Assessment of environmental flow requirements for hydropower projects in India

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Increasing water withdrawals from many rivers of the world is leading to severe degradation in river ecosystems. Water is allocated for environmental needs so that a river can perform its natural functions. Environmental flows (EF) try to strike a balance between the use of water of a river for economic development, societal needs and delivering ecosystem services. This article describes a framework to assess environmental flows for a hydropower project in India in a situation where limited hydrological and very limited ecosystem data are available. It recommends that in such a situation, an acceptable EF regime can be arrived at by analysing hydrological data, supplemented by whatever ecosystem data are available and creating various scenarios of EFs. Benefits and impacts of different EF scenarios can then form the basis to determine an appropriate EF regime. Application of the framework is demonstrated in a case study in India. Adaptive management, where feedbacks are used to update and improve the decisions is helpful in such situations.

Keywords: Environmental flow, flow duration curve, hydropower projects, river ecosystems.

INCREASING demands and withdrawals of water are responsible for large reductions in natural flows of many rivers in many parts of the world. Since flowing water is one of the important determinants of the health of a river, a large reduction of flows can cause many adverse impacts, including degrading river ecosystems[1,2]. According to the natural flow paradigm of Poff *et al.*[3], the flow regime is the primary driving force that influences aquatic ecosystems. Flow is considered as the master variable because it exerts great impact on aquatic habitat, river morphology, biotic life, river connectivity and water quality[4].

Based on the hypothesis that the health of a river progressively deteriorates as more and more water is withdrawn, and it significantly falls if the flow is below some threshold value, the concept of minimum flows in rivers came into practice in the 1970s. Subsequent studies have shown that all elements of a flow regime, including high, medium and low flows, are important from the ecosystem point of view[5]. Specifically, high flows are necessary for channel flushing, maintaining floodplain connectivity and riparian vegetation; medium flows help in fish growth and migration, and low flows are important in river connectivity[6], and maintaining water quality (although control of pollution by dilution is not a good strategy). The perennial flow of water is the best evidence that the river exists.

Even a small change in the flow regime of a river can influence its ecosystem. Hence, no or very few rivers in the world can be said to be in pristine conditions; the term quasi-pristine denotes the condition of rivers that are close to the natural undisturbed condition. However, rivers of the world are regulated to varying degrees to meet societal needs such as domestic use, irrigation, industrial use, hydropower generation[7] and biodiversity loss[8]. Poff[9] noted that the many economic benefits provided to human society from maintaining healthy aquatic and riparian ecosystems, coupled with the high costs and difficulty of restoring degraded ecosystems have fuelled the growing awareness of the need for closer integration of ecosystem science and water resources management.

The UNCED Conference in Rio de Janeiro in 1992 established the idea that the health and integrity of the entire ecosystem is fundamental to sustained human well-being. According to the Brisbane Declaration[10], environmental flows (EFs) are the quantity, timing, duration, frequency and quality of flows required to sustain freshwater, estuarine and near-shore ecosystems and the human livelihoods and well-being that depend on them. According to Krchnak *et al.*[11], 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 water bodies, including rivers, coastal waters, wetlands (mangroves, sea-grass beds, floodplains) and estuaries[12]. Note that besides the amount, one should also specify the temporal pattern of the flows.

EF requirement of a river depends on the properties (including the sensitivity) of the aquatic ecosystem,

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Table 1. Main hydrologic requirements for 'Green Hydro' development

Feature	Requirement for a run-of-river (RoR) project	Requirement for a storage project
Instream flows	Under modified conditions, these should follow seasonal changes and variability of natural discharge pattern	Under modified conditions, these should follow seasonal changes and variability of natural discharge pattern.
Flushing flows	Not applicable	Flushing flows should be released only during high flow periods.
Hydro-peaking	Some RoR projects use the diurnal storage for peaking. Sudden and large change in release should be avoided. Warning/alert must be issued before large increase in releases.	These activities should be implemented so as to allow aquatic organisms to migrate to safe areas.
River fragmentation	Horizontal: Flow should be uninterrupted Vertical: Connectivity should be maintained by providing fish passes, bypasses, etc. Groundwater: Ensure same connectivity as in pre-project situation.	Horizontal: Flow should take place uninterrupted if this was the case in pre-project period. Vertical: Connectivity should be maintained by providing fish passes, bypasses, etc. Groundwater: Ensure same connectivity as in pre-project situation.
Morphology	Flow regime in diverted river reaches should enable channel processes, sediment erosion and deposition as in the natural case.	Flow regime in downstream river reaches should enable channel processes, sediment erosion and deposition as in the natural case.

Note: Adapted from Renofalt *et al.*[39], and Bratrich *et al.*[40].

development stage of the area, and the societal requirements. Exact values of EFs for a project can be established using detailed hydrological data, river cross-sections and channel morphology, plus quantitative water needs of the biotic life and its sensitivity to respond to reductions in river flow, combined with knowledge of the preferences of all stakeholders[13]. Frequently, the desired data are not available and the task is to judiciously use all existing information to compute an EF.

