Environmental Flows

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1.0 INTRODUCTION

Rivers have been integral to human development and welfare since historical times because many of us are dependent on them for water, which is essential for life. Rivers provide numerous benefits to the mankind including water for drinking, agriculture, food (fish), energy (hydropower, cooling of thermal stations), means of transportation, fertile sediments, and many other products. Rivers have also acquired a central place in the social, cultural and religious activities in certain civilizations, such as India.

Different groups of people perceive rivers in different ways. For hydrologists, rivers are channels to transport water and sediments. For energy planners, these are sources of hydro-power generation and for land planners these are essential components of landscape. Rivers provide water to farmers to irrigate crops. For religious leaders, river water has spiritual value. But the river water is not always favourable. Along with the beneficial uses, rivers can also be hazardous when they are in flood.

With the growth in population and consequent rise in water use, humans began to progressively manage rivers and to draw and divert more water, in many cases this resulted in almost no flow in some of the rivers in dry season. This was found to be highly detrimental to the river and its ecosystems (Vörösmarty et al., 2010). With time a realization came that survival of rivers is of utmost importance to the human society in view of many eco-system services provided by the river water. Although freshwater ecosystems contain only 0.01% of the Earth's water and cover a small fraction of the planet's surface, rivers, lakes and wetlands harbor a disproportionately high fraction of the Earth's biodiversity (Combes 2003).

Discussions gradually expanded to consider a range of issues such as geomorphology, sediment movement, freshwater habitats and requirement of species other than fish and gradually the concept of environmental flows began to take shape. The principle governing environmental flows recognizes that these flows are necessary to maintain downstream ecosystems and the communities that depend on them.

There are many definitions of environmental flows. According to the widely quoted Brisbane Declaration (2007), "environmental flows (EFs) are the quantity, timing, duration, frequency and quality of flows required to sustain freshwater, estuarine, and near shore ecosystems and the human livelihoods and well being that depend on them" (Arthington, 2012). The term "environmental flows" is confusing to many people but it is so widely used that replacement is likely to cause more confusion. Thus, while retaining this term, there is a need to clarify that EFlows are meant to provide healthy river systems and consequently benefits to the entire society.

In the context of EF, normally three terms are in use: instream flows, ecological reserve, ecological flows and environmental flows. The term instream flows is interpreted by some people to exclude floodplains which are important for lateral connectivity of riverine ecosystem with terrestrial ecosystems. Further, the term 'ecological flows' is perceived as the flow which is required to meet the ecological functions of the flora and fauna present in the water body. Some authors prefer to use the term 'flows' rather than 'flow' because the word flow refers to a single value of discharge whereas ‘flows’ refers to a complete flow regime with temporal variations.

1.1 Scope

The concept of environmental flows is often closely linked with the idea of uninterrupted flow or river connectivity longitudinally through its entire length and laterally between the river and floodplain. A river is not only a medium to transport water and energy, but is also a pathway for the movement of nutrients, sediments, and aquatic biota from upstream to downstream. Aquatic biota may move in both directions – upstream and downstream - in a river. If there is no flow in the river for some time all these movements will also stop. At certain times and certain frequency, floods water spread out from the main channel and inundate the adjoining floodplains. This helps establishing a hydraulic connection between the river and the flood plains, allowing ecosystem cross-subsidy of food, nutrients and carbon. Hydraulic connectivity between a river and its flood plains one of the principal driving mechanisms for the interactions, productivity, and diversity of the major biota in river-flood plain environment. This demonstrates that EFs can be viewed as a mechanism for delivering requires of the river continuum concept in the longitudinal direction (Vannote et al., 1980) and the flood pulse concept (Junk et al., 1989) laterally.

2.0 Evolution of Environmental Flows Concept

It is widely accepted that ecological processes maintain the planet’s capacity to deliver goods and services, such as water, food and medicines and much of what we call “quality of life” (Acreman 2001). With growing universal concern about the healthy and sustainable use of the planet and its resources, the United Nations convened the UN Conference on the Human Environment, in Stockholm in 1972. It was a landmark event which laid the groundwork for the new environmental agenda for the world. In the same year, the United Nations established the United Nations Environment Programme (UNEP) which leads the efforts, among the other things, for environmental governance. In 1983, the World Commission on Environment and Development chaired by Brundtland published a report entitled “Our Common Future”. This report heralded the concept of sustainable development which is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Subsequently, the United Nations Conference on Environment and Development was held in Rio de Janeiro in 1992. This conference adopted a document outlining the blueprint for the 21st century, popularly known as “Agenda 21”. *Agenda 21* represented the culmination of two decades of focused attention. By this time, the link between environment and development, and the imperative need for sustainable development was recognized worldwide.

