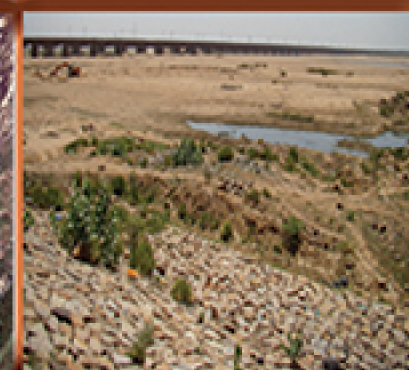
Environmental Flow Requirements : A case study of River Sone



CIFRI

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Absar Alam
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Central Inland Fisheries Research Institute
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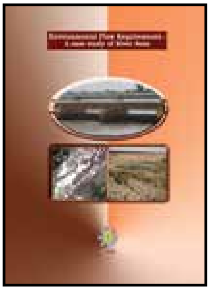

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PROJECT TEAM

This valuable document is emanated from the extensive studies conducted by Allahabad Regional Centre of Central Inland Fisheries Research Institute from December 2007 to March 2013 on the river Sone under institutional project **"To estimate environmental flow requirements of various categories of rivers in India"**. Following team of scientists and technicals were involved in this project under different capacities and period:

Scientists

1. Dr. V.Pathak, Principal Scientist, P.I. (December 2007 to October 2011)
2. Dr. K.D. Joshi, Principal Scientist & Head, P.I. (November 2011 to March 2012) & CO-P.I.(December 2007 to November 2008)
3. Dr. A.K. Sahoo, Scientist (CIFRI, Barrackpore)
4. Dr. D.N. Jha, Scientist
5. Mr. Md. Absar Alam, Scientist

Technicals

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Authors

Preface

River modifications by construction of dams and barrages for electricity generation and irrigation purpose are the major ongoing activities in the most of the potential rivers in India. Environmental flow regulations were not devised and followed in the projects commissioned in last few decades; hence these river projects immensely affected the river's flow regime, downstream water availability, water quality and riverine ecosystems. The flow of river Sone a tributary of the river Ganga was obstructed by construction of Indrapuri Barrage in Bihar state in the year 1968, without considerations of downstream water requirements. Under the present study, the flow regimes of the river were estimated by using 36 years discharge data on the software-Global Environmental Flow Calculator. To maintain the river in moderate condition and to keep basic ecosystem functions intact at least 18.9% of Mean Annual Runoff (MAR) has been estimated, while the actual discharge of the river was occasionally reduced to mere 5.2 % of MAR. As a result, the river below the barrage has almost lost its riverine character and reduced to pools and pockets. Though the river presently holds 89 fish species but 20 species reported in an earlier study were not observed, while 13 new fish species were encountered for the first time during the study period. Authors have also studied the effect of low discharge on sediments, water and macro-benthic biota of the river.

The issues of environmental flow assessment and management are high on the global agenda at present. The present study aims to estimate Environmental Flow requirements of a river downstream to a commissioned barrage. It's a preliminary study done using hydrological data with the help of Global Environmental Flow Calculator, software developed for desktop rapid assessment of Environmental Flows (EFs). Environmental Flow estimation studies are still in nascent stage in our country and required database on ecological and fishery aspects is lacking. Hence, the present study would provide important baseline data in the field of Environmental Flow estimation for the rivers under modified condition. Further studies to estimate the Environmental Flow using latest versions of holistic approaches with provision to meet the specific requirements of riverine ecology, biota, fish species and issues related to other stakeholders are required. I am hopeful that this Bulletin will be immensely useful for researchers, students, policy makers, engineers and other stakeholders in understanding of the issue to maintain the ecosystem in balanced state. I compliment the authors for this important contribution.

Anil Prakash Sharma
Director, CIFRI

Introduction:

A number of water related challenges, including increasing water scarcity and competition for water between different sectors and states are being faced presently at global level. Freshwater and freshwater-dependent ecosystems provide a range of goods and services for humans, including fisheries, flood protection, wildlife etc. To maintain these services, water needs to be allocated to ecosystems, as it is allocated to other users like agriculture, power generation, domestic use and industry. Balancing the requirements of the aquatic environment and other uses is becoming critical in many of the worlds' river basins as population and associated water demands increase. On the other hand, the assessment of the requirements of freshwater-dependent ecosystems also represents a major challenge due to the complexity of physical processes and interactions between freshwater ecosystem components. For day-to-day management of particular rivers, Environmental Water Requirements (EWR) are at present often defined in a form of a suite of flow discharges of certain magnitude, timing, frequency and duration. These flows jointly ensure a holistic flow regime capable of sustaining complex set of aquatic habitats and ecosystem processes and are referred to as *"environmental flows", "environmental water requirements", "environmental water demand"* etc. Many methodologies for determining these requirements have been emerged in recent years. They are known as *Environmental Flow Assessments* (EFA).


Fig. 1. Downstream river Sone at Koilwar near Arah

Most of the Indian rivers are excessively exploited to fulfill ever increasing demand from power, agricultural, industrial and municipal sectors. Damming of rivers or tributaries is the root cause of river obstructions causing severe modifications and perturbations to the river flow, velocity, depth, substratum, pools, ecology and fish habitats. Each river system has an individual flow regime with particular characteristics such as seasonal pattern of flows, the timing, frequency, predictability and duration of extreme events (e.g. floods and droughts), rates of change and other aspects of flow variability. Each of these hydrological characteristics has individual as well as interactive regulatory influences on the biophysical structure and functioning of the river and floodplain ecosystems. This also includes physical nature of river channels, sediment regime and water quality, biological diversity/riverine biota and key ecological processes sustaining the aquatic ecosystem. Deviations from natural flow regime result in drastic change in the riverine ecosystems and fishery structures in the downstream. Disruption of the natural flow regime can alter entire river ecosystems and the socio-economic activities that depend on them. Because of altered natural flow regimes, species in freshwater ecosystems are endangered at rates far higher than those in terrestrial and marine ecosystems.

The cumulative effect of hydrological degradations has resulted in severe fishery declines in the river Ganges and its tributaries. But, river management issues including estimation of environmental flow and their effective implementations are still in the developing stage in India. It's a general apprehension among the environmentalists, planners and common masses that the construction of dams and barrages causing great loss to the rivers, so the consequences need to be estimated or quantified.

The need for environmental flows

Rivers and streams need water to maintain the ecological integrity of the system's. Particular flow patterns determine the shape of the stream channel, stream habitats and biotic components. At the same time, water is required for domestic supply, irrigation, and industrial purposes, but taking too much water for these purposes can change the natural flow patterns and affect habitat variability, water chemistry and nutrient processing. The alteration can lead to depletion in water quality, establishment of invasive species and loss of biodiversity.

What are environmental flows?

Rivers, streams and wetlands need certain amounts of water to support healthy aquatic ecosystems. The normal riverine flow is changed owing to construction of dams, water abstractions. In other situations, where water is added to a river, such as outflow from a sewage treatment plant also alters the natural flow of the river. To compensate for changes of flow, water may be released from dams or protected from abstraction (this is where water is removed from a river for irrigation or some other purpose), at certain times to allow rivers to function normally. There are two broad classes of environmental flows: releases of water below dams, and protection of flows in unregulated rivers. Environmental flows are designed to mimic the natural condition of rivers. It is not just about the amount of water but also timing and quality. Rivers also naturally experience periods of very low or no flow and at other times there are floods. It is important that environmental flows mimic this variability of flows. Releasing substandard water quality can severely impair the functioning of aquatic ecosystems.

Fig. 2. River Sone below Indrapuri barrage near Dehri-on-Sone

Terminology related to EFs

Environmental Flows (EFs): It refers to a flow regime designed to maintain a river in some agreed ecological condition.