Current attention on EFs has emerged because some researchers believe that the dams and diversions constructed to regulate rivers for direct societal needs have significantly and (mostly) adversely impacted the rivers with loss of ecosystem services; although there are contrary views to this as well. However, besides the dams and diversions, many other changes in the catchment affect the flow regime of a river. As the population in a river basin rises, cumulative impact of numerous (and increasing) small withdrawals may significantly decrease river flows. Further, quality of water is an integral part of EFs. Climate change may lead to significant alterations in river flows in future and this may already be occurring in some river basins. River water quality is chiefly damaged by disposing untreated municipal and industrial waste in the river and return flows from those agricultural areas where large quantities of chemical fertilizers and pesticides are applied. A comprehensive framework for assessment and implementation of EF should also account for these issues.

This article describes a framework to assess EFs for a hydropower project in a situation where limited hydrological and very limited ecosystem data are available.

Hydropower generation

Many current and future problems and challenges, such as climate change, water and food security, industrial development and socio-economic growth are concerned with energy. Consumption of energy is globally increasing at about 2% per year. Currently, renewable energy sources meet 17% of the global primary energy and this could increase to between 30% and 75% by 2050. Renewables offer many benefits, such as environment protection, mitigation of climate change and sustainability of use. Among the renewable energy sources, hydropower is a mature, predictable and price-competitive technology whose annual global technical potential is 14,576 TWh with a corresponding estimated total capacity potential of 3721 GW (ref. 14). Besides, hydropower has the best efficiency of all energy sources and a very high energy payback ratio[15]. Hydropower dams provide the society with substantial benefits, but if poorly planned, designed or operated, they can also have serious consequences for the ecological health of rivers and the economic and social well-being of communities dependent upon the goods and services provided by healthy rivers[11].

In a long-term perspective, green growth is growth without unsustainable deterioration of the environment or growth with 'modest' negative impact on the environment in the short term[16]. A green growth strategy (see Table 1) makes the process resource-efficient, cleaner and more resilient without slowing down growth. Hydroelectric power comes under the green energy category, but this form of energy generation has environmental effects, especially in the case of reservoir-based projects.

Hydropower projects can be classified in many ways[17]: based on size (large, medium, small and mini), purpose (single or multi) and on the way the incoming river flows are stored and regulated to generate energy (run-of-river (RoR), storage). Classification according to storage capacity is most frequently used in operational hydrology and so will be employed here.

Run-of-river projects

A run-of-river hydropower plant generates electricity from the flow of the river as available. Some RoR plants may have small storage to generate more energy during the peak hours and increase the project benefits. In order to create and harness high head of water, in many RoR projects river water is diverted through a tunnel or pipe to the powerhouse located at a distant lower elevation. The reach of the river between the diversion point and the point where the tailrace channel from the powerhouse joins the river again is called the 'diverted reach' (Figure 1). RoR projects can generate energy with minimal damage to the environment. EFs are released to ensure that flow in the diverted reach is adequate for ecological needs.

Storage (reservoir) projects

Many rivers have considerable seasonality, i.e. the flow varies over a wide range with time of the year and the pattern of natural flows may be quite different compared to that of energy demands. In storage-based hydropower projects, a reservoir of water (or potential energy) created behind a dam is used to regulate the inflows and generate energy in accordance with the demands. When the powerhouse is at the toe of the dam, water from the powerhouse joins the river just downstream of the dam. Hence, when the powerhouse is running, flow in the river will be equal to the outflow from the powerhouse plus other releases from the dam. When the powerhouse is not running, it is necessary to release water to meet the requirements of the riverine ecosystem. If the powerhouse is some distance away from the dam, water exits from the powerhouse and joins the river at a distance downstream of the dam or diversion structure (Figure 1). Flow in the river reach between the dam and the tailrace of the powerhouse consists of EF, any other release from the dam and flow generated by the intermediate catchment.

In RoR projects, the diverted reach is important for EF estimation and hydrologic or hydraulic rating methods should provide the solution in most cases. For storage projects and basin-level studies where competing multiple uses exist and detailed hydrological, biological, and social databases are available, holistic methods will provide the best answer.

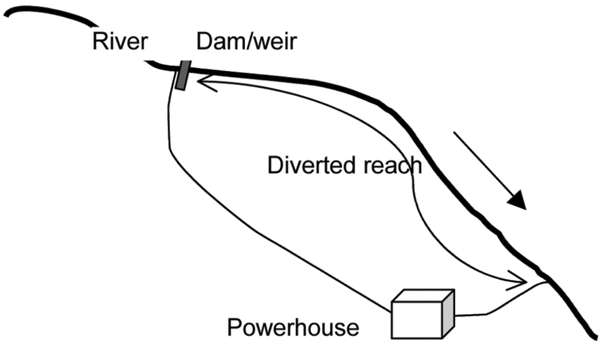

Figure 1. Diverted reach of a river when the powerhouse is away from the dam.

Hydropower generation requires large quantities of water, but almost all of it simply passes through the turbines with negligible losses. A small quantity of water is evaporated from reservoirs. Reservoirs of a multipurpose project provide other beneficial services, e.g. municipal and industrial needs, flood control, irrigation, recreation, etc.

