ENFRAIM review

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1 Introduction

1.1 Scope

The natural flow of rivers has been altered by human activity around the world (Richter *et al.* 1997; Dunbar *et al.* 1998; Petts 1989) and the impacts of these alterations on the river biota have been intensively researched and documented (e.g. Calow and Petts 1992; Drijver and Marchand 1985; Strange, Fausch, and Covich 1999; Tunbridge and Glenane 1988). Many types of alternations and their impacts have been described. For example impaired flood regimes and water quality, destruction of habitats and coastal erosion due to excessive irrigation schemes and dams in upstream parts of rivers. This led to the need for an integrated approach of water management where eventually coastal and river management should be considered interdependent (see UNEP/MAP/PAP 1999).

However, the still increasing demand on fresh water resources for agricultural, domestic and industrial uses has led to the perception by many developers that fresh water that flows naturally to the oceans is a *loss* that has to be prevented. On the other hand there is a recognition by developers and environmentalists alike that freshwater storage does have serious negative side-effects, both environmentally and socio-economically. This understanding can be illustrated by the fact that at least twenty-nine countries seek to minimise ecosystem impacts from large dams by using an *Environmental Flow Requirement* (EFR) to meet predetermined ecosystem maintenance objectives (Dunbar *et al.* 1998). As a result of this need to define an EFR, many methods have been developed. Some of these are very specifically designed for a certain river or requirement (e.g. fish habitats), others are more widely applicable and of a more general context.

1.2 Objectives

Over time the question has risen whether it would be possible to define a method for determining EFRs which can be applied on a very broad scale, taking integrated river basin and coastal management into account. Also, today's existing EFRs often remain fairly descriptive and quantifications are difficult. The ENFRAIM project objective is therefore to develop the concept of EFR into an adequate (i.e. effective and efficient) planning tool for integrated river and coastal management. For this, a solid background in existing practical and theoretical knowledge concerning this topic is required, not only regarding existing EFRs but also regarding the rivers that they were designed for.

The main objective of this report is to give a theoretical framework which describes river systems based on classification methods, developed by different disciplines. This, together with a description of existing EFR-programs can be used within the ENFRAIM project as a starting point for further research on Environmental Flow Requirements.

1.3 Readers guide

This report starts with a short review on EFAs to indicate possible advantages and disadvantages of existing methods (Figure 1). A short review on existing river classifications systems is given after this. These classifications are grouped into three main areas of research (geomorphological, hydrological and biological). Where possible features and submits are described. However for both the review on EFAs as on classification systems the reader is referred to the original text for full explanation of the method described in this report. After these short reviews a description of the functions present within river systems is given, followed by the conclusions. A glossary of much used terms is given in appendix A.

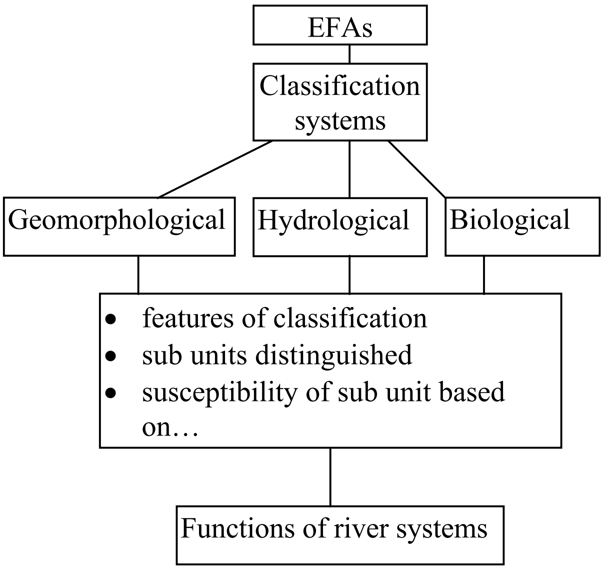


Figure 1 Overview of report structure

2 Environmental Flow Requirements

2.1 Introduction

The term Environmental Flow Requirement (EFR) has developed into a much used and broad term encompassing many issues that all have one major characteristic in common: the need for a definition of a 'healthy and sustainable river system' especially in rivers that have been regulated to a certain extent as a result of human influence (e.g. building dams for hydro-electricity, extraction of water for irrigation purposes or industrial needs). Other common terms for EFR are frequently used as well, such as Ecologically Acceptable Flow Regime (EAFR) (Petts 1996), Minimum Flow (MF) or Instream Flow (IF). The latter two are often used in the USA (Anonymous 2001).

An EFR is a measure of any future flow regime of a river often based on the results of an Environmental Flow Assessment (EFA) (King, Tharme, and Brown 1999) that provides a sustainable river system. The methods first developed (in the 1960s) were based on the judgement of biologists, but were soon followed by simple methods using some measure of the unregulated stream flow (Gordon, McMahon, and Finlayson 1992). Several extensive reviews have been addressing issues related to methods for setting EFRs (e.g. (King *et al.* 1999; Dunbar *et al.* 1998; Jowett 1997; Smakhtin 2001)).

Petts (1996) designed a very general figure that explains the general procedure for deriving an EFR (Figure 2). It describes the setting of an EFR following four steps: (i) performing an ecological assessment by classification of the river into major sectors and reach types, each classified part gets a primary ecological objective, based on a full review of available data (hydrology, morphology, ecology, management etc.). Based on these data ecological targets are set; (ii) setting benchmark flows (flows required to meet the ecological targets); (iii) defining acceptable hydrographs for wet, normal and dry years; (iv) combining these acceptable hydrographs into a flow duration curve.

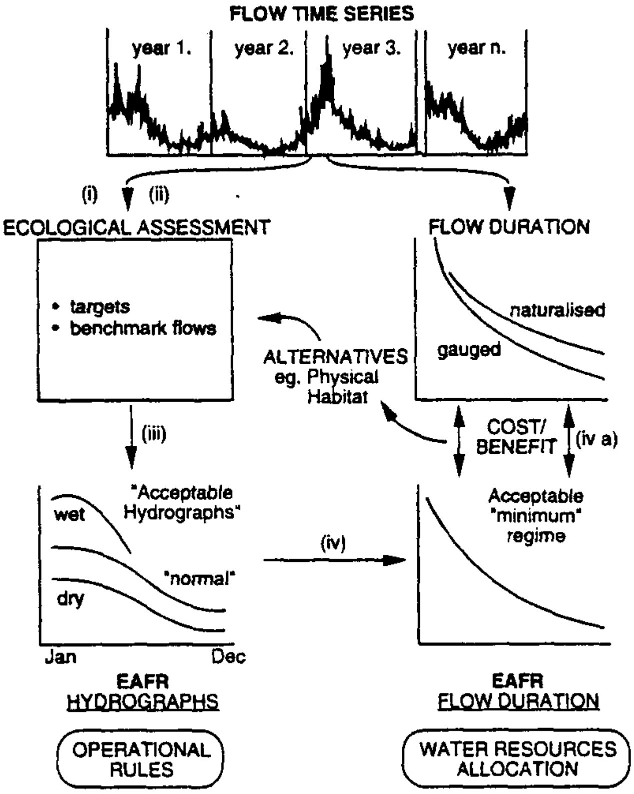


Figure 2 A general procedure for deriving an ecologically acceptable flow regime represented as one or more hydrographs for defining operational rules and as a flow duration curve for assessing abstractable volumes. The procedure allows the evaluation of alternatives including physical habitat improvement as part of the decision-making process. Source (Petts 1996).

Since many different types of EFAs are presently used in different parts of the world, these EFAs can be classified in one way or another. In their review, King *et al* (1999) classified EFAs according to type of methodology. They distinguish I) Hydrological type methodologies II) Hydraulic rating methodologies III) Habitat simulation methodologies IV) Holistic methodologies and V) Methodologies geared towards specific ecosystem components. Other authors (e.g.Jowett 1997; Gordon *et al.* 1992) classified EFAs into historic flow methods, hydraulic methods, habitat methods and transect methods.

Regardless of which type of EFA classification is used, this list of classifications already indicates the broad spectrum which is involved in setting EFRs and the amount of available methods for doing so. A number of EFAs has gained a global recognition and is used in more than one country. These 'international approved methods' will be further discussed here, to give a short overview of successful methods. The classification based on King *et al* (1999) will be used to address these methods. Appendix B gives an overview of many existing EFAs in tabulated form.

2.2 Hydrological methodologies

Hydrological methodologies rely mainly on available hydrological data (e.g. long term monitoring, historical monthly or daily discharge records) and are also termed ‘look-up’ methods (Petts 1996) that aim on determining a ‘minimum’ environmental discharge, which is vital to the ecological functioning of the river. There are at least 15 frequently referenced, hydrology-based methods, of which several are fairly specific focussing on a certain region or context (King *et al.* 1999).

One of the strengths of hydrological methods is that they are usually inexpensive and quick, since only historical flow records are necessary. However, from an ecological perspective this type of methodology is limited in that it does not adequately address the dynamic and variable nature of the hydrological regime. Moreover, the long term effects of maintaining the minimum flows are rarely the same as the naturally occurring infrequent, short-term effects reflected by instantaneous events in the historic record. King *et al* (1999) suggest that the disadvantages of hydrological methodologies make them only appropriate at a reconnaissance level and in cases where no negotiation is involved in the decision-making process. They should be used with caution in regions with hydrological regimes that differ vastly from the rivers for which the method was designed originally and also when river systems have a high conservation importance.

Dunbar *et al* (1998) select the Tennant method (also known as the Montana Method (King *et al.* 1999)) as one of the more promising methods. It is currently the second most widely used EFA in North America. In the Tennant method (Tennant 1976) the percentage of the average annual flow (AAF) is used to formulate baseflow regimes on a seasonal basis, since it assumes that some percentage of the mean flow is needed to maintain a healthy stream environment. This is done using a table linking the percentage of AAF to different categories of instream habitat condition. Tennant examined cross-section data from 11 streams in Montana, Nebraska and Wyoming and found that stream width, water velocity and depth all increased rapidly from zero flow to 10% of the mean flow, and that the rate of increase declined at flows higher than 10%. At less than 10% of the mean flow, he considered that water velocity and depth were degraded and would only provide for ‘short-term’ survival of aquatic life. He considered that 30% of the average flow would provide satisfactory stream width, depth and velocity for a ‘baseflow regime’. He showed that 30% of average flow or higher provided average depths of 0.45-0.6 m and velocities of 0.45-0.6 m/s and considered these to be good to optimum range for aquatic organisms. However, it should be noted that these figures indicate that the examined waterbodies should be classified as ‘streams’ rather than ‘large’ rivers.

Jowett (1997) names a few extra methods based on hydrological parameters, such as the minimum flows used in New Zealand (Forlong, 1994 in (Jowett 1997)) which takes a percentage (30-75%) of the 1 in 5 year low flow and the flow equalled or exceeded 96% of the time. In Denmark a proportion of the median of the annual minima has been recommended as a minimum flow (Miljoestyrelsen, 1979 in (Jowett 1997)).

From a water quality perspective, the “7Q10” method (seven day average flow over a 10 year period) is common for incorporating flow into a water quality plan in several states of the USA. This method is used as part of a Total Maximum Daily Load (TMDL) assessment to determine a waterbody's assimilative capacity. It is based on flow measurements (Anonymous 2001).

The Range of Variability Approach (RVA) (Richter *et al.* 1997) has recently emerged as a more sophisticated form of hydrological index methodology. It aims at providing a comprehensive statistical characterisation of ecologically relevant features of the flow regime, focussing on the role of hydrological variability in sustaining riverine ecosystems. According to its developers the method is intended for application to rivers where protection of natural ecosystem functioning and conservation of natural biodiversity are the primary management objectives. The methodology comprises six basic steps, starting with the characterisation of the natural range of hydrological variation using 32 hydrological indices termed Indicators of Hydrological Alterations (IHA) grouped into five regime characteristics (Table 1). Ranges of variation are set for each of the 32 IHA parameters, for example mean ± 1 Standard Deviation, as flow management targets. For each parameter a management target is set (a range of acceptable values based on the range of natural occurring variation for that value), after which targets are combined into a management system which tries to achieve the targeted flow conditions every year of most of the years (a certain percentage). Monitoring and comparison of the monitoring results with the targets is following these steps after which the target values are evaluated.

Table 1 Indicators of Hydrological Alterations (Source Richter *et al*, 1997)

IHA Statistics Group	Regime characteristics	Hydrological parameters
Group 1: magnitude of monthly water conditions	Magnitude timing	Mean value for each calendar month
Group 2 Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: timing of annual extreme water conditions	Timing	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum
Group 4: frequency and duration of high/low pulses	Frequency duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year (days) Mean duration of low pulses within each year (days)
Group 5: Rate/Frequency of water condition changes	Rates of change frequency	Means of all positive differences between consecutive daily values Means of all negative differences between consecutive daily values No. of rises No. of falls

2.3 Hydraulic rating methodologies

Hydraulic rating methodologies relate various parameters of the hydraulic geometry of stream channels to discharge and are based on surveyed cross-sections, from which parameters such as width, depth, velocity and wetter perimeter are determined. The advantage of hydraulic rating methods above hydrological methods is that they incorporate ecologically-based information on the instream physical habitat requirements of biota. However, they rely on the simplistic assumption that a single hydraulic variable or group of variables can adequately represent the instream flow requirements of a target species for a particular activity. The focus on instream parameters also implies that 'out of channel components' of a river corridor are often overlooked or neglected.