Flow Duration Curves (FDCs): A Flow Duration Curve is a cumulative probability distribution function of flows. Any FDC can be represented by a table of flow values covering the entire range of probabilities of occurrence.

Mean Annual Runoff (MAR): It is the amount of water running over the land surface during the year.

Environmental Management Classes (EMCs) : Environmental flows aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition also referred to as ‘desired future state’, ‘environmental management class’ (EMC), ‘ecological management category’, ‘level of environmental protection’ etc 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. There are different number of EMCs are available in literature but six EMCs are often used. It starts with the **unmodified and largely natural conditions (rivers in classes A and B)**, where no or limited modification is present or should be allowed from the management perspective. In **moderately modified river ecosystems (class C rivers**), the modifications are such that they generally have not (or will not – from the management perspective) affected the ecosystem integrity. **Largely modified ecosystems (class D rivers)** correspond to considerable modification from the natural state where the sensitive biota is reduced in numbers and extent. **Seriously and critically modified ecosystems (classes E and F)** are normally in poor conditions where most of the ecosystem’s functions and services are lost. Rivers which fall into classes C to F would normally be present in densely populated areas with multiple man-induced impacts. Poor ecosystem conditions (classes E or F) are sometimes not considered acceptable from the management perspective and the management intention is always to “move” such rivers up to the least acceptable class D through river rehabilitation measures.

Status of research and use of Environmental Flow Methodologies in India

In many developing countries, such as India, the issues of environmental water demand have not yet received the required attention. The first National Workshop on Environmental Flows, held at New Delhi, in March 2005, brought together over 60 participants from national agencies and research institutions. The workshop generated a significant interest to the concept of environmental flows in the country and it also revealed the existing confusion in this field.

Since independence in 1947, India has witnessed rapid urbanization, industrialization and intensification of agriculture, all of which have greatly affected the rivers in different ways. Most Indian rivers, at present, are highly regulated. In India, very limited (negligible) efforts have been given to assess the environmental flows in river systems. By using hydrological desktop method an attempt has been taken to quantify the environmental flow requirements (environmental demand) of major river basins including Cauvery, Krishna, Godavari, Narmada, Mahanadi, Brahmani and Baitarani and some others. These environmental flows assessments (EFA) were focused on single issues. One of the major problems with developing environmental flow work in countries like India, is that despite existing significant knowledge on some aquatic ecosystem components (e.g., fish), it has never been interpreted in the context of environmental flow assessments. However, managing flows without consideration for other ecosystem components may fail to capture system processes and biological community interactions that are essential for creating and sustaining the habitat and well-being of the aquatic species like fish. Since fish species are very sensitive to flow, it has been argued that if the flow is appropriate for them, it will probably serve most other ecosystem needs. Recent advances in EFA methodologies like holistic approach can be considered for taking care of these problems.

Global trends in research and use of environmental flow methodologies

Hydrology-based EFMs constituted the highest proportion of the overall number of methodologies recorded (30%, followed closely by habitat simulation EFMs), with a total of 61 different hydrological indices or techniques applied. 23 Hydraulic rating methodologies have been reported, representing roughly 11% of the total global methodologies. The most commonly applied hydraulic rating methodology worldwide today is the generic wetted perimeter method. In the method it is firstly assumed that river integrity can be directly related to the quantity of wetted perimeter. Habitat simulation methodologies ranked second only to hydrological EFMs at a global scale (28% of the overall total), with approximately 58 methodologies recorded from countries throughout the world. Although currently representing only 7.7% of the global total, with in the order of 16 methodologies, holistic EFMs have contributed greatly to the field of environmental flow assessment in recent years.

Environmental Flow Assessment Methods (EFAMs)

Environmental water requirements, also referred to as 'Environmental Flows' are a compromise between water resources development and the maintenance of a river in some ecologically acceptable or agreed condition. Existing environmental flows assessment methods reflect the diversity of opinions on this subject and range from comprehensive expert panel approach to holistic approach.

Prescriptive and Interactive Approaches: The type of approach is closely linked to the objective of the EFA. When clear objectives are defined (e.g. protection of certain species, flooding of specific areas, achievement or maintenance of certain river conditions), a prescriptive EFA recommends a single environmental flow. By using this prescriptive approach, however, insufficient information is supplied on the implications of not providing the recommended flow. Interactive EFAs focus on establishing the relationship between river flow and one or more attributes of the river-system. This relationship may then be used to describe environmental/ecosystem implications (and resulting social/economic implication) of various flow scenarios. Interactive methodologies thus facilitate the exploration of trade-offs of several water allocation options. Interactive approaches may, of course, be used prescriptively.

From Bottom-up to Top-down Approaches: The basis of most EFAs is a bottom-up approach, which is the systematic construction of a modified flow regime from scratch on a month-by-month (or more frequent) and element-by-element basis, where each element represents a well defined feature of the flow regime intended to achieve particular objectives. In contrast, top-down approaches define the environmental flows requirement in terms of accepted departures from the natural (or other reference) flow regime. Thus, top-down approaches are less susceptible to omission of critical flow features than bottom-up approaches.

Description of methodologies

A vast number of formal methodologies now exist for addressing EFRs. The majority of EFAMs described can be grouped into four distinct categories, namely hydrological, hydraulic rating, habitat simulation and holistic methodologies. The four types are briefly described below

(i) Hydrological methodologies: These are the simplest and most widespread EFA methods. They are often referred to as desktop or look-up table methods where, at a desktop level, hydrological data, as naturalised, historical monthly or average daily flow records, are analysed to derive standard flow indices which then become the recommended environmental flows. Commonly, the EFR is represented as a proportion of flow (often termed the 'minimum flow', e.g. Q95 – the flow equalled or exceeded 95 percent of the time) intended to maintain river health, fisheries or other highlighted ecological features at some acceptable level, usually on an annual, seasonal or monthly basis. In a few instances, secondary criteria in the form of catchment variables, hydraulic, biological or geomorphological parameters are also incorporated. Most methods simply define the minimum flow requirement, however, in recognition of the 'Natural Flow Paradigm' more sophisticated methods have been developed that take several (up to 32) flow characteristics into account (such as low-flow durations, rate of flood rise/fall etc). The most frequently used methods include the Tennant Method (Tennant, 1976) and RVA (Range of Variability Approach), both developed in the USA.

Hydrological Index Methods provide a relatively rapid, non-resource intensive, but low resolution estimate of environmental flows. The methods are most appropriate at the planning level of water resources development, or in low controversy situations where they may be used as preliminary estimates.

(ii) Hydraulic rating methodologies: Hydraulic Rating Methods are based on historical flow records and cross-section data in critically limiting biotopes e.g. riffles. They model hydraulics as function of flow and assume links between hydraulics (wetted perimeter, depth, velocity) and habitat availability of target biota. In other words they use hydraulics as a surrogate for the biota. 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 decreases 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. These relatively low-resolution hydraulic techniques have been superseded by more advanced habitat modelling tools, or assimilated into holistic methodologies. The Wetted Perimeter Method is the most commonly applied hydraulic rating method.

(iii) Habitat simulation or microhabitat modelling methodologies: Habitat simulation methodologies also make use of hydraulic habitat-discharge relationships, but provide more detailed, modelled analyses 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 microhabitat are modelled in various hydraulic programs, typically using data on depth, velocity, substratum composition and cover; and more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within 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 (or life-history stages, assemblages and/or activities), commonly using habitat suitability index curves. The resultant outputs, in the form of habitat-discharge curves for specific biota, or extended as habitat time and exceedence series, are used to derive optimum environmental flows. The habitat simulation-modelling package PHABSIM (Physical HABitat SIMulation model) within the Instream Flow Incremental Methodology (IFIM), is the most commonly applied habitat simulation methodology.

