An Assessment of Environmental Flow Requirements of Indian River Basins

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Introduction

India faces a number of water related challenges, including increasing water scarcity and competition for water between different sectors and states. Some of the river basins in the southern and western states are experiencing physical or economic water scarcity. Basins in the east of the country are often perceived as having 'surplus' water and encounter recurrent floods. The National River Linking Project (NRLP) has been proposed as *the solution* to water related problems in India. The NRLP envisages transferring flood water of the Ganga, Brahmaputra and Meghna Rivers to the water scarce basins in the south and west (e.g., http://www.riverlinks.nic.in/). However, the NRLP is a contentious issue in Indian society, the media and amongst academics (e.g., Jain et al. 2005). Many scholars argue that the needs assessment of NRLP is inadequate. Others are of the view that the assessment of water surplus/deficits in Indian river basins, conducted as part of the NRLP proposal, has ignored environmental issues. Yet, others think that the very definition of "surplus water" needs to be clarified and that alternative water management options - less costly, easier to implement and more environmentally acceptable - have not been considered (e.g., Vaidyanathan 2003; http://www.lk.iwmi.org/nrlp/main; http://www.sdnpbd.org/river_basin/). Indeed, no assessment of ecological impacts of the future developments of water resources in the country seems to exist.

In India, as elsewhere in the world, freshwater and freshwater-dependent ecosystems provide a range of services for humans, including fish, flood protection, wildlife, etc. (e.g., Postel and Carpenter 1997; Revenga et al. 2000; http://www.maweb.org). 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 world's river basins as population and associated water demands increase. India is no exception. On the other hand, the assessment of water requirements of freshwater-dependent ecosystems represents a major challenge due to the complexity of physical processes and interactions between the components of the ecosystems. For day-to-day management of particular rivers, environmental requirements are often defined as a suite of flow discharges of certain magnitude, timing, frequency and duration. These flows ensure a flow regime capable of sustaining a complex set of aquatic habitats and ecosystem processes and are referred to as *"environmental flows", "environmental water requirements", "environmental flow requirements", "environmental water demand"*, etc. (Knights 2002; Lankford 2002; Dyson et al. 2003; Smakhtin et al. 2004a, 2004b). Many methods for determining these requirements have emerged in recent years. They are known as *environmental flow assessments* (EFA). The mean annual sum of estimated environmental flows represents a total annual water volume, which could be allocated for environmental purposes. In this report, we use the term 'environmental flows' (EF) to refer to the ecologically acceptable flow regime and the term 'environmental water requirements' (EWR) to refer to the total annual volume of EF.

The issues of EF assessment and management are high on the world agenda at present. At the same time, it remains a new research field. In many countries, including India, there has not even been a crude nationwide assessment of water requirements of rivers and their associated aquatic ecosystems. It is prudent to start addressing these issues which, in India, have become particularly relevant in the view of the major inter-basin water transfers planned under the NRLP.

This report starts with the description of India's physiography, water resources and water resources related problems. It proceeds by reviewing the emerging development of EF philosophy in India. It then reviews the current status of quick desktop EF estimation methods in the world and examines the applicability of those in the Indian context. It further formulates a simple EF assessment method which takes into account the limitations of available information in the country and illustrates its application using several major Indian river basins as examples. This is followed by recommendations on the immediate next steps in EFA in the context of the NRLP and for a longer-term EF research program.

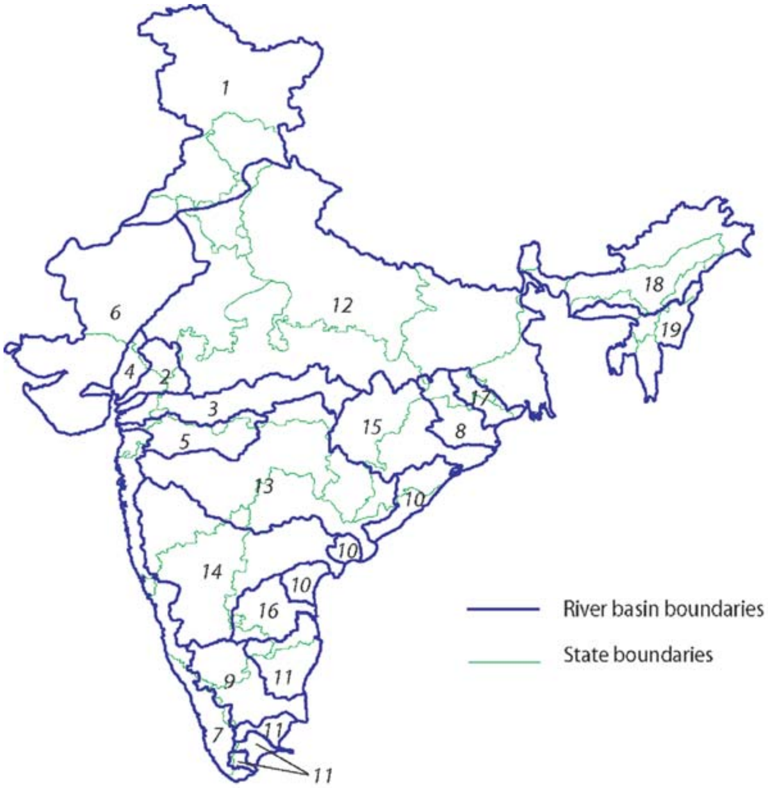
The study does not intend to give prescriptions for EF estimation in India or elsewhere. It suggests one potentially useful technique, which needs further development with more input from Indian hydrologists, aquatic ecologists, water engineers and other relevant specialists. The primary purpose of this work is therefore to stimulate the debate about EFA in India. It should be seen as a step towards the development of more detailed and comprehensive future national EF tools and policies and towards building the national capacity in the field of EFA. This study is a small component of a larger and longer-term research project which aims to assess multiple aspects of NRLP and the future of India's water resources in general.

Rivers in India

Hydrography

India has a large network of rivers, all of which are characterized by very large seasonal variation in their discharge due to seasonal rainfall and prolonged dry periods. The Indian mainland is drained by 15 major (drainage basin area >20,000 square kilometers [km^2]), 45 medium (2,000 to 20,000 km^2) and over 120 minor (<2,000 km^2) rivers, besides numerous ephemeral streams in the western arid region (Rao 1975). These river systems are traditionally grouped, according to their origin - into Himalayan and Peninsular rivers, or according to the direction of flow - into east flowing and west flowing rivers (NCIWRDP 1999; Amarasinghe et al. 2005). For large-scale analyses of water resources, the country is often separated into some 19 major river basins/drainage regions, which are shown in figure 1 (Amarasinghe et al. 2005). The main characteristics of these 19 river basins/drainage regions are given in Table 1.

Figure 1. A map of India, showing the boundaries of the major river basins/drainage regions and states.



River basins

1. Indus
2. Mahi
3. Narmada
4. Sabarmati
5. Tapi
6. West Flowing Rivers - group 1
7. West Flowing Rivers - group 2
8. Brahmani and Baitarani
9. Cauvery
10. East Flowing Rivers - group 1
11. East Flowing Rivers - group 2
12. Ganga
13. Godavari
14. Krishna
15. Mahanadi
16. Pennar
17. Subarnarekha
18. Brahmaputra
19. Meghna

Source: Amarasinghe et al. 2005

Table 1. Characteristics of the major river basins/drainage regions in India.

	River basin	Corresponding number in figure 1	Catchment area[a] (km^2)	Mean Annual Runoff[a] (BCM)
Basins of the West Flowing Rivers	Indus (to the border of Pakistan)[b]	1	321,000	73.3
	Mahi	2	35,000	11.0
	Narmada	3	99,000	45.6
	Sabarmati	4	22,000	3.8
	Tapi	5	65,000	14.9
	WFR1	6	334,000	15.1
	WFR2	7	113,000	201
Basins of the East Flowing Rivers	Brahmani and Baitarani	8	52,000	28.5
	Cauvery	9	81,000	21.4
	EFR1	10	87,000	22.5
	EFR2	11	100,000	16.5
	Ganga	12	861,000	525
	Godavari	13	313,000	110
	Krishna	14	259,000	78.1
	Mahanadi	15	142,000	66.9
	Pennar	16	55,000	6.3
	Subarnarekha	17	29,000	12.4
East India	Brahmaputra	18	194,000	585
	Meghna	19	42,000	48.4

Notes: [a] based on NCIWRDP 1999

[b] Indus system includes the river Indus and its tributaries: Jhelum, Chenab, Ravi, Beas and Sutlej

WFR1 = West Flowing Rivers - group 1 (rivers in Kutch and Saurashtra districts of Gujarat and the Luni River)

WFR2 = West Flowing Rivers - group 2 (rivers south of Tapi)

EFR1 = East Flowing Rivers - group1 (rivers between Mahanadi and Pennar basins)

EFR2 = East Flowing Rivers - group 2 (rivers between basins of Pennar and Kanaya kumari at the southern tip of India)

BCM = Billion Cubic Meters

Climate and Flow Regimes

The Indian climate is marked by a large spatial and temporal variability in precipitation, and a large potential evapotranspiration. There is considerable spatial variation in the Mean Annual Precipitation (MAP) which ranges from about 100 millimeters (mm) in the western Rajasthan State to more than 2,500 mm in Northeastern areas with a maximum of some 11,000 mm near Cherrapunji. High MAP values (over 2,000 mm) are also typical to the western slopes of the

Western Ghats. This, coupled with a variety of geological and topographical conditions of the river basins, results in a large spatial variability of flow regimes ranging from rivers flowing from the Himalayan Mountains and partially fed by snowmelt in spring and summer to alluvial plains' rivers, which receive considerable base flow from groundwater in autumn (Bandyopadhyay 1995).

Most of the rainfall in India takes place under the influence of the southwest monsoon between June to September except for the Tamil Nadu State, which is primarily impacted by the northeast monsoon during October and November. It is estimated that in Himalayan Rivers, where some flow is attributed to snowmelt, about 80 percent of the total annual flow takes place within the four southwest monsoon months. In Peninsular Rivers, where there is no contribution from snowmelt, monsoon flow accounts for more than 90 percent of the annual flow. Agrawal (1998) suggests that the entire annual rain in basins of the semi-arid tropics may fall within 100 hours, which is reflected in river flow regimes.

Degradation of Rivers

Since independence, India has witnessed rapid urbanization, industrialization, and intensification of agriculture, which all affected the rivers in different ways. Most Indian rivers, at present, are highly regulated (Agrawal and Chak 1991). Hundreds of multi-purpose reservoirs for water supply, irrigation, hydropower and fisheries have been constructed, as well as numerous barrages for water diversion. Many floodplains have been cut out from rivers by embankments and remaining riparian lands are under intensive agriculture and grazing pressure. Human settlements, deforestation, mining and other activities have degraded the river catchments and increased sediment loads of all rivers. Also, during the past few decades, rivers have received increasingly large discharges of industrial effluents, fertilizers and pesticides from agricultural practices and domestic wastes (CPCB 1996). All this affected riverine biota. Species composition has changed and many species have nearly disappeared. The loss of feeding and breeding habitats in the floodplain water bodies due to the construction of embankments (Mukherjee 2005), and increased silt load and macrophytic growth are major causes for declining fish resources (Jhingran 1991). It is symptomatic that out of the 30 world river basins marked as global level priorities for the protection of aquatic biodiversity by Groombridge and Jenkins (1998), nine (9) are from India due to their extensive and continuing development. These basins include Cauvery, Ganges-Brahmaputra, Godavari, Indus, Krishna, Mahanadi, Narmada, Pennar and Tapi. With an exception of Ganges-Brahmaputra, all the above basins have also been categorized as "strongly affected" by flow fragmentation and regulation (Nilsson et al. 2005).