The most obvious impact of construction of a dam across a river is the barrier effect that prevents organisms such as fish migrating up and downstream. Connectivity and continuity in the river corridor is important for the functioning of the ecosystem and particularly necessary for growth and maintenance of regional biodiversity, which can be supported to some extent by EFs. In the case of a low dam, some of the adverse impacts can be overcome by mitigation works, such as a fish ladder, but these tend to be of limited use as dam height increases. Further, storage projects can significantly impact water temperature, water quality and sediment movement.

Hydropower generation in India

India is currently facing big shortages in base and peak electricity. As of 2014, the country has 255 GW of installed generation capacity out of which thermal-based projects account for 178 GW, nuclear sources 4780 MW, renewable 31.7 GW and 40.8 GW is contributed by hydropower plants (http://www.cea.nic.in). Each means of electricity generation has its own advantages and limitations. Fossil fuel-based plants emit polluting gases, require transport systems to move the fuel, foreign exchange is required for import of fuel, and there are problems of disposal of fly-ash in coal-based plants. Among the renewable sources, hydropower is the most attractive, but these projects are facing stiff opposition in India because of displacement of population, submergence of forests and perceived adverse impact on river ecosystem and surrounding environment. There are additional issues in the construction of projects on the Ganga river because it is considered sacred and some people may oppose any project in its headwaters on religious grounds.

Due to opposition of storage-based projects and delays in their completion, there are proposals to convert storage projects to RoR projects. However, in this process there is a loss of hydropower potential and other benefits which will arise due to river flow regulation by storage. If storages are constructed in the headwater region, in addition to other benefits, stored flood water can beneficially supplement the natural flows in the lean months.

Considering all these factors, the country should promote energy generation technology which causes the least damage to the environment and is sustainable. Hydropower generation has numerous advantages and with judicious river regulation, the adverse impacts of these projects can be largely minimized.

Hydropower generation and EFs

Any development effort, big or small, has some impact on the environment. EF requirements of a river depend on the properties of the aquatic ecosystem, development stage of the area and the societal requirements. A crucial decision concerns the desired condition or level at which the ecosystem of a region is to be maintained. Sustainability concept suggests that we need to maintain the ecosystems so that they yield the greatest benefit to present generations, while retaining the ability to meet the needs and aspirations of future generations[18]. If the current demands exceed the renewable potential of a resource (water), we have to decide how much water should be utilized directly by the society for the current needs and how much of it should be used indirectly to maintain ecosystems so that they continue to provide environmental goods and services.

Acreman[18] provided a conceptual depiction of the trade-off between natural and highly managed systems (Figure 2). As natural systems are increasingly modified, the benefits from the natural part decline, but those from the managed part increase. Usually the latter reach a plateau, while those of the natural part may decline to zero (or even become negative) at some point. The total long-term benefits are the sum of the benefits from the natural and highly managed parts. Typically, the total rises to a maximum before declining and this is the point where the returns from the whole system are optimum. Obviously, the value that the society places on goods and services and ethical considerations will determine the shapes of these curves and the optimum; these will vary between different countries/regions and individuals. It is essential that the costs and benefits to society of allocating water to maintain ecosystems and for social use are quantified[18]. Halleraker *et al.*[19] observed that multidisciplinary approaches are needed to establish functional links between the physical conditions and aquatic organisms, and they are powerful tools for a more optimized management of regulated rivers.

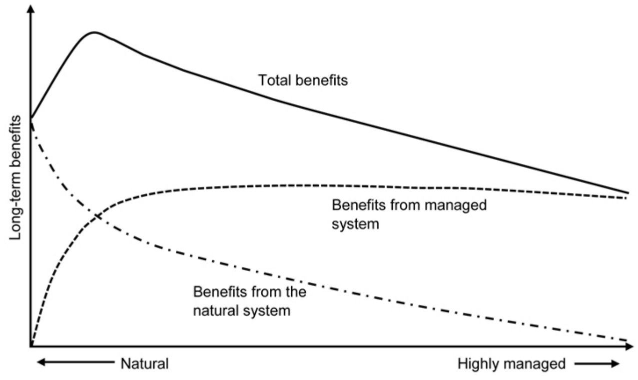

Figure 2. Trade-offs in river regulation showing typical variation of benefits from natural and managed systems (after Acreman[18]).

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 2). Consequently, before computing EFR, broader objectives must be determined to indicate the type of river desired. For some rivers, EFR is set to achieve specific pre-defined ecological, economic or social objectives. This is called objective-based flow setting[12].

