ENVIRONMENTAL FLOW ASSESSMENT USING VARIOUS TECHNIQUES IN A TYPICAL RIVER BASIN OF INDIA

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ABSTRACT *Environmental flows are extremely essential to protect and maintain the environment, ecology, river morphology, aquatic life, pollution, and water transfer among surface water and groundwater. Zero flow in some of the river reaches due to construction of water storage structures, hydropower generation and other uses have created numerous problems in river basins. In the present work, various information and data have been collected to estimate environmental flows at different location of River Brahmani using different commonly used methods. Further, a modified approach has been evolved considering environmental flows required for different losses (seepage and evaporation) in addition to flow requirement for various purposes. The results obtained are very encouraging and the estimated environmental flows can be maintained with very small percentage of mean annual flow. It has been observed that the environmental flows in a river basin has very high socio-economic values with no revenue losses and the same amount of water should flow through out the year as unrestricted flow (Aviral Dhara) in the river system.*

Key words: Environmental flows, flow duration curve, hydrology index, method, holistic method

INTRODUCTION

Water is an important part of any ecosystem, both in qualitative and quantitative terms. Reduced water quantity and deteriorated water quality both have serious negative impacts on ecosystems. The environment has a natural self-cleaning capacity and resilience to water shortages. But when these are exceeded, biodiversity is lost, livelihoods are affected, natural food sources (e.g. fish) are damaged, and high clean-up and rehabilitation costs result. The river system is one of the most important natural ecosystems and has a quite intimate relationship with human beings. In India, as elsewhere in the world, the primary freshwater riverine functionalities, such as water transfer, sediment transportation, flood release, stream's self-purification, landscape for recreation, aquicolous biotope maintenance, navigation, hydropower generation, religious activities and so on, have provided much convenience for human activities (Luo *et al.*, 2004; Postel and Carpenter 1997; Revenga et al. 2000). During the past century, the global human population enhanced exponentially, the area of irrigated agricultural land multiplied more than six-fold, and water withdrawals from freshwater ecosystems increased eight-fold (Gleick, 1998; Postel, 1999), in general. Natural river systems around the world are heavily modified to serve a variety of human purposes, including supplying water to cities and farms, generating electric power, facilitating navigation, and controlling floods.

While human manipulation of the planet's river flows has provided many societal benefits, it has also caused considerable ecological damage and the loss of important ecosystem services valued by society (Baron *et al.*, 2002; Postel and Richter, 2003; Fitzhugh and Richter, 2004). River ecosystem health deteriorates when natural flows of water, sediments, and organic materials through a river system are substantially disrupted or modified by human activities (Poff *et al.*, 1997; Richter *et al.*, 2003).

Natural river flow alterations, sediment transport patterns, water pollution influx and water temperature are now widely recognized as a leading cause of declines in freshwater biodiversity globally (Richter *et al.,* 1998; Revenga *et al.,* 2000; Pringle *et al.,* 2000; Bunn and Arthington, 2002). Human interventions have further implicated in the change of morphology, ecological water balance, climate change, change in land use pattern, loss of commercial fisheries in many estuaries and coastal areas, and in the degradation of other natural ecosystem products and services worldwide (World Commission on Dams, 2000). Recognition of the escalating hydrological alteration of rivers on a global scale and resultant environmental degradation, has led to the establishment of the science of environmental flow assessment whereby the quantity and quality of water required for ecosystem conservation and resource protection are determined (Figure 1).

Looking at the river basin characteristics (topography, land use, soil texture), rainfall pattern, groundwater availability, urban and rural population, industrialization, water pollution from point sources, water pollution from non-point sources (urban areas and agricultural areas), location and demand of water for religious purposes, socio-economic aspects, irrigation water requirement with high irrigation efficiency, cost of water conservation for different purposes, and revenue loss due to release of water as environmental flows, proper methods for environmental flow assessment should be evolved. In fact, environmental flows are one such phenomena, which needs to be given due attention by the planners and policy makers. Nowhere is the problem more urgent than in developing countries, in which fast-growing human populations are reliant on very limited water resources and often on a range of other river resources as well (King and Brown, 2006).

STATE-OF-THE-ART

During the past several decades, a number of methods have been developed (Figure 2). A global review of the present status of environmental flow methodologies revealed the existence of more than 200 individual methodologies. These could be differentiated into hydrological, hydraulic rating, habitat simulation

