans in lakes. Mezquita & Miracle (1997) found historical evidence in sediment cores for alternation in the composition of chydorid assemblages of Lake La Cruz, Spain which could be associated with water level variation. Very low and fluctuating water levels or reduced area of shallow water promote *Pleuroxus laevis*, *Alona guttata* and *Graptoleberis testundinaria*, whereas more constant water level under conditions where a sublittoral zone may develop promoted *Chydorus sphaericus*, *Alona quadrangularis* and *Alona affinis*.

Scharf (1997) observed changes following emptying of a lake in Lower Saxony. Small residual ponds contained only creeping ostracod species, whilst the most successful coloniser on re-filling was the good swimmer *Physocypria kraepelini*.

Humphries (1996) found that invertebrate species were unevenly distributed amongst macrophytes in a pool of a lowland Tasmanian river, leading him to suggest that changes in water level and their influence on macrophytes as invertebrate habitat may play an integral part in determining the abundance, richness and assemblage of invertebrates in such situations.

5.4.3 Fish

Clark *et al*. (1998) modelled the effects of water level fluctuation at Brownlee Reservoir, Idaho-Oregon, on reproductive success of smallmouth bass, *Micropterus dolomieu*. The most significant effect indicated was that of magnitude of water level fluctuations during the peak spawning period on egg-to-dispersal survival.

Prokes & Barus (1995) reported survival of fragments of the native population of nase *Chondrostoma nasus* after 17-18 years of diurnal water level fluctuations exceeding 10 m, following impoundment of a river section to create the Mohelno reservoir, Czech Republic. Although fish could reach full spawning condition, natural reproduction appeared to fail under this water level regime, so that survival of adults only was implicated.

Karenge & Kolding (1995) obtained evidence from Lake Kariba to contradict the view that fluctuating water levels have an adverse effect on fisheries. Here, fish catches per unit effort show high correlation and synchroneity with changes, and in particular rises, in water level; and little correspondence with absolute water level even during drought. This effect is attributed to nutrient inputs associated with water supply to the lake.

The cyprinid *Thynnichthys thynnoides* spawned during periods of high water level which resulted in flooding of the littoral zone in a Malaysian reservoir (Ali & Kadir 1996). Similarly, in Pomme de Terre and Stockton Lakes, Missouri, intense spawning activity of gizzard shad (*Dorosoma cepedianum*) occurred during rising water levels, creating relatively few weekly cohorts of hatchlings. The distribution and initial abundance of larvae among weekly cohorts was also influenced by water level, as well as temperature. However, subsequent growth and survival of this species could be related only to other factors, such as temperature, food abundance and density (Michaletz 1997).

6. DISCUSSION

This review has uncovered more than 160 papers and reports relevant to the topic of research in one or more ways. The literature points to a great availability of information regarding hydrological regimes, the ecological impacts of changes in regime, and the management activities which can be undertaken in order to represent river interests. The level of sophistication in the sphere of management activities has been seen to be considerable. However, over the past 5-10 years, a number of research schools addressing these questions have emerged and made considerable progress (see Section 3), so the Scottish requirement for methods of this sort must benefit from recent progress around the world.

The SNIFFER project at hand requires development of a method for the assessment of anthropogenic impact on hydrological regime. Some of the key requirements of the methodology include:

- Reporting of results on a straightforward integer (1-5) numerical scale
- Impact to be indicated on an ecologically meaningful basis
- Impact assessments to be obtainable on any type of watercourse in Scotland, and in any of a range of physical environments
- Assessments should relate only to changes in hydrological regime, even though other site-specific characteristics (e.g. water quality) may also play an important part in controlling ecosystem health
- Assessments should incorporate the concept of risk of ecosystem damage, i.e. recognising that ecosystem response in any given situation cannot be predicted with certainty

6.1 Critique of available general methods

This review of literature has indicated that there has been some considerable development of the methods for assessing the severity and extent of hydrological change – certainly there has been a profusion of variables presented for identifying / quantifying changes in regime, and some of the methods for assessing change claim to be well founded in ecological research, such that 'significant changes' may be considered just that in ecological terms.

Importantly, in moving towards Stage 2 of this project, an overall assessment of the utility of the various methods offering potential for a Scottish hydrological regime classification must be made. The key selection of methods appears in Section 3.2 above. Here, each of these is critically evaluated.