(iv) Holistic methodologies: Over the past decade, river ecologists have increasingly made the case for a broader approach to the definition of environmental flows to sustain and conserve river ecosystems, rather than focusing on just a few target fish species. Holistic methodologies are actually frameworks that incorporate hydrological, hydraulic and habitat simulation models. They are the only EFA methodologies that explicitly adopt a holistic, ecosystem-based approach to environmental flow determinations. From the conceptual foundations of a holistic ecosystem approach, a wide range of holistic methodologies have been developed and applied, initially in Australia and South Africa and recently in the United Kingdom. This type of approach reasons that if certain features of the natural hydrological regime can be identified and adequately incorporated into a modified flow regime, then, all other things being equal, the extant biota and functional integrity of the ecosystem should be maintained. It is also suggested that rather than optimising water regimes for one or a few species, a better approach is to try to approximate the natural flow regime that maintained the "entire panoply of species". Importantly, holistic methodologies aim to address the water requirements of the entire "riverine ecosystem".

These methodologies are underpinned by the concept of the "natural flows paradigm" and basic principles guiding river corridor restoration. They share a common objective - to maintain or restore the flow related biophysical components and ecological processes of in-stream and groundwater systems, floodplains and downstream receiving waters (e.g. terminal lakes and wetlands, estuaries and near-shore marine ecosystems). Ecosystem components that are commonly considered in holistic assessments include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates, fish and other vertebrates with some dependency upon the river/riparian ecosystem (i.e. amphibians, reptiles, birds, mammals). Each of these components can be evaluated using a range of field and desktop techniques and their flow requirements are then incorporated into EFA recommendations, using various systematic approaches as discussed in more detail below. Holistic environmental flow assessments may include evaluation of a range of other mitigation measures, for example, how to restore longitudinal and lateral connectivity by providing fish passes or altering the configuration of levee banks on a floodplain. Management of storage water levels may also be examined and recommendations made on the benefits of more, or less, stable water levels. Some holistic methodologies also take into consideration the influence of threatening processes and disturbances unrelated (or less directly related) to flow regulation and advise on possible mitigation measures such as riparian and habitat restoration, or the management of invasive vegetation and fish.

The Instream Flow Incremental Methodology **(IFIM)**, developed in the USA, is the most commonly used and best documented holistic methodology, while the Downstream Response to Imposed Flow Transformation **(DRIFT)** developed in South Africa, is one of the newest, offering promising and innovative advances to interactive, top-down EFAs. DRIFT has emerged from the foundations of the widely used prescriptive, bottom-up holistic method, the Building Block Method **(BBM)**, also developed in South Africa. In Australia, The Holistic Method and the Benchmarking Method, are the most used holistic methodologies, with the latter being the only EFA specifically designed to assess the risk of environmental impacts due to river regulation at basin scale. Recently a 'holistic desktop method' **ELOHA** (Ecological Limits of Hydrologic Alteration) has been developed.

207 different methods within 44 countries have been recorded in recent review of international environmental flows assessments. Several different categorizations of these methods exist, three of which are shown below.

Organisation	Categorization of methods	Sub-category	Example
IUCN (International Union for Conservation of Nature)	Methods	Look-up tables	Hydrological (e.g. Q95 Index)
			Ecological (e.g. Tennant Method)
		Desk-top analyses	Hydrological (e.g. Richter Method)
			Hydraulic (e.g. Wetted Perimeter Method)
			Ecological
		Functional analyses	BBM, Expert Panel Assessment
			Benchmarking Methodology
		Habitat modelling	PHABSIM
	Approaches		Expert Team Approach
			Stakeholder Approach (expert and non-expert)
	Frameworks		IFIM, DRIFT
World Bank	Prescriptive approaches	Hydrological Index Methods	Tennant Method
		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	
		Holistic Approaches	BBM
	Interactive approaches		IFIM, DRIFT
IWMI (International Water Management Institute)	Hydrological index methods		Tennant Method
	Hydraulic rating methods		Wetted Perimeter Method
	Habitat simulation methodologies		IFIM
	Holistic methodologies		BBM, DRIFT, Expert Panels, Benchmarking Methodology

The following table shows major advantages and disadvantages of environmental flow assessment methodologies.

Methods	Major advantages	Major disadvantages
Hydrological Index	Low cost, rapid to use	Not site-specific, ecological links assumed
Hydraulic rating	Low cost, site specific	Ecological links assumed
Habitat simulation	Ecological links included	Extensive data collection and use of experts, high cost
Holistic	Covers most aspects	Requires very large scientific expertise, very high cost, not operational

Environmental Flow Calculator

The Global Environmental Flow Calculator (GEFC) is software developed by International Water Management Institute (IWMI), Srilanka for desktop rapid assessment of Environmental Flows (EFs). The calculator uses monthly time series flow conditions and its corresponding Flow Duration Curve (FDC) – a cumulative distribution function of flows for EF estimation. The FDC is represented by 17 percentage points on the probability (X) axis. EFs aim to maintain an ecosystem or upgrade it to some prescribed or negotiated condition – “Environmental Management Class (EMC).” The higher the EMC, the more water is needed for ecosystem maintenance. Six EMCs are used in the calculators ranging from “Unmodified” to “Critically Modified.” Each EMC is represented by its unique FDC. The FDC for each class is determined by the lateral shift of the original reference FDC to the left along the probability (X) axis by one percentage point. Each EMC is effectively an EF scenario. The EMC best suited for the river in question may be selected-based on expert judgment. A FDC established for each EMC can be converted into an EF time series. By using this software, month-wise discharge from the barrage had been estimated and recommended for moderately modified class (Class C) of EMC of the river.

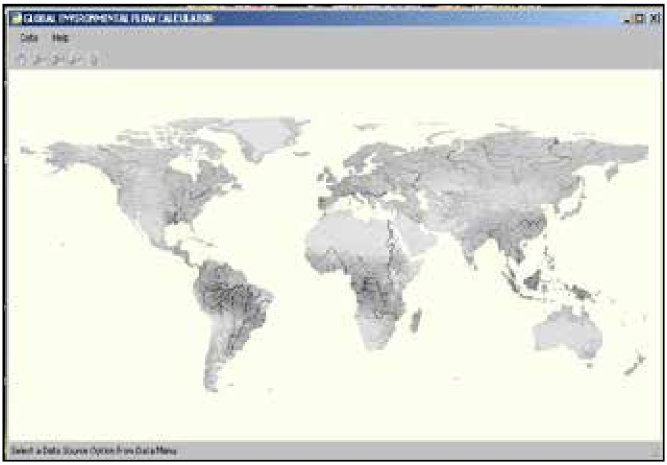
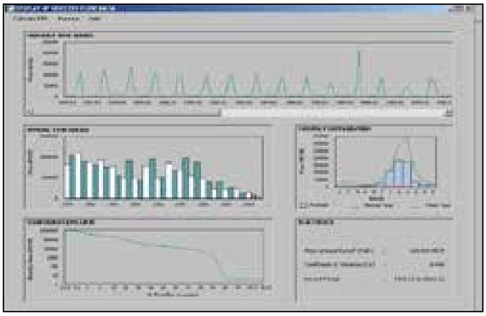


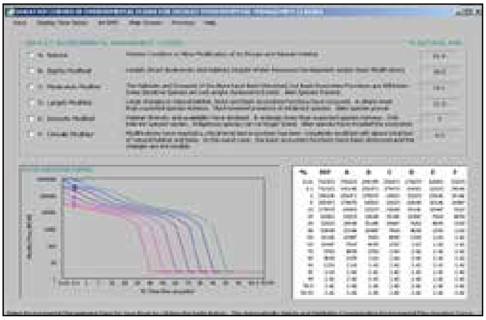
Fig. 3.Global Environmental Flow Calculator

