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Assessment of environmental flow requirements

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Introduction

Rising demands and increasing withdrawals are causing large reduction in the flows in some rivers. Among other things, this is degrading river ecosystems. The health of a river's ecosystem depends on several factors: discharge, structure of the channel and riparian zone, water quality, river management works, level of utilization, and the presence of barriers to connectivity (Norris and Thoms, 1999). Storage dams or diversions can profoundly impact these features. Among the factors influencing aquatic ecosystems, the flow regime is the primary driving force (Richter *et al.*, 1997). Flow is termed as the master variable because it exerts great impact on aquatic habitat, river morphology, biotic life, river connectivity, and water quality.

Based on the premise that the health of a river ecosystem deteriorates significantly if flow falls below some threshold, the concept of minimum flow in rivers came into practice in the 1970s. Subsequent studies led to the understanding that all elements of a flow regime, including high, medium, and low flows, are important from the ecosystem point of view (Poff *et al.*, 1997). High flows are important for channel flushing, maintaining flood plains, and riparian vegetation; medium flows are needed for fish growth and migration; and low flows are important to avoid river fragmentation, maintain water quality, and as evidence that the river exists. Environmental flows (EFs) are an important aspect in integrated water management.

Any change in the flow regime will influence the river ecosystem, and to maintain it in a pristine condition, EFs will have to closely follow the natural flow regime. However, this is not always possible, and most rivers are managed to different degrees to meet societal needs. Some uses, such as irrigation, require diversion of water from the river while others, such as bathing, do not require water abstraction. In some uses (hydropower generation or cooling of a thermal power plant), diverted water is returned to the river after use.

Definition of EF

The concept of EFs has been developed to check the harmful impact of large withdrawals on the river ecosystem. The overarching idea is that the health and integrity of the entire ecosystem are fundamental to sustaining human well-being. 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 (Acreman and Ferguson, 2010). According to Krchnak *et al.* (2009), the term EF refers to a variable water flow regime that has been designed and implemented—such as through intentional releases of water from a dam into a downstream reach of a river—in an effort to support desired ecological conditions and ecosystem services. EFs are necessary to maintain the health and biodiversity of downstream water bodies, including coastal waters, wetlands (mangroves, sea grass beds, floodplains), and estuaries. Besides the amount, one should also specify when this flow should be ensured.

Figure 1 depicts the trade-offs in environmental cost and economic benefit as water is abstracted from a river. As abstraction increases, economic gains initially increase sharply, and environmental degradation is low. With further rise in abstraction, the incremental benefits are lesser but costs rapidly increase. When abstraction is very high, marginal economic benefit is low, but marginal environmental cost is high. Depending upon the hydrologic, ecological, social, and economical situation, the problem of EF assessment is to find what fraction of mean annual runoff (MAR) can be abstracted to achieve the desired balance of economic benefits and environmental cost.

Adverse impacts from storage and diversion of river flows can be minimized by releasing water to meet EF requirement (EFR), which is a compromise between water resources development and maintenance of a river in ecologically acceptable or agreed conditions (Figure 1). In view of the importance of EFR, many countries have formulated policies and laws to ensure priority allocation of water for EFs after basic human needs have been satisfied.

EFR depends on a number of factors, including the size of river, the desired state, sensitivity of river ecosystem, preference of the society, and the uses of river water. Consequently, before computing EFR, broader objectives must be determined to indicate the type of river desired. For some rivers, EFR are set to achieve specific pre-defined ecological, economic, or social objectives. This is called objective-based flow setting (Acreman and Dunbar, 2004). The Water Framework Directive of the European Union (Acreman and Ferguson, 2010) requires member states to achieve 'Good status' (GS) in all surface and ground waters. GS of a river is a combination of good chemical status and good ecological status (ES). ES is defined qualitatively as slight deviation from the reference status, based on populations and communities of fish, macro-invertebrates, macrophytes and phytobenthos, and phytoplankton. To define the reference state, an assemblage of component species is required that would be found in an 'undisturbed' state.

Methodologies To Assess EFR

Since the mid-1970s, there has been a rapid proliferation of methods for estimating EFR for a given river, ranging from relatively simple, low-confidence, desktop approaches, to resource-intensive, high-confidence approaches (Tharme, 2003). Comprehensive methods are based on detailed multi-disciplinary studies that often involve analysis of large amounts of hydrological, geomorphological and ecological data and experts from different disciplines. Typically, such studies may take many months, sometimes years, to complete.