The Millennium Development Goals included the need for environmental sustainability, such as reducing the rate of loss of species threatened with extinction. The concept of ecosystem services (Barbier 2008, Fisher et al. 2009) brought to prominence in the Millennium Ecosystem Assessment (MEA 2005) demonstrates that healthy freshwater ecosystems provide economic security, e.g. fish, medicines and timber (Emerton and Bos 2004, Cowx and Portocarrero Aya 2011); social security, e.g. protection from natural hazards, such as floods and ethical security, e.g. upholding the rights of people and other species to water (Acreman 2001). Thus, water allocated for the environment also supports people by maintaining the ecosystem services on which we depend (Acreman 1998, MEA 2005).

Establishment of the natural flow paradigm (Poff *et al*, 1997) marked a significant point in the conceptual development of environmental flows. This paradigm takes the natural system as its starting point and considers that the natural dynamic character of the flow regime of a river - described by six components of magnitude, frequency, duration, timing, rate of change and overall variability of flow - is central to sustaining biodiversity and ecosystem integrity. It is under the natural flow regime that organisms adapt and communities are assembled and are maintained (Lytle and Poff, 2004). Modification of the natural flow regime can adversely affect riverine, riparian and floodplain species and processes and there are limits to hydrological change beyond which significant (or unacceptable) ecological alteration takes place (*e.g*. Richter *et al*., 1997; Arthington *et al*., 2006).

Until this time it was considered that merely ensuring a constant low flow was sufficient to maintain the river ecosystem. We now consider that if a river ecosystem is to be maintained in a pristine condition, the environmental flow will have to be set to closely follow the natural flow regime. However, this will not always be possible and most river ecosystems are managed to different degrees to meet the needs of the society. Certain needs, e.g., municipal water supply, irrigation require removal of water from the river. Societal needs, such as bathing in the river, do not require that water be removed from the river. In some uses (hydropower generation or cooling of a thermal power plant), diverted water is returned to the river after use. This type of use of water is termed as non-consumptive use.

In recent times the environmental flows concept has been integrated into water management in many countries. For example, the water law of South Africa recognizes that water for the maintenance of the environment should be accorded the highest priority along with that for basic human needs (King and Pienaar 2011). This concept was followed by other countries such as Tanzania (Acreman *et al*., 2009). To maintain natural beauty and fisheries, the UK Water Resources Act 1963 required minimum acceptable flows and the clean Water Act of USA (1972) sets the objective of restoring and maintaining the chemically physical and biological, integrity of nations' waters. Environmental flows have also become a key study topic of major international institutions, such as the World Bank (Hirji and Davis 2009) and the International Union for the Conservation of Nature (IUCN) (Dyson et al. 2003).

3.0 Trade-offs in Development and Conservation

There is a trade-off between development (using water for growing food, domestic use, driving industry and generating power) and conserving the natural water body. As the natural systems are progressively modified more and more, usually the benefits from them (or ecosystem services) gradually decline (and may reach zero or even negative) at some point. However, as the degree of control in the managed systems increase, the benefits from the managed systems rise but they reach a plateau after certain limit. Evidently, the total long term benefits are the sum of the benefits from the natural and managed systems. Fig. 1 shows a typical variation of the benefits as well as the trade-off between natural and managed systems. It is noted that the sum of these two rises to a maximum and thereafter begins to decline. The point corresponding to the maximum benefits can be taken as the optimum development of resources. It is clear that the shapes of the two curves and the optimum point depends upon the value that the society assigns to the goods and services from the systems and ethical considerations; these will vary between different countries/regions, communities and individuals.

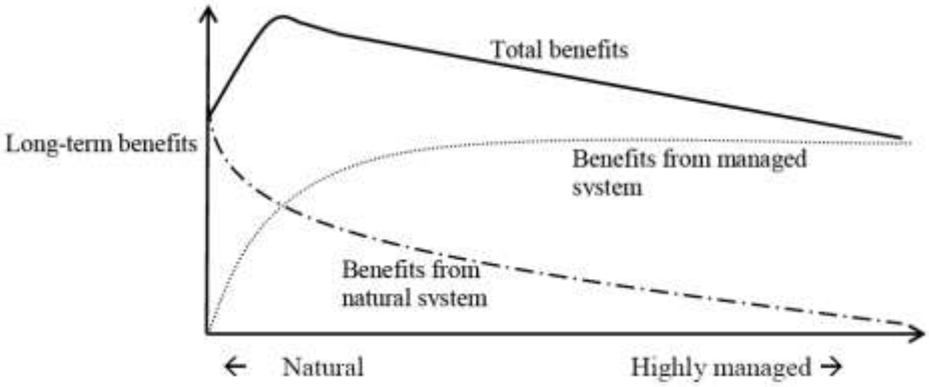

Figure 1. Trade-offs in river regulation showing typical variation of benefits from natural and managed systems (after Acreman, 2001).