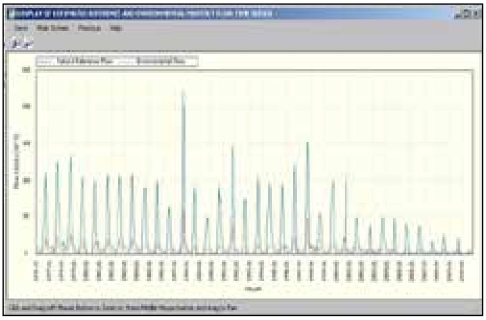
Steps for calculating EFs through GEFC:

Step 1: Select a Data Source



Step 2: Display Hydrological Characteristics





Step 3: Calculate EF and Select EMC

Step 4: Save Calculated Flow Tables

Step 5: Display EMF Time Series

Step 6: Save EMF Time Series

Fig. 4. Steps for Calculating EFs through GEFC

Sone River

Sone is also called Maikalsut (whose source is in Maikal) as it originates from a mountain called Amarkantak in the Maikal Ranges. In ancient times, Sone was known as Shona. The river Narmada also originates from Amarkantak, though it flows westward, while Sone journeys towards the east. The Sone River is an important right bank tributary of the Ganga River.The river Sone originates at an elevation of 600 msl near Amarkantak plateau in Madhya Pradesh and debouches in the river Ganga near Patna, Bihar. The total length of the river is 784 km, out of which about 500 km lies in Madhya Pradesh, 82 km in Uttar Pradesh and the remaining 202 km in Bihar. The river meets the Ganga River about 16 km upstream of Dinapur in the Patna district of Bihar. The important tributaries of the river Sone are Rihand, Kanhar, Ghaghar, and Koel. The total catchment area of the river is spread over 71,259 km^2. The river has a

Fig. 5. River Sone during flood at Indrapur barrage

steep gradient with quick run-off and ephemeral regimes, becoming a roaring river with the rain-waters in the catchment area but turning quickly into a formidable stream. The river being wide and shallow leaves disconnected pools of water during summers (lean period). The river Sone was very notorious for changing course but this tendency has been checked by the formation of anicut at Dehri in the year 1873-74 and construction of Indrapuri Barrage in 1968. The Rihand Dam was also constructed in the upstream catchment of the river Rihand, a tributary of river Sone in 1962. Further the Bansagar Dam in Madhya Pradesh was constructed and commissioned in the river in 2008.

Sampling sites: The river Sone was studied at four sampling sites on seasonal basis for water discharge, ecology and fishery parameters from April 2007 to March 2012. The sampling sites were Tilauthu (84° 4` 57`` E, 24° 48` 2`` N), Dehri-on-Sone (84° 11` 35`` E, 24° 54` 8`` N), Andhari (84° 30` 35`` E, 25° 12` 54`` N) and Koilwar (84° 47` 44`` E, 25° 34` 17`` N). Out of these, the Tilauthu is situated upstream of Indrapuri barrage

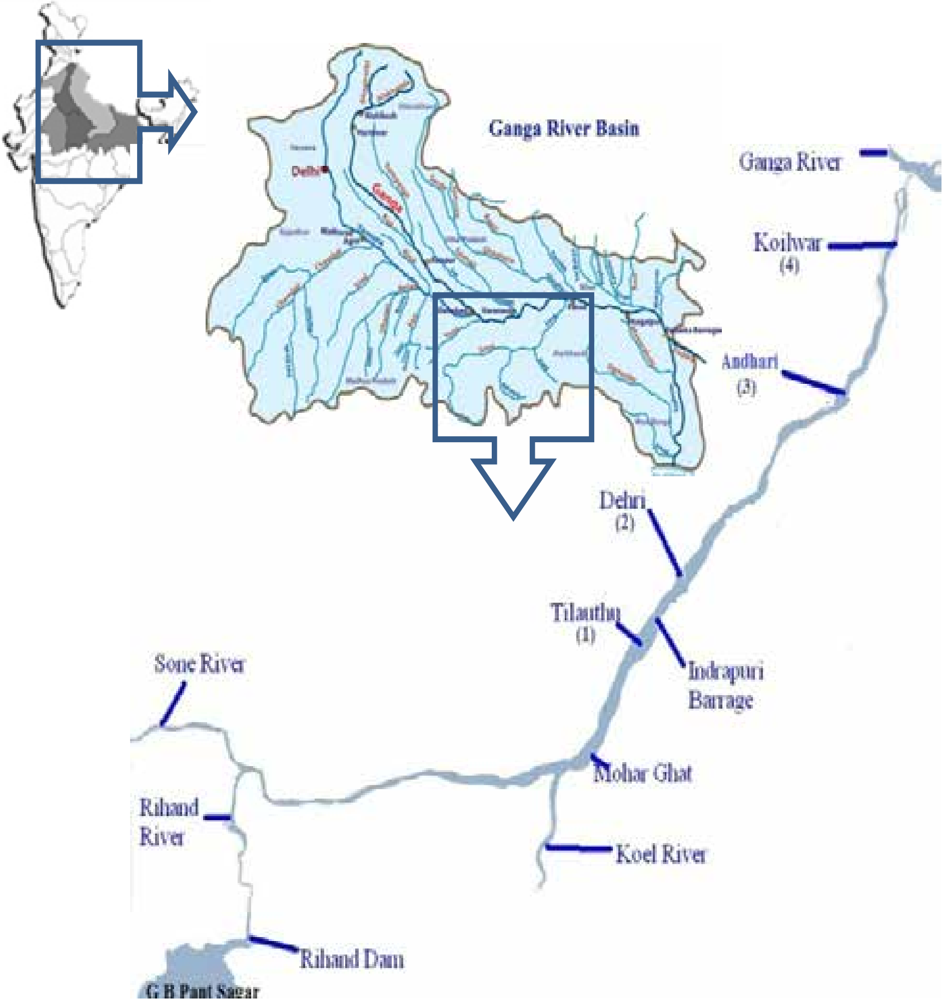


Fig. 6. Schematic map of the Sone river and sampling sites

and the rest three are in the downstream stretch. The sites were selected on the basis of reasonable distance, accessibility and habitat variability. Incoming and discharge data of Indrapuri barrage had been collected for the period January 1976 to December 2011 from Indrapuri barrage Authority. The incoming and discharge data were collected in cusecs and converted into cumecs and Million Cubic Metres (MCM) for analysis purpose. The Global Environmental Flow Calculator (GEFC) was used to calculate environmental flow requirement of the river Sone.

Materials and methods

Incoming and discharge data of Indrapuri barrage had been collected for the period January 1976 to December 2011 from Indrapuri barrage Authority. The data were collected in cusecs and converted into cumecs and Million Cubic Metres (MCM) for analysis purpose. The Global Environmental Flow Calculator (GEFC) was used to calculate environmental flows requirement of the river Sone. The Global Environmental Flow Calculator (GEFC) is software developed for rapid assessment of Environmental Flows (EFs). The calculator uses monthly time series flow conditions and its corresponding Flow Duration Curve (FDC) – a cumulative distribution function of flows for EF estimation. The FDC is represented by 17 percentage points on the probability (X) axis. EFs aim to maintain an ecosystem or upgrade it to some prescribed or negotiated condition – "Environmental Management Class (EMC)." The higher the EMC, the more water is needed for ecosystem maintenance. Six EMCs are used in the calculators ranging from "Unmodified" to "Critically Modified." Each EMC is represented by its unique FDC. The FDC for each class is determined by the lateral shift of the original reference FDC to the left along the probability (X) axis by one percentage point. Each EMC is effectively an EF scenario. The EMC best suited for the river in question may be selected-based on expert judgment. A FDC established for each EMC can be converted into an EF time series. By using this software, month-wise discharge from the barrage had been estimated and recommended for moderately modified class (Class C) of EMC of the river.