The last couple of decades have seen the evolution of various methods and approaches to estimate EF. Based on evolution, Tharme (2003) presented a classification of methods to estimate EFRs: hydrological methods, hydraulic rating methods (HRM), habitat simulation methods (HSM), and holistic methods.

Since hydrology provides the foundation for water resources management, hydrological methods are frequently employed to get initial estimates of EF. Generally, time series of river flow data are available at many places, and indices based on these can be easily calculated. Allocation based on percentage of MAR or values read from flow duration curves (FDC) fall in this category. The Tennant (1976) method shows the likely status of the habitat from various levels of EFs in two six-monthly groups by separating the entire range of MAR at a site into several ecologically relevant ranges. Tennant specified percentages of the MAR that provide different quality habitat for fish. Although Tennant developed the indices for the USA, these have been used in other countries. In the UK, Q_{95} (flow which is equaled or exceeded 95% of the time) is often used to define EFs (Acreman and Dunbar, 2004). Richter *et al.* (1997) developed the range of variability approach which uses 32 indices to reflect different aspects of flow variability. EFs aim to maintain or upgrade an ecosystem in some prescribed "environmental management class (EMC)". DWAF (1997) defined six EMCs, from A (natural) to F

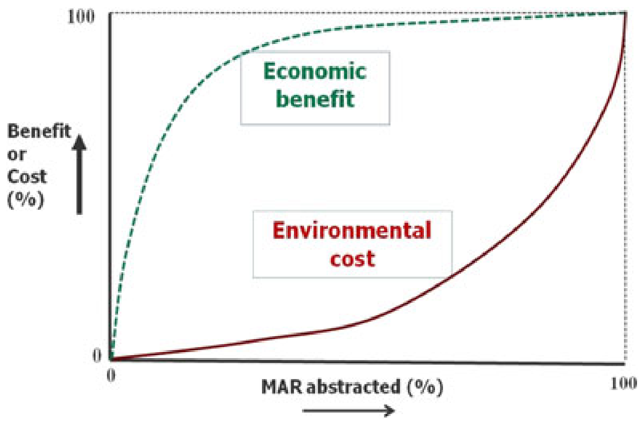

Figure 1. Typical variation of economic benefit and environmental cost as functions of water abstracted from a river. MAR: mean annual runoff

(critically modified). The FDC for the site for natural conditions is drawn, and depending upon the desired EMC (decided by expert judgment), the FDC is shifted to the left to obtain the desired EF regime.

A limitation of hydrologic methods is the difficulty in relating parameters of the flow regime to the response of aquatic species and communities. This led to the development of Hydraulic Rating Methods (HRM) which use basic hydrologic, hydraulic, and ecological data and expert opinion from these fields. Easily measurable hydraulic characteristics of a river are water depth, velocity, wetted perimeter, etc. Methods based on wetted perimeter use the relationship between the flow, cross-section properties, ecological variables, and wetted perimeter to calculate EF. Breakpoints where habitat quality significantly degrades with reduction in discharge are identified in the habitat–discharge response curve. EFR is set as the discharge producing a fixed percentage reduction in the particular habitat attribute (IWMI, 2007).

The next level of improvement in EF methodology is based on suitability of the physical habitat of indicator species as a function of river flows. Methods based on simulating the response of species using the hydrological, hydraulic, and biological response data are called Habitat Simulation Methods (HSM). Fish is commonly taken as the indicator species of river habitat, whose productivity is determined by flow regime, physical habitat structure, water quality, and energy and nutrient inputs. Bovee (1986) developed the Physical Habitat Simulation Model which is housed within the instream flow incremental methodology (IFIM). King and Louw (1998) provide a description of IFIM.

A broader view in EF assessment is that EFs should suit all aspects of the river ecosystem and should be determined by a holistic approach. Holistic methods are frameworks that combine hydrological, hydraulic, and habitat simulation models. They are the only EF methodologies that explicitly adopt a comprehensive ecosystem-based approach. One of the most popular and versatile methods in this category is the building block method which assumes that different flow regimes play different roles in a river for the growth and maintenance of the ecosystem. Building blocks are different components of river flow and, when combined, yield a complete flow regime to maintain the river in the desired condition.