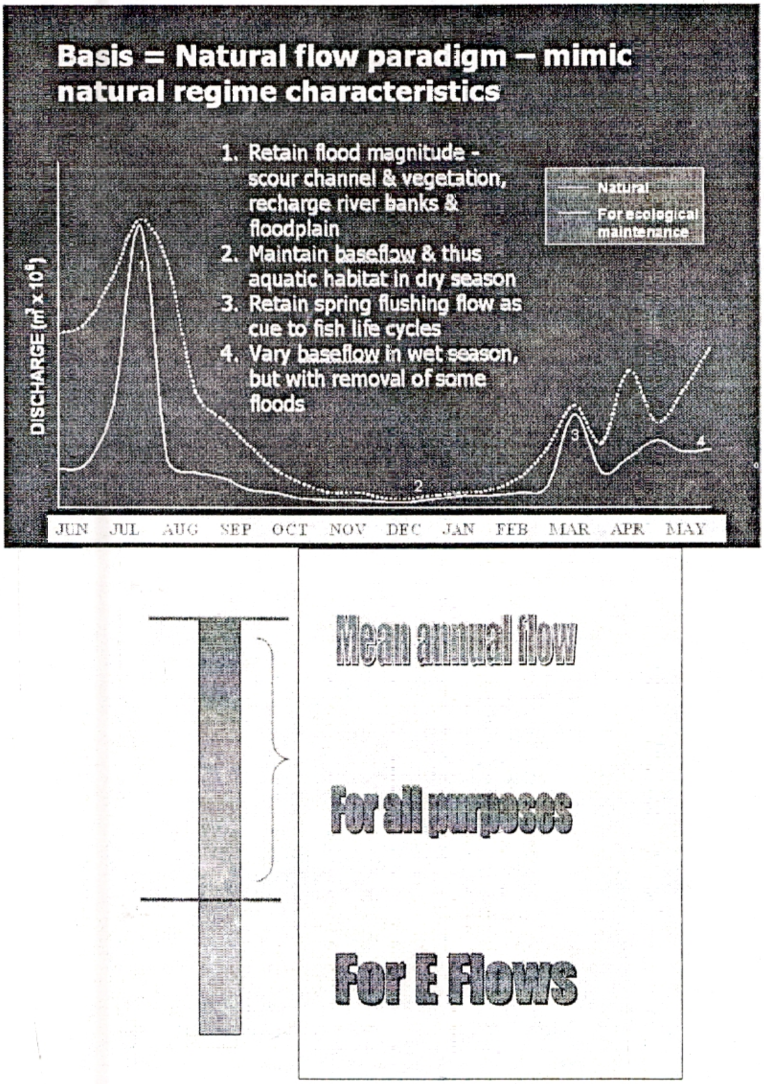


Fig. 1 Environmental flows as part of the available water resources

and holistic methodologies, with a further two categories representing combination type and other approaches (Tharme, 2003). Although, historically, the United States has been at the forefront of the development and application of methodologies for prescribing environmental flows, using 37% of the global pool of techniques, parallel initiatives in other parts of the world have increasingly provided the impetus for significant advances in the field. For example, the American simulation model PHABSIM has been used in the USA and some European countries to determine minimum flow requirements and to evaluate the ecological consequences of instream flow regulation on the basis of the hydraulic habitat availability for specific species (Jorde and Schneider, 1998). Five hydrologically based methods, the Tennant method, 25% Mean Annual Flow (MAF) method, the median monthly flow (Q sub (50)) method, the 90% flow duration (Q sub (90)) method, and the minimum 7-day average flow per 10-year period (7Q10) method, and a habitat preference PHABSIM model were applied to Catamaran Brook, a small drainage basin in New Brunswick, Canada (Caissie *et al.*, 1998 Tharme, 1997; Dunbar et at., 1998). PHABSIM can be used to develop a rating curve, which relates total habitat area to river discharge for a particular species during a particular stage in its life. This rating curve is then combined with an FDC to produce a habitat-duration curve. Estes and Orsborn (1986) and Gordon et al. (1992) reviewed a variety of methods for determining in-stream flow requirements ranging from rule-of-thumb methods to computer simulation models. Estes and Osborn (1986) and Gordon et al., (1992) illustrated the use of FDC for the assessment of river habitats in estimation of instream flow requirements.

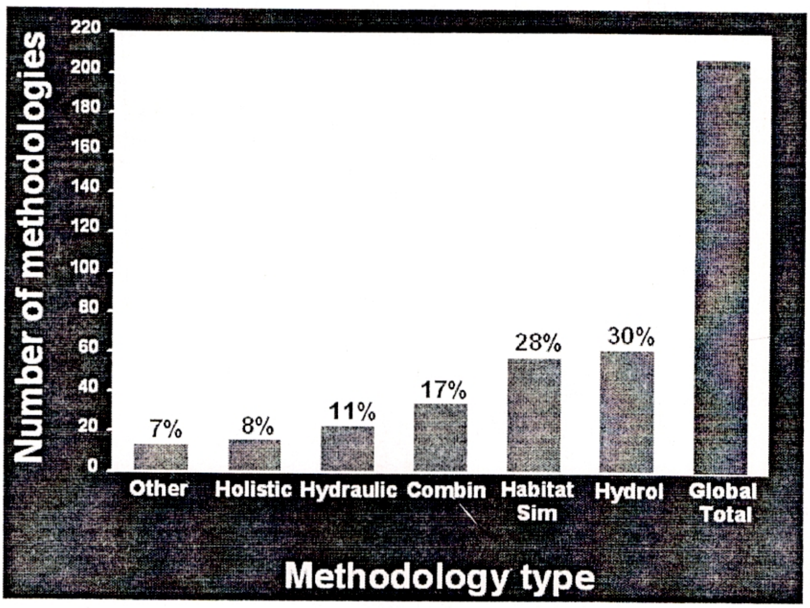


Fig. 2 Global diversity of methodologies

During the late 1980s and 1990s, IFR in South Africa was quantified using the 'Building Block Methodology' (BBM) (King and Louw, 1998; Hughes, 2001). A method which uses less data than the Instream Flow Incremental Methodology (IFIM) but gives results of the same order of magnitude as the IFIM is proposed and illustrated by using data from streams in Indiana (Rao *et al.*, 1992). Tharme (1996) and Dunbar et at. (1998) consider 'hydraulic rating' (also known as habitat retention) methodologies to be the precursors of more sophisticated habitat rating or simulation methodologies, also referred to as microhabitat or habitat modelling methodologies.

Another frequently cited hydrological environmental flow assessment technique is the Range of Variability Approach (RVA) (Richter et al. 1997), which aims to protect a range of flows in a river. Thirty two hydrological parameters 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.

In Poland, the minimum available discharge is perceived as the flow, which maintains the river for biological and social benefits. In Byelorussia, the minimum flow for nature conservation is selected as 75% of the minimum average discharge with a 95% probability. In the USA, instream flows are set with regard to individual rivers, which should take into account all users of the water resources, and have different values as a percentage of the MAF (Vladimirov and Lobanova, 1998). In China, Li and Zheng (2000) pointed out that the ecological and environmental instream flow (EEIFR) is the minimum flow, which must be reserved and consumed to maintain special ecological and environmental functions by surface water body. As an example, the EEIFR including basic EEIFR, instream flow for sediment transportation, and EEIFR for lake and wetland of Huai and Luan River basin, were estimated(Liu *et al.*, 2002b). Aiming at the main ecological function, the minimum ecological IFR for the lower Yellow River was estimated (Ni *et al.*, 2002). More and more scientists have realized that the instream flows need to be maintained according to the hydrological and ecological characteristics of rivers, including flow regime, river scale and geomorphology. In recent years, dual active or restrictive approach (Shiau and Wu, 2010) and multiple criteria analysis tools (Marinoni, 2009) are used to estimating environmental flows.

Indian Scenario

The status of environmental flow research in India at present may be characterized as being in its infancy. The National Commission for Integrated Water Resource Development Plan (NCIWRDP 1999) estimated a provisional projection of the environmental needs 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 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. 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. 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). Jha et al (2008, 2011), critically evaluated the applicability of existing hydrological approaches, and suggest a suitable scientific approach for the assessment of environmental flows based on hydrological data.

ENVIRONMENTAL FLOW ASSESSMENT METHODS

Hydrological Index Methodologies

Montana or Tennant Method

The Tennant (or Montana) method (1976) is the most common hydrological method applied worldwide, and has been used by at least 25 countries in either the original or modified form (Tharme, 2003). This is suggested by working group of WQAA, India too. Its appeal is in its simplicity and ease of use, as the Tennant method uses a percentage of the mean annual flow (MAF) for two different six month periods to define conditions of flow regarding "instream flow regimens for fish, wildlife, recreation, and related environmental resources" (Table 1).