Conservation and restoration of rivers have become vital for the overall sustainable development of the country. However, until recently, this "conservation" has been limited to "cleaning" of rivers by treatment of wastewater, occasional symbolic removal of garbage and enforcing the treatment of industrial effluents (Gopal and Chauhan 2003). So far, these efforts have not resulted in major improvements. Overall, there has been limited appreciation of the nature of rivers as ecosystems whose ecological integrity depends upon their physical, chemical, biological characteristics and interactions with their catchment.

Environmental Flows in the Indian Context

Development of Environmental Flow Philosophy

As in much of the world, Indian water planning and management considered water flowing to the sea as 'wasted'. The approach was to harness river waters through dams and other structures to the extent that was technically feasible. Even the *new* National Water Policy (MOWR 2002) still ranks "ecology" as the fourth item in the list of priorities for water-allocation. As the progressive degradation of the water environment became evident, environmental concerns have started to gain strength. This is, perhaps, where and when the term 'minimum flow' originated from. Minimum flow was understood as a flow, which is needed (to be released) downstream from the dams for environmental maintenance. As the term implies, such releases were minimal. In fact, there is no documented evidence suggesting that such releases were actually made.

The first National Workshop on Environmental Flows, held in New Delhi in March 2005, brought together over 60 participants from national agencies and research institutions and highlighted a great interest in the concept of environmental flows in India. Several relevant studies and activities currently conducted in the country have been presented and the issues of terminology were high on the agenda.

Iyer (2005) suggested that expressions such as "environmental flows" or "water for nature" imply that in allocating water for different uses, an allocation must be made "for nature as well". This may be seen as inappropriate in principle because "water itself is part of nature and one cannot presume to allocate water to nature". Therefore, aquatic ecology should be seen as a user of the highest priority. Ecological considerations may impose constraints on other uses of water and ecological imperatives must guide the water-use and water resources development of the future. Iyer (2005) further pointed out that while the idea of a "minimum flow" or "environmental flows" in streams and rivers is welcome in so far as some flow is better than no flow, this may not necessarily imply any major change in thinking; abstractions and diversions continue to be the norm and "minimum flow" clearly implies maximum abstraction. If "environmental flow" is understood as a synonym of "minimum", then the only change is in semantics. He further suggested that impacts on rivers are quantified against a reference condition of "natural flow", which, for all practical purposes could be accepted as the flow which existed prior to major river regulation. Most of the above statements are similar to that of Silk et al. (2000) or to the philosophy adopted in South Africa, for the protection of aquatic ecosystems, whereby EF – known as 'ecological Reserve' - are estimated for a water body first. Then only the difference between the total available water resource (natural flow) and the Reserve is considered to be utilizable. Such school of thought represents a very pro-environment position and is unlikely to succeed, in the short-term, in a country without strong pro-environmental traditions and practices in the conditions of increasing water scarcity.

Iyer (2005) also advocated the importance of distinguishing between in-stream flows for different purposes: "Flows are needed for maintaining the river regime, making it possible for the river to purify itself, sustaining aquatic life and vegetation, recharging groundwater, supporting livelihoods, facilitating navigation, preserving estuarine conditions, preventing the incursion of salinity, and enabling the river to play its role in the cultural and spiritual lives of the people." The latter appears to be a very important component in the Indian context (Sharma 2005), as water is necessary, amongst others, for cultural festivals and reduced flows can lead to depreciation of some religious places (e.g., Sinha and Prasad 2005). While several in-stream flow needs listed above can be satisfied by the same flow at the right time simultaneously, it appears important to agree on what 'ecological flows' or 'environmental flows' actually include. Mohile and Gupta (2005) suggested that requirements for drinking water, commercial fisheries, livelihoods and navigation as well as water for dilution of effluents are not included as part of EF, but rather considered as water for people, livelihoods and industries and estimated separately. As for effluents, they should be treated at source.

Mohile and Gupta (2005) also examined a wider concept of environmental water requirements and suggested that it should include the requirements of both terrestrial and aquatic ecosystems. The former would include direct evapotranspiration through forests, wetlands and other lands, all supporting distinct ecologies, while the latter would then be understood as EF. This is an interesting view given first, that the requirements of terrestrial ecosystems are currently not explicitly considered, and, second, that at present the '*environmental flow requirements'* and *'environmental water requirements'* are normally taken as synonyms (except rare cases when EWR is used to denote the total volume of EF (e.g., Smakhtin et al. 2004a)). At the same time, expanding the term EWR beyond the requirements of aquatic ecosystems will only add confusion to the already existing terminology. The issues of water requirements of terrestrial ecosystems are not considered in this report.

Previous Environmental Flow Assessment Work and Related Activities

The status of EF research in India at present may be characterized as being in its infancy. The National Commission for Integrated Water Resource Development Plan (NCIWRDP 1999) effectively accepted that it was not possible to estimate the amount of water needed for environmental purposes. They pointed out that the knowledge base for making any approximate calculation of this requirement was very limited. A provisional projection of the environmental needs has been given as 5 cubic kilometers (km^3), 10 km^3 and 20 km^3 in the years 2010, 2025 and 2050, respectively. The reason for such growth is unclear, but less important in the context of the fact that overall the water requirement for 'environment and ecology' has been estimated at about 2 percent of the total national water requirements. The values given were not referenced to rivers, wetlands or groundwater and were just bulk volumes for the entire country without any geographical specification. The NCIWRDP 'estimates' do not appear to be based on any scientific reasoning.

The issue of minimum flow was highlighted in a judgment of the Supreme Court of India, which in 1999 directed the government to ensure a minimum flow of 10 cubic meters per second (m^3/s) in the Yamuna River as it flows through New Delhi for improving its water quality. Since then the minimum flow requirement in rivers has been discussed at several forums (but primarily in the context of water quality). In 2001, the Government of India constituted the Water Quality Assessment Authority (WQAA) which in turn constituted, in 2003, a Working Group (WG) to advise the WQAA on 'minimum flows in rivers to conserve the ecosystem'. Despite the continuous use of the term 'minimum flow', the emphasis on 'ecosystem' is noteworthy (Prof. B. Gopal, NIE, personal communication). The WG reviewed the existing EFA practice and suggested that due to a variety of reasons, including the high hydrological variability, difficult tradeoffs between environment and agriculture, expensive waste treatment, disputes for water between States, etc., the practices adopted in other countries for assessment of EF are unlikely to be applicable in India. The WG also suggested that only a simple method (like Tennant, see section: *Review of Environmental Flow Assessment Methods*) may be adopted for estimating ‘minimum flows’ to be maintained in the rivers in India. These flows would primarily serve the purpose of maintaining prescribed water quality standards.

Perhaps, the first scientific attempt to assess EF for entire India has recently been done in the report by Amarasinghe et al. (2005). This estimate is based on the global study conducted by Smakhtin et al. (2004a; 2004b) and was made separately for major river basins/drainage regions in India, as shown in figure 1. The estimate turned out to be about 476 km^3, which constitutes approximately 25 percent of the total renewable water resources in the country. This, however, was not in fact an estimate of EF *per se*, but rather an estimate of the total volume of EF (i.e., EWR). The approach was based on hydrological data simulated by a global hydrological model, which was not calibrated for Indian conditions. No observed flow data from Indian rivers were used and no ecological data were present in the approach, although the hydrological hypotheses used were ecologically based. Also, it was an estimate representing only one scenario of environmental management – that all major river basins are maintained in “fair” conditions as explained in Smakhtin et al. (2004a).

The known attempts to approach the issue of EF in India (CWC, WG on Minimum Flows; Amarasinghe et al. 2005) addressed it at the scale of the entire country. More detailed, basin-specific EF research has not yet been initiated. One known exception is the project carried out by the National Institute of Hydrology (NIH) at Roorkie aiming at the EFA in the Brahmani-Baitarani River System (Table 1; Figure 1), where a hydrology-based Range of Variability Approach of Richter et al. (1997) (see section: *Review of Environmental Flow Assessment Methods*) is used. Preliminary recommendations for the Baitarani River have been formulated based on the need to maintain 7-day minimum and 1-day maximum flows in the river and its water quality within its current state (R. Jha, NIH, Roorkie, personal communication). This and some other EF-related activities in India are yet to be documented.

Review of Environmental Flow Assessment Methods

Basic Principles

‘Environmental Flows’ is a very simple concept. First of all, this term should always be used in plural, implying that a synonym to environmental flows is *an ecologically acceptable flow regime* designed to maintain a river in an agreed or predetermined state. Therefore, second, EF are a compromise between water resources development, on one hand, and river maintenance in a healthy or at least reasonable condition, on the other. Another useful way of thinking about EF is that of ‘environmental demand’ similarly to crop water requirements, industrial or domestic water demand. Despite the simplicity of the concept, difficulties arise in the actual estimation of EF values. This is primarily due to the inherent lack of both the understanding of and quantitative data on relationships between river flows and multiple components of river ecology.

Ecologists agree that the major criteria for determining EF should include the maintenance of both spatial and temporal patterns of river flow, i.e., the flow variability, which affect the structural and functional diversity of rivers and their floodplains, and which in turn influence the species diversity of the river (Ward and Tockner 2001; Ward et al. 2001; Knights 2002). Thus, EF should not only encompass the *amounts* of water needed, but also *when and how* this water should be flowing in the river. All components of the hydrological regime have certain ecological significance (Knights 2002). High flows of different frequency are important for channel maintenance, bird breeding, wetland flooding and maintenance of riparian vegetation. Moderate flows may be critical for cycling of organic matter from river banks and for fish migration, while low flows of different magnitudes are important for algae control, water quality maintenance and the use of the river by local people. Therefore, many elements of flow variability have to be maintained in a modified-EF-regime.

The focus on maintenance of flow variability has several important implications. First, it moves away from a 'minimum flow attitude' to aquatic environment. Second, it effectively considers that aquatic environment is also 'held accountable' and valued similarly to other sectors – to allow informed tradeoffs to be made in water scarcity conditions. Because wetland and river ecosystems are naturally subjected to droughts or low flow periods and can recover from those, then building this variability into the picture of EFA may be seen as *environmental water demand management.* This brings us back to the issue of 'compromise' and implies that EF is a very pragmatic concept: it does not accept a bare minimum, but it is prepared for a trade. Bunn and Arthington (2002) have formulated four basic principles that emphasize the role of flow regime in structuring aquatic life and show the link between flow and ecosystem changes:

- Flow is a major determinant of physical habitat in rivers, which in turn is the major determinant of biotic composition. Therefore, river flow modifications eventually lead to changes in the composition and diversity of aquatic communities.
- Aquatic species have evolved life history strategies primarily in response to the natural flow regimes. Therefore, flow regime alterations can lead to loss of biodiversity of native species.
- Maintenance of natural patterns of longitudinal and lateral connectivity in river-floodplain systems determine the ability of many aquatic species to move between the river and floodplain or between the main river and its tributaries. Loss of longitudinal and lateral connectivity can lead to local extinction of species.
- The invasion of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. Inter-basin water transfers may represent a significant mechanism for the spread of exotic species.