Choosing methodology for EF assessment

Choice of methodology is important in assessment of EFs. This choice depends upon factors such as the availability of data, technical expertise, finances, time, etc. Tharme (2003) found that hydrology-based methods were globally followed in the highest number of cases (30%) closely followed by habitat simulation methods. In developing countries, the proportion of hydrology-based methods is still higher, mainly due to the paucity of data on ecology and biotic components. Application of HRMs and holistic methods requires a multi-disciplinary team and huge resources which may be bottlenecks in certain cases. At times, it is difficult to assemble desired data and an adequate research team, and secure the requisite resources.

Hierarchy of EF assessment

Environment flows are best assessed in a multi-tier hierarchical framework. Smakhtin and Anputhas (2006) mention two major tiers: (1) Desktop, rapid assessment, using primarily ecologically relevant hydrological indices or analysis of hydrological time series, and (2) Detailed assessment, using primarily holistic methods or habitat modeling. Methods from the first group are diverse, require fewer data, and are more suitable for initial, reconnaissance, or planning-level assessments of EF. Methods from the second group often adopt a whole-ecosystem view. Ecological and social factors are identified, and EF regime is defined by a multi-disciplinary panel of experts. These methods include substantial field work, and consume considerable time and resources. Arthington *et al.* (2003) proposed a three-tiered hierarchy where each level offers methods appropriate to particular circumstances and management objectives, scales of investigation, resources, knowledge base, and expertise. Level 1 consists of hydrological and other precautionary EF methods. Level 2 consists of holistic scientific panel methodologies. Finally, Level 3 includes detailed biological and ecological response models.

Locations for estimating EF

EFs are most frequently computed at water resources projects. Storage or diversion of large quantities of water by a project can adversely affect a river's ecosystem, and the basin managers have to specify and ensure EFs downstream of projects. Additional locations are places where EFs are critical for integrity of aquatic ecosystem or where the bio-diversity and habitat conditions are highly responsive to flow reduction.

Issues In Estimation And Implementation Of EF

Several issues may arise in estimation and implementation of EF.

Data. Data availability is a limitation in most studies to compute EF, particularly in developing countries. Besides hydrology, data are needed from, amongst others, the environmental, ecologic, and socioeconomic sectors. If the study area is in the mountains, the situation becomes more difficult because the hydrometric network at higher altitudes is generally scarce. River discharge, cross-sectional form, and velocity of flows may not be measured at the site of interest. Data about water quality and aquatic species are collected at even fewer places and with less frequency. It is generally not possible for the study team to launch a field campaign to collect the required data. Visits to the study region, preferably in different seasons, are helpful but cannot overcome data deficiencies. Limitation of data may constrain the choice of methods that can be applied.

A wide range of data from various sectors is required for EF estimations. Required hydrologic data are time series of flow depth, discharge, and sediment transport. In addition, river cross sections at desired locations, slopes, and bed profiles are needed. Data of aquatic fauna include the species present in the river, their numbers/density, water depth and velocity requirements, migration behavior, etc. Regarding flora, the data required include the details about the species and their water requirements. The data on flora and fauna in the pre-project scenario are also needed to create a baseline. Data pertaining to social sector such as the time series of demand of water at different locations for various purposes are needed. While computing EFs, it is also important to be aware of the provisions of the relevant government policies.

Quality of EFs. EFs are helpful only if, besides quantity, the quality of water is up-to-mark. If good quality of water is not ensured, one may finally see polluted water masquerading as EF. Polluted water may do more harm than good and will defeat the very purpose of EF. Note that EFs are not provided to maintain river water quality by dilution.

Reluctance to Release EF. Rivers have steep slopes in mountains which have the best locations to generate hydroelectric energy. Since the concept of EFs was not practiced in earlier times, no such requirement was placed on hydropower projects that were built more than 20 years ago. EFs may typically range from 5% to 30% of MAR. Reduction in energy generation due to EFR may typically be up to 25% or even more. Some operators of hydropower projects consider that water bypassing turbines is lost revenue. Understandingly, some project owners are reluctant to allow water to bypass the powerhouse to serve environmental needs. Hence, it is necessary to create awareness and develop a mechanism to ensure compliance with the stipulated EFs.