Suen and Eheart[20] presented a regime-based approach considering ecosystem and human needs in a multi-objective water resources management project. The objective of the ecosystem needs is to maximize the similarity of managed flow regimes and predevelopment flow regimes, which are taken as ecosystem preserving. Jager and Smith[21] suggested three steps for bringing multi-objective reservoir operation closer to the goal of ecological sustainability: (i) conduct research to identify which features of flow variation are essential for river health and to quantify these relationships; (ii) develop valuation methods to assess the total value of river health, and (iii) develop optimal control software that combine water balance modelling with models that predict ecosystem responses to flow. Suen *et al.*[22] proposed an ecological flow regime-based approach in which reservoir operation was guided by six hydrologic indicators selected to meet the specific flow needs of the local indigenous fish community and to satisfy authorized reservoir operational rules. The approach incorporates ecology and life-history requirements of the fish community in the decision making process to define and meet flow needs. Fish community data are perhaps the most widely available ecological information and often exist when there is an absence of plant, algae or invertebrate data. Suen[23] presented a framework to determine the ecological flow regime for locations downstream of existing reservoirs. In this framework, a regionalization procedure groups gauging stations with similar physiographic, climatic and hydrologic characteristics. The trade-off between hydropower production and EF requirements for the River La Nga system in Vietnam was determined by Babel *et al.*[24] by simulating the system under different operation policies. The hydrologic alteration due to different operation policies was computed using the range of variability approach (RVA) method and the present operating policy was found to cause severe alterations to the natural flow regime. The alteration of the natural flow regime in a river can be controlled by changing system operating policies. Babel *et al.*[24] recommended that the best choice for the hydropower system at the La Nga river is when it is operated such that all the flow parameters at a downstream site fall within 25th–75th percentile of the RVA target range.

In the following sections, methodologies to estimate EF are reviewed. Thereafter, a framework to assess EF is proposed and demonstrated with a case study.

Methodologies to assess EF

In response to a growing international demand, a large number of methodologies have been developed over the past 30 years to estimate EFs for a given river. These range from relatively simple, low-confidence, desktop approaches to resource-intensive, high-confidence approaches and can be classified into four broad types: hydrological methods, hydraulic rating methods, habitat simulation methods and holistic methods[25]. Simple methods are based on limited data and quick analysis. Comprehensive methods are based on detailed multidisciplinary 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 holistic methods explicitly adopt a comprehensive ecosystem-based approach and combine hydrological, hydraulic and habitat simulation models. The building block method (BBM) assumes that different flow regimes play different roles in a river for the growth and maintenance of the ecosystem. A new framework known as ecological limits of hydrologic alteration (ELOHA)[26] offers a flexible, scientifically defensible compromise for broadly assessing EF needs when there are limited in-depth studies in a region. A review of the EF methods is given by Tharme[25].

A scan of EF assessments for water resources projects shows that hydrology-based methods have been used in most of the cases. A key strength of these methods is that indices based on statistical properties of river flows can be readily calculated for natural and regulated flows and compared to determine the degree of alteration of flow conditions by operation of the project[24]. Since the change in river ecosystem depends on the degree of alteration, such a comparison helps in determining how much alteration is acceptable and thereby the size and extent of the interventions. Most studies conducted in India have also used the hydrological methods. A recently completed study[27] applied BBM and several studies exploring the advanced method are in progress.

Streamflow characteristics offer some of the most useful and appropriate indicators for assessing river ecosystem integrity over time[5]. Many other abiotic characteristics of riverine ecosystems such as dissolved oxygen content, water temperature, suspended and bed-load sediment size and channel bed stability vary with flow conditions. On a larger scale, channel and floodplain morphology are shaped by fluvial processes driven by streamflow, particularly high-flow conditions. In many regions, biological data are scarce, temporal and spatial coverage is small but the coverage of streamflow data is much better. Where such data are not available, hydrological tools can provide a surrogate to many river processes. Long series of streamflow data help quantify the magnitude, range, variability of flows and impact of anthropogenic activities on rivers. Tharme[25] reported that hydrology-based methods are globally followed in the highest number of cases (30%).

Multi-sectoral participatory methodology for EF assessment for HP projects

Setting EF is a political process that balances environmental objectives with other potentially conflicting goals[21]. Selection of a methodology is the first and important step in the assessment of EFs. The methodology chosen in a particular case depends upon factors such as the availability of data, technical expertise, finance, time, etc. In India also, the use of hydrology-based methods is quite high and is likely to remain so in the near future, mainly due to the paucity of data on ecology and biotic components. Application of hydraulic rating methods (HRMs) and holistic methods requires a multidisciplinary team and huge resources. In many cases, it is extremely tedious and time-consuming to compile the desired data, form a team of investigators, and arrange the requisite finances. However, there is growing interest in EF and many studies related to EF estimation employing different methods are being taken up.

An integrated environmental flow assessment (EFA) was undertaken by IUCN (International Union for Conservation of Nature) with the Pangani Basin Water Board (PBWB) to understand, among other things, the links between the ecosystem and the social and economic values of the resources of a river. Possible pathways from 2005/2006 until 2025 were explored by developing different scenarios (PBWO/IUCN)[28]. Trade-offs are involved in every scenario. No scenario was beneficial in terms of all three criteria – economic, social and ecological, and some strategies were recommended to decision makers.

Among the challenges posed in practising IWRM is the translation of the environmental objective into a well-defined and quantitative measure that can be used to evaluate the effect of different water management policies. Maran[29] developed environmental score to quantify and compare the environmental performance of different policies in the Vomano basin in Italy. However, only environmental aspects connected to river habitat were included in this approach. To entirely include the environmental aspects in IWRM, it would be necessary to define similar scores for each aspect such as water diversions, variations of the hydrological regime, etc.