One of the most commonly used hydraulic methods considers the variation in wetted perimeter with discharge (Reiser and Wesche 1989). This method assumes that river or habitat integrity can be directly related to wetted habitat area, typically that of riffle biotopes, since those are very sensitive to changes in discharge. The approach relies on plotted wetted perimeter-discharge curves showing a rapid increase in wetter perimeter with increased flow up to a point, after which the wetter perimeter increases gradually as discharge approaches bankfull. Minimum or preservation flows, usually for fish rearing or maximum production by benthic invertebrates, are generally identified from a discharge near the breakpoint, which is presumed to represent the optimal flow (Gippel and Stewardson 1996). Hydraulic methods are not usually used to assess seasonal flow requirements (Jowett 1997).

2.4 Habitat simulation methodologies

Habitat simulation methodologies evolved out of the previous types of EFAs to create a better understanding of habitat requirements. These methods are assessing the instream habitat in terms of hydraulic variables, such as depth, average column velocity and benthic shear stress. Hydraulic variables are combined with information on the suitability of microhabitat conditions for particular species, life stages or assemblages to predict optimum discharges. When this is done for a range of flows it is possible to see how an area of suitable habitat changes with flow. Jowett (1997) states that since habitat methods are quantitative and based on biological principles, habitat methods are considered (in the USA at least) to be more reliable and defensible than assessments made by other methods.

Habitat methods are more flexible than either hydrological or hydraulic methods since it is possible to examine the variation of the habitat of many species and the life stages throughout the year and to select flows that provide this habitat. However, this means that it is necessary to have a good knowledge of the stream ecosystem and some clear management objectives in order to resolve potential conflicting habitat requirements of different species or life stages (Jowett 1997). Often the computer-based habitat simulation methods have the disadvantage of focussing on a set of specific target species, with the risk of failing to consider other essential components of a stream ecosystem (Jowett 1997; King *et al.* 1999). Also, habitat simulation methodologies require extensive expert knowledge of the stream ecosystem, and proper training and location specific knowledge.

One of the most famous habitat methodologies is the Instream Flow Incremental Methodology (IFIM) (Anonymous 2001; Rushton 2000) originally developed by the Instream Flow Group of the US Fish and Wildlife Service, Colorado in the late 1970s and adapted by many others (King *et al.* 1999). IFIM comprises a collection of computer-based modelling techniques that look at habitat availability as it varies with stream flows, stream depth and substrate, *i.*e., what is on the stream bed. In its entirety IFIM is said to evaluate for selected riverine biota the effects of incremental changes in river flow on the microhabitat features of channel structure, water quality and temperature, as well as on the availability of physical microhabitat within a study reach. Figure 3 gives an overview of the theoretical feedback system of IFIM (Bovee 1982). The different habitat models within IFIM are more detailed represented by Figure 4.

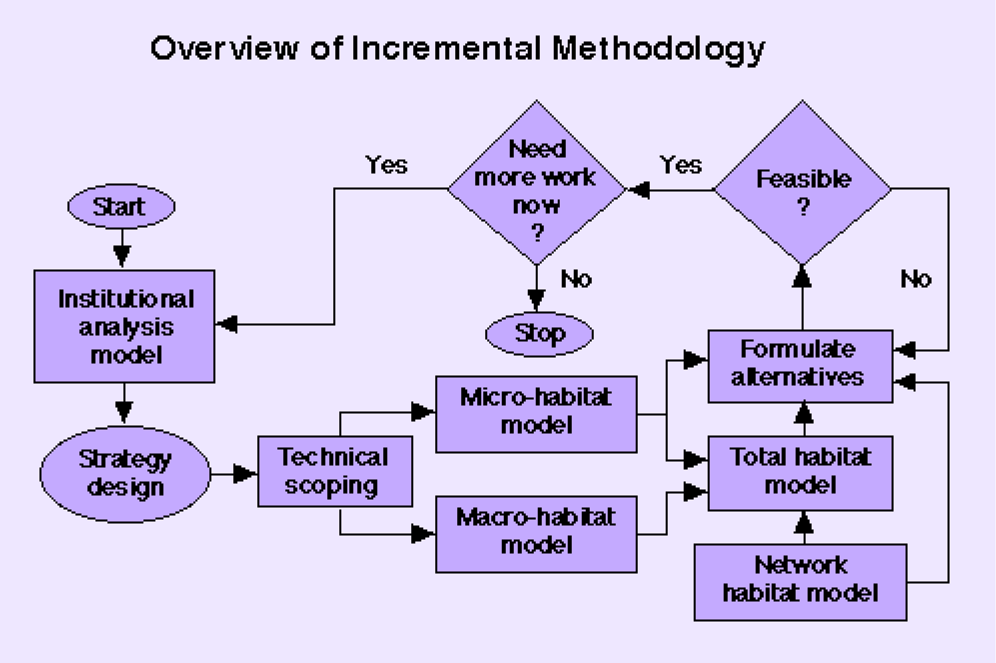


Figure 3 IFIM feedback system

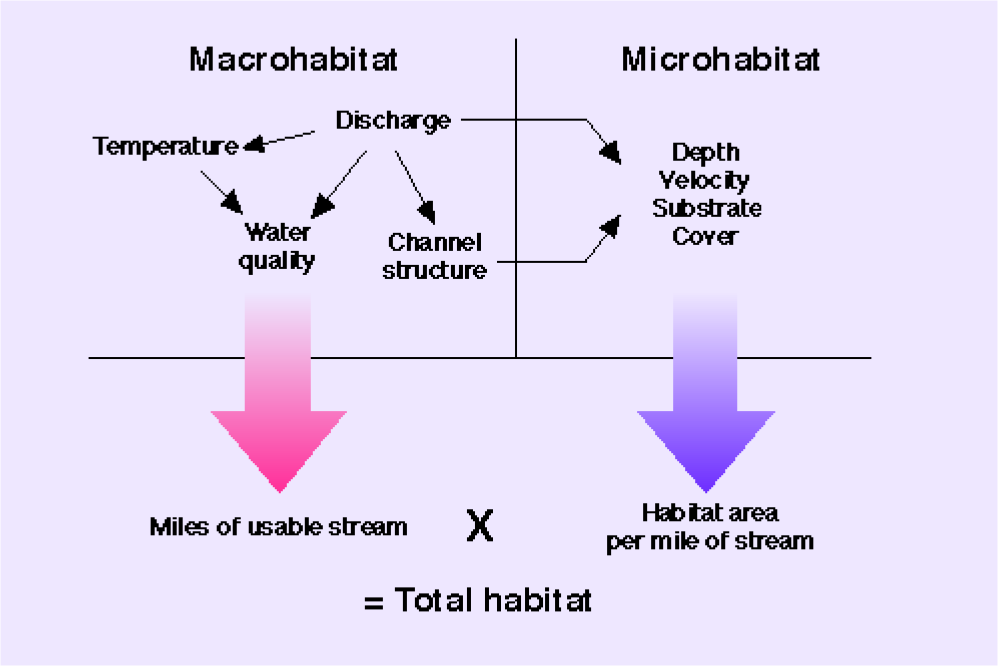


Figure 4 Overview of theoretical background of the habitat models within IFIM (also known as PHABSIM)

The primary component of IFIM is known as the **P**hysical **HA**Bitat **SIM**ulation (PHABSIM, Figure 4) (Smakhtin 2001) and is used to relate total habitat area for particular species to river discharges. This is then combined with a Flood Duration Curve (FDC) and a habitat duration curve is produced (Figure 5). IFIM can also be used to describe other physical habitat conditions that vary with stream flow, particularly quality and other parameters. The product of IFIM is known as Weighted Useable Area (WUA) for the range of discharges that are being examined and their relationship to the target species and their lifestage of interest. It needs to be mentioned that IFIM gives a range of values rather then a specific number for a stream flow. Generally, IFIM follows the natural hydrograph for a particular stream. It is best adapted for use in trade-off analyses but is also very complex and requires considerable time, money and technical expertise.

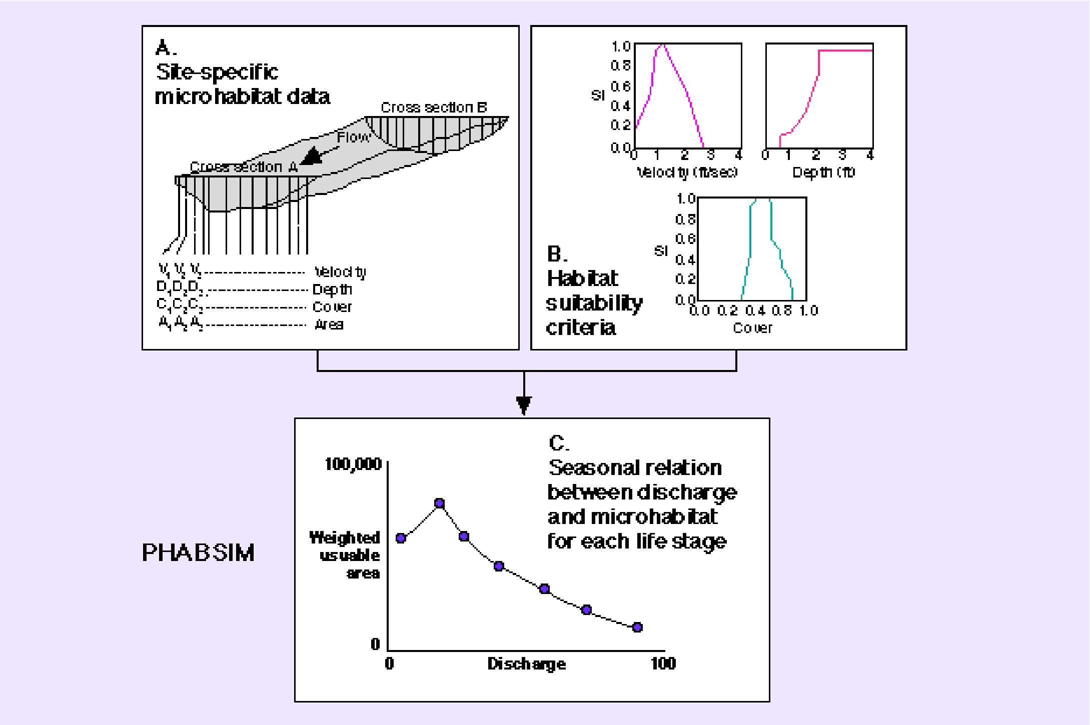


Figure 5 How PHABSIM calculates habitat values. Conceptualisation of how PHABSIM calculates habitat values as a function of discharge. (A) First, depth (***Di***), velocity (***V***i), cover conditions (***C***i), and area (***A***i) are measured or simulated for a given discharge. (B) Suitability index (***SI***) criteria are used to weight the area of each cell for the discharge. The habitat values for all cells in the study reach are summed to obtain a single habitat value for the discharge. The procedure is repeated through a range of discharges to obtain the graph (C)

In Germany another similar type of habitat simulation model was developed called CASIMIR (Computer Aided Simulation Model for Instream Flow Requirements). CASIMIR has been applied for benthic invertebrates as a benthic shear stress model, and new models are under development for fish habitat and riparian zone plant communities. The Mean of Minimum Daily Flows for each year (or a fraction thereof) and expert opinion have been used to assess 100 flows (Jorde 1996). Also, the method developed in New Zealand called RHYHABSIM (River Hydraulics and Habitat Simulation Program, Jowet 1995 in (King *et al.* 1999)) has the basic methodologies like CASIMIR and is thus based on IFIM like approaches.

2.5 Holistic methodologies

Holistic methodologies are all based on the concept that the complete riverine ecosystem (including floodplains, estuarine and offshore coastal systems) is affected by the complete flow regime, so an adequate description of these flows in terms of magnitude, duration, timing and frequency and their incorporation in the regulated flow regime should allow the biotic characteristics and functional integrity of the river to persist (Arthington *et al.* 1992).
It is further assumed that some baseflows and floods within the complete flow regime are more essential than others for maintenance of the riverine ecosystem.

As a result of the multidisciplinary nature of holistic methodologies, many data requirements and types of expertise are required. Comprehensive hydraulic and hydrological data are essential, together with data on biotic features and data on the needs of the local people, which depend on the river for their livelihood (the PAR) are also essential.

A few methods have become widely known. These are the South African Building Block Methodology (BBM) (King and Tharme 1994) and the Australian Holistic Approach (Arthington *et al.* 1992). DRIFT (Downstream Response to Imposed Flow Transformations) later evolved from the BBM. BBM and the Australian Holistic Approach rely on a bottom-up approach to construct a modified flow regime based on month-by-month and element-by-element basis, where each element represents a well-defined feature of the flow regime intended to achieve particular, well motivated ecological, geomorphological, water quality or social objectives in the modified riverine ecosystem. They require intensive baseline data collection, followed by multidisciplinary input in a workshop situation.

Like the BBM, DRIFT is a holistic approach, addressing all biophysical aspects of the river of concern, but this is a top-down approach which focuses primarily on the identification of water levels associated with a particular set of biophysical functions and of specific hydrological and hydraulic character. DRIFT takes the present-day flow regime as a starting point, and describes the consequences for all aspects of the river of further reducing (or, if relevant, of increasing) the flow regime in different ways. Also, it is designed to detail and quantify the links between changing river condition and the social and economic impacts for the riparian people who rely on the river for subsistence (Population at Risk or PAR). The output of DRIFT is a set of EFR scenarios, usually four, that can assess a range of options for operation of a particular water resource development. Each scenario quantitatively describes:

- a modified flow regime;
- the resulting condition of the river, or species, whichever is being addressed;
- the likely social impacts of the resulting condition of the river;
- the monetary costs of mitigation of, or compensation for, the negative social aspect;
- the effect on yield for offstream users.