Analysis of variance (ANOVA) has been used to show the significant variation between upstream and downstream values of soil and water parameters. Mean differences of the parameters over locations and periods were tested at 5% level of significance. The ecological parameters were studied following standard methods. The information on piscine diversity was collected through experimental fishing conducted at the selected sites using cast, gill and drag nets, fishes caught by the local fishers, market survey at fish landing centres, published data and opinions of the active fishers and experts along the course. The fishes were identified and taxonomic discrepancies were resolved based on available literature and also by using http://www.fishbase.org. In addition to primary data on fish diversity collected from different centres, the secondary data from available publications had also been used to know the time scale change in availability of fishes.

Estimation of Environmetal Flow for Sone river

The incoming water in the river Sone registers strident annual variations, which was recorded at the Indrapuri barrage and discharge from the barrage also varied accordingly. In general, the incoming water registered depletion during the time period between 1976 and 2011. The highest flow was registered in 1978 at 1255407 MCM and minimum 167829 MCM in 2010. There was almost declining trend in incoming flow after 1999 till 2010. But it drastically increased to a tune of 829014.5 MCM in 2011 due to heavy rains in the upper catchment area.

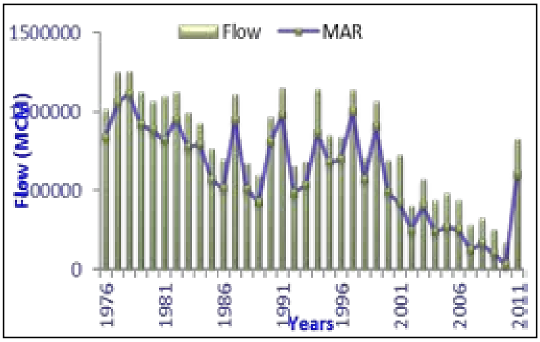


Fig. 7. Annual incoming water in the river Sone at Indrapuri barrage (1976-2011)

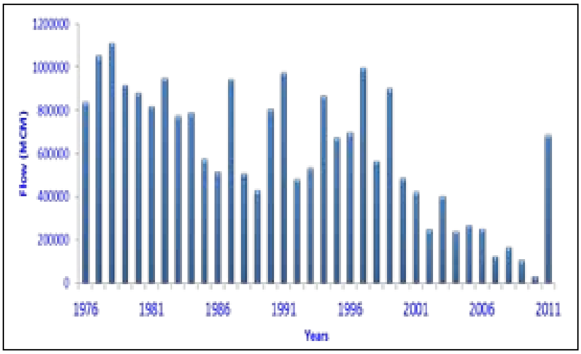


Fig. 8. Annual water discharge from Indrapuri barrage (1976-2011)

The water discharge from Indrapuri barrage also showed similar declining trend over the period. It was 839206 MCM in 1976 and 1111996 MCM in 1978, but reduced to mere 31408 MCM in 2010. There was almost declining trend in discharge values since 1999 onward till 2010. Time series data of monthly discharge from Indrapuri barrage shows almost similar annual trend in different months till 1999, which was gradually declined later on. Maximum water discharge at the tune of 221991 MCM was recorded in the month of September 1987, while there was no discharge during several other months.

Due to severe reduction in flow and meager discharge during most of the years (1999-2010), the river has completely lost its riverine character below the barrage and reduced to pools and pockets of water. The wetted perimeter reduced to mere 2-5 % of the original span. Even during flood season the river was in pathetic condition with a maximum wetted parameter of 5% and velocity 0.2 to 0.4 km hr-1. Observation on past discharge data revealed that the river received maximum discharge (>80 %) during flood season. During time interval of 1976 - 80 the discharge at the barrage was very high (366234 m3sec-1 with average 30519 m3sec-1) of which 82.6% was

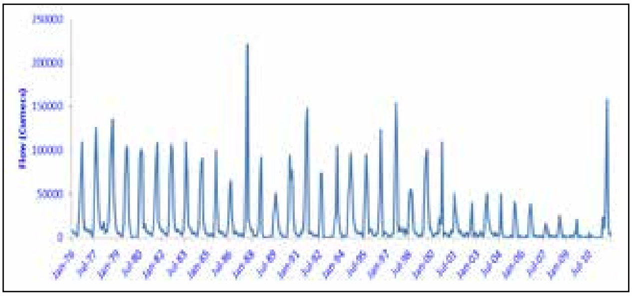


Fig. 9. Monthly water discharge from Indrapuri barrage (1976- 2011)

discharged during flood season (302524 m3sec-1) and 17.4% (63710 m3sec-1) during lean period. Till then the river was in a healthy state. After a lapse of two decades during 1996-2000 the discharge still remained high 276146 m3sec-1 (Av.23012 m3sec-1) of which 83.6% was discharged during flood period and 16.4% during lean month. Later during 2006-10 the discharge showed a drastic reduction and remained only 56363 m3sec-1 (Av. 4680 m3sec-1) of which 81% was discharged during flood and 19% during lean period. From the flow records it is clear that the river below the barrage remained ecologically balanced up to 2000 with wetted perimeter ranging between 40 to 70 % of the total, but in recent years the entire riverine character had changed due to severe reduction in discharge from the barrage. The situation became critical during 2010 with practically no discharge during most part of the year.

Unusual rainfall in the year 2011 augmented the river flow substantially, hence released 21.78 times (683923.6 MCM) more water from Indrapuri barrage. Due to massive flood condition maximum discharge was 1,58,331 m^3sec^{-1} in the month of September 2011 but there was almost zero discharge during January – March 2011. The water discharge from the barrage during 2011 was considerably higher than the recommended value of 18.9 % of MAR or 1,14,065 MCM. The heavy monsoon rains and flood slightly improved the riverine characteristics and increased its wetted perimeter during lean period from 2-5 % to 12-15 %. On the contrary, the discharge from the barrage during 2010 was only 31022 MCM, therefore the river was almost in a critical stage of modification with 5.16 % of MAR.

Estimated environmental flow:

The environmental flow requirement of river Sone below the barrage was estimated on the basis of Flow Duration Curve (FDC) using GEFC. The method categorises the river discharge into Six Environment Management Classes (EMC) spreading from Natural to Critically modified condition. The Mean Annual Runoff (MAR) of the river during January 1976 to December, 2011 is estimated at 603514 MCM. Six Environment Management Classes with percent allocation of discharge have been categorized on the basis of the available discharge data. The Calculator estimated 18.9% of Mean Annual Runoff (MAR) i.e. 114065 MCM discharge from the barrage to maintain the downstream stretch of the river Sone in moderate condition and to keep basic ecosystem functions intact. On the basis of estimated discharge data, month-wise water requirement in the river Sone was calculated for July-September, which coincides with the breeding season of important fishes.