The **Montana method** is an early, rather simple method based narrowly on avoidance of low flows below some fraction of mean flow. This presents a very restricted characterisation of regime compared with other methods which claim ecological relevance, and is therefore excluded in favour of others. Similarly, the **Basque method** is focused on the geometric mean discharge, therefore offering only very indirect and limited relevance to other flow characteristics, and so is also excluded.

The **holistic approach** appears attractive in view of its inherent flexibility, thus offering an ability to take account of a wide range of ecological and geomorphological considerations. However, this flexibility is offered only at a price, namely the suggested need to involve an expert panel for consideration of each river to be studied. In view of the need to assess anthropogenic impact on regimes of rivers and lakes across Scotland, it is felt that this approach would be impractical in view of the human resources required, and is therefore not recommended. However, it should be noted that the quality of decisions obtainable by use of this method may be high, and it is therefore suggested that the holistic approach be noted as worthy of further consideration as a backup method.

The **building block** method appears to be well-founded in terms of being based on the most ecologically important elements of the hydrological regime, but this appears a much more persuasive argument in theory than in practice. How do we define the most ecologically important elements of the hydrological regime; how can these be adapted to different freshwater conditions across Scotland? As with the holistic approach, there appear to be practical difficulties with this method.

The **Environmentally Acceptable Flow Regime** is a recent development from England, and might be expected to offer some utility as such. However, it is focused on the requirements of a target species, rather than the whole of the aquatic ecology. Because of the need for a comprehensive view of the ecological impact of hydrological regime alterations, the EAFR work cannot be adopted for future use.

Finally, the **Indicators of Hydrological Alteration/Range of Variability Analysis** work based on the initial hydrological work of Poff and subsequent developments by Richter and co-workers is considered. Much has been achieved by these scientists in the last five years. Their approach is a highly comprehensive one, characterising each pre- and post-change hydrological series by use of more than 30 variables. By this, it is possible to identify more types of change than is possible with any other method. The various published papers then suggest that, in any individual watercourse, attention is focused on those changes of greatest magnitude, and five groupings of indicators are provided, as a means of condensing information. Ecological calibration is not achieved in a specific way, but ecological relevance is argued, on the basis that the fundamental requirement of aquatic ecosystems is that of variability – a point which the authors argue strongly, and which they support by reference to more than 100 published papers. This school of thought is unchallenged in the literature: a minor point on statistical independence has been made by Puckridge *et al.* (1998) but, so long as only small numbers of variables are used in practice, this does not provide a barrier to application. This proviso underlines the suggestion made by the authors that, while many indicators of alteration may be calculated, only those showing major change need be used – indeed the precise application can be chosen by the user. Therefore, this approach may not be as complex in practice as may first be thought. It is undeniable, however, that the effort required in initially calculating the indicators of alteration will be greater than with other methods – the practicalities of this are not thought to be insuperable, and can be discussed with the Steering Group.

In summary, the IHA/RVA approach is recommended on the following grounds:

- Breadth of assessment of regime alteration
- Acceptance of variability as vital to maintenance of ecological status
- Flexibility

Calibration with reference to local ecosystems remains to be explicitly addressed using this approach. In essence, it is proposed that the general approach of the IHA/RVA system is adopted, namely a comprehensive and flexible assessment of damage incorporating an account of regime variability. This will then require calibration in Scottish conditions, as would any of the other approaches outlined above. Such matters are dealt with further in Section 7.

Calibration of the ultimately-required 5-fold classification of impact to ecologically significant levels is likely to provide the greatest challenge in the whole process of developing a system for Scotland. Practical considerations will need to be borne in mind when attempting to comply with the project Statement of Requirements. Calibration could (theoretically) be attempted at every site by means of empirical data collection but, in practice, this would be highly demanding of staff effort and unlikely to be realistic in relation to application across Scotland.

Any alternative method, departing from this ideal, must therefore be regarded as incorporating some inherent degree of uncertainty, which must be expected to increase with the level of generalisation built into any model. In specifying a model for the prediction of ecological impact due to hydrological regime alteration, the object must therefore be to design a system which will generate the lowest overall uncertainties / errors for application to water bodies across all of Scotland.