Framework to estimate EF

Each means of generation of energy has some advantages and some drawbacks. Commonly, the objective of the governments is to choose that particular means where the benefits outweigh the costs so that affordable, reliable and sustainable energy can be provided to the users. Thus, the typical objective of determining EF for a hydropower project in India is to ensure an optimum balance between energy generation and preservation of river ecosystems.

Since trade-offs are involved in development and conservation which are difficult to derive, explicitly a way out particularly for hydropower projects is to make conjunctive use of hydrologic and power generation data. Regarding hydrology, the natural flow variability is best described by the time series of daily discharge[30]. Flow duration curve (FDC) at a site can be considered to be the thumbnail of a catchment which summarizes the hydrologic response of the catchment. A FDC is constructed using long-term observed data of a river at the desired location. It is the graphical representation of discharge versus the exceedance probability (Figure 3). Among the numerous applications of a FDC is its use in estimation of EFs.

In India the major limitations in defining EFs are: (a) lack of biological data; (b) lack of river morphological data and sediment transport data, and (c) lack of understanding of ecological impacts of flow alteration. Any method of EF assessment in India will need to work within these constraints to provide solutions for the following reasons:

(a) Clearance for many hydropower projects is held up or delayed in the absence of 'acceptable' EF; 'acceptable' because frequently recommended values are perceived to be 'too little' by some groups and 'too high' by others, including project proponents.

(b) Rivers are an important aspect of religious and cultural life, and there is growing demand to have clean and living rivers and restore ecosystems.

(c) Stakeholder interest and participation in water issues is rising as evidenced by coverage in media and discourses.

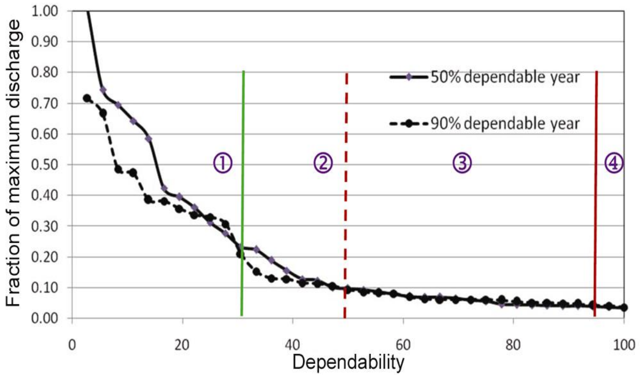

Figure 3. Flow duration curve of a headwater stream in the Himalayas.

Time series of stream flow data of about 30–40 years is available at nearly 400 stations in India and this can be gainfully employed for EF assessment through hydrological approaches until the requisite ecological databases and understanding develop. Keeping all these factors in view, the following framework is recommended to estimate EF in India with particular reference to the hydropower projects:

(a) Appraisal of the hydrology of the river and flow regime which is best described by the time series of daily discharge[30]. The flow regime can be summarized as a FDC, which is the graphical representation of discharge versus the exceedance probability. A great advantage of using FDCs is that they can be readily transferred between sites in the same basin and thus are useful in estimating flows at ungauged locations. FDCs corresponding to different dependability years help understand the response of the basin in different hydrologic scenarios. In India, 90% dependable flows are used for hydropower planning[31].

(b) A number of scenarios of EF are constructed using, for example, FDC for the 90% dependable year. Note that any other dependability may as well be chosen, but the 90% dependability is convenient from implementation point of view since there is very low probability that the actual flow in the river will be less than these flows.

(c) The water requirements of the biotic life in the river are estimated in terms of the depth and velocity that is necessary for their sustenance in different seasons[32,33]. This information is used to estimate minimum required discharge (Q_{min}) at different times. If in the EF scenarios, the flow in any period is below (Q_{min}), then it is reset to Q_{min}.

(d) The EF scenarios constructed in the above steps are employed to determine hydropower generation from the project. A comparison of these values with hydropower generation when no water is released for EF will give the loss in hydropower generation benefit for each EF scenario.

(e) Expected degradation to the river ecosystem needs to be assessed for each EF scenario. In a simple case, the amount of water diverted may be taken as an indicator of such loss; more the diversion, greater is the loss.

(f) Information from steps (d) and (e) depicts trade-off between degradation of ecosystem and economic benefit and can be used to arrive at an acceptable EF.

Assessment of EF for a HP project in India

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

Table 2. Hydrologic features of flows at the focus project site

Feature	Mean value (cumec)	Minimum value (cumec)	Maximum value (cumec)
Daily flows	381.74	52.01	3472.01
7-day flows	381.92	53.65	2191.75
10-day flows	379.38	53.58	1969.02
Monthly flows	379.49	56.19	1715.92
June	502.64	277.67	828.30
July	989.98	590.28	1597.23
August	1128.46	701.28	1715.92
September	692.57	352.12	1539.81
October	280.43	164.07	666.42
November	164.32	96.01	444.59
December	114.79	75.18	307.81
January	95.47	62.41	209.90
February	87.61	56.19	166.23
March	98.06	62.59	152.62
April	136.23	72.61	191.14
May	263.28	142.11	462.34

satisfied. In India, guidelines for EF are gradually evolving and these are specified by different agencies such as the Ministry of Environment and Forests (MoEF), Pollution Control Boards and Water Resources Departments. The State Government of Himachal Pradesh (India) has issued a directive to allocate 15% of minimum observed flow in lean season or post-monsoon as EF while in Uttarakhand 10% of lean season flow (subject to minimum value of 0.3 m^3/s) has been set aside as EF. MoEF have specified EF requirement for some projects in the recent past.