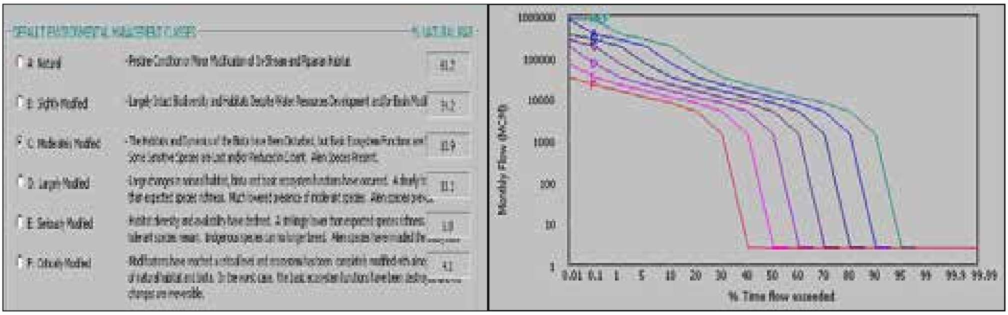


Fig. 10. Flow Duration curve of discharge data and size EMC

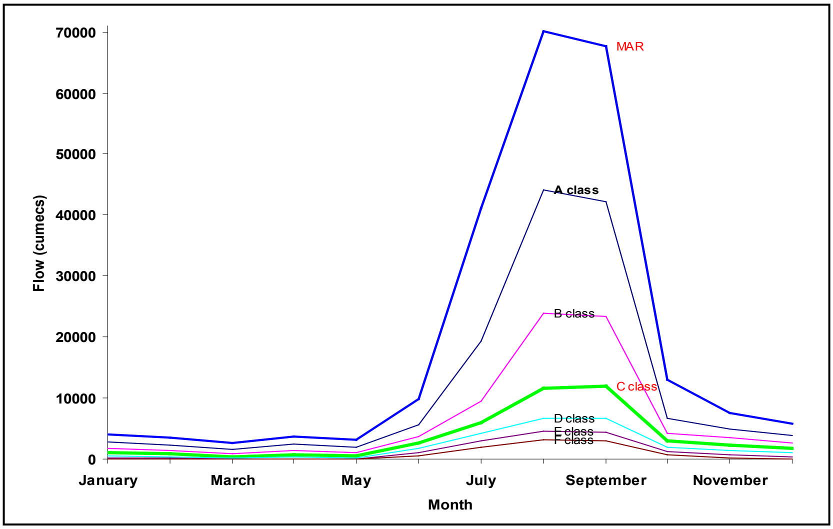


Fig. 11.Estimated Monthly discharge from Inrapuri barrage for different EMC

Biodiversity of Sone River

Fish diversity and fishery

The river has torrential flow at its up and midstream segments and passes through gorges in this section. The substratum in the upstream and midstream segments generally consists of bedrocks and boulders; while gravels, sand, silt and clay in downstream. Due to variations in the substratum and the habitat, river holds rich fish diversity. A total of 89 fish species belonging to 63 genera 25 families and 10 orders have been collected from the river (Appendix-I) during the study. Species richness at Tilauthu, Dehri-on-Sone, Andhari and Koilwar stretches was 80, 77, 77 and 76 respectively. The family Cyprinidae showed its versatile presence represented by 36 species belonging to 20 genera followed by Bagridae (7 species and 3 genera) and Schilbeidae (6 species and 5 genera). Fish fauna of the river in general is Gangetic in character with admixture of Himalayan and peninsular elements, hence important from the zoogeographical point of view. The peninsular forms are represented by *Labeo boggut* and *Salmophasia boopis* and recorded from Tilauthu centre only. About seventy percent of the total species recorded were common at all centers showing their long range distribution pattern. As per IUCN red list, among the total 89 species recorded from the river, eight species are listed as Threatened in which 7 are near threatened and 1 vulnerable.

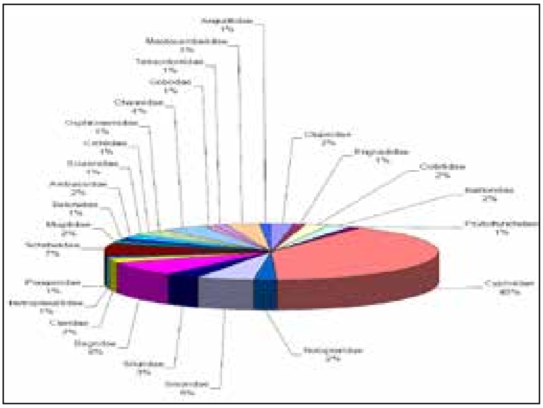
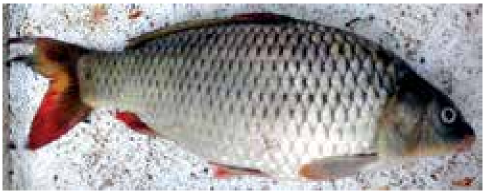


Fig. 12. Percentage Distribution of fish species in different families of the river Sone

The present fish diversity in the river Sone witnessed drastic changes in comparison to earlier studies. The impaired river habitat resulted in alterations of fish diversity and composition in the river in general and downstream to the barrage in particular. A total of 95 species belonging to 20 families were observed from the river in a study conducted in the river during fifties, while 89 species were recorded presently. Though the present investigation recorded loss of 6 species in comparison to the earlier investigation, but analysis of the diversity structure indicates disappearance of a total of 20 species recorded earlier. The species not observed during the present investigation were *Tenualosa ilisha, Chela cachius, Barilius vagra, Danio rerio, Garra gotyla gotyla, Labeo fimbriatus, Tor tor, Tor khudree, Puntius amphibius, Salmophasia clupeoides, Pangio pangio, Nemacheilus denisoni, Schistura dayi, Clupisoma montana, Amblyceps mangois, Glyptothorax annandalei, Erethistoides montana, Glyptothorax indicus, Glyptothorax telchitta* and *Pseudolaguvia ribeiroi*. Disappearance of above species and drastic depletion in Indian major carps (IMC) in the affected river stretch could be attributed to cumulative effect of obstruction, reduced discharge, narrowed wetted perimeter and decrease in average depth. In addition to this, construction of barrage at Farraka (West Bengal) in the river Ganga has resulted in disappearance of the *Tenualosa ilisha* from its upstream tributaries. All these multiple stressors also resulted in depletion of *Pangasius pangasius, Anguilla bengalensis* and potamodromous fishes like *Tor tor* and *Bagarius bagarius*.

	
Anguilla bengalensis	*Ompok pabda*
	
Cyprinus carpio	*Oreochromis niloticus*
	
Hypophthalmichthys molitrix	*Labeo calbasu*

Some important fishes of river Sone

Furthermore, 13 fish species - *Hypophthalmichthys molitrix, Cyprinus carpio, Clarias gariepinus, Oreochromis niloticus, Labeo angra, Botia lohachata, Mystus tengara, Mystus bleekeri, Setipinna phasa, Psilorhynchus balitora, Neotropius atherinoides, Glyptothorax stoliczkae* and *Ompok pabda* not evidently reported from the system in earlier studies were now observed from the downstream stretch. Among the species reported for the first time, 4 species – *Clarias gariepinus*, *Hypophthalmichthys molitrix*, *Cyprinus carpio* and *Oreochromis niloticus* are exotic. The altered river habitat favored establishment of resilient native and exotic fishes.

Benthos

A total of 20 benthic forms were recorded from 4 sampling centres on the river Sone during the study period. Among these, 9 each are bivalves and gastropods, one chironomid and one annelid. Benthic maro-invertebrates comprised of *Bellamya bengalensis, Lymnaea accuminata Melanoides tuberculata, Brotia costula, Tarebia lineata, Gyraulus convexiusculus, Thiara scabra, Physa acuta, Pila globosa* among gastropods, *Parreysia andersoniana, Parreysia corrugata, Parreysia caerulea, Parreysia favidens, Corbicula striatella, Lamellidens corrianus, Lamellidans marginalis, Scabies crispate* among bivalves, *Tubifex* spp. among annelids and *Chironomus* spp. among dipterans. Species richness at Tilathu, Dehri-On-Sone, Andhari and Koilwar were 18, 16, 9 and 13 respectively. Least abundance at Andhari, situated below the barrage may be attributed to the low and fragmentation of the river into pools and pockets during major span of the year. The population ranged from 228 m^{-2} to 582 m^{-2}, being maximum during winter and minimum during monsoon. The gastropods dominated in the entire downstream stretch possibly due to almost negligible discharge during most parts of the year. No significant differences were observed in the distribution and abundance of the biota along the river.