2.6 Methodologies geared towards specific ecosystem components

Several EFAs are focussed on a specific part of the riverine ecosystem and are most often also linked to a specific river. For example, the maintenance of channel form and fluvial geomorphological and sedimentological processes is focussed on by flushing flow methodologies. These are methodologies which emphasise the need for an occasional extreme water discharge which provides transport of sediment and maintaining channel morphology dynamics. They are also intending to support riverine ecosystems and biota (esp. fish habitats) (Reiser, Ramey, and Wesche 1989). All include a description of channel geometry, cross-section hydraulics, flood frequencies, sediment particle size distributions and transport velocities as well as sediment input types.

King *et al* (1999) note that there are no recognised standard or state-of-the-art office or field methods for this type of methodology. Although more than 25 are used throughout the world (mainly in the USA) many are still prone to uncertainties and subjectivities.

Another type of EFA focuses on water quality purposes. Tharme (1996) mentions a few EFRs focussed mainly on water quality but also notes that IFIM and holistic methodologies are capable of taking water quality into account. Although the water quality modelling of rivers is fairly well developed the extreme complexity of water quality-discharge interrelationships and of biotic responses to changes in quality, makes it difficult to reliably predict environmental flows for water quality, even with models of high resolution. Furthermore, with most water quality models for regulated rivers, guidelines are seldom provided on how the outputs can be used to generate EFRs for the maintenance of downstream water quality (King *et al*, 1999).

Habitat-focussed methodologies also play an important part. For example riparian vegetation, wildlife, types of wetlands, floodplains and estuaries and groundwater and its links with surface flow in rivers can be of importance in such EFRs. It needs to be mentioned that these methodologies are often very specifically designed for a unique situation and many different methods have been designed. Even though this vast amount of specific models exist they most often have the setting of EFRs not as their main goal, but have been created from objectives which focus primarily on the needs for a specific part of biota.

2.7 Concluding on EFAs

There are many different types of EFR methodologies which range from very simple and inexpensive to very complex and expensive. Generally, the results obtained from an EFA are considered more valuable when more effort is spent and more knowledge of the system is available. However, the underlying question for assessing a river system strongly influences the choice of a certain method. Appendix B gives an overview of different EFA methods (source Dunbar *et al.* 1998).

Within the scope of the ENFRAIM project it should be mentioned that all discussed methods have their own advantages and disadvantages. The search for a simple and sufficient method which comprises everything might need to use ideas from a range of methods mentioned in this chapter. It is remarkable that within all these methods the functional properties of a river (socio-economic base) is only included in the DRIFT method. Also, the methods do not mention any actions which focus on determining the cause of the problems that exist in a river system. For example, questions like ‘why is there a shortage of water in the downstream part?’ is not explicitly stated. Often methods directly focus on the technical data gathering with emphasis on the hydrographs of a river and what these should be looking like. Neither do they make distinct remarks on the difference between up- and downstream stream locations.

3 River Classification systems

3.1 General

Most often river alterations have been made in a specific part of the river but affect other parts of the river (e.g. upstream vs. downstream or instream vs. out-of stream systems) in different classes of intensity. For example, the impacts of a large dam are influencing the area downstream of this dam in a different way than the area upstream of this dam (Drijver and Marchand 1985). Therefore, in order to make a proper description of the impacts and results of river alterations and management, it is advisable to have a proper understanding of how EFRs can be used to improve these different parts within a river system. Petts (1996) made a schedule in which the degree of flow regulation, habitat management and stock management are combined to give a classification of rivers according to the degree of artificial influence (Figure 6).

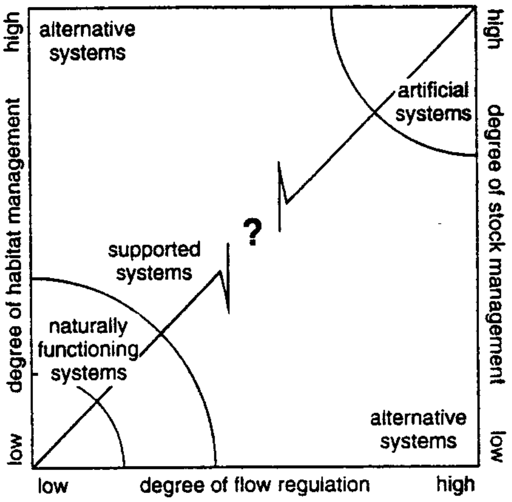


Figure 6 Classification of rivers according to the degree of artificial influences. Alternative systems retain some natural characteristics. An example of an artificial system is a channelized river with an intensively regulated flow regime and a fish population sustained by stocking. In many cases the aim of restoration is to establish supported systems in the same biogeographical region. However, the magnitude of support is uncertain especially when long time-scales are considered. (Source Petts 1996)

Thus, a proper knowledge of the complete river corridor and the different distinguishable parts therein is fundamental to give a sound advise on how to implement an EFR. A way to gain better knowledge of the river corridor system is by classifying the river corridor into subsystems. In this way the several subsystems can be used not only to describe the influence of system alterations but also to describe the effects of a EFR on a specific part of the river corridor.

Over time, a broad range of river classification systems has emerged. Classification systems can be divided in several different ways. A logic division is to group these classification systems into four main groups, based on the expertise field from which they evolved: Geomorphological (I), hydrological (II) and ecological (III) classifications. Also several classification systems exist that (IV) combine several of these groups and link them to a more integrated concept. Concepts can be based on existing features or on dynamic processes in rivers. Within all these different types of classifications it is good to make a remark on the scale for which is was designed, since different spatial scales have a different sensitivity and recovery time (Figure 7). An overview of existing methods will be given, based on the division into the four groups as mentioned above, after taking different temporal and spatial scales into account.

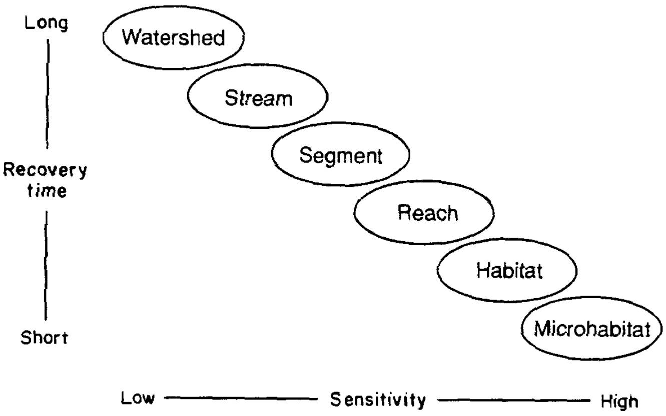


Figure 7 Relation between recovery time and sensitivity to disturbance for different spatial scales associated with stream systems (Source Frissel *et al* 1986)

3.2 Classifications on different temporal and spatial scales

It is important to be aware of the hydrological, geological, morphological and vegetational setting of a stream. Climate is a major factor controlling streamflow patterns and the shaping of landforms and vegetation communities. It provides the energy and water necessary to drive catchment ecosystems. Geology influences the shape of drainage patterns, bed materials and water chemistry. Catchment soils are the weathering products of rock materials, which influence upland erosion potentials, water-infiltration rates and vegetation types. Vegetation is a source of biological production; in turn, it affects channel bank stability and upslope resistance to erosion, water loss through evapotranspiration and rate of runoff (Gordon *et al.* 1992).

Spatial and temporal scales of patterns and processes of fluvial systems can be described in terms of a hierarchy of scales (Frissell *et al.* 1986). Processes and phenomena are coupled according to their scale. Kirkby (1990) presents an example for the wide variety in scales for river systems, see Figure 8.

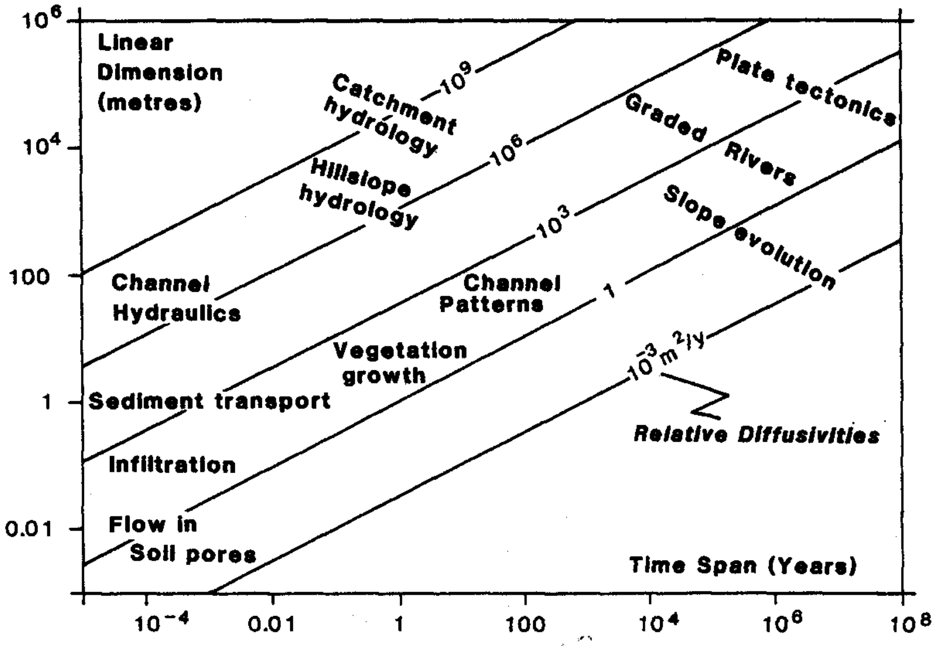


Figure 8 Temporal and spatial scales for river systems, (source Kirkby, 1990)

A hierarchical classification for linked processes at multiple scales is a common method to cope with scale linkage problems of landscapes (Klijn 1994). For river basins these hierarchical classifications have also been made. Naiman *et al.* (1992) give an overview of various hierarchical approaches for stream and catchment classification. Useful approaches are the classification of Frissell *et al.* (1986) and Cupp (1989). Frissell presents a framework for hierarchical classification in which streams and their watershed environments are classified within the context of geomorphic features and events, and spatio-temporal boundaries are identified. Frissell *et al.* distinguish between the *stream system*, *segment system*, *reach system*, *pool/riffle system* and the *microhabitat system* (Figure 9).

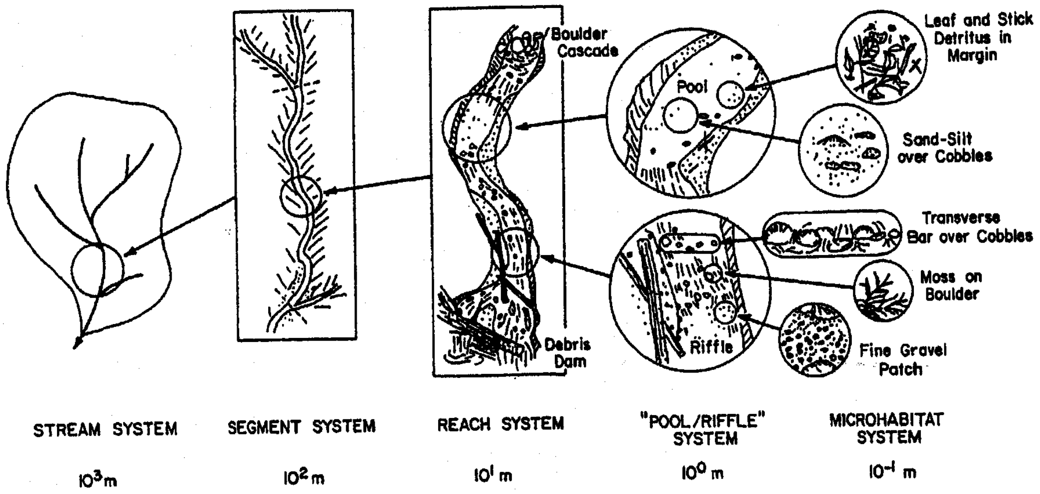


Figure 9 Hierarchical organisation of a stream system, from Frissell *et al.* (1986)

According to Naiman *et al.* (1992) advantages of the classification by Frissell *et al.* are the usefulness at several scales, it is highly adaptable and can describe both temporally stable (e.g. valley segment) and temporally unstable units (e.g. dynamic stream types).

River basin scale

On the scale of the entire river basin, for an idealised river, Schumm (1977) distinguishes three zones in terms of the overall water and sediment balance. These zones are the *production zone*, the *transfer zone* and the *deposition zone*. The production zone is the uppermost zone from which water and sediment are derived. This zone is primarily eroding. Downstream from the drainage basin lies the transfer zone in which the sediment input equals the sediment output. Eventually the sediment is deposited in the deposition zone (Figure 10) (Schumm 1977).