To incorporate EF demand in existing hydropower projects, it will be helpful to formulate a policy in consultation with the various stakeholders so that the same procedures can be consistently implemented and there is minimum resistance to their implementation. Different norms for existing and new projects can be prepared, and the existing projects can be suitably compensated for the shortfall in energy generation by such measures as tax breaks. It may also be necessary to make structural changes in some existing projects to enable release of EFs in all seasons.

Religious and cultural aspects of Rivers. Rivers have great religious and cultural significance for vast populations in many countries. Water of many rivers is used for social and religious rituals and festivals. Rivers are considered sacred and worshipped in India. Some rituals of the Hindu religion are best performed adjacent to a flowing river. On auspicious days, pilgrims assemble on the banks of rivers and lakes to bathe; at times, the number of devotees may be in the millions. Similarly, the Nile and Jordan rivers have religious and cultural values attached to them. River water is reserved for the natives in some places in the USA and Australia. In view of this, the governments have to ensure that there is enough depth and discharge of good quality water in the rivers to meet religious and social needs. Requirements for this purpose can be termed as a religious/social flow requirement.

Concluding Remarks

Many negative impacts on river ecosystems due to construction and operation of dams can be minimized by careful planning and operation. Development objectives that protect biodiversity and ecosystem service should be the bedrock of planning and decision-making. Ideally, EFRs should be estimated in the planning stage of a project itself; it will be difficult and costly to modify the design and operation of existing projects to take care of EF needs. An important research question is to quantify relationships between hydrological and ecological indicators in rivers. Creating baseline data of the relevant sectors will be of immense help. This is particularly true for the rivers in the mountains.

An emerging challenge is to utilize water resource to provide sustainable social benefits while minimizing adverse impacts on natural ecosystem. EF critically depends upon the development stage, per capita water availability, and expectation of the society from the river. Developing societies with high per capita water availability are likely to allocate higher quantities for EF. However, in societies with increasing demands for food production and energy generation, and consequently rising pressure on dwindling water resources, allocation for EF is likely to be reduced. To that end, it is important and helpful to involve all the stakeholders in deciding EFR to find acceptable and implementable solutions. Framework, such as the ecological limits of hydrologic alteration (ELOHA), is a synthesis of many existing environmental flow methods. This framework is expected to allow the water managers, researchers, and stakeholders to analyze and synthesize information into ecologically based and socially acceptable goals and standards for management of environmental flows (Poff *et al*., 2010).

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References

Acreman MC, Ferguson AJD. 2010. EFs and the European Water Framework Directive. *Freshwater Biology* 55: 32–48.

Acreman M, Dunbar MJ. 2004. Defining environmental river flow requirements a review. *Hydrology and Earth System Sciences* 8: 861–876.

Arthington AH, Rall JL, Kennard MJ, Pusey BJ. 2003. EF Requirements of Fish in Lesotho Rivers Using the DRIFT Methodology. *River Research and Applications* 19: 641–666.

Bovee KD. 1986. Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. USDI Fish and Wildlife Service, Instream Flow Information Paper #21 FWS/OBS-86/7, Washington, DC; 235 pp.

DWAF. 1997. *White paper on a National Water Policy for South Africa*. Department of Water Affairs and Forestry: Pretoria, South Africa.

IWMI. 2007. *Water Policy Briefing, Issue 24*. International Water Management Institute: Colombo, Sri Lanka.

King JM, Louw D. 1998. Instream flow assessments for regulated rivers in South Africa using the building block methodology. *Aquatic Ecosystem Health and Restoration* 1: 109–124.

Krchnak K, Richter B, Thomas G. 2009. Integrating EFs into Hydropower Dam Planning, Design, and Operations. Water Working Note No. 22, World Bank, Washington DC.

Norris RH, Thoms MC. 1999. What is river health? *Freshwater Biology* 41: 197–209.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* 37: 231–249.

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'keeffe JH, Olden JD, Rogers K, Tharme RE, Warner A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* 55: 147–170.

Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* 37: 231–249.

Smakhtin VU, Anputhas M. 2006. An assessment of EF requirements of Indian river basins. Research Report 107, International Water Management Institute, Colombo, Sri Lanka.

Tennant DL. 1976. Instream Flow Regimes for Fish, Wildlife, Recreation and Related Environment Resources. *Fisheries* 1: 6–10.

Tharme RE. 2003. *A global perspective on EF assessment: emerging trends in the development and application of EF methodologies for rivers*. Freshwater Research Institute, University of Cape Town: South Africa.