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REVIEW PAPER

Global Trends in Environmental Flow Assessment: An Overview

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Abstract Diminution of riverine ecosystem is one of the major challenging issues which is caused due to the alteration of river flow in order to meet the day to day increase in requirements of human being. These alterations in river flow is mainly due to the construction of storage, diversion and control structures which are primarily for generation of electricity, irrigation and flood control. Recently, environmental flow assessment has advanced in the past decade in order to improve the environmental degradation to certain degree. This paper reviews various methods for assessing environmental flow (EF) and provides global trends. We observe that, most of the methods involve different set of data and time requirements. Moreover, the reliability of results and the level of experience required to apply the different methods are different and that no method is superior over the other. The procedure of environmental flow analysis and application is adaptive which involves likewise fluctuation in EF due to increase in the available information and change in priority and infrastructure. This review of case studies of global rivers provides an insight into the environmental flow assessment obtained through hydrological and hydraulic rating method ranged from 30 to 50% of mean annual flow. Other methods for environmental flow assessment are dependent on various ecosystems. Furthermore, the discussion on various methodologies applicable for EF assessment of Indian rivers is also provided in the article.

Keywords Environmental flow · Instream flow · Methodologies · Eco-hydrology

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Introduction

Environmental flow (EF) is an important component of a hydrological ecosystem that plays a key role to conserve or protect biodiversity and ecological integrity [1, 2]. Figure 1 depicts importance of EF regime (EFR) in different aspects [3]. Flow alterations caused by anthropogenic activities through both consumptive and non-consumptive use have resulted in physical, chemical and ecological changes in the properties of rivers [4–6], e.g., hydro peaking operations [7]. Climate change leads to warmer climate depleting phosphorous due to its increased uptake [8] and alters hydrology of catchment due to higher rate of evapotranspiration [9]. Dispute for water among various sectors, regions, states and nations undermines the necessity of EF [10]. The fluctuations in quantity, quality and regimes of river flows are adversely affecting the usefulness of the water bodies as well as the wholesomeness of the ecosystem [11].

Among all the modifiers introduced by human, dams are considered to be the significant one which results in direct and irreversible modification of river flow, affecting its ecological health and ecosystem services. It has been estimated that around 58,500 dams were constructed everywhere throughout the world till year 2011. The number of these dams with respect to their purpose is shown in Fig. 2. About 292 large river systems are present around the globe, and above 50% of them are affected by dams [12, 13]. India is the third largest

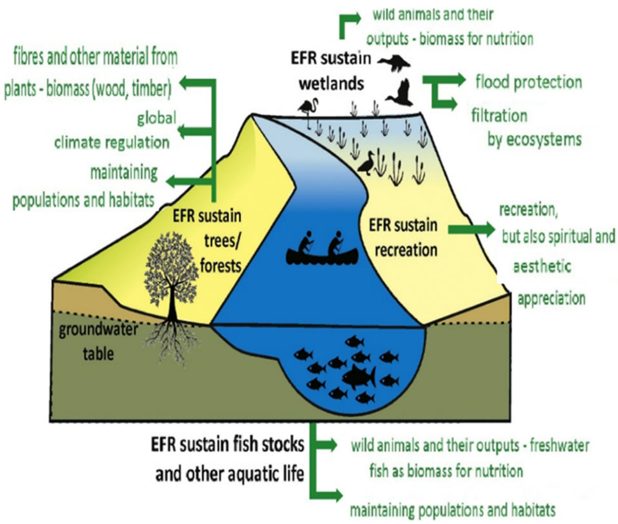

Fig. 1 Importance of environmental flow regime (EFR)

dam builder in the world after China and USA which is presented in Table 1.

Keeping note of growth in hydropower projects, Ministry of Environment and Forest (MOEF), Government of India, issued guidelines for environmental impact assessment of such projects, emphasizing on significance of EF, biodiversity and their cumulative impact study [14]. This paper elaborates various methods used around the world for environmental flow assessments (EFA) and dilates limitations for their use.