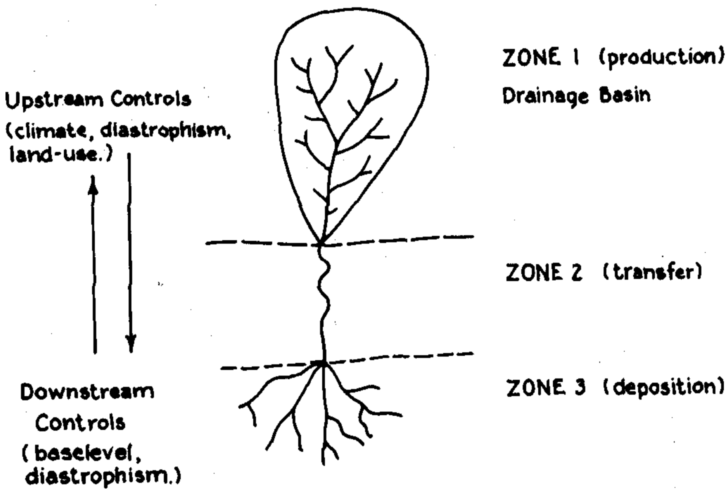


Figure 10 Idealised fluvial system, from Schumm (1977). Each zone is defined by control factors such as climate, diastrophism (tectonic processes), land-use etc.)

At this highest hierarchical level, the spatial and time scales of the developmental processes and patterns are very large, ranging from hundreds to ten thousands of kilometres and thousands to hundreds of thousands of years. Dominant processes for the development and physical characteristics are tectonic movements, climatic change and sea level changes. Typical indicators for classification are the biogeoclimatic region, the slope and shape of the longitudinal profile and the drainage network structure (Frissell *et al.*, 1986).

Segment scale

A river segment is a portion of the river basin delineated by major topographic discontinuities in the structure of the bed, slope, river discharge and sediment quantities. At this hierarchical level, the spatial and temporal scales of the evolutionary processes and patterns are large. Characteristic dimensions for river segments are lengths of hundreds to one thousand kilometres. Within segments, channel planforms can be defined. These planforms remain in a dynamic equilibrium for hundreds to thousands of years (Frissell *et al.*, 1986; Rademakers and Wolfert 1994; Gregory *et al.* 1991).

The development of a specific type of river planform is dependent on abiotic parameters, such as discharge, slope, median grain size, stream power, and width/depth ratio, but also on the biotic factor of vegetation cover. The channel planform of alluvial river segments can be classified into four main types, viz. those with straight, meandering, braided or anabranching planforms, but within each type there is a range of morphologic characteristics (Figure 11). Thorne *et al.* (1997) provide many classification schemes and figures from literature.

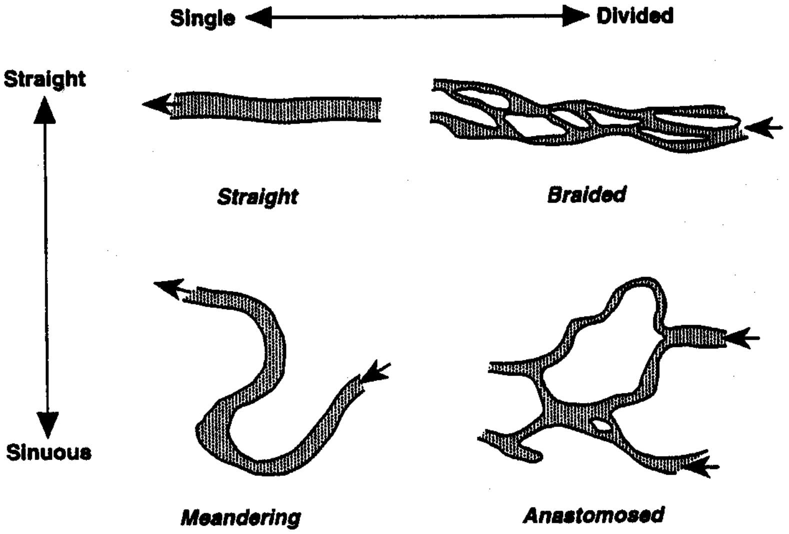


Figure 11 Classification of channel pattern, from Thorne *et al.* (1997)

Developments in vegetation cover, for example due to climate change, can alter river runoff and the relation between resisting power and stream power and therefore change the channel pattern (Starkel 1990). Starkel designed a figure which represents these changes on a global scale level and distinguishes river types based on their latitude (Figure 12).

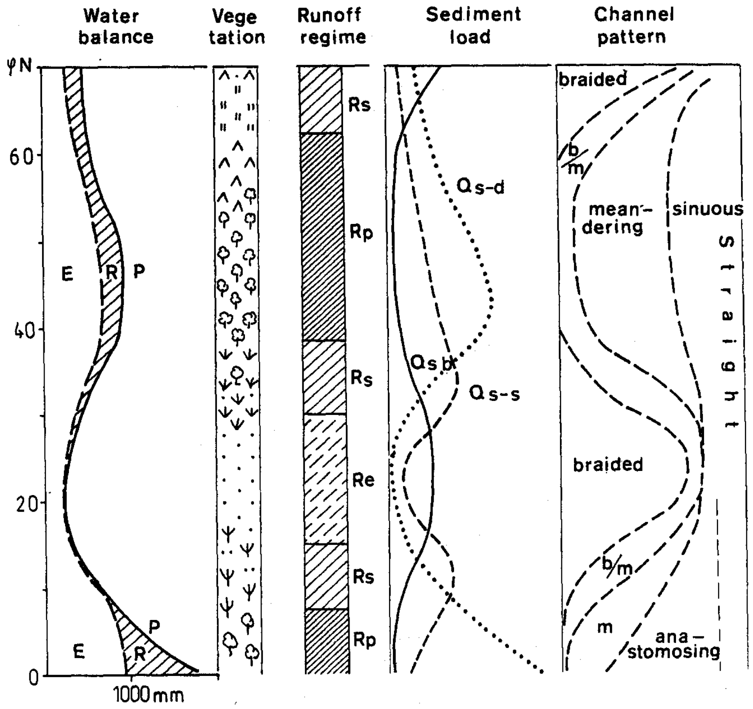


Figure 12 Changes of elements of fluvial systems in N-S transact Europe-Africa, source Starkel (1990)

Reach scale

The river reach is defined as a length of a river segment lying between breaks in channel slope, local side slopes, valley floor width, vegetation and / or bank material (Frissell *et al.*, 1986). The river reach is primarily defined on the basis of *longitudinal* characteristics or gradients. At the hierarchical level of river reaches, spatial and time scales of the developmental processes and patterns are smaller than for river segments. An important ecological concept on the functioning of streams that can be applied to the reach scale is the River Continuum Concept (RCC) (Vannote *et al.* 1980) (see also 3.5.1). The RCC couples the macrofauna communities found in different reach sections to the dynamic physical conditions in the channel.

Effects on river channel process by influencing the channel roughness can be due either to over-channel vegetation, viz. the vegetation that occurs alongside the channel including riparian growth, and the within-channel vegetation (Gregory and Gurnell 1988). The riparian zone is defined as that part of the biosphere supported by and including recent fluvial landforms and is inundated or saturated by the bankfull discharge (Hupp and Osterkamp 1996). Together with the within-channel vegetation they have considerable impact on the hydraulic roughness and the transport of sediment.

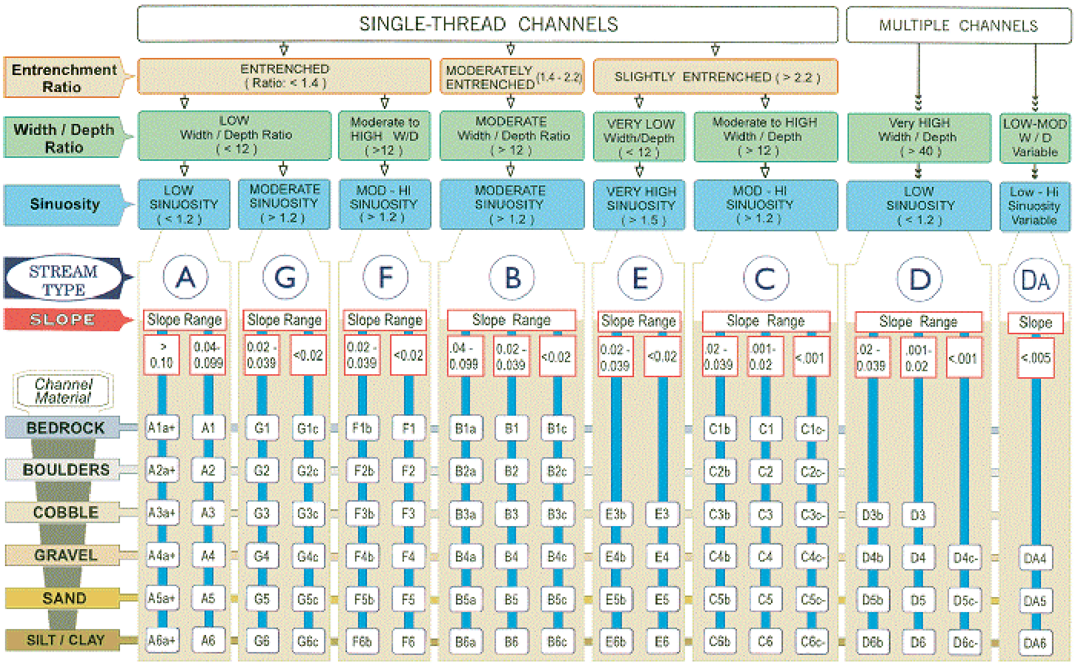
Ecotope scale

A river ecotope is a subsystem of a reach determined by bed topography, water depth and current velocity and position relative to the main channel (Frissell *et al.*, 1986). The definition of a river ecotope is mainly based on *lateral* gradients within a river reach. At the hierarchical level of river ecotopes, spatial and temporal scales of processes and pattern development are small. Characteristic ecotopes range from tens of metres to one kilometre and typical time scales of development range from one to tens of years (Baptist, 2001; Wolfert, 1996).

3.3 Geomorphological classification

Geomorphological processes occur on time scales ranging from microseconds, which are relevant for turbulence velocities, up to hundred millions of years for geological processes. The spatial scales are similarly wide, from millimetres for capillary flows in sediments up to the continental and global scales. Goodwin (1999) gives a review on reach scale geomorphological classification systems. He states that morphological classifications implementing a classical view have been popular since many of these have used the global property of river shape in plan form as the primary delimiter. Therefore they can be used fairly general and comparisons between different riverine systems are easily made. The following eight examples give an indication of the variety within the geomorphological classifications:

1. Already in 1957 Leopold and Wolman distinguished between braided, meandering and straight rivers reflect patterns associated with a combination of several hydraulic factors (see also Figure 11) (Leopold and Wolman 1957).
2. Kellerhals *et al* (1976) designed an aid to summarise descriptive field data (valley, valley flat, stream characteristics channel pattern, islands, channel bars and major bedforms. (Kellerhals, Church, and Bray 1976).
3. Rosgen (1994) developed a classification of natural rivers with heavy emphasis on dimensional properties to define eight primary stream types using a hierarchical decision tree and features like channel threads, dimensional properties of entrenchment ratio, width-depth ratio, sinuosity. Sediment size and channel slopes are used to classify these types into subcategories (Figure 13).

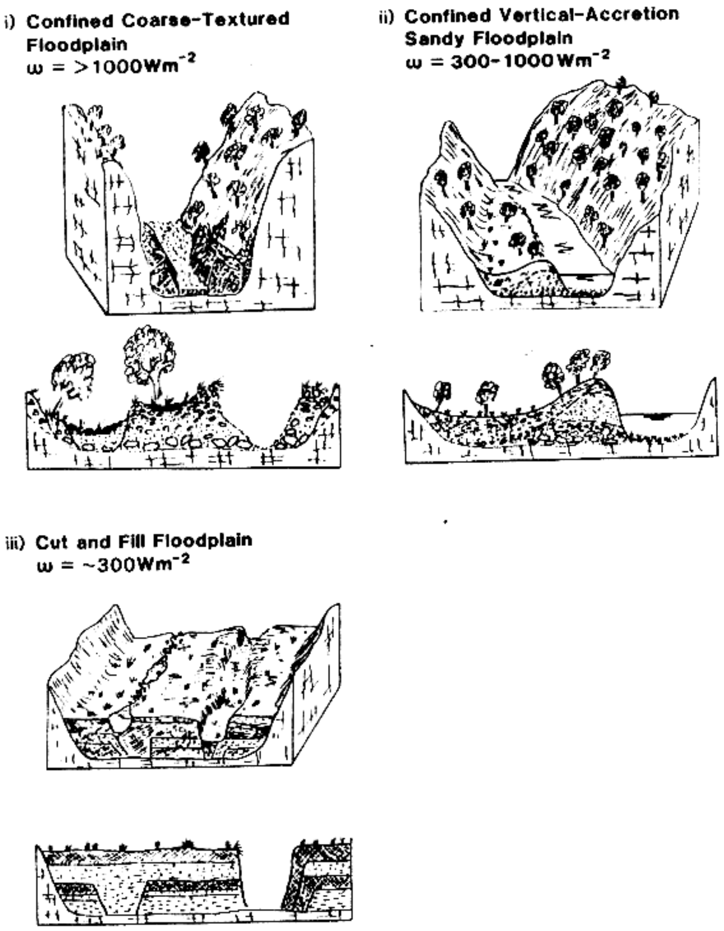


KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Figure 13 Classification system of natural rivers (Rosgen 1994)

4. A classification which defines and predicts the sedimentation and erosion regimes across the entire spectrum of channel styles defining eight categories that relate the rates of channel to floodplain aggravation and degradation (rate of change of channel elevation and rate of change of floodplain elevation) was suggested by Woolfe and Balzary (1996).
5. Whithing and Bradley (1993) made a classification system for headwater streams with 42 classes defined on the basis of domains in three two-dimensional phase space 'panels' where the domains represent different and distinct physical processes and their relative rates (dimensional properties, morphological features including channel gradient, channel width, valley width and median sediment size) (Whiting and Bradly 1993).
6. Montgomery and Buffington (1997) distinguished 7 channel types based upon overall qualitative morphological character. It uses adjective feature descriptions identifying typical and dominant variation (Montgomery and Buffington 1997).
7. Miall (1996) describes a sedimentology based system in which 16 styles are grouped into three major classes (1) gravel dominated, (2) sand dominated high-sinuosity and (3) sand-dominated low sinuosity. These three types represent identifiable depositional environmental and may be identified by sinuosity, braiding parameter, sediment type and characteristic architectural elements. Styles are named based upon predominant characteristic (e.g. flashy, ephemeral, sheetflood, sand-bed rivers). This is a very descriptive method and can only be used for gravel and sand dominated systems (Miall 1996).