Major Categories of Environmental Flow Assessment Methods

Many EFA methodologies, which directly or indirectly encompass the above principles, have emerged in recent years. They differ significantly in accuracy and required input information. The discussion of these techniques may be found in many published sources including reviews by Jowett (1997), Tharme (2003), Acreman and Dunbar (2004) and is not repeated here. Different EFA methods should be used for different purposes – from general water resources planning to managing dam releases. In some countries, there is a move towards hierarchical multi-tier

EFA frameworks, driven by the availability or access to resources, including data, time, technical capacity and finances (http://www.dwaf.gov.za; Dyson et al. 2003). The two major tiers include:

- Detailed assessment, using primarily holistic methods, or methods based on habitat modeling
- Desktop, rapid assessment, using primarily ecologically relevant hydrological characteristics (indices) or analysis of hydrological time series

Methods from the first group often adopt a whole-ecosystem view in assessing EF, whereby ecologically and/or socially important flow events are identified and an ecologically acceptable flow regime is defined by a multi-disciplinary panel of experts. These methods include substantial amounts of field work and may take significant amounts of time (e.g., 2 to 3 years for a basin like Krishna – due to the need for ecological data collection at certain times of the year and the mere size of the basin) and resources to complete for a single river basin (e.g., King and Louw 1998; King et al. 2003). Habitat models, also included in this group are different from holistic methods, as they primarily focus on fish. However, they are very complex and also require a lot of input data and field work. They are used to assess the impacts of changing flow regime on physical habitat for key life stages of target fish species. Flow-habitat models quantify changes in physical in-channel hydraulic characteristics arising from flow regulation. Hydraulic output is combined with the physical habitat preferences of target species (e.g., Parasiewicz and Dunbar 2001). Both the habitat modeling approach and some holistic methods (e.g., King et al. 2003) are designed to address trade-offs. They are naturally suited to scenario analysis and are commonly used where negotiation is a feature of EF setting.

Methods from the second group - desktop EFA - are much more diverse, more suitable for initial, reconnaissance or planning-level assessments of EF. They can take a form of a look-up table (e.g., Tennant 1976; Matthews and Bao 1991) or be based on the detailed analysis of hydrological time series (e.g., Richter et al. 1997; Hughes and Hannart 2003). The look-up tables take a significant amount of time to develop, before they can be used, while the methods based on the time series naturally require either observed or simulated discharge time series (or both).

The number of available EFA techniques is sometimes grossly overstated (Tharme 2003). Most of them are simple hydrological indices which have existed and been used in various hydrological and water resources applications for decades. However, the number of ‘genuine’ EFA techniques continues to grow thus reflecting the quest for a better technique which suits the specifics of a particular task, region, data available, importance of an ecosystem and many other factors. Any classification of EFA methodologies is, however, rather arbitrary and different authors sometimes use different categories to refer to the same method (compare, for example, Dunbar et al. 1996; and Tharme 2003).

Regardless of the type of the EFA methods, all of them have been designed and/or applied in a developed country context. Distinct gaps in EF knowledge and practice are evident in current approaches to water resources management in almost all developing countries, including India, most of which lack technical and institutional capacity to establish environmental water allocation practices (Tharme and Smakhtin 2003). The existing EFA methods are either complex and resource-intensive (holistic approaches) or not tailor-made for the specific conditions of a particular country, region or basin (desktop methods).

The above ‘classification’ into comprehensive (detailed) and planning-type (desktop) methodologies, is therefore useful in the context of this study as most of the discussion below is focused on the second type - quick desktop EFA methods. The use of such methods may be seen as the starting point towards the understanding of EF and their importance in principle. While such methods provide estimates of low confidence (due to the lack of ecological data involved), they may be used to set the feasible limits for future water resource exploitation. Their application may change the still dominant perception about the insignificance of environmental water allocations in river basin planning and about the very nature of such allocations.

Desktop Environmental Flow Assessment Methods

The first example from this group is the Tennant method, which attempts to separate *a priori* the entire range of the Mean Annual Runoff (MAR) at a site of a river into several ecologically relevant ranges. All suggested ranges correspond to different levels of aquatic habitat maintenance or degradation and have been justified by observations in many streams in the USA. A threshold of 10 percent of the MAR reserved for an aquatic ecosystem was considered to be the lowest limit for EF recommendations (corresponding to severe degradation of a system). Fair/good habitat conditions could be ensured if 35 percent of the MAR is allocated for environmental purposes. Allocations in the range of 60 to 100 percent of the MAR represent an environmental optimum. This technique is still widely used in North America (Tharme 2003), but is somewhat outdated by now and is scientifically weak as a threshold selection (% of the MAR) is arbitrary and no flow variability is accounted for. One positive aspect of Tennant is the awareness that 10 % of the MAR may be considered the lowest and highly undesirable threshold for EF allocations and that at least some 30 % of the total natural MAR may need to be retained in the river throughout the basin to ensure fair conditions of riverine ecosystems.

Another frequently cited hydrological EFA technique is the Range of Variability Approach (RVA)(Richter et al. 1997), which aims to protect a range of flows in a river. The 32 hydrological parameters, which jointly reflect different aspects of flow variability (magnitude, frequency, duration and timing of flows), are estimated from a natural daily flow time series at a site of interest. It is further suggested that in a modified (ecologically acceptable) flow regime, all 32 parameters should be maintained within the limits of their natural variability. For each parameter, a threshold of one standard deviation from the mean is suggested as a default arbitrary limit for setting EF targets in the absence of other supporting ecological information.

The RVA may be applied as a desktop EFA tool. It can ensure that sufficient water is available for human uses and effectively accepts that the full range of natural streamflow variability will not be possible to maintain in regulated or otherwise affected river systems. However, despite the relatively advanced nature of the RVA, the number of parameters used in it is too large for the level of subjectivity associated with their selection. In addition, many parameters are either likely to be correlated with each other, or there is little difference between their values. Smakhtin and Shilpakar (2005) justified and illustrated the simplification of this technique through a significant reduction of the number of parameters. At the same time, even the simplified RVA approach requires a great deal of hydrological data (daily flow time series, which are not readily available - see section: *Developing a Prototype Desktop Environmental Flow Assessment Tool*) and, ideally, ecological data (for better setting of acceptable thresholds on parameters). It should be possible, for pilot assessment, to use monthly instead of daily flow data, select a limited number of flow parameter values and develop a stepwise decrement procedure for each of these parameters. This could effectively lead to a new, much simpler method, where all flow parameters are estimated by the same principle and data requirements are consistent with availability (at least in the Indian context at present).

The environmental water allocation procedures practiced by UK Environment Agency (2001) are known as CAMS (Catchment Abstraction Management Strategies). This allocation is determined through consideration of four elements: (i) physical characterization; (ii) fisheries; (iii) macrophytes; and (iv) macro-invertebrates (e.g., Acreman 2002). Each element is given a score from 1 to 5 based on its sensitivity to reductions in flow. In terms of physical characterization, rivers with steep gradients and/or wide shallow cross-sections score 5, since it is assumed that small reductions in flow result in a relatively large reduction in wetted perimeter. At the other extreme, lowland river reaches that are deep are assumed to be less sensitive to flow reduction and score 1. Scoring for fisheries is determined either by flow-habitat modeling, or by using *expert opinion* to classify the river according to description of each of the score classes. Once a score for each of the four elements has been defined, the scores are combined to categorize the river into one of the five environmental weighting Bands, where Band A is the most sensitive (mean score of 5) and Band E is the least sensitive (mean score of 1).

The next stage in CAMS is the definition of a target *flow duration curve* (FDC) that guides the setting of limits on abstraction (Petts 1996). First, a naturalized FDC is produced, either by a deterministic process of adding abstractions and subtracting discharges from a recorded flow time-series or by a regional steady-state model based on catchment characteristics (area, geology) and climate. A set of simple tabulated rules is then used to determine the percentage of natural low flow that can be abstracted, depending on the environmental Bands defined above. A low flow is defined as the flow exceeded 95 % of the time (95 *percentile on the FDC*). Rules for determining percentage of allowable abstractions at other flow *percentiles* at FDC are also provided. In this way, an entire target *environmental FDC* can be derived. The output figures are based largely on *professional judgment* of specialists, since critical levels have not been defined directly by scientific studies at present. Any such figures are open to revision, but with no clear alternative, this provides a pragmatic way forward. The entire procedure provides a first level estimate and any catchment may then be subjected to a more detailed analysis using habitat simulation models or other, more detailed methods (Parasiewicz and Dunbar 2001; Extence et al. 1999). This is effectively, an example of a two-tier approach mentioned earlier.

Perhaps the most advanced existing hydrology-based desktop EFA method has been developed by Hughes and Münster (2000) and further refined by Hughes and Hannart (2003). It is known as the 'Desktop Reserve Model' (DRM). The 'ecological Reserve for rivers' is effectively a South African term for 'environmental flows' (there are also procedures developed for the determination of ecological reserve for wetlands, estuaries and aquifers). Quantifying the ecological Reserve involves determining the volumes and discharges which will sustain a river in a predetermined condition. The latter is referred to as an 'Ecological Management Category' (or Class) – EMC (or, more recently, 'Level of Ecological Protection' - LEP) and is related to the extent to which this condition deviates from the natural. There are four LEPs - A, B, C, and D - where A rivers are largely natural and D are largely modified. These categories are determined by a sophisticated *scoring system* based on a number of indicators related to river importance and sensitivity.

The DRM originates from the Building Block Methodology (BBM) (King and Louw 1998). 'Building Blocks' (BBs) are environmental flows, which jointly comprise the ecologically acceptable, modified flow regime. The major BBs are low flows, small increases in flow ('freshes') and larger high flows, which are required for floodplain flooding and for river channel maintenance. BBs are defined for each of the 12 calendar months and differ between 'normal years' and 'drought years'. The first are referred to as 'maintenance requirements' and the second as 'drought requirements'. The set of BBs, therefore, include maintenance low flows, maintenance high flows, drought low flows and drought high flows.

The DRM uses similar BBs and was developed as a rapid, low confidence EFA approach. The basis for the model was an extrapolation of higher confidence EWR determinations (with specialist inputs from ecologists and geomorphologists) using the hydrological characteristics of the river flow regimes. Hughes and Münster (2000) analyzed the results of previous *comprehensive EFAs* of South African rivers in the context of hydrological variability of these rivers, and developed empirical equations which related the above BBs with flow variability and EMCs (Hughes and Münster 2000). The main variability characteristic - hydrological variability index - is calculated from the coefficients of variation (standard deviation/mean) of several calendar month flows and the baseflow index (baseflow contribution divided by total flow). The higher the variability index, the more variable is the river flow regime.

The main result of this analysis and the basic assumption of the DRM is that the rivers with more stable flow regimes (a higher proportion of their flow occurring as baseflow) may be expected to have relatively higher environmental low flow requirements in normal years ('maintenance low flow requirements' in Reserve terminology). Rivers with more variable flow regimes would be expected, from a purely hydrological perspective, to have relatively lower maintenance low flow requirements and/or lower levels of assurance associated with them. *The consequence of these assumptions is that the long-term mean EWR would be lower for rivers with more variable flow regimes*. The DRM therefore explicitly introduces the principle of 'assurance of supply' into EFA. The estimated BBs are then combined into a time series of EF using a set of assurance rules and the natural flow time series.

The underlying concepts of the DRM are attractive and, to an extent, ecologically justified, as they emerge from the results of comprehensive EFAs, which involve a variety of ecological disciplines. Smakhtin et al. (2004a, 2004b) have used the principles behind the DRM in their *global* assessment of EWR. One stumbling block for direct DRM applications in other countries (e.g., in India) is that regional DRM parameters have been estimated on the basis of South African case studies, but are not generally available for other areas. Symphorian et al. (2002) used DRM to study reservoir operation for environmental water releases in Zimbabwe, where hydrological conditions are similar to South Africa. The DRM has recently been tested for several rivers in England (M. Acreman, CEH, personal communication) while Smakhtin et al. (2006) attempted to use DRM in Nepal. In both cases, the general conclusion was that the direct application of DRM or any other desktop EFA method outside of the region, it was originally developed for, requires recalibration in new conditions. One possible alternative is to simplify the DRM so that the use of regional parameters can be avoided, while the main principles are retained. One additional advantage of the DRM is that it is originally based on *monthly flow data* which are more readily available or accessible in developing countries like India.