Table 1: The Tennant (Montana) method (1976)

Narrative description of general condition of flow	Recommended flow regimens (% of MAF) October to March	Recommended flow regimens (% of MAF) April to September
Flushing or maximum	200%	200%
Optimum range	60-100%	60-100%
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
Fair or degrading	10%	30%
Poor or minimum	10%	10%
Severe degradation	<10%	<10%

Flow Duration Curve Analysis

A flow duration curve is one of the most informative means of displaying the complete range of river discharges, from low flows to flood events (Smakhtin, 2001). Using average daily discharge data, flow duration curves are cumulative frequency distributions that show the percent of time that a specified discharge is equaled or exceeded during a period of interest (daily, monthly, annual, or entire period of record). In FDCA, virgin or present-day historical flow records are analysed over specific durations to produce curves displaying the relationship between the range of discharges and the percentage of time that each of them is equaled or exceeded (Gordon *et al.* 1992). Discharges representing specific flow percentiles are calculated from the curves, and then used in a variety of ways to produce specific environmental flow recommendations. For example, Hoppe and Finnell's (1973, cited in Stalnaker and Arnette 1976) used percentiles for salmonid fishery requirements: Q17 (the discharge equalied or exceeded on 17% of the time on record) for flushing fines from substratum interstices of spawning grounds, Q40 to maintain suitable habitat conditions for spawning, and Q80 for invertebrate (food) production, cover and maintenance of minimum adult habitat. Smakhtin (2001) indicated that the "design" low flow range of a flow duration curve is the 70%-99% range, or the Q70 to Q99 range. The Q95 and Q90 flows are most often used as low flow indices. Q75, Q84, Q96, Q97, Q98, and Q99 flows are occasionally noticed in the literature as well. Monthly median flows during summer months are another common flow duration index. Some less conventional indices include the percentage of time that 25% average flow is exceeded. Similarly to the ratio Q20/Q90, which may be interpreted as a measure of stream flow variability (Arihood and Glatfelter, 1991), the ratio (Q50/Q90) may represent the variability of low-flow discharges. The reverse ratio (Q90/Q50) may be interpreted as an index representing the proportion of stream flow originating from groundwater stores, excluding the effects of catchment area.

The 7Q10 Flow

The 7Q10 flow is the commonly used single flow index. There are numerous and diverse reasons applied to the use of the 7Q10 flow for regulation purposes, ranging from: i) protection or regulation of water quality from wastewater discharges or waste load allocations, ii) habitat protection during drought conditions, iii) chronic criteria for aquatic life, and iv) a local extinction flow. The original use of the 7Q10 flow is related to stream water quality standards to regulate pollution, however the uses have expanded to include and serve many other interests. The procedures for computing 7Q10 flow duration curve (Sugiyama, 2003) are as follows:

- Construct flow duration curve of each water year by plotting and arranging the daily discharge values in descending order.
- After construction of FDC for each year, read values of daily discharge at every 5% probability of exceedance.
- Make separate table for each year Discharge Vs Probability of exceeedance.
- Rank in ascending order of the discharge values read from each flow duration curve of a given N year term.
- Calculate the plotting position with the following Weibull plotting formula, select the type probability paper to be used, and plot the data on the probability paper

  $$P = \frac{m}{(n+1)} * 100 \tag{1}$$

  where, P is the probability of all events less than or equal to each discharge value, m is the rank of the event, and n is the number of events on record.
  Now, The flow duration curve for various recurrence year are developed by using the distribution characteristics of a set of probability plots of stream now calculated by the Weibull plotting formula at suitable time intervals from 0to 100 percent on the time axis.
- Visually fit a straight line through the estimated values.
- Using straight line equation, get the discharge value down from the best fit line at the chosen probability value for various return period (1 year, 2 year, 5 year, 10 year, 20 year, 50 year and 100 year).
- Repeat steps 3 to 6 at suitable time intervals from 0 to 100 percent of the time axis (in the present case it is taken at every 5%).
- The developed FDC were used to evaluate the severity of high, ordinary, and low flow regimes of Brahmani-Baitarani River Systems.
- The developed FDC were used to evaluate the severity of high, ordinary, and low flow regimes of Brahmani-Baitarani River Systems.
- Plot probability daily discharge values read at suitable intervals and draw a smooth FDC of return period of 1 year, 2 year, 5 year, 10 year, 20 year, 50 year and 100 year.

Range of Variability Analysis

Recently, the Range of Variability Approach (RVA), developed by Richter *et al.* (1996, 1997) has emerged as a more sophisticated form of hydrological index methodology and merits further investigation. It is aimed at providing a comprehensive statistical characterization of ecologically relevant features of the flow regime, recognizing the crucial role of hydrological variability in sustaining riverine ecosystems. According to its developers, the method is intended for application to rivers where protection of natural ecosystem functioning and conservation of natural biodiversity are the primary management objectives. The methodology comprises six basic steps, the first of which is the characterisation of the natural range of hydrological variation using hydrological indices, termed Indicators of Hydrologic Alteration (IHA) (see Richter *et al.* (1996) for IHA methods).

The IHA calculates a total of 67 statistical parameters. These parameters are subdivided into 2 groups, the IHA parameters and the Environmental Flow Component (EFC) parameters. There are 33 IHA Parameters and 34 EFC Parameters. The IHA statistics are grouped into five categories based on virgin regime characteristics:

- The *magnitude* of the water condition at any given time is a measure of the availability or suitability of habitat and defines such habitat attributes as wetted area or habitat volume, or the position of a water table relative to wetland or riparian plant rooting zones.
- The *timing* of occurrence of particular water conditions can determine whether certain life-cycle requirements are met or can influence the degree of stress or mortality associated with extreme water conditions such as floods or droughts.
- The *frequency* of occurrence of specific water conditions such as droughts or floods may be tied to reproduction or mortality events for various species, thereby influencing population dynamics.
- The *duration* of time over which a specific water condition exists may determine whether a particular life cycle phase can be completed or the degree to which stressful effects such as inundation or desiccation can accumulate.
- The *rate of change* in water conditions may be tied to the stranding of certain organisms along the water's edge or in bonded depressions, or the ability of plant roots to maintain contact with phreatic water supplies.