8. Nanson and Croke (1992) made a genetic classification of floodplains of alluvial channels. They recognise three main classes of floodplains: high-energy non-cohesive, medium-energy non-cohesive and low-energy cohesive. These three classes are further subdivided into thirteen suborders based on nine factors. These nine factors are all geomorphic or fluvial factors. This classification system is often referred to and Figure 14, 15 and 16 give an indication of the underlying method. Nanson & Croke's genetic classification uses the variables Valley width, Gross stream power, Individual channel width, Specific stream power, Quantity of sediment load, Calibre of sediment load and Discharge.


i) Confined Coarse-Textured Floodplain $\omega = >1000 Wm^{-2}$

ii) Confined Vertical-Accretion Sandy Floodplain $\omega = 300\text{-}1000 Wm^{-2}$

iii) Cut and Fill Floodplain $\omega = \sim 300 Wm^{-2}$

Figure 14 High energy non-cohesive floodplains (Source Nanson & Croke, 1992)

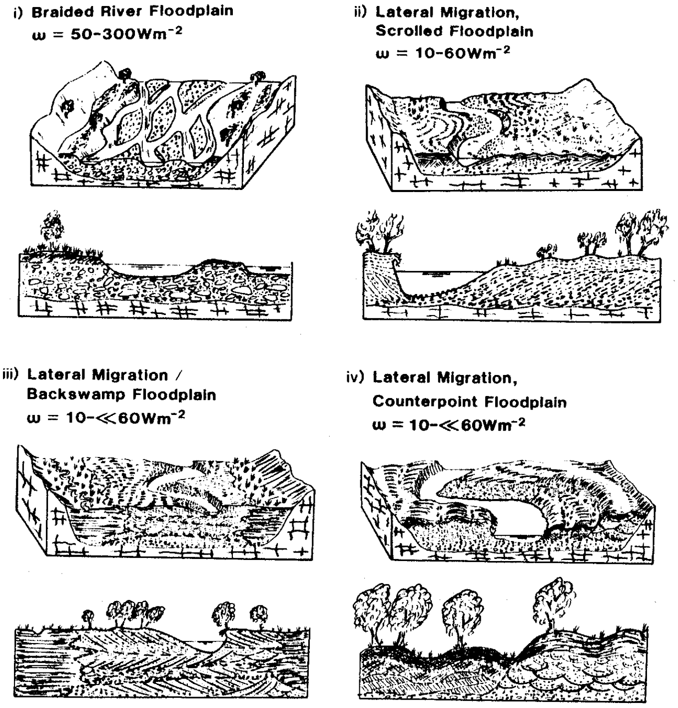


Figure 15 Medium energy non-cohesive floodplains (source Nanson & Croke, 1992)

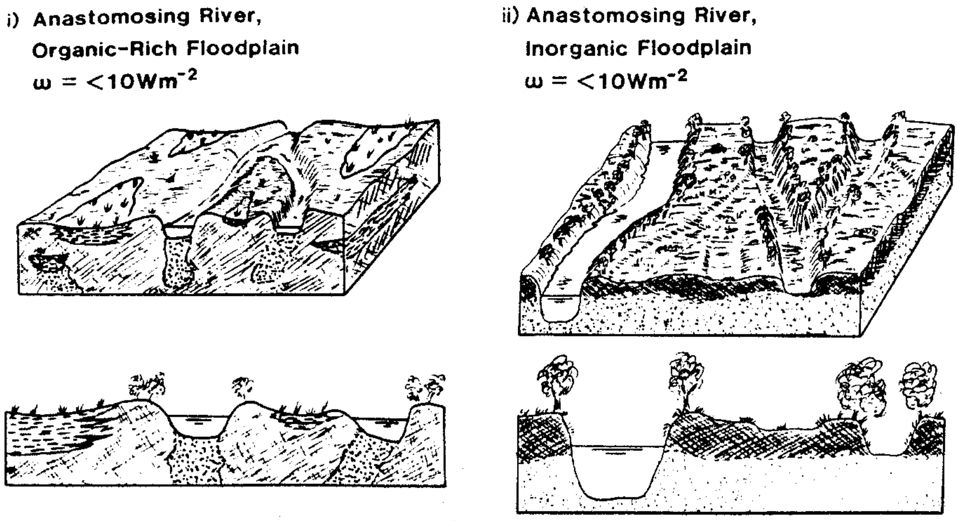


Figure 16 Low energy cohesive floodplains (source Nanson & Croke, 1992)

Gregory and Walling (1973) wrote an extensive work on drainage basis forms and processes in which they stress the importance of spatial differences between rivers. The spatial contrast in low flows are controlled primarily by the rainfall input and storage characteristics of individual drainage basins (Figure 17). The latter influences the extent to which the basin can store water for release during drought periods and the former determines the volume of water available to recharge this storage and the magnitude and frequency of drought event. Storage properties are governed by rock type and to a lesser extent by soil type and can vary markedly within a small region (Gregory and Walling 1973).

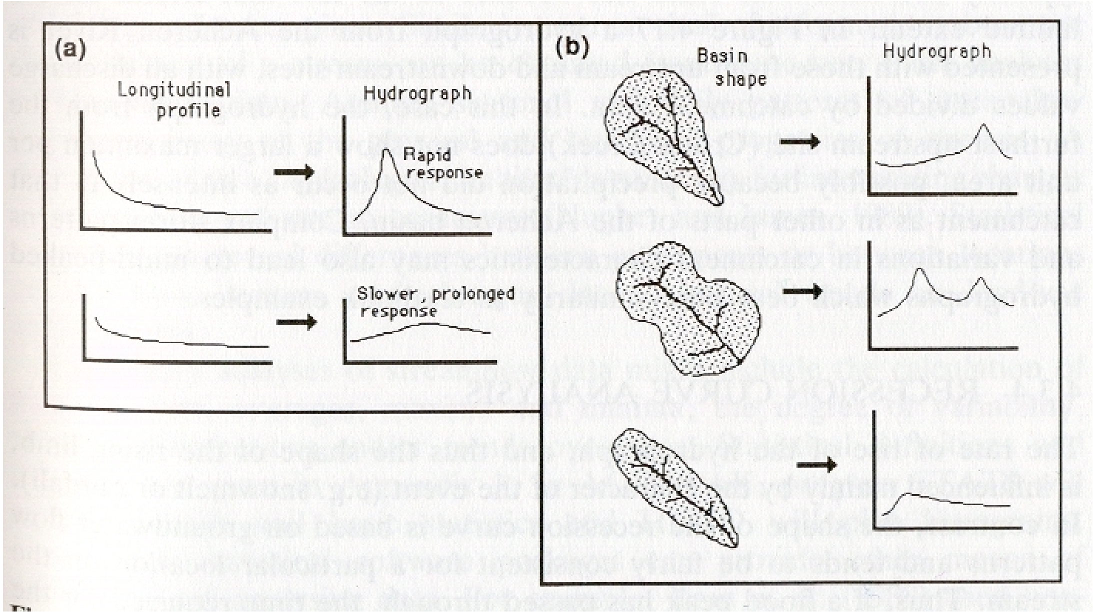


Figure 17 Effect of various factors on hydrograph shape: (a) stream slope and (b) catchment shape. (source Gregory and Walling 1973 in Gordon *et al*, 1992)

Gregory and Walling (1973) state that drainage density is perhaps the most useful single index. The density of a stream network reflects the climate patterns, geology, soils and vegetation cover of a catchment. Drainage density is highest in semi-arid areas where surface runoff from intense thunderstorms erodes sparsely vegetated slopes. High sediment yields reflect a more highly developed channel system (Junk, Bayley, and Sparks 1989; Knighton 1984) thus the relationship between drainage density and precipitation is similar to that proposed for sediment yield.

3.4 Hydrological classification

Annual, seasonal and daily patterns of streamflow determine many of the physical and biological properties of a stream (Gordon *et al.* 1992). Statistical measures can reveal differences between catchments or between locations on the same stream, and changes due to natural trends or land-use modifications. The regime of a river has an important influence on instream biota, along with average and extreme water temperatures. Haines *et al* (1988) made a global classification of rivers based on differences in river regimes and distinguishes 15 groups based on average flows expressed as percentages of the means annual flow (Figure 18).

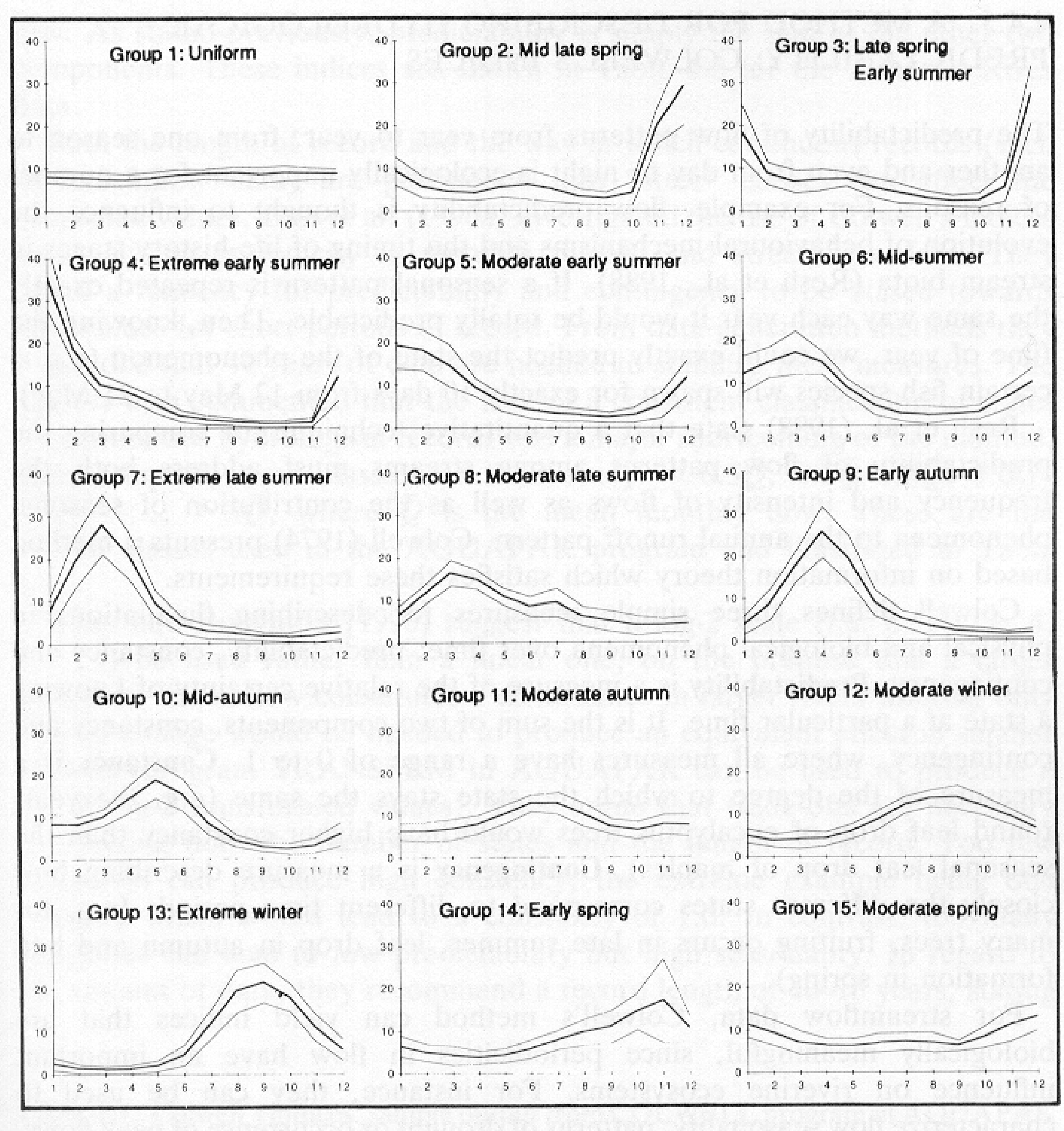


Figure 18 River regime patterns for the global classification of Haines *et al* (1988). Average flows are expressed as percentages of the mean annual flow, and are shown with bands of plus and minus one standard deviation. Month 1 in the classification is the first month of summer.

Brinson (1993) developed a hydrogeomorphic classification for wetlands. Even though designed to be used for wetlands this is a good example of the combination of hydrology and geomorphology into one classification system. This classification system is designed to be used for evaluation of wetland functions. It is being used increasingly as a means of assessing the physical, chemical and biological functions of wetlands and is extremely useful for comparing the level of functional integrity of wetlands within a functional class, or for evaluating the impact of proposed human activities on wetlands and mitigation alternatives. It is primarily based on hydrodynamic differences as they function within four geomorphic settings. Thus, the three core components of the classification are geomorphology, water source and hydrodynamics (Brinson 1993). Brinson also mentions the progenitor of the current classification developed by Odum, Copeland, and McMahan (1974) for coastal ecosystems. They proposed a classification "according to the most prominent processes dominating the functional activity of the system."