Implications for Future Environmental Flow Assessment in India

There are different ways of developing EF research and environmental water allocation practices in a country with limited exposure to EF concepts, like India at present. It is possible to develop a simple prototype assessment tool which illustrates the main EF concepts and allows preliminary EFA to be made in real river basins, using available national data. This should also allow unsound past practices/concepts (e.g., 'minimum flow') to be gradually left behind and further development of planning EFA tools to be stimulated, with input from the national eco-hydrological community. This approach would build the EF-related expertise and prepare a ground for more comprehensive, detailed and resource intensive EFA in the future.

Alternatively, EF-related capacity can be built through national workshops, which would aim to undertake detailed EF studies in specific national river basins and use the expert opinion of local ecologists and hydrologists who know their rivers. Even if this knowledge is not 'EF tailor made', and the results are uncertain, attempting such comprehensive EFA develops team building and interactions between experts in different disciplines.

Both approaches are complementary. The very limited time available for the current study, speaks in favour of the first approach, which may also be seen as a stimulus for more EFA tool development, more comprehensive EFA studies in the future and as a starting point for capacity building in EFA overall.

The above review of desktop EFA methods highlights several important considerations for the development of a prototype EFA method for India.

- To sustain ecological processes and associated animal and plant communities in river freshwater ecosystems, it is necessary to maintain ecologically relevant elements of natural hydrological variability (e.g., frequency, duration, magnitude of some flows, etc.). *Therefore, the method has to take flow variability into account.*

- *The method has to be commensurate with the current level of understanding of river ecology and flow data available.* The simpler and less information consuming the better at this stage. This allows EF issues to be explicitly highlighted for some or most of the major river basins in India within a short-term. Given the extreme level of uncertainty and data limitations in which this study is conducted, the method to be developed should be seen as a 'rule of thumb', be as generic as possible to form the basis for future refinement and application for river basins of various sizes.

- In most of the desktop methods, EF depend upon the category of protection in which a river ecosystem needs to be maintained. The closer this category to the natural state of an ecosystem, the higher the EWR should be and the more elements of natural flow variability should be preserved. While these categories are simply a management concept, it facilitates desktop EFA and allows preliminary EF estimates to be made. *It is therefore logical to design a prototype desktop EFA method so that it relates flow variability, conservation category and EF.*

- As evident from the above review, *all* existing EFA methods (comprehensive or desktop) *leave a lot to professional judgment or expert opinion,* which means that a strong scientific basis is not always present, even in detailed approaches and they remain essentially subjective. For example, various scoring systems are commonly used to determine current ecological status or the desired level of environmental protection of a river basin or reach. In the absence of other alternatives this allows expert knowledge to be formalized and 'quantified' and also brings at least limited ecological information/consideration into the EFA. *If existing ecological knowledge is limited and the scale of the EFA is coarse, aggregate environmental indicators, which reflect different features or conditions of a river basin, could be used for scoring.*

Developing a Prototype Desktop Environmental Flow Assessment Tool

Observed Flow Data

One primary aspect associated with the desktop EFA method development and application is the *observed flow data*. Due to the need to relate hydrological characteristics to EWR, the availability, type and quality of observed flow data determines how reliable the EFA method could be. Considering that *daily* flow time series carry much more information about flow variability and that monthly flow data can naturally be calculated from daily values, *the daily flow time series are always the preferred data type.* The reality, however, is that almost no daily flow time series are publicly available in India, and when the data are made available their quality appears to be low.

The lack of daily flow data may not be a major problem in itself as some EFA methods (e.g., DRM) successfully work with good quality monthly flow data. The minimum requirement for desktop EFA application at any site in a river basin is therefore *sufficiently long (at least 20 years) monthly flow time series reflecting, as much as possible, the pattern of natural flow variability*. However, the availability of monthly flow data in India is also limited. Some monthly flow time series for Peninsular Rivers (primarily for the last 15-20 years) have been provided by the Central Water Commission (CWC) of India. Additional monthly flow data (for years prior to the 1980s) for several Indian rivers may be downloaded from several websites on the Internet (these sites also contain data on other world rivers):

(i) http://www-eosdis.ornl.gov/

(ii) http://dss.ucar.edu/catalogs/ranges/range550.html

(iii) http://webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml

(iv) http://grdc.bafg.de/servlet/is/Entry.987.Display/

The data available at these sites for Indian rivers are the same and therefore do not help to expand the available observed dataset. The origin of these data is also not specifically indicated but it is most likely that they have been provided by the Indian government to the international community in the past in the context of some global water resources assessment project(s).

Most of the monthly flow time series available from the Internet are very short (1 to 8 years), ending in the early 1980s or late 1970s and with many gaps due to missing data. They are therefore largely unsuitable for any meaningful hydrological analysis. The data found on the Internet therefore have been considered for use only if the total number of months without missing data was over 120. This allowed stations with a minimum of 10 years of observations to be included (if they had no missing data), or stations with longer records to be included (even if they still had some missing data). In any case, such selection has been based on an arbitrary *minimum, which is effectively below the requirements stipulated above.* In summary, over 50 monthly flow time series (acquired from CWC and the Internet) for various river basins were considered for use. Due to severe data limitations described above, only a few of those were finally selected (Table 2).

Simulating Reference Hydrological Conditions at the Outlets of Major Basins

The desktop EFA method suggested and tested in this study is built around a period-of-record FDC and includes several subsequent steps. The first step is the calculation of a representative FDC for each site where the EWR are to be calculated. In this study, *the sites where EF are calculated are coincident either with outlets of the major river basins or with the most downstream flow observation station.* The sites with observed flow data are further often referred to in this report as ‘source’ sites. The sites where reference FDC and time series are needed for the EF estimation (e.g., basin outlets) are further referred to as ‘destination’ sites. The destination sites are either ungauged or significantly impacted by upstream basin developments. Therefore, representative ‘unregulated’ monthly flow time series, or corresponding aggregated measures of unregulated flow variability, like FDCs, have to be simulated/derived from available observed (source) records.

Any FDC can be represented by a table of flow values (percentiles) covering the entire range of probabilities of occurrence. All FDCs in this study are represented by a table of flows corresponding to the 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent. These points (i) ensure that the entire range of flows is adequately covered, and (ii) easy to use in the context of the following steps. For all source sites listed in table 2, FDC tables were calculated directly from the observed record or from part of the record which could be considered ‘unregulated’. Normally the earlier part of each record - preceding major dams’ construction - was used to ensure that monthly flow variability, captured by the period-of-record FDC, is not seriously impacted.

For each destination site, a FDC table was calculated using a source FDC table from either the nearest or the only available observation flow station upstream. To account for land-use impacts, flow withdrawals, etc., and for the differences between the size of a source and a destination basin, the source FDC is scaled up by the ratio of ‘natural’ long-term mean annual runoff (MAR) at the outlet and the actual MAR calculated from the source record. The application of such ratio effectively ‘naturalizes’ the observed flow source time series and ‘moves’ it to the basin outlet. The estimates of ‘natural’ MAR for major rivers are available from Indian sources (e.g., Table 1). The estimates of ‘natural’ MAR for smaller basins in India could be obtained by means of hydrological regionalization (e.g., Kothyari and Garde 1991; Kothyari 1995).

The scaling up of the curves is effectively equivalent to the scaling of the actual time series. It is important to stress that both the calculated FDC and the corresponding time series reflect the flow amounts and variability which no longer exist at the outlets of river basins. They are perceived to represent the hydrological reference conditions that existed in the past prior to major basin developments.

Table 2. Details of selected observed monthly flow data sets.*

Lat DD. decimal	Long DD. decimal	River	Location	Area (km^2)	Record Period	Comment
26.1	91.7	Brahmaputra	Pandu	405,000	1956-1979	Missing data patched using the mean monthly flow. No recent data available. The entire record was used as an indicator of reference ‘natural’ flow variability.
12.4	76.6	Cauvery	Krishnaraj Sagar	10,600	1934-1979	Missing data patched using the mean monthly flow. The earliest part of the record (1934-1957) was used as an indicator of ‘natural’ variability.
10.8	78.8	Cauvery	Musiri	66,243	1990-2002	An indicator of present day hydrology
24.8	87.9	Ganga	Farakka	951,600	1949-1973	Missing data in 1961-1964 patched. No recent data available. The entire record was used as an indicator of reference ‘natural’ flow variability.
16.5	81.5	Godavari	Davlaishwaram	299,300	1901-1979	The record was used as an indicator of reference flow variability.
N/A	N/A	Godavari	Polavaram	307,880	1990-2005	An indicator of present day hydrology
16.5	80.6	Krishna	Vijayawada	251,360	1901-2005	The earlier part of the record (1901-1959) is used as an indicator of reference ‘natural’ flow variability, the latest – as an indicator of present day hydrology.
N/A	N/A	Mahanadi	H. K. Sambalpur	83,400	1926-1956	The record was used as an indicator of reference flow variability.
N/A	N/A	Mahanadi	Basantpur	57,780	1990-2003	An indicator of present day hydrology
22.3	73.0	Mahi	Sevalia	33,670	1968-1979	No recent data available. The record was used as an indicator of reference flow variability.
21.9	73.6	Narmada	Garudeshwar	89,345	1948-2004	The earlier part of the record (1948-1970) was used as an indicator of reference flow variability, the latest – as an indicator of present day hydrology.
22.2	76.0	Narmada	Mortakka	67,000	1948-2001	The record 1980-2001 is an indicator of present day hydrology.
14.6	80.0	Pennar	Nellore	53,290	1965-1979	No recent data available. The record was used as an indicator of reference flow variability.
21.3	72.9	Tapi	Kathore/Ghal	63,325	1923-2004	The earlier part of the record (1939-1979) was used as an indicator of reference flow variability, the latest as an indicator of present day hydrology.
10.2	76.7	Periyar	Planchotte	5,387	1967-1979	Example of a ‘small’ river from the West Coast. Located in the south of the WFR2 drainage region (table 1). No recent data available. Record is used as an indicator of reference flow variability.
23.1	73.4	Sabarmati	Ahmedabad	12,950	1968-1979	No recent data available. Record is used as an indicator of reference flow variability.
23.0	85.0	Subarnarekha	Kokpara	N/A	1964-1974	No recent data available. Record is used as an indicator of reference flow variability.

*Most of the data were used to simulate reference monthly flows at the ungauged basin outlets with the subsequent EWR estimation from simulated time series. Shaded rows show stations with observed data which were used for comparison with estimated EWR.

Defining Environmental Management Classes

EF aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition/ status also referred to as “desired future state”, “environmental management class”/ “ecological management category”, “level of environmental protection”, etc. (e.g., Acreman and Dunbar 2004; DWAF 1997). This report uses the term ‘environmental management class’ (EMC). The higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and more flow variability will need to be preserved.

Ideally, these classes should be based on empirical relationships between flow and ecological status/conditions associated with clearly identifiable thresholds. However, so far there is insufficient evidence for such thresholds (e.g., Beecher 1990; Puckridge et al. 1998). These categories are therefore a management concept, which has been developed and used in the world because of a need to make decisions in the conditions of limited lucid knowledge. As shown in the review section (see section: *Review of Environmental Flow Assessment Methods*), placing a river into a certain EMC is normally accomplished by expert judgment using a scoring system. Alternatively, the EMCs may be used as default ‘scenarios’ of environmental protection and corresponding EWR and EF - as ‘scenarios’ of environmental water demand.

Six EMCs are used in this study and six corresponding default levels of EWR may be defined. The set of EMCs (Table 3) is similar to the one described in DWAF (1997). 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 (DWAF 1997). This restriction is not however applied in this report, primarily because the meaning of every EMC is somewhat arbitrary and needs to be filled with more ecological substance in the future. Some studies use transitional EMCs (e.g., A/B, B/C, etc.) to allow for more flexibility in EWR determinations. It can be noted, however, that ecosystems in class F are likely to be those which have been modified beyond rehabilitation to anything approaching a natural condition.