Details of the framework described above are explained through a case study of EF assessment for a planned RoR hydropower project in a Himalayan basin. Himalayan river basins are exposed to a monsoon climate and are fed by snow/glacier melt as well as rainfall. The catchments of the headwater streams have steep slopes and the rivers mostly flow in narrow valleys. Hill slopes have thin soils and loose fractured rocks. Higher mountains experience snowfall from November till April. Monsoon rains occur mainly from June to September and result in high river flows in these months. Post-monsoon, flows start decreasing and are at the annual minimum during February or March. As the temperature begins to rise from April, river flows begin to rise again. In this region, rivers transport a large quantity of sediments and landslides in the monsoon season.

The focus project consists of a low dam across a river to divert the flow to a powerhouse to generate electricity. A small reservoir behind the dam will regulate flow to generate more energy during the peak hours. After generating electricity, diverted water will rejoin the river at about 4 km downstream of the diversion point. At the project site, temperature varies from about 2°C to nearly 43°C; annual rainfall is about 1000 mm (it does not snow). Now the task is to estimate EFs so that the diverted river reach has enough water for the needs of the ecosystem and maintains balance between ecosystem health and economic benefits from the use of river water.

Observed daily discharge data were available for a period of 40 years. From these data, time series of various durations, including weekly, 10-day and monthly were compiled. Table 2 gives mean, minimum and maximum values for daily, weekly, 10-day and monthly flows computed from the observed flows near the project site. From the available river flow data, annual flow volumes were computed and these were arranged in decreasing order. In this series, years corresponding to 50% and 90% dependability were identified. FDCs were plotted for each of these years showing the flows corresponding to various dependabilities (Figure 3). For instance, the value on the *Y*-axis corresponding to 20% dependability is the discharge which is present in the river 20% of the time. Monthly flows at the site as percentage of annual flows have been plotted for the different months (Figure 4). It can be seen from Figure 4 that the flows have very high seasonality; about 21.74% and 24.78% of annual flow takes place in July and August respectively, while in February the flow is just 1.92% of the annual flow.

Flow regimes are a key factor shaping the ecology of rivers[1]. Diversity, distribution and growth of aquatic organisms largely depend on the complex interaction between river flows and physical habitat. Based on the hydrological response, the flow regime shown by FDC in Figure 3 can be divided in four zones: (a) zone 1: dependability between 0% and 30%, (b) zone 2: between 31% and 50%, (c) zone 3: between 51% and 90%, and (d) zone 4: between 91% and 100%. In the first zone of FDC, the slopes are very steep due to high concentration of flows in the short monsoon season. Zone 2 is a transition between the high flows and low flows. In the third zone, the FDCs have very low slope partly because here most of the flow in the river is due snow/glacier melt and baseflow. It is also noted that in the zone of 51–90%

dependability, there is hardly any difference between FDC for a site for 90% and 50% dependable year. Finally, in the fourth zone, FDCs have nearly flat slope; of course, this zone occupies a small part in FDC. It is hypothesized that the flows in different zones have different roles to sustain river ecosystem.

A wide range of information was collated from earlier studies in the Himalayan region (e.g. WWF-India[27], WAPCOS[34], AHEC[35]). These included inputs from various stakeholders, such as feedback from hydropower project owners. All the collated information was considered to produce five different EF regime options for this study. As noted earlier, the rivers have a high degree of seasonality and it is assumed that the river ecosystem has evolved and adapted to this seasonality. Hence, the overarching guidance was to create the EF regimes by lowering the FDC to different extents in different zones (depicted in Figure 3), subject to the condition that the EF should never be less than the minimum flow required for survival of the fishes present. Use of FDCs will help maintain the seasonality and natural variation in the streamflows. Ideally the EF regimes should cover a wide range from the smallest required flow to large feasible flows. It may be noted that progressively lesser water is set aside as EF from scenario EF1 to EF5. Among these EF regimes, it was assumed on the basis of basic hydro-ecological principles, that EF1 will result in least degradation to the river ecosystem, but energy generation will also be the least. On the other hand, regime EF5 will yield the highest generation of energy but will also cause most degradation of the river ecosystem.

In the absence of detailed information about all the various species and communities in a river ecosystem, fishes are frequently taken as indicator species. The primary assessment of ecological impacts of different flow regimes was undertaken by analysing the physical habitat available for various key fish species. The area above 2500 m elevation is typically no-fish zone in the Himalayas. The species of fishes found in Himalayan basins include the Golden Mahaseer, the Silver Mahaseer, the Snow Trout, the Lesser Barils, the Hillstream Loaches, the Stone Suckers, the Indian Torrent cat fish, the Sucker throat cat fish, and the Chola barb. Information concerning physical habitat requirements of fish present in the river was collated from published literature[27,35]. The primary physical habitat requirements for these fish varieties are minimum 1.0 m depth and 0.5 m/s flow velocity. These were related to the river cross-section in a simple hydraulic analysis to define the flows required for fish survival. During low flow period, based on the river cross-section, the wet width of the flow can be taken as about 80 m near the site of interest. In this area, the river has an average slope of 10 m/km. Application of the Manning's equation shows that a minimum 40 m^3/s (cumec) of flow is needed to maintain the requisite water depth and velocity. Hence, the five EF regimes were subjected to the condition that EF in the river would always be at least 40 m^3/s.