The Statement of Requirements introduces the concept of risk, and it is the researchers' interpretation that there is a link between this concept and that of uncertainty. As noted above, the response of a biological community to some change in hydrological regime cannot be predicted with certainty, due to site-specific factors such as water quality, the individual species present, or random factors. However, an effective method of predicting ecological impact will, by definition, generate smaller uncertainties in prediction than will an ineffective one. This can be expressed in an alternative form, using the concept of risk: the risk of correct prediction of ecological impact is proportional to model effectiveness. Therefore, risk and uncertainty can be seen to be directly proportional. This indicates that the use of the risk concept will be advantageous in the implementation of any model in which uncertainty may be a feature. However, if the model is able to predict an impact without the need for reference to risk, then no argument is advanced for the use of this concept. In practice, this consideration of risk and uncertainty leads to the suggestion that the terms used in the final system, corresponding to five classes (as required) should be as follows:

Class	**Description**
1	Undisturbed conditions
2	Low risk of disturbance
3	Moderate risk of disturbance
4	High risk of disturbance
5	Severely disturbed conditions

Note that risk is explicitly identified in classes 2-4, but not in classes 1 and 5.

It is likely, drawing on the literature reviewed above, that impact assessments will need to have regard for multiple aspects of hydrological regime change, and so this consideration would be built in to an initial uncalibrated model for predicting impact. Indeed, it is hoped that, by using an overview of the literature presented in this report, such an initial model may have a functional form which is appropriate to assessing ecological impact in Scottish aquatic ecosystems. However, the process of calibration would then be used to refine the initial model to the range of conditions found in Scotland (see Section 7).

Other important issues, when considering Stage 2 of the project, are:

- Methods needed for obtaining hydrological regime indicators for unimpacted conditions, bearing in mind the lengthy history of some major impacts on Scottish rivers and lochs, and the relative recency of river flow gauging. Methods will need to be established for generation of the hydrological variables required.

- Field survey requirements which might need to be implemented for the sake not only of calibrating methods for assessing ecologically-meaningful assessments of hydrological change, but also for assessing the success of management activities designed to reduce the impact of hydrological regime changes.

It is proposed to develop proposals for these two items as early parts of Stage 2 of the research, in consultation with the Steering Group.

In summary, therefore, this discussion of the available methods of assessing anthropogenic impact on hydrological regime suggests that the methods developed by Poff, Richter and co-workers offer the greatest scope for identifying hydrological change amongst all the methods reviewed. These methods are not limited by some of the fundamental difficulties associated with other methods, as outlined above. The authors do not present their methods as being specifically calibrated on the requirements or characteristics of any one water body, but suggest that, by characterising variability in a comprehensive manner, ecosystem impact will be represented. Recommendations as to how such methods be developed are made in Section 7 below.