State of the Art in Environmental Flow Assessment

Environmental flow is the water left in our rivers to ensure downstream environmental, social and economic benefits [15]. Across the globe, it is also termed as Ecological flow

Table 1 Top twenty countries on the basis of number of dams [12, 13]

S. no.	Country	Number of dams	Percent of total dams
1	China	23,842	41.4
2	USA	9265	16.1
3	India	5102	8.8
4	Japan	3116	5.4
5	Brazil	1392	2.4
6	Korea (Rep. of)	1305	2.3
7	Canada	1166	2.0
8	South Africa	1114	1.9
9	Spain	1082	1.8
10	Turkey	976	1.7
11	Iran	800	1.4
12	France	713	1.2
13	UK	607	1.1
14	Rest of world	7171	12.5

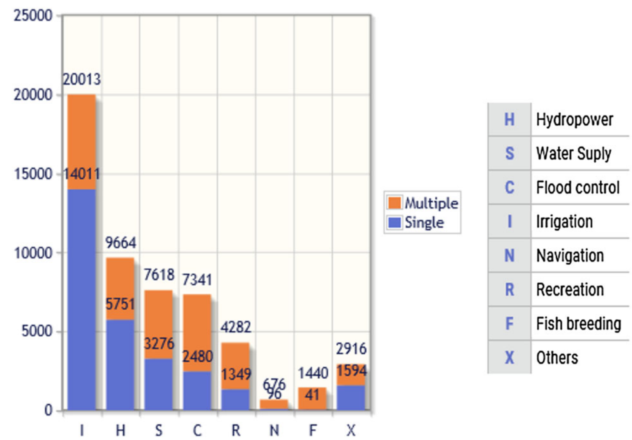

Fig. 2 No. of dams in world based on their purpose. *Source*: http://www.icold-cigb.org/GB/world_register/general_synthesis.asp

[16] and Instream flow [17]. Figure 3 depicts a flowchart for environmental flow assessments.

Currently there are three major classifications for Environmental Flow Assessment Methodology (EFAM):

- *International Union for Conservation of Nature (IUCN) Classification* [18] Three categories were mentioned, namely methods, approaches and frameworks, which were further subdivided into subcategories.
- *World Bank Classification* [1] The methodologies were classified into two approaches, namely perspective and interactive.
- *International Water Management Institute (IWMI) Classification* [19] The methodologies are classified as shown in Fig. 4, and their discussion follows in next section.

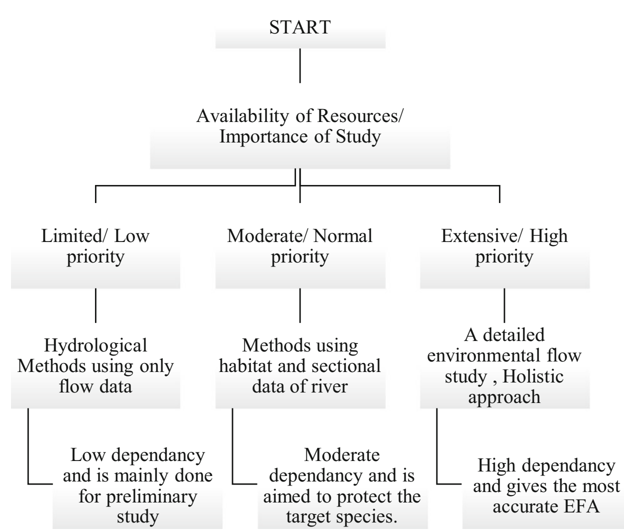

Fig. 3 Flowchart of environmental flow

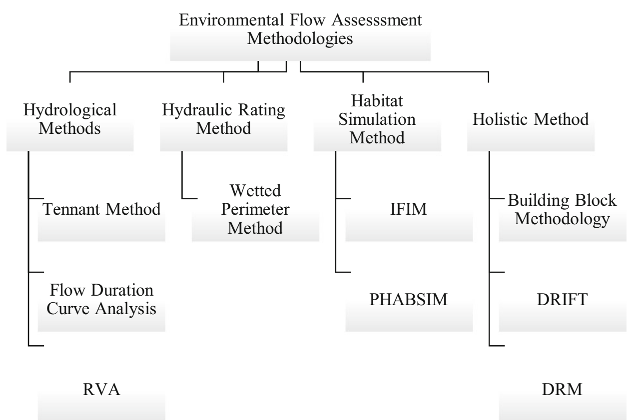

Fig. 4 IWMI classification

IWMI Methodologies

Hydrological Methods (HM) [20–23]

These are based on the analysis of historic (existing or simulated) stream flow data and do not work at a species-specific level. The basic approach of hydrological methods is that the more quantity of water will provide the best way to ensure the safety of biotic components of river and prolong some low threshold leading to reduction in danger to the biota.