It is essential that the costs and benefits to society of allocating water to maintain ecosystems and for social use are quantified (Acreman, 2001). Halleraker et al. (2007) observed that multidisciplinary approaches are needed to establish functional links between the physical conditions and aquatic organisms and are powerful tools for a more optimized management of regulated rivers.

4.0 Estimation of Environmental Flows

The environmental flow requirement of rivers depends on a number of factors, including the physical, chemical and biological character of the river and its drainage basin; natural state of the river; the desired state of the river; and the uses of river water. A typical EF assessment (EFA) exercise can be divided into several stages, as discussed here.

4.1 Typical Stages of an EF Assessment

A typical EFA process can be divided in five stages.

Stage 1: Define the issue: what is the key reason for changes in the river that means in no longer reaches expectations or is perceived to be degraded or changed? These could be abstraction (surface or ground water), impoundment, diversion of water for generation of hydropower, upstream land-use land cover changes, etc.

Stage 2: Define the scope and objective of setting EF. This requires an agreement on the type of river required and the present day condition; it is best done with participation of stakeholders.

Stage 3: Decide the sites along the river where EFs are to be estimated. These maybe based on classification of the river based on morphology or biology, or at strategic points related to degradation and restoration issues.

Stage 4: Collect hydrological and ecological data. EFAs require the integration of information from a range of scientific disciplines: hydrology, ecology, geomorphology and hydrogeology. In some cases, this integration includes information from the economic and social sciences. Typical data requirements are:

- Hydrological data: time series of river flow depth and discharge, channel cross-section properties, and sediment transport. Locations selected for EFA are rarely close to existing gauging sites. For such ungauged locations, flow time series needs to be estimated.
- Ecological data: e.g. fish species/abundance, invertebrates, riparian vegetation
- Economic data: e.g. economic value of fisheries or recreation

- Social data: e.g. degree of cultural connection with the river
- In parallel, preliminary processing of collected data is carried out.

Stage 5: Data analysis and consultations: Dependencies between flow events, channel hydraulics and ecological/social components are established. A suitable method is applied and EFs are computed. Adequacy for different ecosystem components for different months/seasons is checked through consultation with various experts and stakeholders.

Stage 6: Implement, monitor, and feedback.

Depending upon the purpose of study and available resources, additional stages may be added. For example, in important studies, field measurements may have to be carried out to obtain the missing data.

In parallel a whole range of other activities may be required, such as revision of the laws on water rights, establishment of new institutions such as a river basin authority, training of specialist to undertake EFs, awareness raising amongst local people to the idea and benefits of EFs.

4.2 Objectives and Factors Governing EFs

In numerous river basins, water resources are over–allocated and ecosystems are highly modified. This leaves little or no water often of poor quality for eco-system, leading to severe degradation that is ultimately detrimental to human well-being (Acreman, 2001). Before defining EFs, broader objectives must be determined to indicate the type of river desired. In objective-based flow setting (Acreman and Dunbar, 2004), EFs are set to achieve specific pre-defined ecological, economic or social objectives. These might be legal obligations under national or international agreements, such as the Ramsar Convention or the Convention on Biological Diversity. In the Europe Union, member states are required to meet at least good ecological status in all water bodies (Acreman and Ferguson, 2010). In scenario-based flow setting (Acreman and Dunbar, 2004) there are no predefined objectives, but the condition of the river under different EFs is assessed against the benefits of using the water for other purposes. Ideally, the objectives are set by involving a range of stakeholders. But the degree of consultation or involvement of stakeholder depends on the political regime. In many cases, objectives are not quantified and are vague and fuzzy. It is also common that different objectives are set for different rivers in a country region and also for different stretches of the same river. For example, a stretch of 165 km in the head water zone of the Ganga River in India has been declared as Eco-Sensitive Zone where no new development and construction activity is allowed. This means the entire flow in this reach is allocated to environment. But, further down, riverflow is used for energy generation, irrigation, and municipal and industrial uses.

Objectives for desired future state of a river can be specified based on multiple processes. Many countries assign a management class (e.g. high, good, moderate ecological condition) to each river through a process of research, stakeholders consultation and negotiation. It is recognized that different rivers will need to meet different social, economic and ecological services.

In the discussions and attempts to restore the river ecosystems, commonly the river conditions at some earlier time are used as a reference. A natural question is how far back one must look? Conditions of most rivers around the world have changed substantially over the past 50 years due to increasing water use triggered by growing population. Hence, it will not be possible in most cases to revert back to the conditions that existed in the 1950s and 1960s, even if sufficient data exist from that time. In looking back, one should not go so much back that the relevance of the subject is lost and the goals are unattainable. Instead EF objectives may be designed to achieve particular ecosystem services rather than any historical reference (Acreman et al., 2014).