It was based on a theory of classification “that includes biological, geological, chemical, and physical classification factors, energy being a common denominator.” Within each of the six major categories, up to 18 types were identified along with their characteristic energy or source of stress. The major categories (with some examples of representative types) are as follows: (a) naturally stressed systems of wide latitudinal range (high energy beaches and sedimentary deltas), (b) natural tropical ecosystems of high diversity (coral reefs and tropical seagrass beds), (c) natural temperate ecosystems with seasonal programming (marshes and bird and mammal islands), (d) natural Arctic ecosystems with ice stress (sea ice and ice-stressed coasts and glacial fjords), (e) emerging new systems associated with man (sewage waste and pulp mill wastes), and (f) migrating subsystems that organise areas (Odum, Copeland and McMahan 1974 in (Brinson 1993)).

3.5 Biological classifications

The third type of classification methodologies are the biological classification methodologies. Only a few have been widely recognised and are often quoted. The classification system by Frissel *et al* (1986) partially distinguishes ecosystem units on habitat level (see §3.2). The River Continuum Concept, the Flood Pulse Concept and the Water Ecotope Classification systems will be discussed here as other biological classifications. The River Continuum Concept (RCC, (Vannote *et al.* 1980)) and the Flood Pulse Concept (FPC (Junk *et al.* 1989)) provide ecological templates which can be used to link hydrology and ecology on drainage basin scale (Petts and Maddock 1994). Where the RCC is a more longitudinal gradient focused concept, the FPC is focussed on the expansion of the water bodies during flood events. Petts (1996) also suggests to subdivide the river into four sectors (headwater stream, middle river, lowland river and estuary) and ecological targets specified for each as a minimum effort have to be made.

Several biological classification methods have mainly evolved out of the need to group landscape features in a logical way. Ecosystem units such as wetlands and forest form the base of this approach to classifying the riverine system. Mitsch and Gosselink (2000) provide a classification of wetlands and a review on several similar approaches. They distinguish tidal salt marshes, tidal freshwater marshes, mangrove swamps, freshwater marshes, peatlands, freshwater swamps and riparian ecosystems. Of course all sub-units in a riverine ecosystem are for a great part defined by the underlying hydrological and morphological features within the river basin, but they are still used frequently because of their utility in mapping and easy identification (Mitsch and Gosselink 2000).

Many of the biological classification models use similar characteristics to describe an ecological unit or habitat. Naiman *et al* (1992) summarised these characteristics and Table 2 gives an overview of the different characteristics. Also, Naiman reviewed a number of methods available and for each method the key variables used and the spatial scale addressed is given (Figure 19).

Table 2 Summary of characteristics used in habitat-based models (source (Naiman *et al.* 1992))

Drainage basin	Channel morphometry and flow	Habitat structure, biological, physical and chemical
Drainage density	Stream discharge	Cover for fish
Stream order	Width	Streambank stability
Mean basin elevation	Depth	Depth and velocity preference
Total stream length	Mean velocity	Invertebrate drift abundance
Stream gradient	Wetter area	Substrate
	Pool volume	Temperature
	Gradient	Water chemistry
	Habitat types	

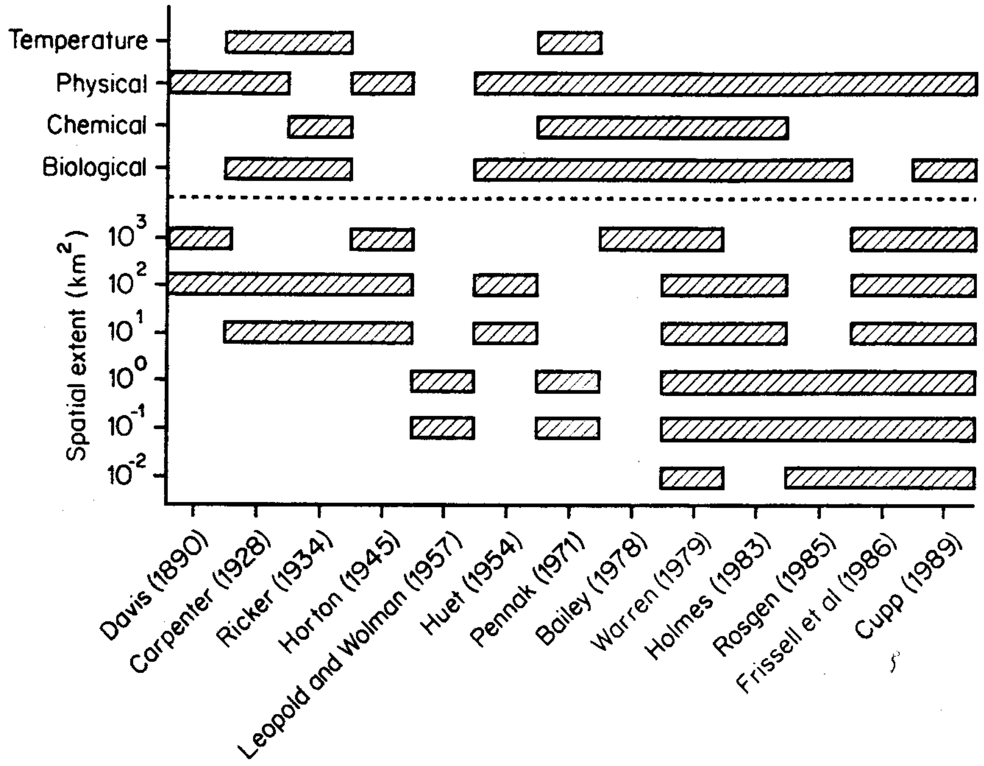


Figure 19 Conceptual overview of the history of stream classification, the key variables used, and the spatial scale addressed (source Naiman *et al.* 1992)

3.5.1 River Continuum Concept

The River Continuum Concept proposes that the longitudinal gradient of physical factors, formed by the drainage network, exerts a direct control upon the biological strategies, biological communities and dynamics of the river system (Vannote *et al.* 1980). The downstream transport of organic matter derived from the headwaters and nutrient spiralling form one of the main ideas of this concept. As a result of this fact, together with hydrological and morphological changes from up- to downstream the type of species alters within the system (Figure 20). For practical purposes the continuum can been divided by zonation according to e.g. species composition based on functional feeding groups. Also, the need to sustain longitudinal connectivity, linking cool, shallow, steep-gradient headwater streams and the warm, deep, shallow-gradient lowland river, is an important principle for river management. Especially during certain times of the year (e.g. spawning season) the longitudinal connectivity may be especially important (Petts 1996).

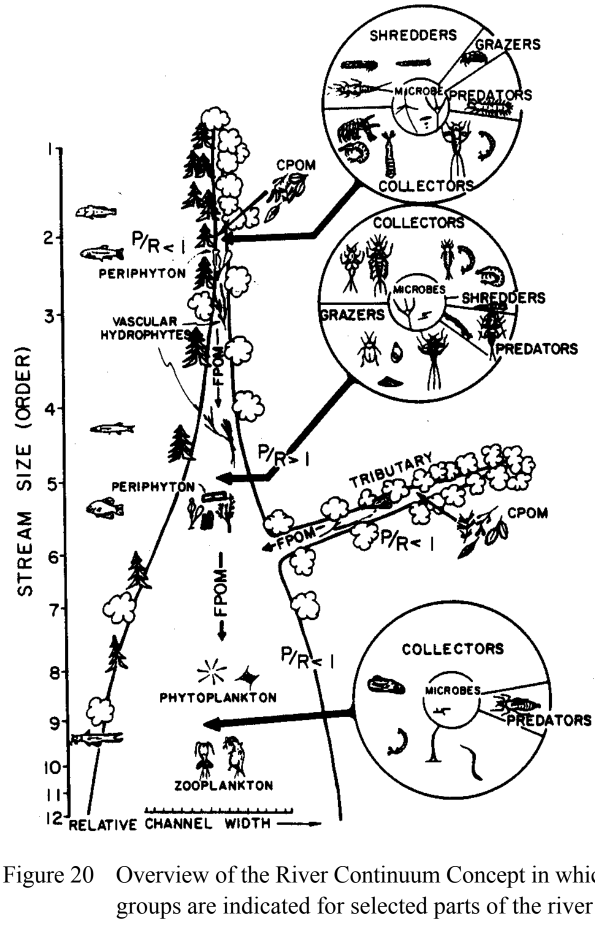


Figure 20 Overview of the River Continuum Concept in which the presence of different functional feeding groups are indicated for selected parts of the river (Source Vannote *et al.* 1980)

The resource spiralling concept (Newbold *et al.* 1982) elaborated on the RCC description of the movement and processing of organic matter and nutrients in stream ecosystems. Because of flow, nutrients have open cycles, or spirals. The length of a spiral is a function of transport rate (stream flow) and retention (physical retention and biological uptake). Spiral length increases from headwater to mouth due to decreased retention and decrease in particle size.

3.5.2 Flood Pulse Concept

The Flood Pulse Concept proposes that the biota of large floodplain rivers are determined principally by the hydrological regime (Junk *et al.* 1989). The biota are adapted to the pronounced aquatic and terrestrial phases: aquatic organisms colonise the floodplain at rising and high water levels, because of feeding and spawning opportunities; terrestrial organisms occupying non-flooded habitats along the boarders are adapted to exploit the floodplain at low water levels. In occurrences, life cycles and abundance's of primary and secondary producers and decomposers are determined by duration, magnitude, frequency, timing and predictability of floods. Timing and predictability may be key factors explaining differences between regions in terms of flood pulse effectiveness (Petts and Maddock 1994).

Unpredictable floods include irregular events to which the biota are unable to develop profitable strategies for occupying the inundated riparian and floodplain areas, and disturbances - catastrophic events that periodically 'reset' the physical and biotic environment. Junk *et al* (1989) stated that the effect of a flood on biota is principally hydrological. From a conceptual viewpoint, flood characteristics may be the driving variable over short time-scales (1-10 years), but over longer time-scales, geomorphological processes play an increasingly significant role.

3.5.3 Water Ecotopes Classification: classification based on ecosystem units

The Netherlands Ministry of Transport, Public Works and Water Management requested the development of an ecotope classification system[1] to be used in the preparation of water management policy and its implementation. The Water Ecotopes Classification system (WEC) is therefore developed, especially focussing on the water bodies managed by the national authorities. WEC is mainly intended to be used on a relatively coarse scale (1:5,000 m. - 1:25,000 m.) and does not address detailed local issues such as the management and monitoring of small (nature conservation) areas, although it caters as a starting point. (Wolfert 1996). For these smaller areas see Van Diepen and Verdonschot (2001).

A characteristic feature of the WEC, other than the integral nature of its units, is the coupling of classification characteristics with policy and management measures (Wolfert, 1996). It aids the prediction and evaluation of the effects of interventions in wetland ecosystems and large water bodies.

One of the primary requirements when developing the WEC focused on the practical use of the system. Ecotopes should be easy to map and assess. Scales are chosen according to this requirement and therefore small spatial elements are not included.

Figure 21 gives an overview of the system in which the ecotopes are identified.

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[1] *An ecotopes classification system is intended for the classification and mapping of ecotopes. Ecotopes are spatially defined ecological units, the composition and development of which are determined by the local abiotic, biotic and anthropogenic conditions.*

The WEC is hierarchical in structure. Different classification characteristics are applied for each of the various levels. At the level of groups of water systems, the positional factors are the most significant: slope, tidal influence and salinity levels. At ecotope level, conditional factors constitute the basis for the classification: morphodynamics, hydrodynamics and management activities.

The classes for each criterion are linked to relevant ecological features of the subdivision in the WEC and categorise different ecological units, e.g. possible presence of a thermocline at a certain water depth in lakes or frequency of flooding related to vegetation in river floodplains.