Regarding the water quality aspect of EF, the quality in the study area is quite good and is not a cause of concern. Finally, corresponding to zone 1, the actual flow in the diverted reaches will be more than the stipulated EF because stream flows in this zone are frequently much higher than the capacity of the hydropower plant and flows exceeding the design capacity will have to be released in the river. These flow regimes are given in Table 3.

Various flows are proposed in the literature for flushing purposes (e.g. the Tennant[36] method), suggesting that flows of 200% of the mean annual value be released for 48 h. Since the mean annual flow for the present case happens to be 304 cumec, a storage-based project should help release @608 cumec for 48 h; this condition is satisfied in the EF-2 regime. Statistical properties of the 90% dependable flow and EF-2 regime are listed in Table 4.

Using the various EF scenarios, operation of the hydropower project was simulated to compute energy generation using the data of installed capacity, hydraulic head

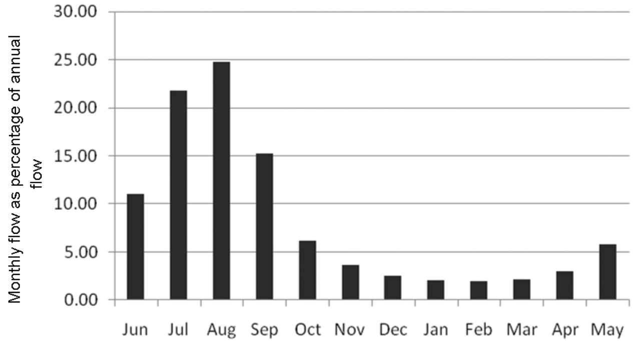

Figure 4. Monthly flows as percentage of annual flow at the focus project site.

Table 3. Scenarios of EF regime studied

EF regime	Description – EF as % of FDC values for 90% dependable year for different zones
EF 1	Zone 1 = 55, Zone 2 = 50, Zone 3 = 50, Zone 4 = 45
EF 2	Zone 1 = 55, Zone 2 = 50, Zone 3 = 45, Zone 4 = 40
EF 3	Zone 1 = 50, Zone 2 = 45, Zone 3 = 40, Zone 4 = 40
EF 4	Zone 1 = 45, Zone 2 = 40, Zone 3 = 35, Zone 4 = 35
EF 5	Zone 1 = 35, Zone 2 = 30, Zone 3 = 30, Zone 4 = 30

Table 4. Key statistical parameters of 90% dependable flow and EF-2 regime

	90% dependable flow	EF-2 regime
Mean	303.99	162.52
Standard deviation	346.29	192.49
Coefficient of variation	1.139	1.1184

Table 5. Flow diverted to generate power and reduction in electricity generation for various EF scenarios

EF scenario	Flow diverted to powerhouse (MCM)	Diverted flow (% of MAR)	Electricity generated (GW-hr)	Reduction in electricity generation compared to baseline (%)
No EF	7182	75.96	1186	–
EF 1	4331	45.81	718	0.39
EF 2	4406	46.60	730	0.38
EF 3	4696	49.66	778	0.34
EF 4	5007	52.95	830	0.30
EF 5	5519	58.37	914	0.23

MCM, Million cubic meters; MAR, Mean annual runoff; GW-hr, Gigawatt-hour.

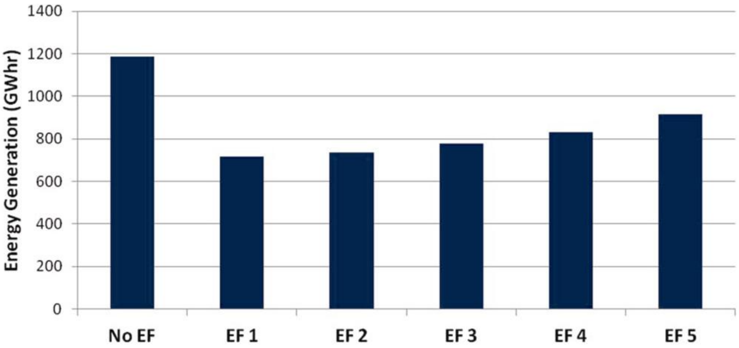

Figure 5. Energy generation from the project in a 90% dependable year under different EF scenarios.