4.3 Locations and Reasons for Estimation of EF

EFs are mostly estimated at locations of major man-made changes (past, current, or anticipated) in river flow characteristics either due to storage or diversion of water, upstream catchment changes including large scale withdrawals from surface or sub-surface sources, or a significant change in water quality. Storage reservoirs are in use over the past many centuries to regulate river flows by diverting/ releasing water to meet the demands of the area being served. Thus, it is very common to estimate EF requirement just downstream of a reservoir or a diversion point. Sites just downstream of a big city or a major industry are other possible locations. If a river is passing through a wild life sanctuary then EF may have to be estimate at the entrance.

EFs may be estimated for several reasons. Most common of these is the desire to stop further degradation of a river or to restore a degraded river to an improved ecological status. A water resources development project may be under planning and it may be desirable to estimate EF at some downstream locations to ensure sustenance of river ecosystems.

5.0 Methodologies for Assessment of Environmental Flows Requirement

Over the last three decades, considerable experience has been accumulated in development and applications of a large range of EF techniques to evaluate the impacts of individual projects as well as undertaking basin-wide studies. Available methods range from relatively simple, desktop approaches to resource-intensive, multi–disciplinary approaches (Tharme, 2003). The comprehensive methods are based on detailed studies that often involve collection and analysis of large amounts of geomorphological and ecological data by multi-disciplinary teams (e.g. King and Louw, 1998). Typical studies may take many months, sometimes years, to complete. A key constraint to the application of comprehensive methods in many countries is the lack of data linking ecological conditions to specific flows. To compensate for this, several methods of estimating environmental flows have been developed that are based solely on hydrological indices derived from historical data (Tharme, 2003).

The last couple of decades have seen evolution of various methods, approaches and frameworks for estimating environmental flows. ‘Methods’ typically deal with specific assessments of the ecological requirement. ‘Approaches’ are ways of working to derive the assessments, e.g. through expert teams. ‘Frameworks’ for flow management provide a broader strategy for environmental flow assessment. Choice of a particular method depends on the type of issue (abstraction, impoundment, run-of-the-river scheme), the management objective (e.g. pristine or working river), expertise, time and money available and the legislative framework within which the flows must be set. While choosing a method to estimate environmental flows, four aspects need to be considered: hydrological aspects, hydraulic aspects, biological aspects, and cultural/recreation/ religious/social aspects (ecosystem services).

Broadly, two paradigms are employed for EFAs (Acreman et al. 2014): (1) the natural flow paradigm based on minimizing alterations to the flow regime from a natural condition to conserve biodiversity and (2) a management-based paradigm in which environmental flows are designed to achieve specific outcomes, such as ecosystem services. These alternatives could be brought together to provide a unified paradigm to environmental flows.

We present and discuss two ways to classify EF methods.

5.1 Approach Based Classification of Methodologies

Based on approach adopted to estimate environmental flow requirements, the methods can be divided into three broad categories (from complex to simple):

1. **Hydro-biology Methodologies:** these methods use hydrologic, hydraulic, and biological data. Examples are Holistic Approach, Instream Flow Incremental Methodologies (IFIM), Downstream Response to Imposed Flow Transformation (DRIFT), and Ecological Limits of Hydrological Abstractions (ELOHA).
2. **Hydrology and Hydraulics Based Methodologies:** These are sort of mid-way between hydraulics and biology, for example, the wetted perimeter method.
3. **Hydrological Methods**: These are the earliest developed methods which make use of only hydrologic data, such as Look-up tables, Range of Variability Approach (RVA), Flow Duration Curve (FDC) based approach, etc.

   Methods under each of these categories are now described in details.

5.2 Hydro-biology Methodologies

Hydro-biology or holistic methodologies are actually frameworks that use biological, hydrological, and hydraulic data and habitat simulation models. They are the only methodologies that explicitly adopt a holistic ecosystem based approach for EF determination. Ecosystem components that are commonly considered in holistic assessment include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates, fish and other vertebrates with some dependency upon the river ecosystem. Each of the components can be evaluated using a range of field and desktop techniques (Tharme 1996, and Tharme 2003) and the flow requirements are then incorporated into EF recommendation, using various systematic approaches. A wide range of holistic methodologies has been developed and applied in Australia, South Africa and United Kingdom.