It is possible to estimate EWR corresponding to all or any of the above EMCs and then consider which one is best suited/feasible for the river in question, given existing and future basin developments. On the other hand, it is possible to use expert judgment and available ecological information in order to place a river into the most probable/achievable EMC. As evident from the above reviews of EFA methods, this approach is widely practiced. One can think of an ‘*ecological water report card’* for a basin. Such a ‘report card’ could include answers to the following three broad questions:

- The first question is: *what is the ecological sensitivity and importance of the river basin?* The rational for this is that the higher the ecological sensitivity and

Table 3. Environmental Management Classes (EMC) and corresponding default limits for FDC shift.

EMC	Ecological description	Management perspective	Default FDC shift limits
A: Natural	Pristine condition or minor modification of in-stream and riparian habitat	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions, etc.) allowed	Lateral shift of a reference FDC one percentage point to the left along the time axis from the original FDC position
B: Slightly modified	Largely intact biodiversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed	Lateral shift of a reference FDC one percentage point to the left along the time axis from the position of the FDC for A class
C: Moderately modified	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present	Multiple disturbances associated with the need for socio-economic development, e.g., dams, diversions, habitat modification and reduced water quality	Lateral shift of a reference FDC one more percentage point to the left along the time axis from the position of the FDC for B class
D: Largely modified	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation	Lateral shift of a reference FDC one more percentage point to the left along the time axis from the position of the FDC for C class
E: Seriously modified	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem	High human population density and extensiv water resources exploitation	Lateral shift of a reference FDC one more percentage point to the left along the time axis fromthe position of the FDC for Dclass
F: Critically modified	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats, etc (if still possible/ feasible) – to ‘move’ a river to a higher management category	Lateral shift of a reference FDC one more percentage point to the left along the time axis from the position of the FDC for E class

importance of aquatic ecosystems in a river basin, the higher the environmental category should ideally be.

- The second is: *what is the current condition of aquatic ecosystems in the river basin?* The more pristine the current condition of the basin, the more incentive in some cases could be to keep it that way. On the other hand, the current condition would determine to a large extent what EMC is achievable.
- The third is: *what is the trend of change?* This question aims to identify whether a river is still changing, how fast and due to what impacts. It may be seen as an attempt to foresee how the river will look like in the short-term (e.g., 5 years) and in the long-term (e.g., 20 years) in case of a ‘do-nothing-to-protect-aquatic-environment’ scenario. The rational is that if deterioration of aquatic environment still continues it will be more difficult to achieve a higher ecological condition, even if it is necessary, due to its high importance and sensitivity.

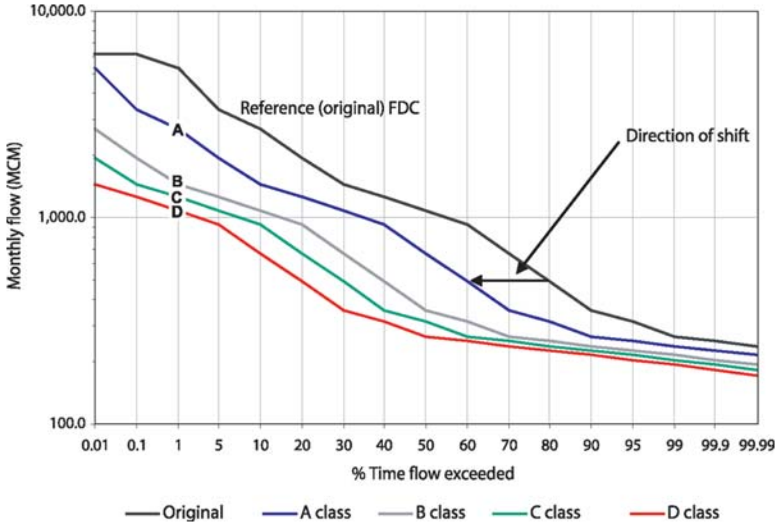
As this is the first time that such an approach is introduced in India, the focus should be on highlighting only the main aquatic features and problems of each basin. Such studies for several river basins, namely Cauvery, Krishna, Narmada, Periyar and Ganges have been initiated as part of this project. Aquatic ecology specialists from several Indian research organizations have been engaged in this research aiming to answer the above questions using several aggregate basin indicators, such as unique biota, aquatic habitat richness, aquatic species diversity, measures of flow regulation and catchment fragmentation, presence of protected areas, etc. The results are being summarized at the time of writing this report and will be presented in a separate publication. The default EMCs described in table 3 have been used in the current report as scenarios of aquatic ecosystem condition.

Establishing Environmental Flow Duration Curves

A simple approach is proposed to determine the default FDC representing a summary of EF for each EMC. These curves are determined by the lateral shift of the original reference FDC – to the left, along the probability axis. The mentioned 17 percentage points on the probability axis: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 percent are used as steps in this shifting procedure. A FDC shift by one step means that a flow which was exceeded, 99.99 % of the time in the original FDC will now be exceeded 99.9 % of the time, the flow at 99.9 % becomes the flow at 99 %, the flow at 99 % becomes the flow at 95 %, etc. The procedure is graphically illustrated in figure 2. A linear extrapolation is used to define the ‘new low flows’ at the lower tail of a shifted curve. The entire shifting procedure can be easily accomplished in a spreadsheet.

The difference between the default shifts of the reference FDC for different environmental classes is set to be one percentage point. In other words, a minimum lateral shift of one step (a distance between two adjacent percentage points in the FDC table) is used. This means that for a class A river the default environmental FDC is determined by the original reference FDC shifted one step to the left along the probability axis. For a class B river the default environmental FDC is determined by the original reference FDC shifted

Figure 2. Estimation of environmental FDCs for different Environmental Management Classes by lateral shift.



two steps to the left along the probability axis from its original position, etc. Any shift of a FDC to the left means several things:

- the general pattern of flow variability is preserved although with every shift, part of variability is 'lost';
- this loss is due to the reduced assurance of monthly flows, i.e., the same flow will be occurring less frequently; and
- the total amount of EF (i.e., EWR), expressed as 'environmental' MAR is reduced.

The method achieves the requirements of simplicity, match with flow data availability, maintenance of flow variability in the estimated environmentally acceptable flow regime and accommodation of different levels of environmental protection in the process. At the same time, it implies that environmental water demand would always be 'smaller' than a reference flow regime in both overall flow volume and flow variability terms. However, in cases of inter-basin water transfers, the EWR may need to be 'capped'. To establish such 'capping' EF at a site, a FDC has to be shifted to the right of its original position and certain degrees of shifting will need to be established for different classes.

Simulating Continuous Monthly Time Series of Environmental Flows

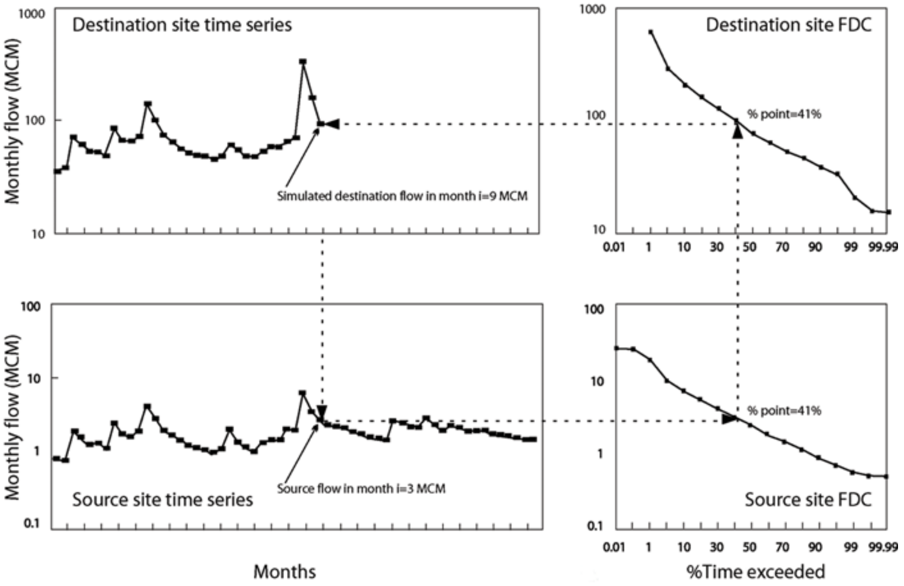
An environmental FDC for any EMC only gives a summary of the EF regime acceptable for this EMC. This summary is useful in its own right and can be used, for example, in reservoir yield analysis. The curve however does not reflect the actual flow sequence. At the same time, once such environmental FDC is determined as described above, it is also possible to convert it into the actual environmental monthly flow time series. The spatial interpolation procedure described in detail by Hughes and Smakhtin (1996) can be used for this purpose. The underlying principle in this technique is that flows occurring simultaneously at sites in reasonably close proximity to each other correspond to similar percentage points on their respective FDCs.

The site at which streamflow time series is generated is called a *destination site*. The site with available time series, which is used for generation, is called a *source site.* In essence, the procedure is to transfer the streamflow time series from the location where the data are available to the destination site. In the context of this study, the destination FDC is the one representing the EF sequence to be generated, while the source FDC and time series are those representing the reference natural flow regime.

For each month, the procedure: (i) identifies the percentage point position of the source site's streamflow on the source site's period-of-record FDC, and (ii) reads off the monthly flow value for the equivalent percentage point from the destination site's FDC (Figure 3). More details about this procedure can be found in Hughes and Smakhtin (1996). Smakhtin (2000) suggested a method of calculating daily FDC from monthly FDC. If similar relationships are established for India, the EF regimes could be calculated similarly with a daily time step.

The generation of EF time series completes the desktop EF estimation for a site. The output is therefore presented in two forms – an *environmental FDC and a corresponding environmental monthly flow time series*. Such outputs should be suitable for interpretation and use by different specialists – those, like aquatic ecologists, who are more used to time series display and those, like civil engineers, who may be interested in aspects of assurance and incorporation of FDC into water resources system yield analysis.

Figure 3. The Illustration of the spatial interpolation procedure to generate a complete monthly time series of EF from the established environmental FDC.



Results and Discussion

Table 4 summarizes the results of EWR estimation at the outlets of several river basins and figures 4 to 6 show the duration curves of EF at these outlets. The estimates presented in table 4 have to be viewed in combination with the figures 4-6. One characteristic feature of the estimated EWR is that higher the flow variability of a river (and therefore the more steep the FDC slope is), the less the EWR are in all classes. Brahmaputra and Ganga, which have the least variable regimes according to simulated flow records and corresponding duration curves, have therefore the highest EWR. Rivers with the most variable flow regimes (and corresponding steeply sloping curves) like Mahi or Sabarmati have the lowest EWR in most of the classes.

Another noticeable feature is that the EWR in all classes for most of the rivers are relatively low compared with the environmental management objective and description of each class. For example, to maintain a river in a relatively high management class B, only 24 to 37 % of the natural MAR would be required, according to Table 4, with an exception of ‘extreme cases’ like Mahi, Brahmaputra and Ganga. The EWR for class D, which is sometimes perceived as the least acceptable, range only within 6.6 to 12.1 % of the natural MAR for different rivers, with exception of the same three rivers.

Table 4. Estimates of long-term EWR volumes (expressed as % of natural Mean Annual Runoff - MAR) at river basin outlets for different Environmental Management Classes obtained using FDC shifting method.