Fish Market at Tilauthu

Fish Market at Dehri-on-Sone

Abiotic parameters of Sone river

Water quality: The common water quality parameters in the river both above and below the barrage indicated rich oxygen (6.51-7.88 mgl^{-1}), alkaline pH (7.73 to 7.76), poor nutrients (PO_4 0.020 -0.031 mgl^{-1}) and moderate dissolved organic matter (1.08 to 1.30 mgl^{-1}). Mean values of free carbon dioxide varied from 1.83-3.76 mgl^{-1}. Certain parameters like alkalinity, conductance, dissolved solids and hardness generally showed an increasing trend from upstream segment Tilauthu (60.57 mgl^{-1}, 164.42 µmhos, 83.28 mgl^{-1} and 94.28 mgl^{-1} respectively) to Koilwar (79.08 mgl^{-1} , 210.0 µmhos, 100.42 mgl^{-1} and 107.14 mgl^{-}

[1]). The vital water quality parameters viz. alkalinity, dissolved oxygen, total dissolved solids, specific conductance and hardness of the upstream Tilauthu and other downstream centres revealed statistically significant variations.

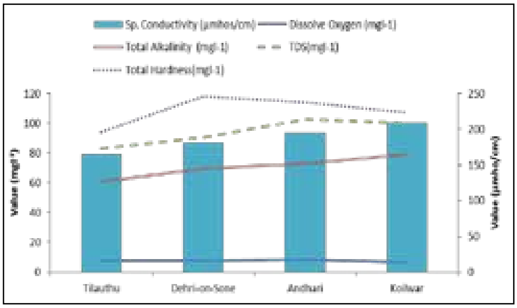


Fig. 13 Changing pattern of vital water quality parameters over location during study period

Sediment: Sediment of the river was dominated with sand in the entire stretch (89.2-96.6). Sediment was alkaline in reaction with pH ranging from 7.5 to 7.7 throughout the river. Availability of organic carbon, available phosphorus and available nitrogen in the upstream Tilauthu (0.272 %, 4.52 mg/100g and 4.654 mg/100g, mean values) centre in comparison to the downstream segments (0.117-0.231 %, 2.92-4.32 mg/100g and 2.906-3.425 mg/100g, mean values) showed significant variations.

Energy Potential: The rate of net energy transformation by producers in Tilauthu, Dehri-on-Sone and Koilwar stretches of river Sone (cal $m^{-2}day^{-1}$) were 2572, 31258 and 3298 respectively. The potential energy resources in these stretches (Kcal ha^{-1}) were 106800, 129500 and 137000 respectively. Studies made during 1998-2000 showed almost similar potential energy resource in all the three stretches.

It is thus clear that reduction in flow rate has not affected the water quality and potential energy resource of the river over the years except slightly increasing trend in the down stretch.

Effect of low flow on biotic and abiotic parameters

In pristine condition, sediment and water quality parameters of upstream and downstream stretches should be in almost similar levels. But variations were observed in certain sediment and water parameters of the river due to construction of barrage which may lead to alteration on river habitat, fish diversity and fisheries.

The annual hydrological regime in the main river channel and the regular flooding of the associated floodplains intensely affects the biology and ecology of fish in large rivers, hence the alterations in fish diversity may be attributed to the cumulative effect of the obstruction and resultant changes in the river. Reduction in discharge also affected distribution of rheophilic fishes like *Garra, Glyptothorax* and *Erethistoides*, as the river reduced to pools and pockets with feeble current. Owing to distinct morphological features and popularity, presence or absence of ornamental fishes like *Danio rerio, Botia lohachata* and *Lepidocephalichthys guntea* may be perceived as strong indicator of river habitats. Among these, *Lepidocephalichthys guntea* was recorded in both the studies, *Danio rerio* reported earlier was not encountered in the present investigation, while *Botia lohachata* encountered in the present study only.

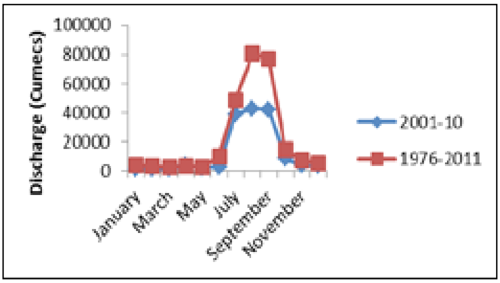


Fig. 14.Average monthly discharge from the barrage during 1976-2011 and 2001-10

Downstream water discharge from the barrage reveals substantial decrease during different months over the period. The average monthly discharge values recorded as 48394.66, 80529.97 and 77443.46 MCM, respectively during 1976-2011 for monsoon months i.e. July, August and September also reduced to 38899.88, 42954.53 and 42107.09 MCM, respectively during last decade (2001-2010). Since, the monsoon flood is essential for spawning of IMC hence; reduction in downstream discharge during monsoon severely affected its breeding and resultant seed availability. The river Sone remained a source of quality fish spawn to the thousands of the fishermen along its course. The past records of sixties and seventies showed an average 4787 hundis (earthen pots with red soil) were collected and transported from the river at and around Koilwar. Spawn availability has been reduced to mere 10-15 % in 2011-12 in comparison to values of 1965, a pre dam baseline. Index of spawn quality also decreased from 80 % to just 3.5% over the same period. Accordingly, commercially important major carp species i.e. Catla catla, Labeo rohita, Cirrhinus mrigala and Labeo calbasu are also affected. Annual landing of these fishes recorded in tonnes during eighties has been reduced to minimal and replaced by the residential fishes.

Conclusion

On analysis of 36 years water discharge data of the river Sone at Indrapuri Barrage by using GEFC, the river is observed in Critically Modified (Class F) condition with discharge of mere 5.16 % of MAR and resultant 2-5 % wetted perimeter. Hence, as per Calculator, the estimated 18.9 % of MAR would be helpful in restoration of the stretch from Critically Modified to Moderately Modified Class (C). Further, to maintain the river in Slightly Modified Class (B), 34.2 % of MAR will be required. Besides, EF estimation the present study also revealed loss to the fish diversity, fisheries and invasion of exotic species owing to decreased flow.

This is the first attempt by CIFRI to estimate Environmental Flow requirements of a river downstream to a commissioned barrage. It's a preliminary study done by using hydrological data with the help of GEFC, software developed for desktop rapid assessment of EFs. This study provides valuable baseline data in the field of Environmental Flow estimation for the rivers under modifications. Further studies in this multidisciplinary direction are required to estimate the Environmental Flow using latest versions of holistic approaches.

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Appendix 1: Fish diversity in the river Sone (reported under present and earlier studies)

S.N.	Name of species	Reported by	
		Motwani and David (1957)	Present study
	Order-Anguilliformes		
1	*Anguilla bengalensis*	+	+
	Order-Clupeiformes		
2	*Gudusia chapra* (Hamilton, 1822)	+	+
3	*Tenualosa ilisha* (Hamilton, 1822)*	+	-
4	*Gonialosa manmina* (Hamilton, 1822)	+	+
	Family-Engraulidae		
5	*Setipinna phasa* (Hamilton, 1822)**	-	+
	Order-Cypriniformes		
6	*Catla catla* (Hamilton, 1822)	+	+
7	*Cyprinus carpio* Linnaeus, 1758**	-	+
8	*Cirrhinus mrigala* (Hamilton, 1822)	+	+
9	*Cirrhinus reba* (Hamilton, 1822)	+	+
10	*Chagunius chagunio* (Hamilton, 1822)	+	+
11	*Osteobrama cotio cotio* (Hamilton, 1822)	+	+
12	*Crossocheilus latius latius* (Hamilton, 1822)	+	+
13	*Labeo rohita* (Hamilton, 1822)	+	+
14	*Labeo calbasu* (Hamilton, 1822)	+	+
15	*Labeo gonius* (Hamilton, 1822)	+	+
16	*Labeo angra* (Hamilton, 1822)**	-	+
17	*Labeo boga* (Hamilton, 1822)	+	+
18	*Labeo boggut* (Sykes, 1839)	+	+
19	*Labeo pangusia* (Hamilton, 1822)	+	+
20	*Labeo bata* (Hamilton, 1822)	+	+
21	*Labeo fimbriatus* (Bloch, 1795)*	+	-
22	*Bangana dero* (Hamilton, 1822)	+	+
23	*Tor tor* (Hamilton, 1822)*	+	-
24	*Tor khudree* (Sykes, 1839)*	+	-
25	*Garra mullya* (Sykes, 1839)	+	+
26	*Garra gotyla gotyla* (Gray, 1830)*	+	-
27	*Hypophthalmichthys molitrix* (Valenciennes, 1844)**	-	+