5.2.1 Building Block Method (BBM)

It is assumed that under the natural flow conditions in a river, different flows (high, medium low) play different roles in the ecological functioning of a river. Developed in South Africa, building block method (BBM) is based on the premise that riverine communities and species are reliant on basic elements or building blocks of the flow regime. Hence, it is necessary to retain key elements of natural flow variation to ensure healthy river. The building blocks are different components of flow which, when combined, create a flow regime that facilitates the maintenance of the river in a pre-specified condition. The flow blocks comprise low flows as well as high flows required for channel maintenance and differ between ‘normal years’ and ‘drought years’. The flow needs in normal years are referred to as ‘maintenance requirements’ and divided between high and low flow components. The flow needs in drought years are referred to as ‘drought requirements’ (Hughes, 2001). Table 2 lists the building blocks suggested by Acreman et al. (2009).

Table 2 List of building blocks

Building block	Purpose
Low flows	Habitat for juveniles and prevention of invasive species
Maintenance flows	Stimulate species migration, spawning and dispersal
Freshets	Stimulate species migration, spawning and dispersal
Small floods	Sort river sediments, connect river and floodplain habitats
Large floods	Remove undesired species, maintain channel structure and evolution

The BBM makes use of the opinion/knowledge of experts. Normally knowledge of experts from two domains is used: physical scientists such as hydrologists, hydrogeologists and geomorphologists; and biological scientists such as aquatic ecologists. A series of structured stages are followed by the experts who assess available data and model outputs. Based on these and their professional experience/judgment, the experts arrive at a consensus on the building blocks of the flow regime. The ten steps that could be followed (Acreman et al. 2009) to construct a flow regime that would maintain the rivers in good ecological state could be obtained by combining the building blocks are given in Table 3.

Table 3 Steps required to define an environmental flow release regime using the BBM

Step	Description
1	Define a natural flow regime for the water body in terms of daily discharge time series for a representative 10-year period
2	Analyse the flow regime in terms of the magnitude, frequency and duration of high, medium and low flows
3	Assemble biological survey data or use models for the water body to determine the expected biological communities and life stages for the river in reference condition
4	Determine flow regime requirements for each species/community and life stage using published literature
5	Verify the requirements by identifying elements of the flow regime in the historical record
6	Check that flow release elements will deliver other important variables such as water quality, including temperature and sediment load
7	Define the building blocks
8	Record results in an environmental flow release regime table
9	Add up individual flow needs to assess overall implications for water resources
10	Repeat the analysis for each water body ensuring that environmental flow upstream are sufficient to meet needs downstream

5.2.2 Ecological Limits of Hydrological Abstractions (ELOHA)

The ecological limits of hydrologic alteration (ELOHA) framework is a synthesis of a number of hydrologic techniques and environmental flow methods that are being used and that can support comprehensive regional flow management. It was developed by a group of scientists (Poff et al. 2010). ELOHA essentially consists of four steps: 1. Build a hydrologic foundation of streamflow data, 2. Classify natural river types, 3. Determine flow-ecology relationships associated with each river type, and 4. Implement policy to achieve river condition goals.

Hydrologic foundation consists of two comprehensive databases of flow time-series representing simulated baseline (minimally altered or best-available conditions) and developed (altered flow regimes associated with the direct and indirect effects of human activities) conditions throughout the region during a common time period. ELOHA assumes that increasing degree of flow alteration from baseline conditions leads to more ecological changes. The hydrologic foundation facilitates the use of ecological information collected throughout the region and provides a basis for comparing present-day flow regimes to baseline conditions. River classification is a statistical process of stratifying natural variation in measured characteristics among a population of streams and rivers to delineate river types that are similar in terms of hydrologic and other environmental features. The classification can be developed within any region of interest. By assigning rivers or river segments to a particular type, relationships between ecological metrics and flow alteration can be developed for an entire river type based on data obtained from a limited set of rivers of that type within the region.

A key element in the ELOHA framework is defining relationships between altered flow and ecological characteristics that can be tested with existing and newly collected field data. ELOHA assumes that these relationships vary among the major river types since ecological responses to the same kind of flow alteration are expected to depend on the natural (historic) flow regime in a given geomorphic context. Developers of ELOHA recognize that assessing the ecological effects of modified flows is only one part of a complex socioeconomic–environmental process to decide on the use and protection of a region's water resources. The decisions to exploit the degree of these resources are taken by governments and stakeholders in the context of their perceived priorities for development and sustainability. In essence, a partnership of managers, scientists and those parts of society that will experience the effects of management actions decides on a redistribution of the costs and benefits of water use within the management area.

Regionalizing environmental flow management involves decisions that would minimize ecological impacts of new water developments, direct development to least-sensitive water bodies, and prioritize flow restoration efforts. These decisions are based on a scientific understanding of how changes in the natural flow regime affect ecological conditions. The ELOHA framework (Poff et al. 2010) helps water managers meet this challenge.