River	Natural MAR (BCM)*	Present day MAR (BCM *(% natural MAR))***	Long-term EWR (% *natural* MAR)					
			Class A	Class B	Class C	Class D	Class E	Class F
Brahmaputra	585		78.2	60.2	45.7	34.7	26.5	20.7
Cauvery	21.4	7.75 *(36.2)*	61.5	35.7	19.6	10.6	5.8	3.2
Ganga	525		67.6	44.2	28.9	20.0	14.9	12.1
Godavari	110	105 *(95.4)*	58.8	32.2	16.1	7.4	3.6	2.0
Krishna	78.1	21.5 *(27.5)*	62.5	35.7	18.3	8.4	3.5	1.5
Mahanadi	66.9		61.3	34.8	18.5	9.7	5.6	3.6
Mahi	11.0		41.9	17.1	6.5	2.3	0.8	0.3
Narmada	45.6	38.6 *(84.6)*	55.5	28.8	14.0	7.1	3.9	2.5
Pennar	6.3		52.7	27.9	14.3	7.3	3.8	2.0
Tapi	14.9	6.5 *(43.6)*	53.2	29.9	16.6	9.0	4.9	2.6
Periyar	5.1		62.9	37.3	21.2	12.1	6.9	3.9
Sabarmati	3.8		49.6	24.2	12.1	6.6	3.7	2.1
Subarnarekha	12.4		55.0	29.9	15.4	7.4	3.4	1.5

Notes: * Taken from table 1, with an exception for Periyar, where natural MAR was calculated directly from the observed flow record at Planchotte (1967-1979).

** Present day MAR is given only for rivers for which recent observed records at sites close to outlets were available (see table 2).

BCM = Billion Cubic Meters

Figure 4. Environmental Flow Duration Curves for Brahmaputra, Cauvery, Ganga and Godavari rivers.

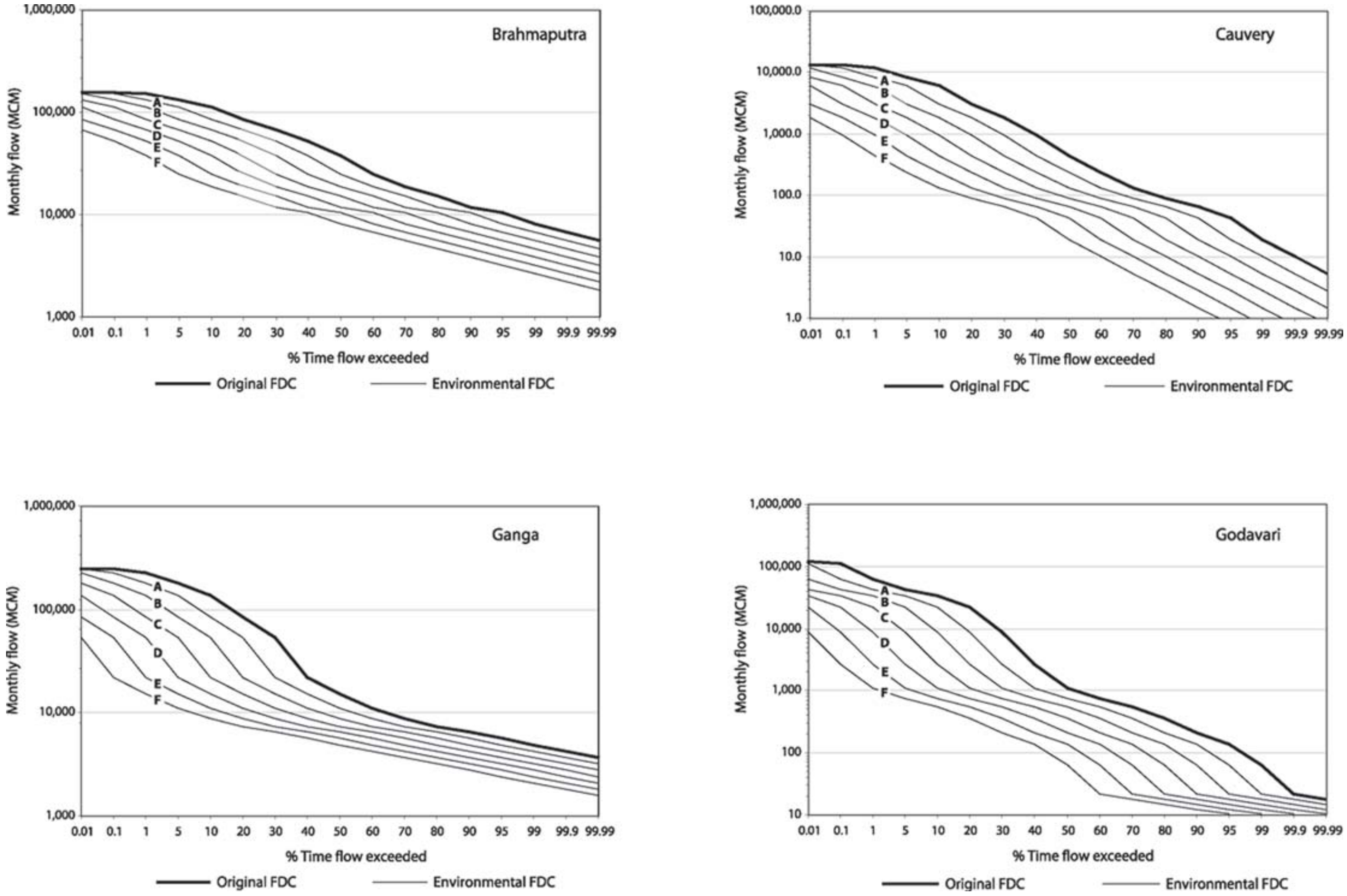


Figure 5. Environmental Flow Duration Curves for Krishna, Mahanadi, Mahi and Narmada rivers.

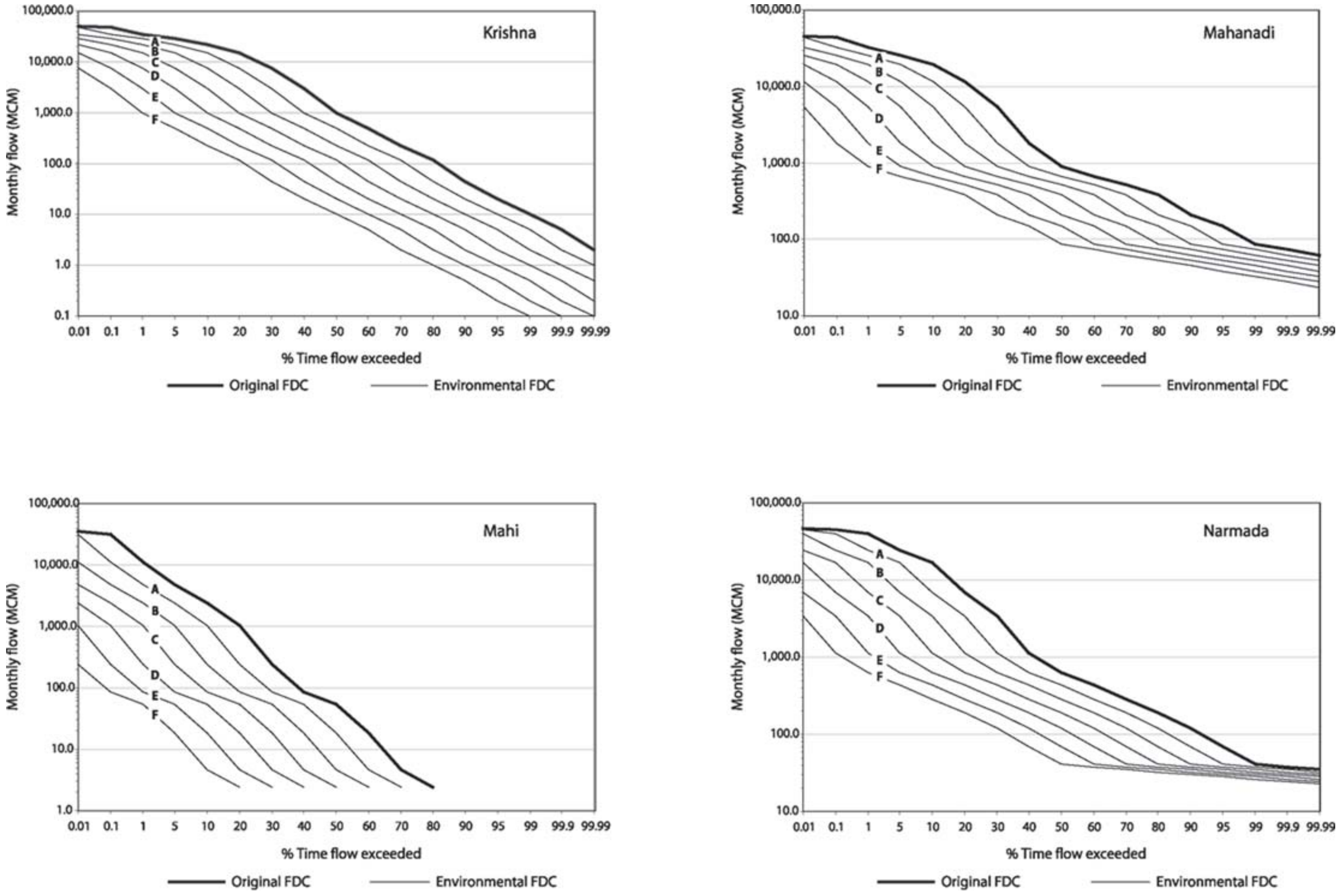
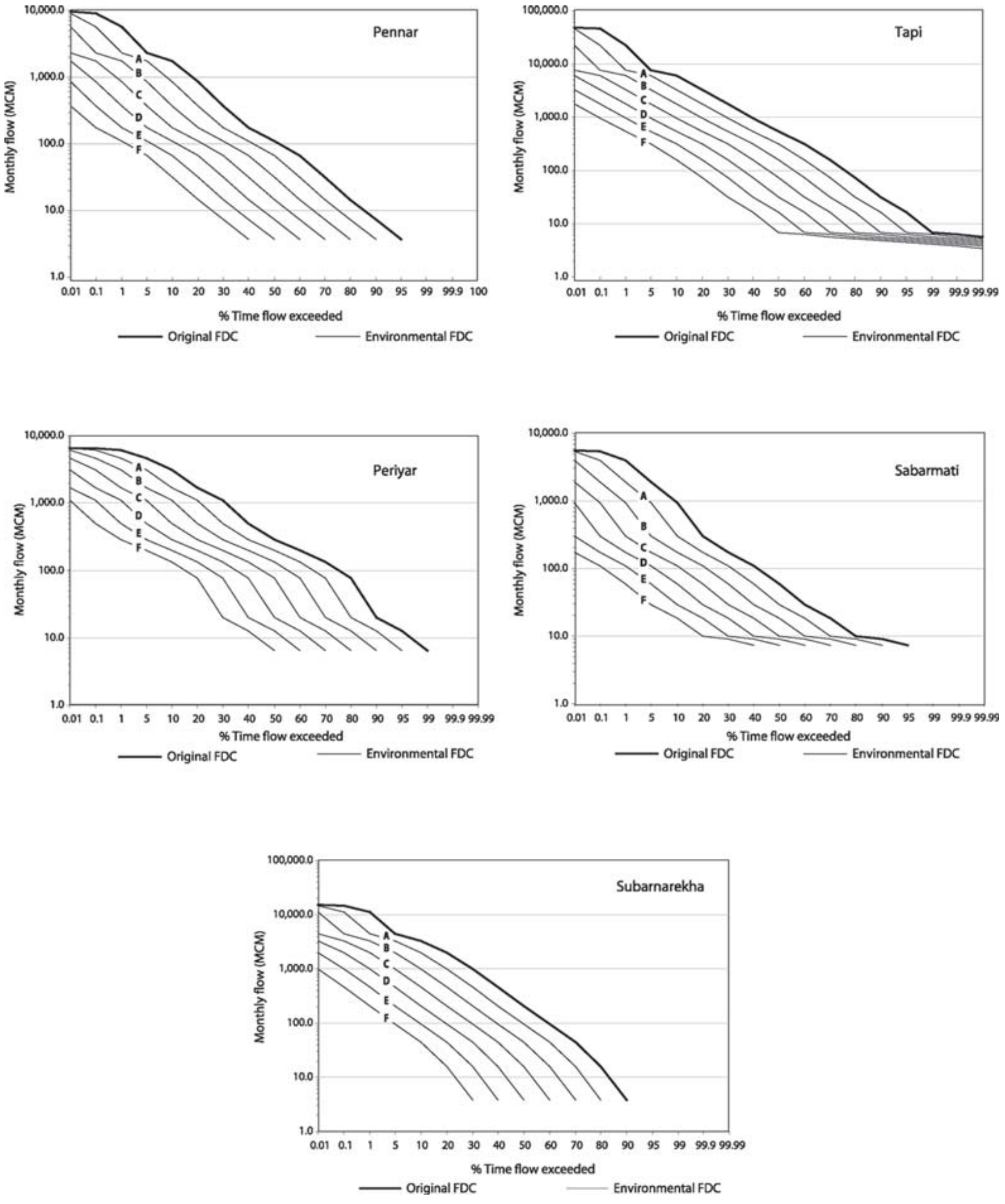


Figure 6. Environmental Flow Duration Curves for Pennar, Tapi, Periyar, Sabarmati and Subarnarekha rivers.