IHA parameters can be calculated using parametric (mean/standard deviation) or non-parametric (percentile) statistics. For most situations non-parametric statistics are a better choice, because of the skewed (non-normal) nature of many hydrologic datasets (a key assumption of parametric statistics is that the data are normally distributed). But for certain situations, such as flood frequency or average monthly flow volumes, parametric statistics may be preferable.

The IHA calculates parameters for five different types of Environment Flow Components (EFCs) also, which are low flows, extreme low flows, high flow pulses, small floods, and large floods. This delineation of EFCs is based on the realization by research ecologists that river hydrographs can be divided into a repeating set of hydrographic patterns that are ecologically relevant. It is the full spectrum of flow conditions represented by these five types of flow events that must be maintained in order to sustain riverine ecological integrity. Not only is it essential to maintain adequate flows during low flow periods, but higher flows and floods and also extreme low flow conditions also perform important ecological functions. The parameters used in EFCs and their values used in the present work are as follows:

- High flow upper percentile threshold: 75th percentile of all flows. All flows above this threshold are classified as high flow events.
- High flow lower percentile threshold: 50th percentile of all flows. All flows below this threshold are classified as low flow events.
- High flow start rate threshold: 25%. When flows are between the upper and lower percentile thresholds, this parameter controls the start of high flow events. It also controls whether the ascending limb of an event is restarted from the descending limb.
- High flow end rate threshold: 10%. When flows are between the upper and lower percentile thresholds, this parameter is used to end high flow events during their descending limb. It also controls the transition between the ascending and descending limb of an event.
- Small flood return interval and large flood return interval: 2 and 10 years. This controls which high flow events are classified as small floods and large floods. These parameters can be between 1.01 and 99, including those values, and can be fractional.
- Extreme *low flow threshold:* 10th percentile of all low flows. This controls what percentage of low flows are classified as extreme low flows.

HOLISTIC METHODOLOGY

The In-stream Flow Incremental Methodology (IFIM)

The IFIM can be thought of as a sophisticated, computer-driven version of the multiple transect method. The IFIM was developed in North America and was originally concerned primarily with salmonid species in snow-melt streams (Bovee & Milhous 1978; Bovee 1982) but has since been implemented in many other regions and many other types of streams (Tharme 1996). Two versions of the IFIM have been used in Australia, differing only in the computer models used, PHABSIM II (Milhous et al. 1989) or RHYHABSIM (Jowett 1989), but not in overall philosophy and intent.

The IFIM consists of a set of analytical procedures and computer methods (including the component PHABSIM II, which many think *is* the IFIM) which seek to evaluate the effects of incremental changes in stream flow on channel structure, water quality, temperature and availability of suitable microhabitat using a combination of hydraulic, hydrological and biological data.

There are several steps in the IFIM process. The identification of study objectives, river study reaches and target species is the first step (Tharme 1996). Such a first step is not limited solely to this methodology but should be included in any study of the environmental flow needs of any river. Study objectives can, however, be highly constrained if the available biological information is limited or poor (Richardson 1986; Gan & McMahon 1990a). Tharme (1996) recommends that species from a wide array of trophic levels be included so as to improve the generality of the predictions made by the IFIM. It should be emphasized that no single flow recommendation will be possible in species-rich assemblages and therefore compromises will be necessary. It is important to note that habitat requirements differ between species and that manipulating the flow regime to suit one species may be to the detriment of another.

The second critical step in the IFIM process is determining whether the catchment is in equilibrium and whether macrohabitat conditions are suitable. King and Tharme (1994) state that while the concept of catchment equilibrium is sound in theory, it is difficult to apply. Tharme (1996) suggests that the assumption of channel stability may limit the applicability of the IFIM in many countries.

The procedure used in the IFIM to simulate changes in microhabitat conditions with changing discharge is contained within the module known as PHABSIM II (Physical Habitat Simulation), which consists of 240 separate programs covering depth, velocity, substrate and cover. Simulations are usually based upon transect data collected on one occasion (ie. one discharge) and a series of measurement relating discharge to river stage height. Thus transect placement, transect number and the accuracy of measurements have great potential to influence subsequent habitat simulation.

The Building Block Methodology

The Building Block Methodology (King & Tharme 1994) was developed in South Africa as a rapid technique for addressing the urgent environmental flow problems that existed at the time of its conception. There are three major assumptions underlying the methodology.

- The riverine biota can cope with naturally occurring base flow conditions but may be reliant on other higher flow conditions in order to fulfil important life history needs.
- The identification and incorporation of these important flow characteristics will help to maintain the river's natural biota and processes.
- Certain flows influence channel morphology more than others and their incorporation into a modified flow regime will aid maintenance of natural

channel structure and the diversity of the physical biotopes within the river (King & Tharme 1994; Tharme 1996).

A key element of the Building Block Methodology is the development of a desired future state at the beginning of the process and it against this desired future state that all subsequent deliberations are made. The Building Block Methodology, is stated to be relatively rapid but does require the collection of substantial data on the integrity of the study river's catchments and riparian vegetation, geomorphology and hydraulic characteristics of key sites, compilation of historical and present-day flow records, compilation of ecological information pertaining to that river, and a statement on the river's economic, conservation and cultural significance. These data are then considered within a highly structured workshop wherein explicit recommendations are made by individual expert participants.

Tharme (1996) lists several advantages of the Building Block Methodology including its strong links to natural hydrology, simplicity, rapidity, structured approach, transparency of the process of arriving at recommendations, and holisticity. However, some disadvantages are also listed by Tharme (1996).

Foremost amongst these is that the Building Block Methodology is highly reliant on the provision of good quality flow data (preferably daily flows) and the reliability of hydraulic data gathered for individual test sites. The methodology is also reliant on professional judgement and specialist experience. It must be said, however, that the rigorous and explicit nature of the workshop component of the Building Block Methodology tends to make obvious the processes and route by which a flow recommendation is ultimately reached. Some, if not all, of these criticisms could be levelled at most environmental flow methods and are not necessarily peculiar to this methodology.

The Building Block Methodology has been applied in the Logan River of south-eastern Queensland (Arthington & Long 1997; Arthington & Lloyd 1998) and is discussed elsewhere in this review. Certain ecosystem components such as water birds, herpetofauna, semi-aquatic mammals and other wildlife are presently omitted from the Building Block Methodology process or are collectively grouped (eg. water quality and macroinvertebrates). Besides the constraints of finance, time and expertise, there is little reason to exclude them from the Building Block Methodology. In fact, their inclusion is highly warranted given that the methodology is intended to be holistic in outlook.