5.3 Hydrology and Hydraulics (HH) Based Methodologies

When detailed biological data are not available, recourse can be made to hydrologic and hydraulic data. HH methods use the relationship between the flow of the river and simple hydraulic characteristics such as water depth, velocity or wetted perimeter to calculate an acceptable flow. HH methods are combined desktop-field method requiring hydrological, hydraulic modeling and limited ecological data and expertise. These methods are an improvement over empirical or hydrological methods. Since the methods require measurement of the river channel, these are more sensitive than the desktop approaches to differences between rivers. Cross-sections are placed at a river site where maintenance of flow is most critical or where instream hydraulic habitat is most responsive to flow reduction, and thus potentially most limiting to the aquatic biota (e.g. riffles). A relationship between habitat and discharge Q, developed by plotting the hydraulic variable against discharge is used to derive the EF. A breakpoint, interpreted as a threshold below which habitat quality becomes significantly degraded, is identified on the habitat-Q response curve, or a minimum EFR is set as the Q producing a fixed percentage reduction in the particular habitat attribute (IWMI, 2007).

Within the total environmental niche required by an individual animal or plant living in a river, it is the physical aspects that are affected by changes to the flow regime. The most obvious physical dimension that can be changed by altered flow regimes is the wetted perimeter area of submerged river bed of the channel. Hydraulic rating method provides simple indices of available habitat (e.g. wetted perimeter) in a river at a given discharge.

Wetted perimeter method is a commonly applied hydraulic rating method. Environmental flows are determined from a plot of the hydraulic variable(s) against discharge, commonly by identifying curve breakpoints where significant percentage reductions in habitat quality occur with decrease in discharge. It is assumed that ensuring some threshold value of the selected hydraulic parameter at a particular level of altered flow will maintain aquatic biota and thus, ecosystem integrity.

5.4 Habitat Simulation Methodologies

These methods compute EFs based on hydrological, hydraulic and biological response data. The habitat simulation model links discharge, available habitat conditions (including hydraulics) and their suitability to target biota. Environmental flow is predicted from habitat-discharge curves or habitat time and exceedence series. PHABSIM (Physical Habitat Simulation Model) (Bovee, 1986) is a commonly applied habitat simulation methodology. Habitat simulation methodologies also make use of hydraulic habitat- discharge relationships but provide more detailed, modeled analysis of both the quantity and suitability of the physical river habitat for the target biota. Thus, environmental flow recommendations are based on the integration of hydrological, hydraulic and biological response data. Flow related changes in physical micro habitat are modelled in various hydraulic programs, typically using data on depth, velocity, substratum composition and cover, complex hydraulic indices, which are collected at multiple cross sections in each representative river reach. Simulated information on available habitat is linked with seasonal information on the range of habitat conditions used by target fish or invertebrate species, by using, say habitat suitability index curves. The outputs in the form of habitat discharge curves for specific biota are used to derive environmental flows. The habitat simulation modeling package PHABSIM housed within the instream flow incremental methodology (IFIM) is the pre-eminent modeling platform of this type.

5.5 Hydrological Methods

Although it is recognized that numerous factors influence the ecology of aquatic ecosystems (e.g. temperature, water quality and turbidity), the flow regime is the primary driving force which influences them (Richter et al., 1997). Streamflow characteristics offer some of the most useful and appropriate indicators to assess river ecosystem integrity over time. Many other abiotic characteristics of riverine ecosystems such as dissolved oxygen contents, water temperature, suspended and bed-load sediment size, and channel bed stability vary with flow conditions. Because flow exerts great impact on aquatic habitat, river morphology, biotic life, river connectivity and water quality, it is termed as the master variable. On a larger scale, channel and floodplain morphology is shaped by fluvial processes driven by streamflow, particularly high-flow conditions.

Analysis of river flow data provides key inputs to understand the hydrologic response of a catchment and for design and management of water resources projects. Time series of river flow data are either available at many gauging stations or can be estimated from a nearby site. In many regions, biological data are scarce, temporal and spatial coverage is small but the coverage of streamflow data is much better. Where such data are missing or the series are of short lengths, hydrological tools can be employed to extend the series. Long series of streamflow data help quantify the magnitude, range, variability of flows and impact of anthropogenic activities on rivers.

In view of these reasons, hydrological methods were naturally the first to be employed to estimate EFs. Allocation based on percentage of mean annual flow (MAF) or values read from flow duration curves (FDC) also fall in this category. Typically, indices based on the hydrologic data are calculated. For example, the French freshwater fishing law (June, 1984) requires that residual flows in bypassed sections of river must be a minimum of 1/40 of the mean flow for existing schemes and 1/10 of the mean flow for new scheme (Souchon and Keith, 2001). In regulating abstraction in UK, an index of natural low flow has been employed to define the environmental flow. In the UK, a flow based index, Q_{95} (flow which is equaled or exceeded 95% of the time) is often used to define EFs (Acreman and Dunbar 2004). The figure of Q_{95} was chosen purely on hydrological grounds. In other cases, indices of rarer events (such as mean annual minimum flow) have been used.