The main methodological issue is the justification of currently used magnitudes of lateral FDC shifts per EMC. The step of a FDC shift currently used has been inferred partially from literature sources and partially through limited 'calibration' against the EF estimates obtained by DRM. Australian experience suggests that "the probability of having a healthy river falls from high to moderate when the hydrological regime is less then two-thirds of the natural" (Jones 2002). Despite the general vagueness of this statement, it could indicate that the EWR of some 60-70 % of natural MAR are likely to be required for the maintenance of rivers in A and B classes. By progressively shifting the curves for different rivers one step at a time and calculating corresponding EWR, it is possible to establish how many such shifts are generally permissible to ensure A and B class rivers. A FDC shift of one percentage point has been found to achieve the above flow reduction in most of the cases (Table 4). On the other hand, the already mentioned Tennant method suggests that the lowest feasible limit for the EWR, corresponding to severe degradation of a riverine ecosystem, is 10 % of the natural MAR. In most cases, this benchmark may be achieved or exceeded by four subsequent FDC shifts to the left along the probability axis (Table 4). This may then be interpreted as the EWR of a class D river.

Overall, the determination of the number of FDC shifts per EMC is difficult without knowing the relationships between ecological characteristics and flow modifications in rivers with different hydrological regimes. In the absence of such knowledge, we use the minimum possible lateral shift per EMC. This may be seen as a conservative 'pro-environmental' approach, as shifts by only one step per EMC minimize losses in flow volumes and variability allocated to an ecosystem. However, as shown in Table 4, even this limited shift step results in significant losses of flow volumes and variability per class.

It is possible that as a result of subsequent future research, the procedure will differ between more variable, mostly non-perennial rivers and less variable, mostly perennial rivers in terms of how much FDC shifts are permissible in different classes. For example, the resilience of aquatic ecosystems is usually the strongest when they are healthy (A and B class rivers). Therefore, larger FDC shifts – by two steps per EMC - and, consequently, larger corresponding flow reductions could be assumed acceptable to derive the default estimates of EWR for 'more natural' classes A and B. Accordingly, smaller FDC shifts (by one step per EMC) could be accepted to derive the default estimates of EWR for moderately to significantly modified ecosystems described by classes C to F.

It is important to stress that the shift limits assumed above for each class are *the defaults*. Furthermore, variable shifts for different percentile flows can be used, if there is a specific justification for this. For example, while estimating environmental FDC for A and B classes, flows exceeded 90, 95 % and more of the time in the reference FDC may need to be fixed at their 'existing positions'; other flows may be shifted as in the default case. Alternatively, various shifts could be used for different percentile flows to define an EF duration curve in any EMC. The same logic can be taken even further. Fixed EMCs may become unnecessary if a limited set of ecologically important flows is identified and permissible shifts in each (determined by the panel of experts for example) will jointly describe the final prescribed/negotiated state of the river. It should be possible to establish better shifting procedure and more justified levels of shift through one or several national specialist workshops involving local hydrologists and ecologists. The proposed approach therefore can provide the basis for further technique development.

The EWR estimates obtained using the FDC shifting technique may also be interpreted in the context of the EWR estimates produced by the Desktop Reserve Model (DRM), described in the Review section (see section: *Review of Environmental Flow Assessment Methods).* Comparing EWR obtained by both DRM and FDC shifting methods should be seen as a form of calibration of the latter. The rational for this is that the DRM is effectively based on the results of more comprehensive and higher-confidence EFA, which, in turn, are based on Building Block methodology with a good 'track record'. Comparing the estimates obtained by two methods is effectively the only possible form of testing the proposed shifting technique at present, since no EF estimates are available in India. It should be noted that the DRM parameters have been regionalized for South Africa only. While it is obviously necessary to modify DRM parameter values for Indian conditions, currently there are no scientific grounds upon which to base any such changes. Direct DRM application for Indian rivers, where there is no specialist science input from ecologists, geomorphologists, etc., is therefore expected to produce highly uncertain EWR estimates.

The DRM-estimated EWR values for sites, where observed and unregulated records were available are listed in Table 5. Similar to the FDC shifting method, the class A results for Ganga and Brahmaputra are unrealistically high and further attention needs to be given to both. Also, the most variable rivers like Mahi, Sabarmati, etc., have the lowest EWR. At the same time, the DRM estimates appear to be consistently more conservative than the FDC shifting method for 'lower' classes, where DRM produces higher EWR (Figure 7). For example, almost all class D EWR requirements calculated by DRM are approximately double that of the FDC shifting method (Figure 7). The higher EWR in lower classes calculated by the DRM may however simply be the reflection of parameter uncertainty mentioned above. Much less difference is present between the EWR estimates produced by both methods for class C, where some of the Indian rivers may still be placed (despite the fact that some, like Narmada, are also heavily committed to future developments). Because classes E and F are not considered acceptable in DRM, they are not included in Table 5.

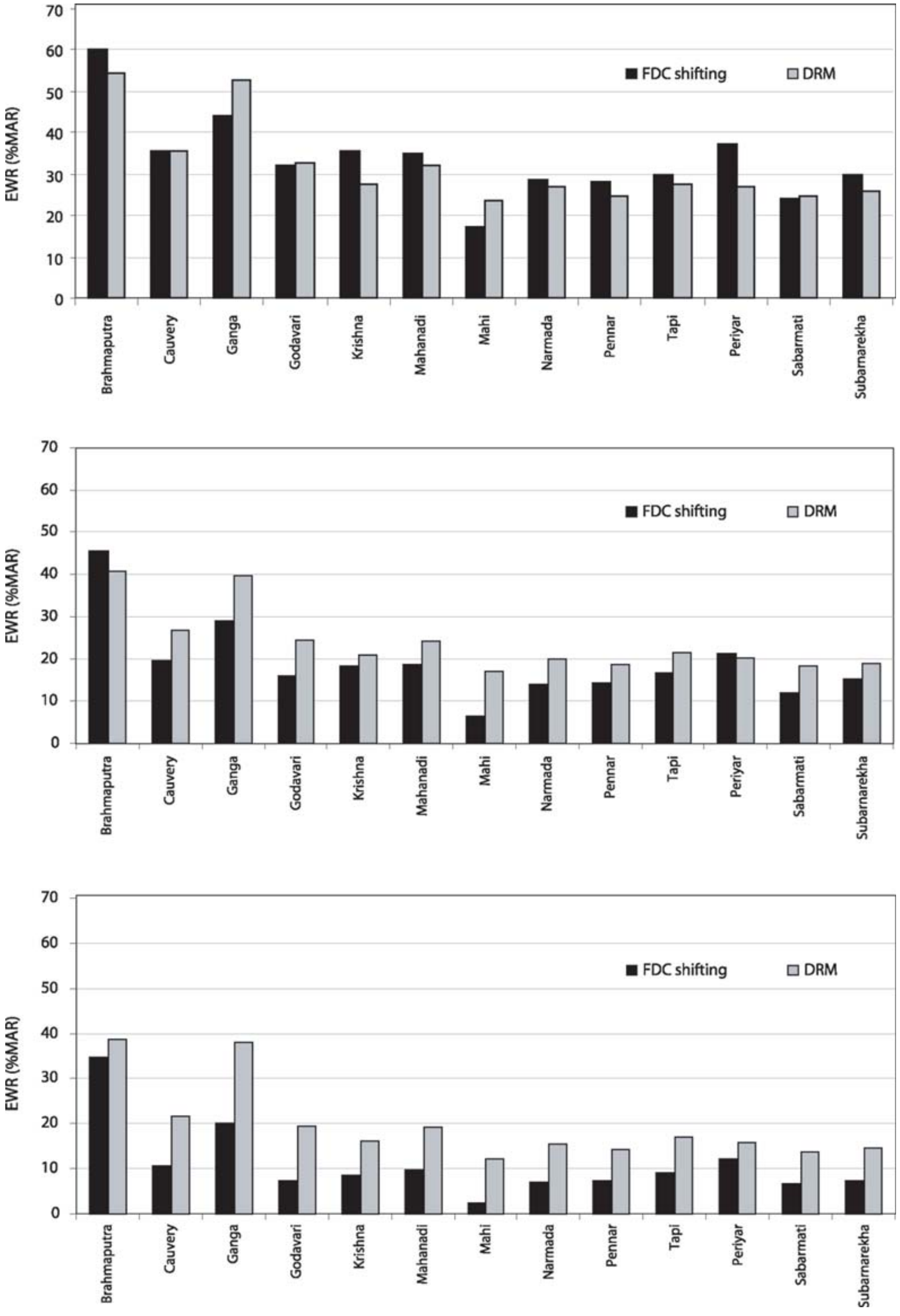
The suggested prototype EFA method is based on *monthly* flow time series. Therefore, the reduction in flow magnitude due to lateral shift of a FDC does not necessarily mean that *daily* flows will be reduced accordingly. It may, however, mean that, for example, the number of high flow events in the wettest months may be allowed to drop, thus leading to the overall

Table 5. Estimates of long-term EWR volumes (expressed as % of MAR) for selected river basins and different Environmental Management Classes obtained using Desktop Reserve Model.