THE MODIFIED APPROACH

In the present work, holistic methodology has been applied considering water requirement for aquatic life, water quality improvement, sediment transportation, seepage losses and evaporation losses. It is essential to preserve environmental flows to maintain the environment, ecology, river morphology, aquatic life, pollution, and water transfer among surface water and groundwater.

Maintenance of Aquatic Life

The environmental flows estimated using 7Q10 flow duration curve has been used for the estimation of maintenance of aquatic life for the following reasons:

- The Brahmani basin is dominated by a humid sub-tropical monsoon climate, so low-flow episodes of sufficient severity usually do not last for long periods during the dry season (March-June). Practically, a 7-day low flow better represents the drought conditions and can be used more effectively in water management (Jha et al. 2008).
- Smakhtin (2001) concluded that a 7-day period which eliminates day-to-day variations of river flow is less sensitive to measurement errors, which offer credence to the applicability of the 7-day 10-year flow (7Q10) FDC approach in the present work.
- The 7Q10 FDC method is the most widely used index in the USA, UK and several other countries (see Jha et al 2008).

The value of probability of exceedance equal to 90% (Q90) was used as environmental flows to maintain aquatic life in the Brahmani River system (see Jha et al 2008).

Stream Self Purification and Water Quality Improvement

Broadly, the surface water pollution in Brahmani River in Orissa, India, occurs due to point-source pollution (municipal and industrial waste) and non-point-source pollution (agricultural lands). The environmental status of Brahmani River is determined mainly by pollution levels which are increasing under conditions of increasing land use/land cover change, accelerating urban development, enhanced irrigation, and enhanced low flow. As a result, self purification capacity of Brahmani River is decreasing with time.

For improvement of water quality from Class-C to Class A and from Class-B to Class-A quality water in the reaches having organic pollution, attempts were made to compute the environmental flows for self purification capacity and water quality improvement using the Newton Raphson optimization technique. Different parameters were estimated from field observations and the earlier work carried out for Indian river systems (see Jain, 1996; Jha et al., 2004; Jha et al., 2005; Jha et al., 2007).

Sediment Transportation and Flushing

Flow and sediment transportation are the basic functions of a river system, as they help maintain the normal development of a watercourse and maintain the morphology. However, the channel siltation due to sedimentation decreases sediment transporting capacity, the utilization efficiency, and operation of water conservancy facilities, which greatly impair flood control, hydropower generation, irrigation, organism diversity, and so on. At the same time, sediment is the carrier of the contaminant in the river. Once stagnated and accumulated in the river, the contaminant, which is attached to the sediment, degrades stream's self-purification capacity, which leads to further deterioration of ecology (Wang, 1998). Therefore, to transport sediment, a certain volume of instream flow must maintain the dynamic balance between water and sediment in the river. Most of the conventional methods to estimate environmental flows are based on hydrological data without taking into account hydraulic and river mechanics data. For example, one typical method proposed by Li and Zheng (2000) is based on the average annual sediment yield (kg/year), the largest monthly sediment concentration (kg/m^3), and average monthly sediment concentration (kg/m^3). Another typical method proposed by Liu *et al.* (2002a) is based on annual runoff (m^3/year), sediment yield (kg/year), and erosion and deposition yield (kg/year). These methods give a first-order estimate.

In this study, based on the analysis of river load movement (Song et al. 2006), it is pointed out that environmental flows should be required to maintain a balanced state of erosion and deposition. Considering a river reach, the main factors that influence sediment erosion and deposition include sediment concentration from the upper reach, sediment transporting capacity and boundary condition (e.g., gradient) characteristics (Liu *et al.* 2002a). When sediment transporting capacity and boundary conditions vary little with flow discharge, the variation of sediment erosion and deposition mainly results from sediment concentration Su (kg/m^3) and sediment transporting capacity Su* (kg/m^3) in the upper reach. The environmental flows (cumec) for sediment transportation should be considered as the in-stream flow required when sediment transportation is in balance between erosion and deposition (Song et al. 2006):

$$if\ S_u \le S_{u^*},\ EFlow(se\dim ent) = \frac{1}{S_{u^*}} \times T_s \tag{2}$$

where T_s is the average sediment yield of one reach at a certain time (kg/s).

Seepage Losses

In the hydrological cycle, there are interrelationships and reciprocal transformations among atmospheric water, surface water and ground water. Both surface water and ground water are re-released into the atmosphere through evapo-transpiration. On the other hand, surface water and ground water exchange water with each other. It is one of the important functions of surface water to maintain kinetic equilibrium and the in-stream flow should be required to keep this function in a good condition. When the water level in a river is higher than that of the river bank, in-stream flow will infiltrate and supply ground water; as for a perennial river, the river bed is saturated. Also, in-stream flow is often recharged from ground water in low-flow periods. Thus, it is not needed to determine the environmental flows required for channel seepage due to over exploitation of groundwater and transfer of stream water to groundwater. For the part of Brahmani River in upper reaches, ground water has been exploited and part of which comes from in-stream flow. This amount of water can be regarded as environmental flows for channel seepage and can be estimated by the following formula (Darcy's law):

$$EFlow(seepage) = K_v \times I \times A \tag{3}$$

where K_v is the streambed vertical hydraulic conductivity (m/s); I is the hydraulic gradient; A is the stream cross-section area (m^2).

Evaporation Losses

It is important to keep channel evaporation to maintain good climatic environment for the river basin and ecological function of the river system. Therefore, environmental flows for channel evaporation should be determined, which can be estimated by the following formula (Song et al. 2006):

$$EFlow(evaporation) = \frac{B \times L \times Z}{T} \tag{4}$$

where B is the average width of surface water(m); L is the length from upper reaches to lower reaches(km); Z is the value of channel evaporation capacity(mm), and T is time(s).

APPLICATION OF ENVIRONMENTAL FLOW IN A TYPICAL INDIAN BASIN

In previous section, we have come across many different methods for the assessment of environmental flow. Now, we will look for the applicability of different models for Brahmani river system, Orissa, India. A comparison of these models are also done to evaluate the validity of different models having different input data sets.

River Brahmani is a water surplus river basins and many water resources projects are proposed in the river system (Figure 4). As discussed earlier, assessment of environmental flows at different locations in the river system is essential to maintain good health and ecology of Brahmani river system. For the analysis daily discharge data from six locations of River Brahmani (Tilga, Panposh, Gomlai, Samal, Talcher and Jenapur) and two locations of River Baitarani (Champua and Anandpur) were collected from Central Water Commission, Bhubaneshwar, Orissa, The time-series plots of discharges of each station is shown in Figure 5 and the analysis of these data sets are presented hereafter.