Indices based purely on hydrological data are more readily calculated for a site as flow data are generally available or can be estimated. Look up tables do not necessarily take account of site specific conditions. Therefore, these are particularly appropriate for low controversy situation but tend to be precautionary.

5.5.1 Tennant Method

Tennant (1976) developed a method using data from hundreds of sites on rivers in the mid-western states of the USA to specify minimum flows to protect a healthy river environment. Percentages of the mean flow are specified that provide different quality habitat for fish, e.g. 10% for poor quality (survival), 30% for moderate habitat (satisfactory) and 60% for excellent habitat. Although often quoted in lists of methods, the Tennant method has never been extensively applied and its statistics have been questioned even for application in mid-West USA. It is important that the application of such empirical methods outside the regions of their development should be undertaken with great caution.

5.5.2 Flow Duration Curve Based Methods

A flow duration curve (FDC) is a plot of flow vs. percentage time equaled or exceeded. FDC can be prepared using the entire time series data of flow or the flow data pertaining to a specific period (such as a month) in different years. Further, it can be developed for a particular site or combining data for different sites on per unit catchment area basis in a hydro meteorologically homogeneous region.

Smakhtin and Anputhas (2006) reviewed various hydrology based environmental flow assessment methodologies and their applicability in Indian context. They suggested a flow duration curve based approach that links EF requirements with environmental management classes. The first step is the calculation of a representative FDC for each site where the environmental water requirement (EWR) is to be calculated. The sites with observed flow data are referred to as ‘source’ sites and the sites where reference FDC and time series are needed for the EF estimation are referred to as ‘destination’ sites. All FDCs are represented by a table of flows corresponding to the 17 fixed percentage points. For each destination site, a FDC table is calculated using a source FDC table from either the nearest or the only available observation flow station upstream. To account for land-use impacts, flow withdrawal, etc., and for the differences between the size of a source and a destination basin, the source FDC is scaled up by the ratio of ‘natural’ long term MAR at the outlet and the actual MAR calculated from the source record. The principles of “natural flow regime” (Poff 2009) dictate that the variation in flows is essential to sustain ecosystem function in rivers. However, this method has no ecological basis and the fixed percentage points are merely empirical arbitrary hydrological statistics.

EFs aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition/status also referred to as environmental management class (EMC). The higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and more flow variability will need to be preserved. Generally, six EMCs are used and corresponding default levels of EWR may be defined. DWAF (1997) has described a set of EMCs given in Table 4.

Table 4 Environmental Management Classes (EMC) and management perspective

EMC	Description	Management perspective
A	Natural rivers with minor modification of in-stream and riparian habitat.	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions etc.) allowed.
B	Slightly modified and/or ecologically important rivers with largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Water supply schemes or irrigation development present and / or allowed.

EMC	Description	Management perspective
C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.	Multiple disturbances associated with the need for socio-economic development, e.g. dams, diversions, habitat modification and reduced water quality
D	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation
E	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation. Generally this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to "move" a river to a higher management category.
F	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats, (if still possible / feasible) etc. - to "move" a river to a higher class.

EFs aim to maintain or upgrade an ecosystem in some prescribed (EMC). Placing a river into a certain EMC is normally accomplished by expert judgment using a scoring system. Alternatively, the EMCs may be used as default 'scenarios' of environmental protection and corresponding EWR and EF- as 'scenarios' of environmental water demand. The FDC for the site for natural conditions is drawn and depending upon the desired EMC, the FDC is shifted to the left to obtain the desired EF regime. Lowering of FDC to determine EF regime appears to be a practical solution when desired inputs from ecological and social sectors are not present.

5.5.3 Range of Variability Approach

In the Range of Variability Approach (RVA) developed by Richter et al. (1997), different aspects of flow variability are expressed through 32 indices. These indices reflect different aspects of flow variability and there is one-to-one relationship between hydrological and ecological variables. Smakhtin et al. (2006) noted that the number of indices used in RVA is too large and either many of these are likely to be correlated or there is little difference between their values.

The Basic Flow Method (BFM) was developed in Spain (Palau and Alcázar 2012) to calculate environmental flow needs for river regulation. BFM assumes that the streamflow conditions are crucial to determine the abiotic structure and biotic composition of riverine ecosystems since they determine bank form, bed width, bed substrate types and the distribution of velocities and depths. Given that the organisms can withstand significantly low flow conditions for limited time periods, the method determines the average duration and magnitude of such periods. Computational procedure for BFM is the following: a) Calculate the moving averages of daily flows, from one-day to 100-day intervals; b) For each year and each interval, extract the minimum flow value, accounting for an annual period starting in the hydrobiological year; and c) calculate the relative increment between each pair of consecutive minima and select the flow with the largest relative increment.