Tennant Method (also called the "Montana" method) makes a general assumption that specific portion of the average annual flow (AAF), equivalent to mean annual flow (MAF), is required to preserve the biological integrity of a river ecosystem. It recommended percentage values of MAF for 11 rivers in Montana, Nebraska and Wyoming. The results were predicted to sustain predefined ecosystem attributes [24].

Flow Duration Curves (*FDCs*) represents an analysis based on graphs developed between historical stream flow variations and time durations. It derives percentage equaled or exceedance values of a particular discharge for given time variations [25–27].

Range of Variability Approach (*RVA*) assesses flow regime alterations by comprehensive statistical analysis of ecological parameters. The method is based on 32 indicators of hydrological alterations (IHA) which are clubbed depending upon the regime characteristics into five groups, namely magnitude, timing, duration, frequency and rate of change of discharge. These are derived from long-term daily flow records. These 32 IHA are analyzed for their individual alterations to reflect variations in flow regime [5, 28].

Hydraulic Rating Method (HRM)

The method (also known as habitat retention or hydraulic geometry methods [19]) is derived through the interrelationship of hydraulic parameters (wetted perimeter and depth) of a river and its discharge. Unlike HM, HRM integrates the flow data with hydraulic parameters, obtained from the site over river cross section [29, 30].

Wetted Perimeter Method is a simplest and dependable method since it has clear concept mathematics of finding the critical point on the curve between wetted perimeter and stream flow. The variation in wetted perimeter at a single cross section, generally across a riffle (as riffles tend to be the most productive benthic habitat), with discharge, forms the reference for an environmental flow recommendation. Optimum discharge, usually for fish spawning or highest production by benthic invertebrates, is generally identified from a discharge near the critical point of the wetted perimeter-discharge curve [31, 32].

Habitat Simulation Method (HSM)

The method enhances the approach used in the HRM by incorporating hydraulic rating with the preferential habitat characteristics of the target species. Several cross sections along the river length are selected on the basis of wetted perimeter, depth and velocity to generate various hydraulic models. Biological sampling of indicator species, combined with hydraulic characteristics where they are found, is used to populate the habitat part of the model. Both the models (hydraulic and biological) are merged into a single model, and the resultant model is used to determine the preferential area for the target species at various flows, and further will help to deduce the required flows [33].

Instream Flow Incremental Methodology (IFIM) and PHABSIM IFIM works in four stages containing a complex system of decision making dealing with various things such as details about the stakeholders, type of scale, data collection. At the last stage, all these components are integrated to give the appropriate environmental flow. A major component of IFIM is a suite of computer models called the Physical HABitat SIMulation model (PHABSIM), which incorporates hydrology, stream morphology and microhabitat preferences to generate relationships between river flow and habitat availability [34].

Holistic Method

It includes methodologies which consider all biotic and abiotic components present in the river ecosystem along with other associated water bodies to evaluate EF, instead of focusing on a few characteristics and livings [35].

Building Block Methodology (*BBM*) segregates the flow regime of a river into components which can be described distinctly in terms of their timing, duration, frequency and magnitude [36]. These components called as "Building Blocks" of flow usually fall into the following categories:

Table 2 List of countries with the most frequently used environmental flow methodology [28, 31, 34, 38–45]