	Subfamily-Barbinae		
28	*Puntius sophore* (Hamilton, 1822)	+	+
29	*Puntius conchonius* (Hamilton, 1822)	+	+
30	*Puntius ticto* (Hamilton, 1822)	+	+
31	*Puntius chola* (Hamilton, 1822)	+	+
32	*Puntius sarana sarana* (Hamilton, 1822)	+	+
33	*Puntius amphibius* (Valenciennes, 1842)*	+	-
34	*Salmophasia bacaila* (Hamilton, 1822)	+	+
35	*Salmophasia boopis* (Day, 1874)	+	+
36	*Salmophasia clupeoides* (Bloch, 1795)*	+	-
37	*Chela cachius* (Hamilton, 1822)*	+	-
38	*Amblypharyngodon mola* (Hamilton, 1822)	+	+
39	*Aspidoparia morar* (Hamilton, 1822)	+	+
40	*Parluciosoma daniconius* (Hamilton, 1822)	+	+
41	*Esomus danricus* (Hamilton, 1822)	+	+
42	*Danio rerio* (Hamilton, 1822)*	+	-
43	*Laubuca laubuca* (Hamilton, 1822)	+	+
44	*Raiamas bola* (Hamilton, 1822)	+	+
45	*Barilius barila* (Hamilton, 1822)	+	+
46	*Barilius bendelisis* (Hamilton, 1807)	+	+
47	*Barilius barna* (Hamilton, 1822)	+	+
48	*Barilius shacra* (Hamilton, 1822)	+	+
49	*Barilius vagra* (Hamilton, 1822)*	+	-
50	*Securicula gora* (Hamilton, 1822)	+	+
	Family-Psylorhynchidae		
51	*Psylorhynchus balitora* (Hamilton, 1822)**	-	+
	Family-Cobitidae		
52	*Lepodocephalichthys guntea* (Hamilton, 1822)	+	+
	Subfamily-Botiinae		
53	*Pangio pangia* (Hamilton, 1822)*	+	-
54	*Botia lohachata* (Chaudhuri, 1912)**	-	+
	Family-Balitoridae		
55	*Acanthocobitis botia* (Hamilton, 1822)	+	+
56	*Nemachelius scaturigina* (McClelland, 1839)	+	+
57	*Nemacheilus denisoni* (Day, 1867)*	+	-
58	*Schistura dayi* (Hora, 1935)*	+	-

	Order-Osteoglossiformes		
59	*Notopterus notopterus* (Pallas, 1769)	+	+
60	*Chitala chitala* (Hamilton, 1822)	+	+
	Order-Siluriformes		
61	*Bagarius bagarius* (Hamilton, 1822)	+	+
62	*Gogangra viridescens* (Hamilton, 1822)	+	+
63	*Gagata cenia* (Hamilton, 1822)	+	+
64	*Sisor rabdophorus* (Hamilton, 1822)	+	+
65	*Glyptothorax stolickze* (Steindachner, 1867)**	-	+
66	*Glyptothorax annandalei* (Hora, 1923)*	+	-
67	*Glyptothorax telchitta* (Hamilton, 1822)*	+	-
68	*Glyptothorax indicus* (Talwar, 1991)*	+	-
	Family-Erethistidae		
69	*Erethistoides montana* (Hora, 1950)*	+	-
70	*Pseudolaguvia ribeiroi* (Hora, 1921)*	+	-
	Family-Siluridae		
71	*Wallago attu* (Bloch & Schneider, 1801)	+	+
72	*Ompok bimaculatus* (Bloch, 1794)	+	+
73	*Ompok pabda* (Hamilton, 1822)**	-	+
	Family-Bagridae		
74	*Sperata aor* (Sykes, 1839)	+	+
75	*Sperata seenghala* (Hamilton, 1822)	+	+
76	*Mystus cavasius* (Hamilton, 1822)	+	+
77	*Mystus bleekeri* (Day, 1877)**	-	+
78	*Mystus vittatus* (Bloch, 1794)	+	+
79	*Mystus tengara* (Hamilton, 1822)**	-	+
80	*Rita rita* (Hamilton, 1822)	+	+
	Family –Claridae		
81	*Clarias batrachus* (Linnaeus, 1758)	+	+
82	*Clarias gariepinus* (Burchell, 1822)**	-	+
	Family-Heteropneustidae		
83	*Heteropneustes fossilis* (Bloch, 1794)	+	+
	Family-Schilbeidae		
84	*Ailia coila* (Hamilton, 1822)	+	+
85	*Clupisoma garua* (Hamilton, 1822)	+	+
86	*Clupisoma montana* (Hora, 1937)*	+	-

87	*Eutropiichthys vacha* (Hamilton, 1822)	+	+
88	*Eutropiichthys murius* (Hamilton, 1822)	+	+
89	*Neotropius atherinoides* (Bloch, 1794)**	-	+
90	*Silonia silondia* (Hamilton, 1822)	+	+
	Family- Pangasiidae		
91	*Pangasius pangasius* (Hamilton, 1822)	+	+
	Family-Amblyceptidae		
92	*Amblyceps mangois* (Hamilton, 1822)*	+	-
	Order- Mugiliformes		
93	*Rhinomugil corsula* (Hamilton, 1822)	+	+
94	*Sicamugil cascasia* (Hamilton, 1822)	+	+
	Order-Beloniformes		
95	*Xenentodon cancila* (Hamilton, 1822)	+	+
	Order- Perciformes		
96	*Chanda nama* (Hamilton, 1822)	+	+
	Genus-Parambassis		
97	*Parambassis ranga* (Hamilton, 1822)	+	+
	Family-Sciaenidae		
98	*Johnius coitor* (Hamilton, 1822)	+	+
	Family-Cichlidae		
99	*Oreochromis niloticus* (Linnaeus, 1758)**	-	+
	Family-Osphronemidae		
100	*Colisa fasciata* (Bloch & Schneider, 1801)	+	+
	Family-Channidae		
101	*Channa marulius* (Hamilton, 1822)	+	+
102	*Channa striatus* (Bloch, 1793)	+	+
103	*Channa punctatus* (Bloch, 1793)	+	+
104	*Channa orientalis* (Hamilton, 1822)	+	+
	Family-Gobiidae		
105	*Glossogobius giuris* (Hamilton, 1822)	+	+
	Order-Tetraodontiformes		
106	*Tetraodon cutcutia* (Hamilton, 1822)**	-	+
	Order-Synbranchiformes		
107	*Mastacembelus armatus* (Lacepede, 1800)	+	+
108	*Macrognathus pancalus* Hamilton, 1822	+	+
109	*Macrognathus aral* (Bloch & Schneider,1801)	+	+

*Species (20) recorded by Motwani and David (1957), not observed in the present study.
** Species (14) observed in present study were not recorded by Motwani and David (1957)