5.5.4 Desktop Reserve Model

Hughes and Munusler (2000) and Hughes and Hannart (2003) developed a desktop method for rivers in South Africa. The user calculates a hydrological index (i.e. coefficient of variation of flows divided by the base flow index (CV/BFI) using river flow data at the site. Hence, the base flow index curves are employed to define the percentages of mean annual runoff (MAR) volume that is required for different components of the environmental flow regime. It is intended to quantify environmental flow requirements in situations when a rapid appraisal is required and data availability is limited (Hughes and Hannart, 2003). The model is built on the concepts of the building block method (described earlier) which is recognized as a scientifically legitimate approach to setting environmental flow requirements (Hughes and Hannart, 2003). The model comprises empirically derived statistical relationships developed through an analysis of comprehensive environmental flow studies conducted in South Africa. It is found that rivers with more stable flow regimes have relatively higher flow requirements than rivers with more variable flow regimes. This is because in highly variable flow regimes the biota would have adjusted to relative scarcity of water, while in more reliably flowing rivers, the biota are more sensitive to reduction in flow (Hughes and Hannart, 2003).

6.0 Implementation of EF

Implementation of environmental flows is challenging due to number of reasons. In most countries, often different organizations and regulatory agencies are associated with different components of environment, viz. rivers, forests, wild life, and aquatic life. Role and importance of these components for aquatic ecosystems may also change as one moves from mountains to estuaries. It is a big challenge to establish coordination among these agencies. Another important factor is that all the water of many rivers is already allocated to various sectors such as irrigation, drinking, hydropower and very little or no water is left unallocated. To allocate water for ecological needs, supplies to some of the existing uses have to be curtailed which will result in economic loss and resistance from the concerned sector. Issues arising due to this adjustment need to be handled fairly and carefully.

Usually, it is difficult to estimate the benefits from e-flows such as improvement environment, healthy rivers and higher bio-diversity. Hence, the application of traditional economic analysis posses challenges. Some models have been developed which can produce ecological outcomes of basin-wide planning but the use of such models is not widespread.

Since at present there is limited experience and expertise in implementing EFs and their consequences, adaptive management is recommended. The basic idea is ‘learn by doing’. This involves estimating and implementing EFs, monitoring the health of the ecosystem, and then revising the decision. Sharing results with all stakeholders and with the global community of environmental flow practitioners will help the practice to grow.

7.0 Future Challenges

Water from many rivers is being used for various uses. It is not possible to undo the developments and return to the conditions that existed, say, 100 years ago. Hence, the attempt should be develop flow regimes that is feasible and provides desired benefits. The science of environmental flows has advanced considerably in the last 25 years from little knowledge and awareness to a focus on individual aquatic species to a broader concern about ecosystem protection or restoration these days. At the same time, there have been considerable advances in basic scientific understanding and the development of EFA techniques. However, many of these advances in knowledge are limited to regions (mostly in developed countries) where the scientific studies have been undertaken. The same kind of understanding of ecological responses is not present in many other areas where EFAs are being applied and the knowledge is not directly transportable.

A wide range of available catchment models can provide assessments of ecologically relevant hydrologic variables. Hydrologic models can estimate the water level, velocity of flows and the extent and duration of floodplain inundation. Some models make use of sediment transport, slope and river cross-section data to compute water levels and changes in river profile. In most EFAs, surface water and groundwater resources are assessed separately. However, these systems are usually interlinked. Further, the changes in land-use land-cover and ground water withdrawals impact river flows. Thus, ideally all these aspects should be jointly considered but currently very few models have the capability to accomplish this task. At the same time, data required for such applications are not always available and thus integration of all these aspects in EFs is challenging.

Ecosystem services on which people depend will be affected in numerous ways by the changes in the volume and timing of flows induced by climate change. Such impacts are not yet properly understood. In addition, climate change will influence the demand for water for various uses. These shifts in location, quantity, timing, and sources of water demand will have implications for providing water for environmental services.

Finally, environmental flows are based on the concept of equitable water sharing of flows in river or groundwater systems. Hydro infrastructure projects typically generate considerable economic benefits, and these benefits often accrue to populations that are distant from the water sources. Benefit sharing provides an alternative approach to water sharing, where the economic benefits from the development project are shared with the affected people. There is disconnect between the water, environment and policy making communities and this hinders promoting environmentally sensitive sustainable development. To that end, appropriate mechanisms need to be developed to bridge the gap.

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