HYDROLOGICAL INDEX MEHODOLOGIES

Montana or Tennant Method

Using the Tennant (or Montana) method (1976), percentage of the mean annual flow (MAF) for two different six month periods were computed to define conditions

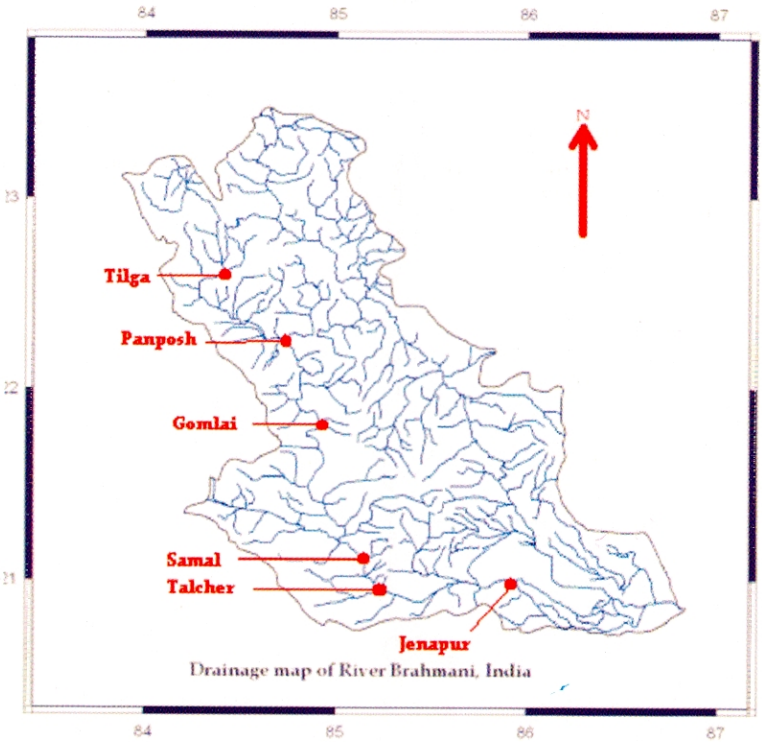


Fig 4: Brahmani River system in Orissa, India

of flow regarding "instream flow regimens for fish, wildlife, recreation, and related environmental resources" and are shown in the Table 2.

Table2: Results of Tennant (Montana) method (1976) in Brahmani river system

Narrative description of general condition of flow (%)	Recommended flow regimens (% of MAF in Mcum) October to March			Recommended flow regimens (% of MAF in Mcum) April to September		
	Tilga	Gomlai	Jenapur	Tilga	Gomlai	Jenapur
Flushing or maximum	4737	27289	41446	4737	27289	41446
Optimum range	1421-2368	8187-13644	12434-20723	1421-2368	8187-13644	12434-20723
Outstanding	947	5458	8289	1421	8187	12434
Excellent	710	6822	6217	1184	6822	10362
Good	474	4039	4145	947	5458	8289
Fair or degrading	237	1364	2072	710	4039	6217
Poor or minimum	237	1364	2072	237	1364	2072
Severe degradation	<237	<1364	<2072	<237	<1364	<2072

Table 2 is useful for water resources managers and planners for allocating water for flushing out the sediment deposits, to maintain the morphology of the river system and to keep river in good health. The lower values indicate the severe degradation in the health, water quality and ecology of the river system.

Flow Duration Curve Analysis

To supplement the results obtained using % of MAR approach, flow duration indices were also used in the present work. For this, most commonly used flow duration indices, namely Q17, Q40, Q80, Q50, Q90 and Q95 were computed for the flow duration curves developed for 1-day, and 7-day mean flow durations. It is to mention here that flow duration index Q17 is used for flushing fines from substratum interstices of spawning grounds, Q40 is to maintain suitable habitat conditions for spawning, Q80 for invertebrate (food) production, cover and maintenance of minimum adult habitat and Q50, Q90 and q95 are most often used as low flow indices (Smakhtin, 2001), as discussed in previous chapter. The results obtained are given in Table 3.

From Table 3, daily flow values required (Q17 or Q95) can be obtained. For example, if Q17 obtained at Jenapur for 7 days mean is made available for one, two and three monsoon months, it volume comes out to be 2167 million cubic meter (Mcum) (10% of MAF), 4334 Mcum (20% of MAF) and 6501 Mcum (30% of MAF) respectively. Similarly, if Q90 values are made available for one, two, three and four months at Jenapur, its volume comes out to be 109 Mcum, 218 Mcum, 327 Mcum and 436 Mcum respectively.

Table 3: Results of Flow indices in Brahmani river system

Flow indices	Tilga (m^3/day)			Gomlai(m^3/day)			Jenapur(m^3/day)		
	1-day	7-day	7Q10	1-day	7-day	7Q10	1-day	7-day	7Q10
Q17	102.0	117.0	63.5	510.0	640.0	340.0	755.0	836.0	610
Q40	20.2	22.5	14.1	87.9	94.7	46.9	305.0	307.0	107
Q50	11.1	12.0	7.3	45.8	47.7	30.5	228.0	236.0	66.5
Q80	2.75	3.1	1.3	16.8	17.5	12.9	84.1	90.8	20.3
Q90	1.0	1.2	0.4	12.5	13.1	10.3	40.4	42.0	16.5
Q95	0.3	0.5	0.0	10.8	11.0	9.3	23.1	24.4	12.2

Further, it can be seen that the total volume of water required for Q90 is 1324.50 (6.4%) Mcum for the whole year out of 20723 Mcum MAF. Table 4 provides volume of water required for Q90 at all the stations of Brahmani river basin.

Table 4: Volume of water in Mcum required for flow indices Q90

Sampling station	Type of flow duration curve		
	1-day(MCM)	7-day(MCM)	7Q10 (MCM)
Tilga (Brahmani)	31.60	37.85	12.60
Gomlai (Brahmani)	394.20	413.10	324.80
Jenapur (Brahmani)	1274.10	1324.50	520.35

The 7Q10 Flow

The 7Q10 flow is the most commonly used single flow index. The results obtained at different sampling stations are shown in Table 4 of previous section. It can be seen that the total volume of water required at Jenapur for flow indices Q90 is 520.35 (2.5%) Mcum for the whole year out of 20723 Mcum MAF. The graphs related to 7Q10 flow duration graphs is shown in Figure 5.