6.2 Lakes

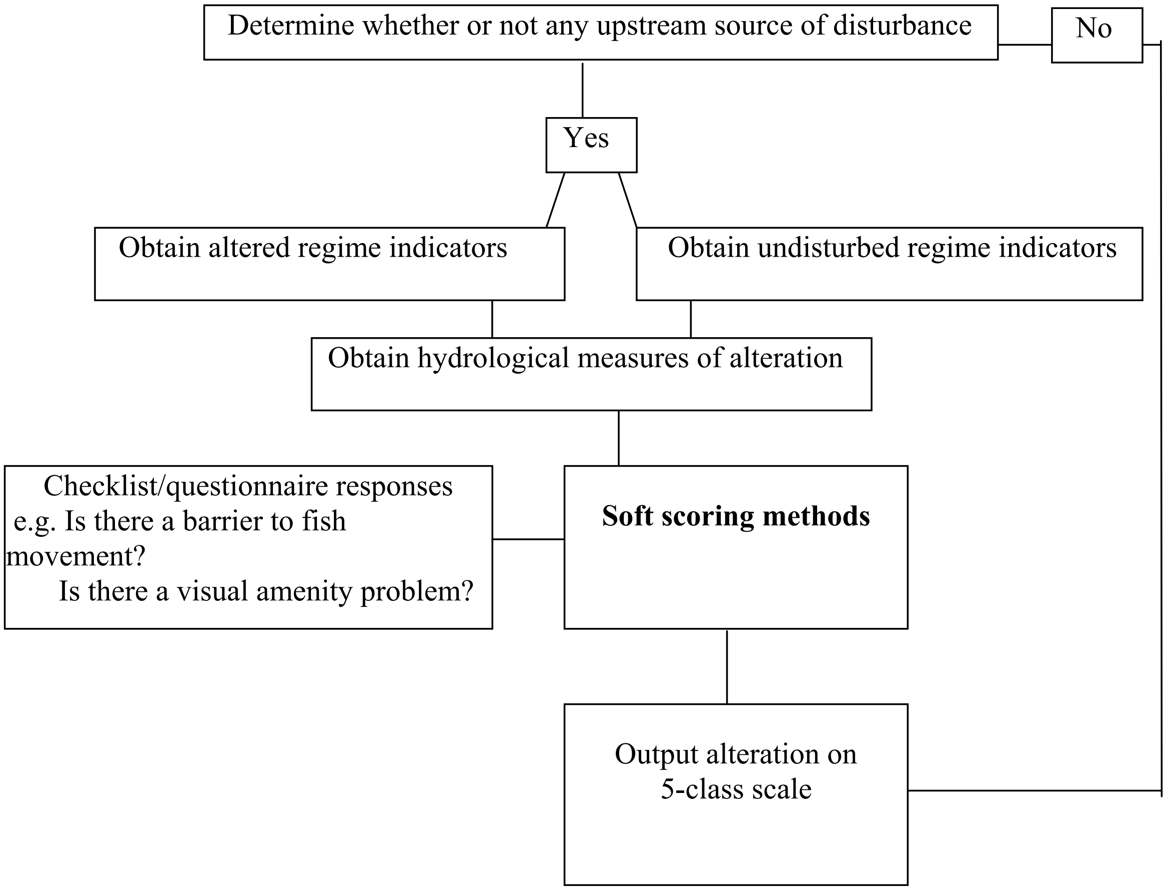
One final point not covered thus far is the application of suitable methods for lakes. This is not helped by the general scarcity of methods addressing the characterisation of hydrological regime changes in lakes. It is proposed, given the strength of argument surrounding the use of variability in addressing rivers using IHA/RVA methods, that the same theme of variability be used in the development of methods for lakes. This would allow for consistency in the treatment of rivers and lakes. In practice, the relative rarity of water level data recording may severely limit the sophistication of what can be developed for lakes. However, it is expected that at least daily time-step data will be available for all lakes operated as reservoirs. It is therefore proposed that a practical sub-set of IHA/RVA variables be adopted for application to lakes, targeted on those lakes in which water level is managed in the context of reservoir operations.

7. RECOMMENDATIONS

This final section of the report puts forward the main thrust and some details of how the research team suggest the project be taken forward.

7.1 Proposed form of assessment method

For river site



The flow diagram above attempts to integrate the key ideas raised in the discussion, and present them as part of a practical system for assessing anthropogenic change in the manner required. Some points should be noted:

The facility for a checklist/questionnaire type of input has been introduced, in order to recognise that there may be particular aspects of hydrological alteration which may not be well recognised by the finally chosen hydrological indicators, but which may nonetheless impact on ecology. For example, construction of an intake dam as part of a water resources scheme will have a greater impact on ecology if it prevents the passage of migratory fish than if it does not. This facility could be developed to take account of factors which may not be well recognised in the derivation of hydrological measures of alteration, and may serve to reinforce assessments made by these means, increasing overall confidence.

Hydrological regime indicators would be obtained by reference to the IHA/RVA type of methods, as justified in Section 6. The precise methods to be used will be developed in Stage 2 of the research.

Soft scoring methods are emphasised (bold type) in the diagram, indicating the important role of this part of the method, in which strictly hydrological and other indicators are used as an input for the estimation of alteration class, being relevant on an ecological basis. It is this element of the methodology which will be required to provide the calibration, discussed above, to ensure that the method is as ecologically meaningful as possible. This is expected to represent a major element of work.

The output is required to take the form of a 5-fold classification, and may be based on the designations suggested in Section 6, bearing in mind the necessity of including a recognition of risk in the output of the methods:

Class	**Description**
1	Undisturbed conditions
2	Low risk of disturbance
3	Moderate risk of disturbance
4	High risk of disturbance
5	Severely disturbed conditions

7.2 Scheduling of method development work

It is proposed to progress the method development work by the following stages. This represents an incremental approach to the requirements of the project, and it is intended that the views and agreement of the Steering Group (or delegated members of it) be obtained at each stage, before proceeding to the next.