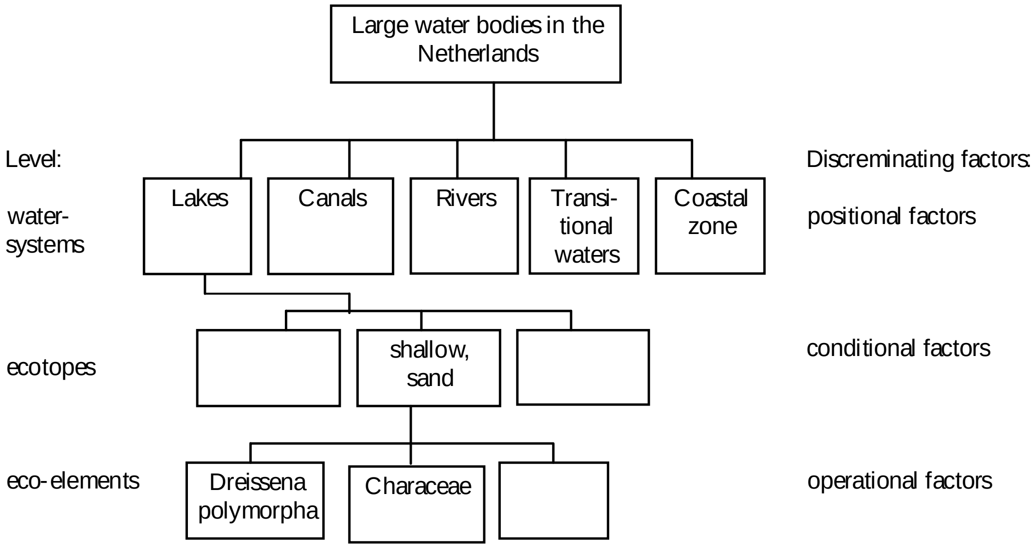

Figure 21 Overview of the construction of the WEC (source Wolfert 1996)

The positional factors divide the WEC in 5 ecotope groups (fresh water delta, brackish water delta, large lakes, canals and the north sea). The first WEC part introduced was the River Ecotope Classification. Since the start of the development of the WEC, several adjustments and changes in opinion have occurred. One of the main remarks about the WEC is that the different classification systems were not always sufficiently ecologically relevant. Also, a number of ecotope types appeared to be overlapping with other types, but using a different set of criteria to describe the same land unit. In response to these remarks two supplements have been made for the WEC: the WEC aquatic and the WEC banks and shorelines. These two supplements are considered to be better ecologically founded and to be applicable to the whole range of surface water bodies under the management of national authorities (except for the coastal zone, which is not included in the WEC aquatic) (Figure 22) (Van der Molen *et al.* 2000)

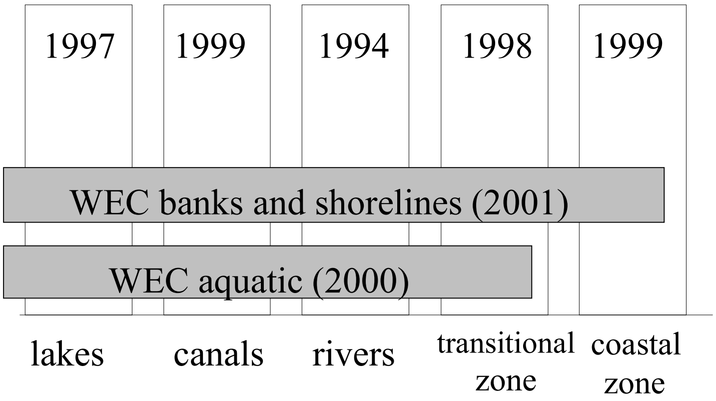

Figure 22 Layout of the WEC (source Van der Molen *et al.* 2000)

3.6 Integrating systems

Often the distinction between different classification systems is rather vague and overlap is common. Not only within a specific field of classifications e.g. biological or morphological, also ‘boarder-crossing’ systems are found often. These types of systems consist of both abiotic and biotic characteristics of the river corridor system.

Goodwin (1999) reviewed existing fluvial classification methods and concluded that many of the existing methods are limited in their approach. He recommends ten types of improvements to the existing methods e.g. by basing classification on natural kinds of rivers, processes or controlling factors, temporal change and thresholds, on theory and a probabilistic view. The calibration and verification of classification when using them for predictions is essential and size factors and proper nomenclature should improve communication. He states that classifications should be treated as hypotheses not as paradigms and indicates that they are just a tool, not a result on themselves.

All the above classification methods are based on existing features in natural rivers. However, there can also be the need to classify rivers according to how severely adjusted rivers are. Unlike e.g. geomorphological classifications of river channel patterns that are based on morphological features, classifications of river channel adjustment are explicitly value laden; adjustment processes are inferred directly from morphological features. Essentially, therefore, the resulting classifications represent a simple summary of an evaluation procedure (Downs 1995).

Imhof *et al.* (1996) provide an example of how a hierarchical classification system can be used to understand the factors that influence stream fish habitat and how these relationships may be affected by disturbance. The paper summarises how factors such as climate, geology, physiography, landcover and flow variability influence the structure and function of stream habitat. The authors then suggest how salmonid life stages relate to the physical environment and dynamic processes and suggest how these linkages may be used to assess the health and integrity of stream habitat.

The hierarchical evaluation system of Imhof *et al.* (1996) emphasise the importance of physical and hydrological variables in determining stream fish habitat. Stream fish habitat is therefore considered dynamic and influenced by the broad scale processes that dictate stream form and function. Stream communities must be adaptable to dynamic habitat in the stream and be capable of reorganising themselves following periodic events. Naiman (1992) described the relations between essential elements of an ideal stream classification system (Figure 23).

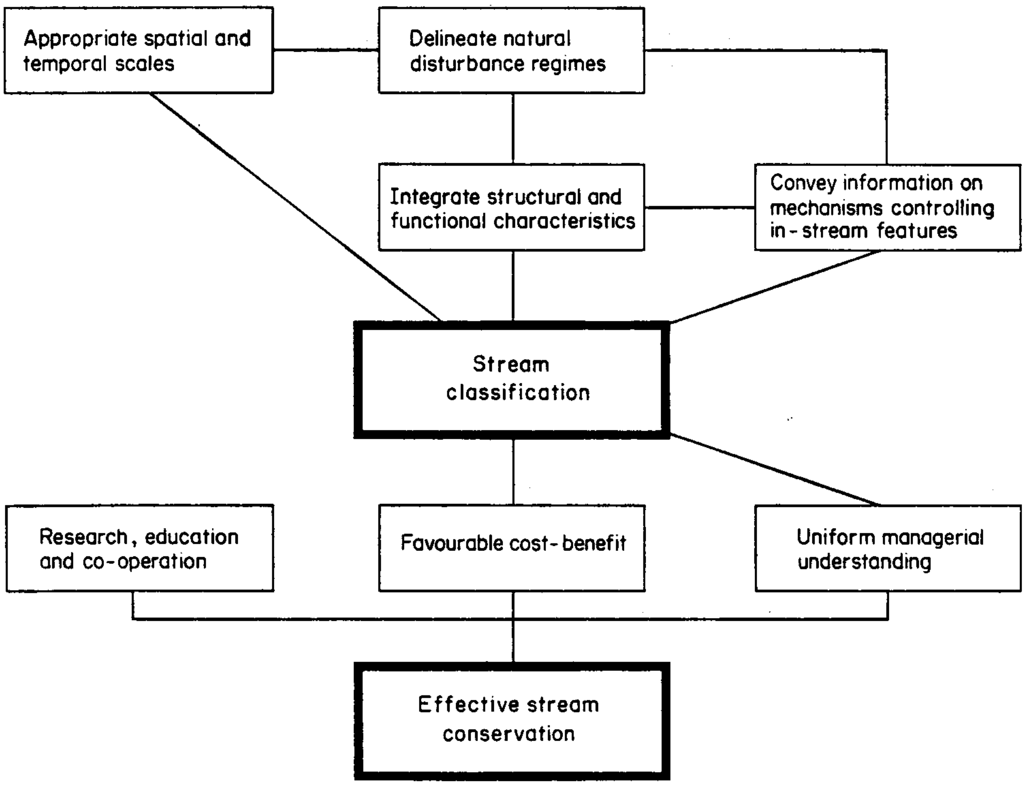

Figure 23 Relations between essential elements of an ideal stream classification system. All components are required to assess conservation potential based on stream classification (source (Naiman *et al.* 1992)

3.7 Concluding on river classification systems

Many of the classification systems as described above have a specific goal, such as describing a river on a certain spatial scale (e.g. braided, meandering, straight on stream level, or habitat types to be found in a specific part of the river) or the use for policy implementation within a specific country. Appendix C gives a few examples of the features or characteristics used for classification systems. The distinction between factors influencing these types of systems remains rather unspecified in many occasions, or the derived information appears not relevant when searching for EFR compatible systems.

The biological methods, such as the Flood Pulse Concept and the River Continuum Concept do take quality into account, but the classification methods remain vague, there is a distinction between upstream and downstream. However, when trying to implement this to rivers in different regions of the world, the concept might have to be altered, since river characteristics can differ especially between arid and non-arid regions, with a resulting difference in biota found and scaling may give problems (Statzner and Higler, 1985). Thus, a climatic difference between river locations should be taken into account, but many systems lack this ability. For a system like the stream order classification, climate is not a necessary factor to be taken into account, however it appears that this classification system is of little use to EFR because of its simplicity.

Also functions of rivers are not discussed and the influence of artificial structures such as dams and canals are not taken into account. In the biological classifications there is no assessment of e.g. fisheries, agriculture, industrial needs.

A classification system should take the functions of a river into account and the system used to describe these features should be easy to use. In this perspective the Dutch Water Ecotope System is designed with a major purpose of mapping ecotopes of water bodies managed by the national authorities of the Netherlands. Although very detailed in description it might be of use as a starting point for defining a practical and suitable classification and description system in the framework of setting EFRs. For this reason the idea of ectopes might be altered in such a way that scale level is coarser and more focussed on functionalities of a landscape unit.

4 Functions of river systems

At the basis of environmental problems in the use of water resources lies a fundamental crisis between the demand on the resources on one hand and the performance of the water resources system on the other hand (UN 1992). Since EFRs are set in order to maintain or improve the different functions of a river system it is necessary to distinguish which functions are present in a river system. Several functions as distinguished in a report by the United Nations on environmentally sound and sustainable development of water resources in Asia and the Pacific are displayed in Table 3.

Table 3 Functions of the water resources system (source (UN 1992))

functions	description	examples	demands on the system
Subsistence functions	Local communities make use of water and water-based products which are not marketed	Local drinking water Traditional fishing Subsistence irrigation	high water quality, groundwater recharge Medium water quality, flooding frequency flooding frequency (floodplain agriculture)
commercial functions	Public or private enterprises make use of water or water-based products which are marketed or otherwise give a monetary value	Urban drinking water Industrial water supply Irrigation Hydropower generation Commercial fishing	high water quality and year round sufficiency high/medium water quality and year round sufficiency seasonal water flow year round water flow medium water quality and natural water regime
environmental functions	regulation functions, non-consumptive use	Purification capacity Regulation of the hydrological cycle Prevention of salt intrusion Recreation and tourism Transportation	high capacity minimize extreme events (flooding, drought) suffiecient year round flow at river mouth a rich and diversified ecosystem, high water qauality sufficient year round water depths
option value	functions or values which in the future may become important	Gene pool	a rich and diversified ecosystem, high water quality
existence value	intrinsic value assigned to entities of the system not derived from other functions or values	Nature conservation value	a rich and diversified ecosystem, high water quality

These functions all have different requirements and demand specific conditions to be present in a water system. Also, not every function is occurring throughout the water system, but often in specifically linked to a certain location within the system. For example, transportation will be an activity that mainly focuses on the main stream and side stream of the river, whereas irrigation is specifically linked to the floodplains where agricult is practised. Together with this lateral distinction there is also a longitudinal separation of functions. For example, hydropower generation will not often be found in upstream parts of the river and spawning habitat of riverine fishes is often found in the smaller parts of the system (upstream or side channels). Table 4 indicates per river system unit the most important functions together with the requirements necessary to maintain these functions.
Areas where problems for a specific requirement may create important problems in particular have been indicated.

Table 4 Functions per river system unit. Indicated in grey are the units in which a function is most often present. Quantity and quality limitation are indicated together with the seasonal requirements in which Qls: Quality limited seasonal dynamics; Qly: Quality limited year round minimum; Qns: Quantity limited seasonal dynamics required, with a minimum amount of water in at least one season required; Qny: Quantity limited year round minimum required

function		required		upstream erosion zone				transport zone					
			source	main stream	side streams	wetland	floodplain	main stream	side streams	wetland	floodplain	stagnant waters	reservoirs
required			qlny ground water	qny	qny	qly	qns	qny	qny	qns	qns	qly	qny
subsistence functions	local drinking water	qly	▨	▨	▨			qly	qly			▨	▨
	traditional fishing	qny		qny				▨	qny			▨	▨
	subsistence irrigation	qns		▨	▨	qns	qns	▨	qns	▨	▨	qls	▨
commercial functions	urban drinking water	qly						▨					▨
	industrial water supply	qny						▨	▨				▨
	hydropower generation	qny											qny
	commercial fishing	qny						▨	qny				▨
environmental functions	purification capacity	qly	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	regulation of the hydrological cycle	qnlys		▨					▨	▨	▨		
	prevention of salt intrusion	qny											
	recreation and tourism	qnlys	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	transportation	qny		▨				▨	▨				
	spawning habitat	qnls	▨	qls	qls	qns	qns		qls	qns	qns	▨	
	fouraging habitat	qly				qly	▨			▨	▨		
	reproduction habitat	qly				▨	▨			▨	▨		
	water storage	qny				▨	▨			▨		▨	▨
	agriculture/irrigation	qns					qns				qns		
	water retention	qny				▨	▨			▨	▨	▨	▨
option value	gene pool	qlys	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
exisitence value	nature conservation	qnlys	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

function		required	sedimentation zone						estuary		coastal system
			main stream	side streams	wetland	floodplain	stagnant waters	reservoirs	freshwater dominated	salt water dominated	
required			qny	qny	qns	qns	qly	qnly	qlny	qly	qly
subsistence functions	local drinking water	qly	▨ qly	▨ qly			▨ qly	▨			
	traditional fishing	qny	▨	▨ qny			▨ qly	▨	▨	▨	▨
	subsistence irrigation	qns	▨	▨	▨	▨	▨	▨	▨	▨	▨
commercial functions	urban drinking water	qly	▨					▨			
	industrial water supply	qny	▨	▨				▨			
	hydropower generation	qny						▨			
	commercial fishing	qny	▨	▨			▨ qny	▨	▨	▨	▨
environmental functions	purification capacity	qly	▨	▨	▨	▨	▨	▨	▨	▨	▨
	regulation of the hydrological cycle	qnlys		▨	▨	▨			▨	▨	
	prevention of salt intrusion	qny	▨	▨				▨	▨ qny		
	recreation and tourism	qnlys	▨	▨	▨	▨	▨	▨	▨	▨	▨
	transportation	qny	▨	▨					▨	▨	▨
	spawning habitat	qnls		▨	▨	▨			▨	▨	▨
	fouraging habitat	qly			▨	▨			▨	▨	▨
	reproduction habitat	qly			▨	▨			▨	▨	
	water storage	qny			▨		▨	▨			
	agriculture/irrigation	qns				▨					
	water retention	qny		▨	▨	▨	▨	▨	▨		
option value	gene pool	qlys	▨	▨	▨	▨	▨	▨	▨	▨	▨
exisitence value	nature conservation	qnlys	▨	▨	▨	▨	▨	▨	▨	▨	▨

A few assumptions have been made to create this table:

- Water is always present in the main stream or in estuaries.
- A source should not dry out, there is a sufficient amount of groundwater/ melting water/ rain required as input through the year or according to the natural seasonal dynamics.
- Several functions require throughout the system (regardless of location) a specific quality or quantity of water. These are mentioned in the first column, if for a specific location within a river system they do need extra requirements these are mentioned.
- Stagnant waters are smaller and shallower than water reservoirs.
- Emphasise is placed on requirements in the grey blocks to indicate that for a specific function this river system unit is essential.
- Spawning habitat is mainly focussed on fish requirements.
- Reproduction habitat is mainly focussed on bird requirements.
- The difference between water storage and water retention is made, in which water storage is defined as water necessary for other parts of the system and water retention as water that will be retained for use within that river system unit.
- Option and existence values are important throughout the river system and do not have a specific minimum requirement but strive towards the highest potential of the system. Only completely natural riverine systems have not been deteriorating from this ultimate goal.