There are numerous and diverse reasons applied to the use of the 7Q10 flow for regulation purposes, ranging from: (i) protection or regulation of water quality from wastewater discharges or waste load allocations, (ii) habitat protection during drought conditions, (iii) chronic criteria for aquatic life, and (iv) a local extinction flow. The original use of the 7Q10 flow is related to stream water quality standards to regulate pollution, however the uses have expanded to include and serve many other interests. There have been concerns about the suitability of applying the 7Q10 flow as a design or index flow.

Range of Variability Analysis

The method is intended for application to rivers where protection of natural ecosystem functioning and conservation of natural biodiversity are the primary management objectives. The Indicators of Hydrologic Alteration (IHA) calculates a total of 67 statistical parameters. These parameters are subdivided into 2 groups, the IHA parameters and the Environmental Flow Component (EFC) parameters. There are 33 IHA Parameters and 34 EFC Parameters. The 33 IHA parameters were computed for all the data sets of Brahmani river systems. Figure 7 the 1-day, 3-day, 7-day and 30 day minimum flows. It is found that the 7-day minimum flow at Tilga in the upper reaches of Brahmani river system is very low, which ranges between 0.5-4.5 cumec. However, the 7-day minimum flow in lower reaches Gomlai and Jenapur ranges between 6-15 cume nd 60-120 cumec respectively. The flow at Gomlai is higher due to confluence of one tributary and flow at Jenapur is high due to construction of Rengali dam ranges in River Brahmani.

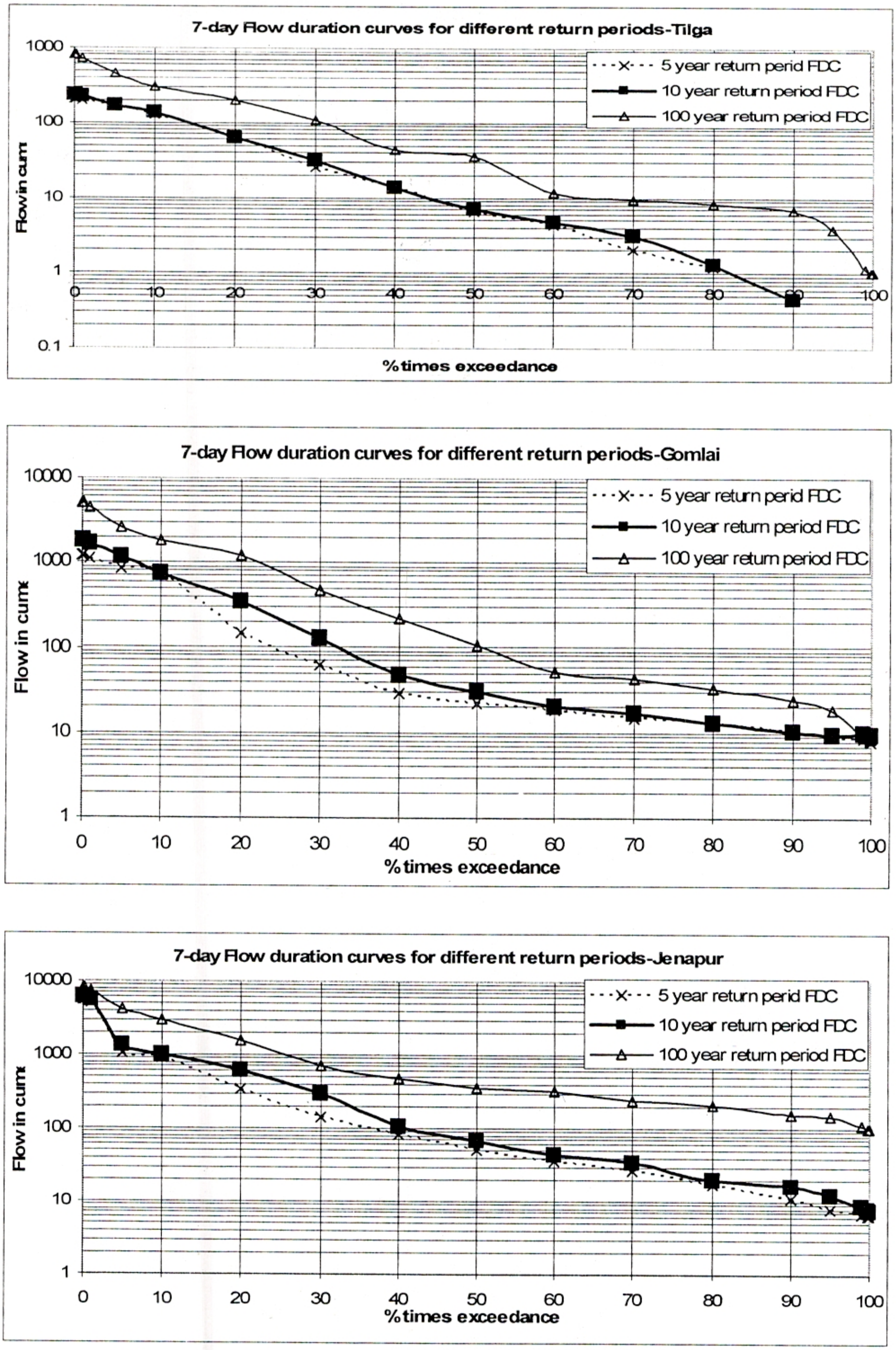
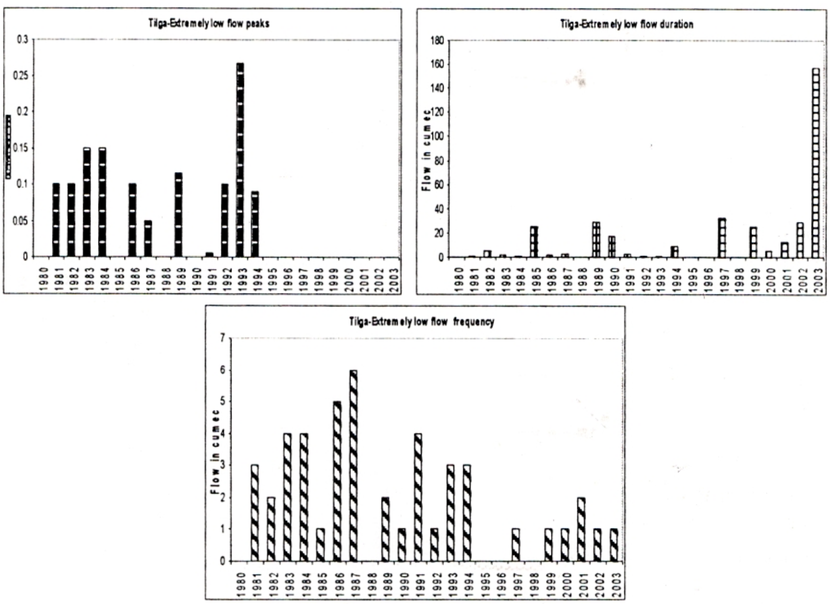