Country	Available environmental flow methodologies in use	River and EF (m^3/s)
USA (Alaska)	IFIM; Tennant method, including modifications thereof on the basis of professional judgment and fish data	Wulik river—98.6
Australia	Tennant method; wetted perimeter method; IFIM; holistic approach	Murray river—66% of MAF
Austria	Habitat modeling; other methods unspecified	NA
Britain and Wales	Various methodologies: IFIM; hydrological tools (e.g., micro low flows); hydrological indices (e.g., Q95); environmentally prescribed flow method; holistic methodologies	Don river—(36–44%) MAF
Canada	Tennant method; including Tessman modification; wetted perimeter method; IFIM	NA
Denmark	FDC analysis and other hydrological methods	NA
Finland	Habitat simulation techniques with detailed use of GIS	Kutinjoki river—(2.4–4.8)
France	IFIM and other habitat simulation methods; various hydrological methods	NA
India	Holistic approaches	Tungabhadra river—NA
	Hydrological methods	Punarbhaba River—0.39 (IHA)
Indonesia	IFIM	Sekampung river—3.5
Italy	Hydrological indices, including FDCA, daily and annual mean flows; IFIM; Tennant method; wetted perimeter method	Vomano river—NA
Japan	IFIM, including multidimensional hydraulic modeling	NA
New Zealand	Modified Tennant method; IFIM; wetted perimeter method	Wairau river—8.4
South Africa	Desktop reserve model; FDC analysis; RVA; IFIM; building block methodology; DRIFT	Buzi river—57% MAR
USA	IFIM; Tennant method, wetted perimeter method; 7Q10 method; professional judgment; R-2 cross method; hydrological methods based on flow records/FDCA; water quality methods; USGS toe-width method; Arkansas method; HEC-2 program	Tennessee River Valley—NA

dry-season base flows (low flows), wet-season base flows, wet-season floods, dry-season freshes and dry-season subsurface flows. The minimum volume of water required for each “block” is described, and the modified flow regime is obtained by combining the building blocks in a manner that it mimics the virgin flow regime.

Desktop Reserve Model (*DRM*) utilizes monthly flow data and separates the total flow into high flows and low flows during “normal years” (maintenance flows) and “drought years” (drought flow). DRM uses two quantities to represent the hydrological variability: the Hydrological Index representing climatic variability, and the Base Flow Index (BFI; proportion of base flow to the total flow) [37].

Currently used environmental flow methodologies in various countries are shown in Table 2.

Technology as an Aid in EFA

Like every other field of study, environmental flow assessment can also be enhanced using different technologies. A new EFA technique is used to assess the suitability of fish habitat with respect to synthetic hydraulic and water quality parameters using Takagi–Sugeno fuzzy logic. Fuzzy approach has an important advantage of utilizing expert knowledge to supplement the scarcity of field data [46].

Another model is developed which deals with stream flow reduction activities, impacts of farm dams and run of river abstractions for estimating present and future scenarios [47]. Use of optimization technique and EF management model to calculate optimal flow [48, 49] and iSTREEM model to evaluate dilution factors in different flow conditions also give positive results [50]. The various software used in the field of environmental flows are: GIS (capture, store and display data related to positions on the earth’s surface), Satellite (real-time crop vegetation monitoring, geo-spatial positioning), HEC (relationship between discharge and time), Winxspro (gives the wetted perimeter and depth of the river), IHA (gives the variation in natural flow regime), USGS tools, Flow Health and Global environmental flow calculators [51–55].

eWater Source

eWater Source is Australia’s national hydrological modeling platform which can be helpful in EFA. It provides various tools like River Analysis Package (RAP), eflow predictor, Eco-Modeller, TREND, The Invisible Modeling Environment (TIME), etc.

RAP has an important module called hydraulic analysis (HA) which can be used to examine hydraulic characteristics of river channels like surface width, area, hydraulic radius and wetted perimeter. Defining habit criteria and calculating the area of habitat of habitat at different flows, importing HEC-RAS files and providing user channel geometry data are many other features of this tool. RAP can also provide summary metrics of discharge (daily, monthly, seasonally or annually), plotting flow duration curves, prediction of flood return interval by time series analysis (TSA) module. Other tools like eflow help to meet EF needs of a stream by augmenting current flow regime, TREND for time series data analysis, TIME for developing hydrological and environmental simulation models, etc., facilitates EFA by policy and governance [56].