5 Conclusions

There is a vast amount of methods developed throughout the world in order to set Environmental Flow Requirements, either for specific rivers or specific regions. Also, the objectives for defining a certain flow regime in a river are of great influence on the methodology chosen to set EFRs. Especially in North America many Environmental Flow Assessments are developed with respect of the conservation of fish habitats, whereas in South Africa, for example, a holistic approach focussing on the complete river system is most frequently used.

Depending on the objectives several types of methodologies can be chosen. These can be distinguished into 6 groups of methodologies as identified by King *et al*, (1999). The more complex and detailed a method becomes, the more it relies on expert judgement and extensive data gathering and monitoring actions, and therefore, the more time and money consuming the EFA becomes.

It appears that no single EFR method is perfect under all conditions. No EFA was found that was designed with the similar objectives as stated in the ENFRAIM project (on a global scale applicable, for rivers under all circumstances, quantified measures).

As for river classification systems the same conclusions can be drawn. The objectives and requirements of each classification system make them applicable to a large range of individual problems. However, not every classification systems seems equally suitable in the scope of EFAs. The level of detail should be applicable to the functional units that can be distinguished within a river corridor and a river corridor in itself needs to be defined from other river corridors in order to get a feeling for the type of river the EFR needs to be set for. Therefore a hierarchical approach, in which first the river and afterwards parts of this river can be described, based on functional criteria, seems a useful method. No such method has been found within the examined literature. The Water Ecotopes Classification system, as used in the Netherlands, might serve as a theoretical starting point for developing such a system on a more global scale, since it used criteria which can be altered by management to describe river system units. The classification into ecotopes makes the system also very usable from a practical point of view.

The setting of an EFR for a specific function (for example fisheries) is possible and has already been performed throughout the world. However, one should strive to create a EFR which defines the status of a river system in such a way that all functions can be maintained or sustainable developed.

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A Glossary

Term	Description
AAF	Average Annual Flow
Benchmark flow	flow required to meet the ecological target
EFA	Environmental Flow Assessment an EFA is used to assess how much water could be abstracted from a river without an unacceptable level of degradation of the riverine ecosystem or, for a highly modified river with much abstraction, how much of its original flow should be reinstated in order to rehabilitate the ecosystem to some required condition (King et al. 1999)
EFR	Environmental Flow Requirement The term EFR is gaining in popularity, because it implies a comprehensive flow regime, dynamic over time and with cognisance of the need for natural flow variability (King et al. 1999)
Environmental Flow	An instream flow measure provided for environmental reasons, designed to enhance or maintain the habitat for riparian and aquatic life (Gordon et al. 1992)
Flushing flow	to remove the salt wedge in the estuary and maintain the freshwater section of the river.(Tunbridge and Glenane 1988)
FPC	Flood Pulse Concept
Low Flow	flow of water in a stream during prolonged dry weather, a seasonal phenomenon and integral component of a flow regime of any river(Smakhtin 2001)
Minimum environmental flow	results in little or no reduction in numbers of fish, for average rainfall years (Tunbridge and Glenane 1988)
RCC	River Continuum Concept
Optimum Environmental flow	allows the full production of fish, especially for recovery after a period of stress (e.g. drought, overfishing) (Tunbridge and Glenane 1988)
Survival environmental flow	causes a reduction in numbers of fish but no loss of species, for low-rainfall years (Tunbridge and Glenane 1988)
WEC	Water Ecotope Classification

B Overview of EFAs

Source: Dunbar *et al*. (1998)

Method/origin	Description
Look up (hydrological)	
‘ 7Q10 (various)	Low flow that is expected to occur for 7 consecutive days only once in 10 years. Has been used to set standards for dilution of wastewater: Dilution at this flow would still maintain quality standard. However considered completely inappropriate for instream flow protection as it would grossly underestimate minimum ecological flows (disagreement on this though)
Q347 = 95 percentile (various, particularly UK)	Used in England and Wales as a low flow index. Annual statistic not generally considered suitable for setting flow objectives, seasonal considerations and durations important
Tennant (US)	Percentage of mean annual flow for various ecological functions, calibrated to Mid-Western US. Modified to consider monthly standards. Potential for development in UK (Texas method also highly relevant). Would require considerable resources, should await discussion as to whether ‘standard setting’ is appropriate in England and Wales. Variations for other US states.
ABF (US)	August median flow, or lowest median monthly flow during spawning months
NGPRP (US)	Group years into dry, normal and wet. Take 90 percentile flow from normal group. Of interest as it attempts to account for climatic conditions and acceptable frequencies.
Hoppe (US)	Daily flow values for various trout life stage functions. Based on flow duration curve
Historical hydrological data analysis	
Texas (US)	Variable percentages of the monthly median flow. Scope for further investigation on a river ecotype basis (see Tennant).
Basic Flow (Spain)	Spanish. Characteristic Basic Flow for a river type. Not thought worthy of further investigation
Range of Hydrological Variability (US)	Indices of hydrological change. Considerable potential for use in characterising hydrological variation. Method includes follow-up monitoring and review of standards. Recommended for further investigation in Phase 2.
Additional biological / hydraulic data collection and analysis Hydraulic methods	
Wetted perimeter (US, Australia)	Identification of break point on graph of wetted perimeter versus discharge. This will be considerably influenced by channel shape. Depth /velocity not directly considered. Not generally seasonal. Potentially useful if correctly targeted with other methods
Singh (US)	Estimates of hydraulic parameters at catchment scale. Of some interest, of considerable interest if easy to use and evidence for validation.

R2 Cross (US)	Simulation of depth and water level over a shallow riffle using field data. For England and Wales, a simplified PHABSIM study would give same results. As above, may be useful if spawning habitat critically limiting
Biological / hydraulic methods	
RIVPACS (UK)	See Environment Agency R&D Report W72
Basque (Spain)	Uses hydraulic for lowland reaches and data on invertebrate – flow relationships in uplands. A relatively coherent system for a relatively narrow range of river ecotypes. Potential for further investigation if a method of this type required.
HQI (US), HABSCORE (UK)	Regression models. Used to predict biomass: site or ecotype specific. EPRI report documents HQI in detail.
Statistical hydraulics (France)	Uses statistical models to predict frequency distributions of physical habitat. Not yet tested with biotic data, but considerable potential in the longer term.
'Habitat', professional judgement	
HEP/HSI (US, Netherlands)	Standard guidelines for habitat – area analysis. Applied in the US, and to aquatic environments in the Netherlands.
Biotopes / functional habitats (UK, South Africa)	Moves away from species to a habitat-based approach. Un-validated, needs more development. Would gain from field comparison with other methods. Existing Agency R&D
Holistic approach (Australia) / Building Block Method (South Africa)	Assess complete river ecosystem, river channel, riparian zone, floodplain, groundwater, wetlands, estuary. To maintain integrity, natural seasonality and variability of flows should be maintained. Field visits, hydraulic rating curves and any supporting information used to formulate flow regime at workshop. A potentially wide-ranging approach of great value. Recommended for more detailed investigation.
Expert Panel Assessment Method	Field visits by interdisciplinary groups of experts to view specific flows, commonly downstream of impoundments. Again, worthy of evaluation for England and Wales
Detailed biological response simulation	
IFIM (US)	A conceptual framework for integration of ecological demands into the water resources planning process. National adaptations (e.g. Spain, Austria)
PHABSIM II (Physical habitat simulation system) (US)	A physical microhabitat simulation model. Freely available from the US National Biological Service. Environment Agency R&D Technical Report W20. Currently used in certain situations in England and Wales, world- wide, undoubtedly the most defensible method, although not without limitations.
RHABSIM (Riverine habitat simulation) (US)	from Thomas Payne Associates, is a commercial version of PHABSIM
Fish Rule Curve (FRC) (Canada	Canadian method for the use of PHABSIM / physical habitat time series to develop minimum, average and optimum flows for instream physical habitat.

RYHABSIM (NZ)	New Zealand microhabitat model
RSS (River System Simulator) (Norway)	Norwegian microhabitat model
EVHA (Evaluation of Habitat) (France)	French microhabitat model
HABIOSIM (Canada)	Canadian microhabitat model
CASIMIR (Germany)	reach-based shear-stress simulation model developed for hydropower impact assessment. Worth investigating these techniques at the research level for use in England and Wales.
Fleckinger method (Spain)	Mentioned in Cubillo ( ).Uses physical habitat simulation.
RCHARC (US)	Riverine Community Habitat Assessment and Restoration Concept. Used to compare habitat hydraulics of a reference situation with alternative scenarios.
AGIRE (France)	GIS system developed by EDF. Combines spatial and temporal data on a range of themes in the manner of WIS (Water Information System). Includes a model of fish-breeding habitat quality for brown trout

C Frequently used EFA criteria

Examples of discharge methods based upon average daily flow (ADF) source (Petts and Maddock 1994)

method	min % ADF	max % ADF
Baxter (1961) flow for salmo salar		
Juveniles in summer	20	25
adult migration	30	70
spawning	12.5	30
incubation	10	17
Tennant (1976)		
absolute minimum	10	
good habitat	30	60
optimum habitat	60	100
flushing flow	200	

Attributes commonly used in habitat-fish abundance relationships (source (Petts and Maddock 1994))

type	characteristics
Catchment	altitude drainage area stream order
flow regime	average daily flow average seasonal flow baseflow index
water quality	maximum temperature ph alkalinity hardness conductivity nitrate concentration
channel structure	average depth maximum depth width velocity %pool %riffle %cover dominant substrate

Summary of NRA (1990) scheme for classifying river channel susceptibility to disturbance (source (Downs 1995))

susceptibility to degradation	score	description
high	8-10	conform most closely to a natural, unaltered, state and will often exhibit signs of free meandering and possess well-developed bedforms (point bars and pool-riffle sequences)
moderate	5-7	show signs of previous alteration but still retain many natural features or may be recovering towards conditions indicative of the high category
low	2-4	substantially modified by previous engineering works and are likely to possess and artificial cross-section (e.g. trapezoidal) and will probably be deficient in channel bedforms and bankside vegetation
channelised	1	awarded to reaches whose banks and/or bed have been subject to hard protection (e.g. concrete walls, sheet steel piling)
Vulverted	0	totally enclosed by hard protection
navigable	-	classified separately due to their high levels of flow regulation and bankside protection, and their probable strategic need for maintenance dredging

Summary of scheme for assessing bridge scour problems and the potential instability of river channels (from Simon and Downs (1995)) Higher overall scores indicate a more unstable channel and field experience suggests that the threshold classification for channel instantly which may threaten the crossing structure occurs where scores exceed 20(Downs 1995)

bed material bedrock 0	boulder/ cobble 1	gravel 2	sand 3	unknown alluvium 3.5	silt/clay 4
bed protection yes 0	no 1	(with)	1 bank protected 2	2 banks protected 3	
stage of channel evolution (see fig 16.5 B) I 0	II 1	III 2	IV 4	V 3	VI 1,5
percent of channel constriction 0-5 0	6-25 1	26-50 2	51-75 3	76-100 4	
number of piers in channel 0 0	1-2 1	<2 2			
Percent of blockage: horizontal (6), vertical (7) total (8) 0-5 0	6-25 1	26-50 2	51-75 3	76-100 4	
Bank erosion none 0	fluvial 1	mass-wasting 2			
Meander impact point from bridge (in feet) 0-25 3	26-50 2	51-100 1	>100 0		
Pier skew for each pier (sum for all piers)	Yes 1	No 0			
Mass wasting at pier (calculated for each pier)	yes 3	no 0			
High-flow angle of approach (in degrees) 0-10 0	11-25 1	26-40 2	41-60 2.5	61-90 3	
Percent woody vegetative cover 0-15 3	16-30 2.5	31-60 2	61-99 1	100 0	