1. Test method of obtaining synthetic daily mean flow series using Gustard *et al.* (1992) methods. This should be documented in sufficient detail to allow any user to apply the same methods for the purposes of applying this method to anthropogenic impact assessment. Testing would be achieved by predicting flows for natural river gauging station sites, such that estimated flows could be compared with observed. The researchers would require some limited access to SEPA installations of the Institute of Hydrology Micro Low Flows package, which implements the Gustard *et al.* methods with the required full HOST (Hydrology Of Soil Types) database (Boorman *et al*. 1995). (3 weeks)

2. Unweighted cumulative index of hydrological alteration, based on Richter IHA/RVA methods. These can be grouped in order to give measures of the average alteration according to each of five aspects of the hydrological regime. Alternatively, the most extreme aspects of change may be identified. This work will build on the derivation of synthetic data series described in 1. above. It is proposed that a list of approximately 20 catchments be adopted for this purpose, combining a set of catchments affected by the main types of anthropogenic change with comparable neighbours not affected. It should be noted that Richter and co-workers have expressed the view that, even without specific calibration on the ecological impacts to be expected in a given situation, the results of an exercise of this sort should be regarded as generally indicative of the level of impact caused – i.e. even if the impact is assessed on an arbitrary scale. (1 week)

3. Weighted cumulative index of hydrological alteration – this represents a modest refinement of 2. above. Here it is proposed to attempt some

elementary weighting of the various indicators of alteration, by attempting a simple weighting based on the results of the literature review. This would attempt to identify those types of change which, being relevant to Scottish conditions, are identified as having especially profound impacts (e.g. loss of many biotic elements, long-term ecological impacts), and afford these higher weightings than other types of change. Comparison of the results, applied to the same catchments, with those of 2. above may be informative. (2 weeks)

4. To progress the test catchment work towards a better level of calibration for Scottish conditions, SEPA biological and chemical monitoring data would then be obtained for the test catchments, and steps be taken to compare ecological status at unimpacted sites with that at corresponding sites affected by the range of major impact types. Some guidance may be sought from SEPA staff in the interpretation of the biological monitoring data; water chemistry data are to be included as a means of identifying factors beyond hydrological alteration which may impact on the ecology. At this stage, the soft scoring element of the work would be developed, including checklist-type information as appropriate. The object here is to obtain appropriate functional forms within the soft scoring, and to develop the methodology as a whole towards a stage where physically meaningful results can be produced. Redundant indicators of hydrological alteration would be discarded, if warranted by this process. (4 weeks)

5. The penultimate part of Stage 2 should be a complete review of the preceding parts, allowing identification of key strengths and weaknesses, preferably in consultation with the Steering Group and well before the end of the time allotted for Stage 2. This should then allow further changes to be made, where possible. (2 weeks)

6. Thus far, the methods described have related specifically to rivers not lakes, not least because of the lack of routine monitoring of natural lake levels, and a rather limited literature on the relationship between lake level regime and ecology. It is anticipated that the methods to be put forward for lakes will be

required to be rather more straightforward than those for rivers. It is proposed that, by leaving development of lake methods until completion of the river methods, the most salient points of that exercise can be appreciated and translated to the needs of lakes. Because of the practical constraints, as mentioned in Section 6, it is intended that methods for lakes will only be developed for those which are managed (i.e. for hydro power or water supply). In these cases, water level data will generally be available, and simple indicators be developed to identify the full range of impacts on the basis of hydrological information.

Following the allocations of time indicated, three weeks remain for writing up the Stage 2 report, and for minor contingency.

7.3 Achieving full calibration

From all the information uncovered in the literature review, and for fundamental ecological reasons set out in the introduction to this document, it seems impossible that any method of assessing the severity of hydrological regime alteration impacts will be absolutely reliable: natural systems are complex, and may incorporate chance elements. Therefore, the object of this research must be to develop a method which will be as accurate and reliable as possible, given the available types of input data. The discussion of risk and uncertainty in Section 6 aims to identify the useful role of these concepts given the problems arising from such natural complexities.

It is intended that by the conclusion of Steps 4-6 in the preceding section, the research will have delivered a methodology which will be functionally appropriate to Scottish conditions. However, it will not be possible to have calibrated the methods for every watercourse or situation in Scotland. It is anticipated that the purpose of the Phase II of this SNIFFER programme will therefore be to take the results of Phase I and attempt this calibration on a much more widespread basis.

7.4 Steering Group meeting

This final section of the report sets out the intended direction for the next stage of the project – it is vital to what is ultimately achieved. The Steering Group are encouraged to critically consider these proposals, and the underlying ideas set out in Section 6, and to share their views at the forthcoming project meeting.

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