River and Site	MAR (BCM)	Hydrological Variability Index	Long-term EWR (% MAR)			
			A	B	C	D
Brahmaputra @ Pandu	573.8	1.0	85.4	54.5	40.6	38.6
Cauvery @ Krishnaraj Sagar	5.37	3.4	50.8	35.8	26.7	21.7
Ganga @ Farakka	380.0	1.0	82.4	52.9	39.7	38.1
Godavari @ Davlaishwaram	96.6	4.7	45.4	32.7	24.5	19.6
Krishna @ Vijayawada	56.7	5.8	38.4	27.8	20.8	16.1
Mahanadi @ H. K. Sambalpur	54.8	5.1	44.7	32.0	24.1	19.2
Mahi @ Sevalia	12.2	13.7	32.7	23.3	16.9	12.3
Narmada @ Garudeshwar	22.6	5.4	37.3	26.8	20.0	15.5
Pennar @ Nellore	2.34	7.7	33.3	24.7	18.7	14.3
Tapi @ Kathore/Ghal	4.50	6.7	36.9	27.6	21.4	17.0
Periyar @ Planchotte	5.15	4.6	38.1	27.1	20.1	15.7
Sabarmati @ Ahmedabad	1.04	8.6	34.1	24.7	18.2	13.6
Subarnarekha @ Kokpara	9.76	8.1	35.3	25.6	19.0	14.6

Note: BCM = Billion Cubic Meters

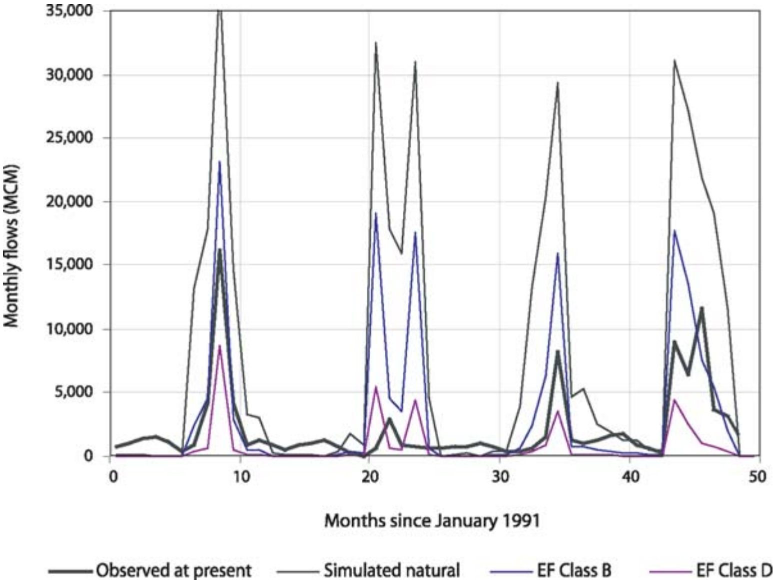
Figure 7. Comparison of Environmental Water Requirements estimated by FDC shifting method and DRM for EMC B (top), C (middle) and D (bottom).



decrease in monthly flow volume. Some comprehensive EFA methods (e.g., DRIFT, King et al. 2003) consider possible scenarios of flow changes in terms of how many events of certain magnitude can be allowed to be "lost" (e.g., can all dry season freshes be lost, or can the number of floods occurring at least once a wet month be halved). Reduction in corresponding monthly flows, which results from the FDC shifting, effectively reflects these daily flow scenarios.

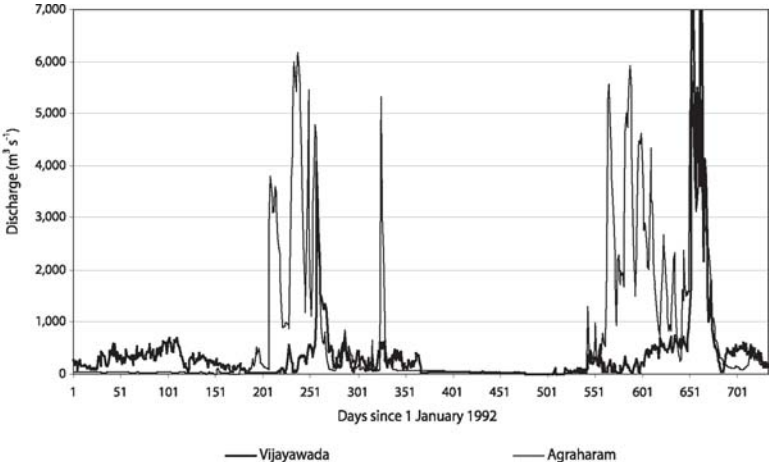
The estimated EF should be interpreted in the context of natural and present day river flows. This could show what level of environmental protection is achievable in principle, given the current extent of water resources development. Figure 8 illustrates the present-day flow conditions at Krishna at Vijayawada town – the closest to the outlet - in the context of naturalized (simulated) flow at the outlet and the simulated EF time series for EMCs B and D. The simulated time series were obtained using the spatial interpolation procedure discussed in the previous section and illustrated in Figure 3. Figure 8 shows that despite the seemingly high present-day 'observed' MAR (28% of the natural MAR) monthly flows at the outlet in certain years drop to the level of the EF corresponding to class D, which is the least acceptable.

Figure 8. Extracts from observed and simulated monthly flow hydrographs for Krishna at Vijayawada.



Low flows during the non-monsoon period normally exceed the simulated 'natural' low flows (Figure 8). This may be due to irrigation return flows or be the result of flow regulation. Figure 9 illustrates this point further by showing extracts from two observed daily flow time series in Krishna. The first time series is from the upstream site of Agraharam town located on the main stream of Krishna. This site commands the catchment area of 132,920 km^2. The second site is located at Vijayawada and commands almost the entire basin area of Krishna (251,360 km^2). The Agraharam site is located upstream of all major dams on Krishna's main channel and may reflect unregulated daily flow conditions. The flow at Vijayawada, on the other hand, is severely impacted by flow regulation from dams located downstream of Agraharam. This

Figure 9. Observed daily hydrographs in Krishna at Agraharam (upstream station, catchment area 132,920 km^2) and Vijayawada (basin outlet, catchment area 251,360 km^2).



regulation effectively removed all major high flow events from the river, increased low flows and distorted their pattern, shifting seasonal flow distribution and completely changing the inflow pattern to ecologically sensitive delta area.

Conclusions and the Way Forward

This study attempted, for the first time, to consistently review the trends and philosophy of EFA in India and to apply the concepts of desktop EFA to Indian rivers. The main purpose of the study is to stimulate the emerging debate on EF and environmental water allocation prospects in the country. The results suggest that river ecosystems may, in principle, be maintained in a reasonable state even with the limited EF allocations (10-20% of natural MAR depending on hydrological variability). Because of severe data limitations, the magnitude of the task and the very coarse scale of the analysis (the entire large river basins only), *the results presented herein should be viewed as illustrative*. At the same time, the prototype desktop EFA method suggested in this study has a number of advantages:

- It is commensurate with existing data and understanding of eco-hydrological relationships, simple and quick to apply and explicitly includes the concepts of hydrological variability, which as the modern hydro-ecological theories agree, caters for the requirement of various ecosystem components.
- It can present the environmental water demand in terms of both – the cumulative measure (EF duration curve) and the actual time series of EF regime. The first reflects the overall pattern of EF variability whereas the second shows the actual sequence of flows in environmentally acceptable flow regime.
- It is generic and can be applied to catchments of any size and in any physiographic conditions.

- It can and should be made more flexible by applying different shifts at different percentile flows and examining the results on the output EF time series. It is therefore important to stress that the method suggested should rather be seen as a step towards a better justified desktop EFA tool in the future.

The main issue with the method at present is a limited justification of the permissible FDC shifts per EMC. The currently accepted step of a shift (one FDC table point per class) is based on limited calibration of the proposed method against a more advanced DRM technique, which however has also not been adjusted for use in Indian conditions and therefore produce uncertain EF estimates itself. It is very difficult to evaluate the results when there are no ecological data available to confirm or deny the suitability of the estimated EF. It is, in principle, possible to collect some limited hydraulic information for rivers and examine the characteristics of the available habitat (water depth, wetted area and velocity, for example) under different flow conditions (natural and FDC shifting method recommendations). This is not, however, a real substitute for scientific information on the relationships between ecological characteristics and flow. It is also recognized that the collection of such information will be very time consuming and expensive.

For rivers with less variable flow regimes (and hence gently sloping FDCs), the technique may reduce high flows significantly more than low flows. However, first, at the monthly time step, this does not necessarily imply the reduction of daily peaks; it could be the number of high–flow events which is reduced. Second, from a management perspective this may not be a major issue. Unless major storage dams exist with substantial high flow release facilities, the high flows may not be controlled. The management focus therefore should be on the low flows, while the assumption can be made that high flows will occur, more-or-less naturally.

For the long-term, the focus of the future EFA in India has to be on the quantification of eco-hydrological relationships in rivers and on inventory of already existing ecologically relevant information. It is necessary to consider initiating several comprehensive EFA projects in different parts of the country and to relate the results to hydrology of the basins. This would also help to better justify and improve the FDC shifting method suggested here.

It is logical to initiate such projects at several sites which will be affected by the planned NRLP inter-basin water transfers. Immediate EFA of some ‘signed’ off links has to be done – like those between Ken River and Betwa River, on which the agreement has been signed by Madhya Pradesh and Uttar Pradesh governments in August 2005. Such detailed EFA studies will effectively initiate a long-term capacity building programme in this field in the country by engaging ecologists and hydrologists who know their local rivers. Even if they have limited information required for such assessment and the results are therefore still uncertain, attempting a detailed EFA develops team building and interactions between experts in different disciplines.

At the same time, simple EFA tools, such as the one suggested in this report, may help to illustrate the type of expected outcome from a more comprehensive EFA. Simple tools do not exclude, but rather encourage capacity building and the use of comprehensive EFA methods at the same time. One possible merge of the two approaches (complex and simple) could be through a workshop of Indian ecologists and hydrologists, which could discuss and/or define the required shifts of FDCs for different EMCs.

Eventually, a set of EFA tools will need to be developed and tested in a specific context of India’s flow regimes, ecology and water resources development. The types of EFA methods have to be selected based on the type of proposed development (abstractions, in-stream or off-channel reservoirs, flow reduction activities, etc.), the level of impact of the proposed development, the ecological importance and sensitivity of the river, the degree to which it is already developed, the socio-economic importance of the river and its proposed development, etc. The more critical the proposed development is from the above issues, the more likely that more comprehensive EFA will need to be used.

It is also necessary to initiate an assessment of ecological importance and sensitivity and ecological conditions of all major river basins in India and with the detailed spatial resolution. The information provided through such assessment is also useful in its own right – outside of the context of EF, because it gives the idea of the ecological condition and importance of aquatic ecosystems (albeit in a semi-quantitative way) and therefore contributes to the vision of India's water future.

The study has effectively not been supplied with observed flow data of reasonable amounts and quality. The data which have been acquired and used were primarily from publicly available sources (Internet) where data are outdated and no conclusions on the accuracy or even origin of the data could be made. If the situation with access to data in India is not changed, any further EFA will be largely speculative. On the other hand, the agencies responsible for hydrological data provision will increasingly realize that the recent advances in global hydrological modeling and remotely sensed data acquisition have been so significant that in the near future (5-10 years) lack of access to observed data may no longer be an obstacle, because the representative and reliable flow time series for any site at any river could be simulated and be more reliable than observed.

One issue, which has not been addressed in this report, is how EF relates to the water quality of rivers. This is an even more complex issue than EF estimation itself, but a few statements can be made to that effect. First, EF should aim to achieve some ecological objective (e.g., provide flow-related habitat or geomorphological function), but not to solve river water quality problems by dilution. At the same time, once EF are recommended and expressed as a time series/duration curve, it should be possible to simulate flow-concentration relationships for important constituents. Through this, the anticipated water quality consequences of modified flows could be explored and examined in the context of some pre-defined water quality classes (Palmer et al. 2005). The latter could be established using some benchmarks - literature or field-data based boundary values. If recommended EF does not allow the agreed water quality targets to be met (e.g., in cases when a river has naturally high salinity and recommended environmental low flows would lead to increased salinity beyond some critical levels) then higher EF should be considered. *Severely polluted Indian rivers are at risk only if the recommended EF remain in the river without non-point source pollution control and without effluent treatment at source.*

Last but not the least is the issue of actual *EF provisions* as opposed to *EF assessment*. No matter how advanced and accurate the EFA is, its output remains on paper if no actual releases are made or if the prescribed limit of water resource exploitation is violated. There are very few examples in the world when environmental water requirement are actually satisfied by EF provisions. Similarly, this may be the major stumbling block on the way to environmentally sustainable water resources development in India. Therefore, a due consideration to relevant policy support and enforcement has to be given to it.

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