Challenges in Assessment of EFs and Their Solutions for Indian Conditions

Suitability of hydrological and hydraulic methods is either in places where information and level of understanding of the ecosystem is lesser or need for protection for an existing ecosystem is alarming [57]. Since, we know that hydrological methods are solely based on historic flow data, but in case of India, the data are scarcely available and are inconsistent. This challenge could be overcome by the use of different data simulation software such as RIBASIM, SWAT, which is capable of generating data up to past 100 years. Wetted perimeter method is very simple and works well with these generated hypothetical data [58]. In HRM, the major issue is the braided nature of Indian rivers, and thus, the hydraulic characteristics of the river such as depth and wetted perimeter could not be obtained. The issue can be solved by using multi-criteria decision making approach [59]. Also, use of eWater tool RAP which can incorporate HEC-RAS could help in calculating hydraulic characteristics (mainly wetted perimeter) of river. These issues can be indirectly resolved by releasing enough water in the river to maintain a single channel of flow.

On the other hand, HSM requires an intensive data such as habitat data at various sections and suitability data for the endangered species, and hence tends to be a major difficulty in its adaptability in Indian subcontinent. The most appropriate solution to this problem is to conduct an exclusive biological research, for habitat study, for all major rivers of the country.

Holistic approach opts for extensive physical, biological and ecological analysis for the entire stretch of river, and the merger of the same can be applied on rivers that are on the top priority list of the nation. The challenges in holistic approach could be met through the involvement of government of country. If the government sanctions a project and look through its proceeding at each level then the desired results and perfect environmental flow model could be generated. Guidelines of MOEF for hydropower projects which highlight EF and mandate study of parameters, namely water quality in basin, status of ecosystem and hydrology, are effective solutions to develop such a model.

Table 3 Flow Health—hydrological impacts of flow regulation with ecologically relevant flow components [55]

Ecologically relevance flow components	Hydrological impacts
Large flow events	Reduced high flow peaks
Moderate and small flow events	Increased interval between flood peaks
High flow season baseflows	Loss of small to moderate sized floods
Low flow season baseflows	Seasonal redistribution of flows
Natural seasonality	Persistent higher flow in low seasons
Possible cease to flow events	Reduced high season flow volume
	Reversal of flow seasonality
	Increased incidence of very low flows
	Persistently lower flows in low seasons

Flow Health, a software developed by International WaterCentre, Australia, is another kit to assist EFA. It is based on Index of Flow Deviation (IFD) which relies on indicators and compares ecologically relevant, hydrological attributes of a river with under period [55]. Since the method utilizes monthly flow data, it is easy to assess EF for Indian rivers having inconsistent data series (Table 3).

Conclusion

Water should be apportioned to the ecosystems as it is done in other sectors such as agriculture, power generation, domestic use and industry, in order to sustain facilities rendered by water from the rivers and various ecosystems. The apportioning system should be made mandatory so as to meet the ecological needs. The system should be designed in such a way that both low and high flow releases remain proportional to the natural flow regime.

Major problem for managing EF by incorporating minor modifications is keeping necessary discharge during least flow periods. This involves major modifications for allocating reservoir water to irrigation canals in months of peak demand. Another challenging area under environmental flow is the evaluation of the most appropriate value of water allocations. These can be overcome by precise knowledge of the relationship between riverine flow and the surrounding biota. In spite of great research in the field of environmental flow, a perfect framework comprising of all the components of ecosystem is yet to be obtained. This framework can be achieved by implying a thorough inter-relationship between physical and biological components of ecosystem convened by different hydrologists, engineers and biologists. Flow Health software is one such solution which considers ecological relevance of hydrological metrics.

The review of EFA through hydrological methods generates an output environmental flow in the range of 30–50% of MAF. Hydrological methods are opted for low data situations, and it serves as a base to carry forward further studies. HSM and holistic approach deals in various areas of expertise, and the results are negotiated after professional judgments through an accord between conflicting interests. Both of them use different variables from the whole ecosystem to determine the environmental flows, and hence, it is difficult to denote a generalized output for both of them. Holistic approach is the best among all the four methods because it involves a detailed study and analyzes all the components of riverine ecosystem, and then trades off a suitable output. It has been already applied in India [35]. However, in current Indian context, due to inconsistency of data, hydrological and hydraulic methods could be used for preliminary study followed by assistance from Flow Health and eWater tools. Further, in future context, holistic approach aided with hydrological methods, as a preliminary study, will be best suited.

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