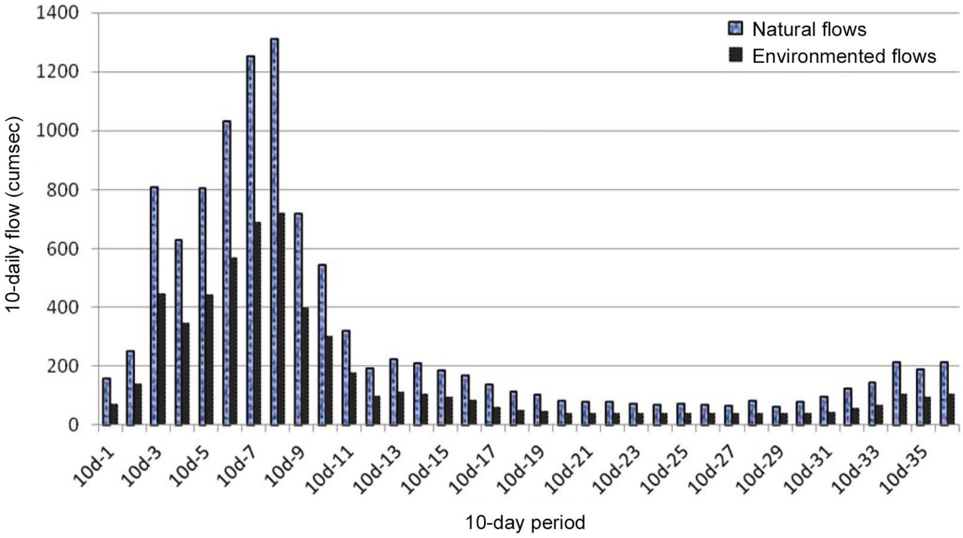

Figure 6. Ten-daily flows for the 90% dependable year and EF-2.

and efficiency of the plant. Figure 5 shows the energy generation in four scenarios as well as when there is no allocation for EF. EF-2 scenario, for example, results in less electricity generation to the tune of 456 GWh. Currently, domestic consumers pay about Rs 3.0 per unit (1 kWh) of electricity. Thus, the economic benefit foregone in the EF-2 scenario, compared to no-EF scenario will be about Rs 1370 million per year. Table 5 gives for various EF scenarios water diverted for electricity generation, electricity generated and reduction in electricity generation compared to baseline. It can noted from Figure 5 that the variability of observed flows has been maintained in all flow regimes. Finalized EF regime in the form of FDC can be converted to 10-daily flows by adopting the procedure described by Smakhtin and Anputhas[37]. Figure 6 shows the 10-daily flows for the

90% dependable year and environmental flows corresponding to EF-2.

In the absence of pertinent data from the ecosystem, impacts of altered flow conditions on the ecosystem can be quantified by indices based on hydrological data which can be used as proxy for ecological costs. The range of variability approach (RVA) by Richter *et al.*[5] employs a set of indicators of hydrologic alteration (IHA) to characterize the altered flow regimes. RVA uses 32 parameters which are computed from daily data and are grouped in five categories. Since this study has used 10-daily data, parameters for the first group (magnitude) were computed, giving rise to 36 parameters (one for each 10-day period). In a RoR project, water storage is negligible and some RVA parameters are not of much relevance. In the IHA software[38], low and high RVA targets for the first group for each 10-day period are the 25th and 75th percentile values. Hence, the violations (VIOL) when the flow falls outside the RVA targets were computed for each of the five EF regimes. Here, a higher value of VIOL implies more degraded river and a value close to zero denotes negligible degradation. It was found that VIOL is highly sensitive to the low RVA target. RVA uses a scheme to classify the degree of alteration in 'low', 'medium' and 'high' class; here we may classify the degree of alteration as 'low', 'moderate', 'high', and 'extreme' for VIOL in the range <25%, 26–50%, 51–75% and >75% respectively. For example, when the low RVA target is set at (μ-2 × SD), VIOL for EF-1 to EF-5 was 42%, 44%, 50%, 55% and 69% respectively.

Information from Table 5 and Figure 5, alteration categories determined plus other relevant factors can serve as the input for the decision makers and stakeholders to decide which EF regime is acceptable.

Concluding remarks

Many negative impacts of hydropower projects on river ecosystems can be minimized by careful planning and allocation of water for ecological needs. Regarding assessment of EFs in India, the following aspects are noted: (a) There is lack of data on ecosystems and the relationships between flows and ecosystem functioning are not available. To develop such relationships, extensive field campaigns involving people from relevant disciplines will have to be launched. Short-term snapshot biological sampling will not be able to document ecological change in flow-altered systems[2]. These data will help in scientifically understanding and setting the thresholds for the degree of alteration; (b) data and studies on values of ecosystem services are also lacking and similar efforts have to be made in this direction.

EFs, however, need to be set in India as a part of harnessing water and hydropower. Reasonable amount of reliable hydrological data are available to apply different methods and determine trade-offs; physical habitat requirements of fish species are known and can be used to set minimum flows. All stakeholders are interested in understanding trade-off of ecosystem conservation versus economic development so that negotiations can be made to arrive at an acceptable solution. The framework proposed in this article utilizes available hydrological and biological data to make practical assessments of EFs for hydropower projects in India. It permits interim flows to be set whilst biological data are collected and analysed to quantify ecosystem response to flow alteration. Since the flow regime of the glacier and snowfed rivers is likely to be impacted by climate change, it will be necessary to periodically review the hydrological situation and EF. Adaptive management, where review and feedbacks are used to update the decisions is helpful in such situations.

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