Fig. 5 7Q10 flow duration curves in Brahmani river system

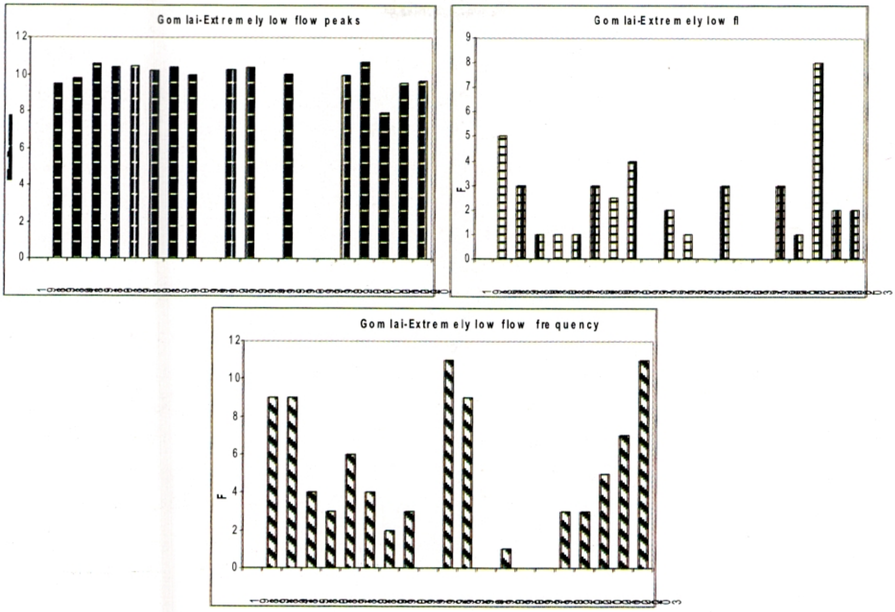
The IHA calculates parameters for five different types of Environment Flow Components (EFCs). They are low flows, extreme low flows, high flow pulses, small floods, and large floods. During drought periods, rivers drop to very low levels that can be stressful for many organisms, but may provide necessary conditions for other species. Water chemistry, temperature, and dissolved oxygen availability can become highly stressful to many organisms during extreme low flows, to the point that these conditions can cause considerable mortality. On the other hand, extreme low flows may concentrate aquatic prey for some species, or may be necessary to dry out low-lying floodplain areas and enable certain species of plants such as bald cypress to regenerate. The results obtained for extremely low flow peaks, duration and frequency in Brahmani river system is shown in Figure 6.

MODIFIED APPROACH

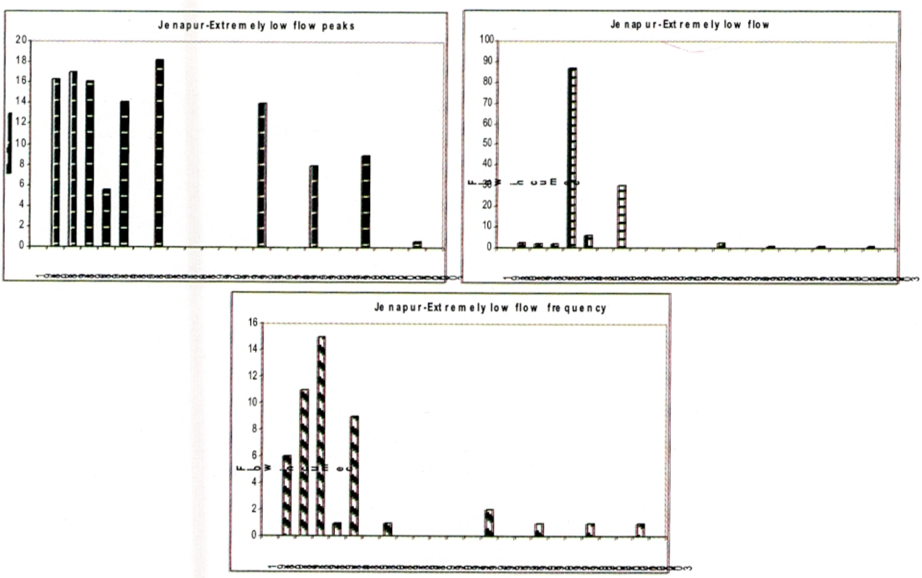
The holistic approach is considered to be the best method. It is really difficult to define the variable considered in holistic approach, but it provides better estimate of water requirement. Based on the available hydrological, water quality and ecological data, environmental flows were estimated in Brahmani river system. Various components of environmental flows considered are water demand for (a) maintenance of aquatic life; (b) stream self-purification and water quality improvement; (c) sediment transportation and flushing; (d) recreational and religious water requirement; (e) channel seepage; and (f) channel evaporation in reaches between sampling stations of the Brahmani River system. The water requirements for religious purposes are region and season specific.



a: Extremely low flow peak, duration and frequency at Tilga



b: Extremely low flow peak, duration and frequency at Gomlai



c: Extremely low flow peak, duration and frequency at Jenapur

Fig. 6 Extreme Low Flows in Brahmani River System

Maintenance of Aquatic Life

It has been observed that for the existing prime productivity, phytoplankton and zooplankton in Brahmani river system as shown in Figure 7, the environmental flows estimated using 7Q10 flow duration curve would be sufficient. The results shown in the water requirement at Tilga, Gomlai and Jenapur are 13, 325 and 520 MCM respectively.

Stream Self Purification and Water Quality Improvement

Comparing measured values with the environmental quality standard value, it is found that nine kinds of main pollutants are dominant at all the gauging stations in Brahmani River. They are Bio-chemical Oxygen Demand (BOD_5), Dissolved Oxygen (DO), Nitrate (NO_3), ortho-Phosphate (o-PO_3), Sulphate (SO_4), Potassium (K), Chromium (Cr), Aluminum (Al) and Iron (Fe),. To assess the self purification capacity of Brahmani River, the study was carried out in two phases. The environmental flows computed for the improvement of water quality from Class -C to Class -A and from Class-B to Class-A quality water are shown in Table 5.

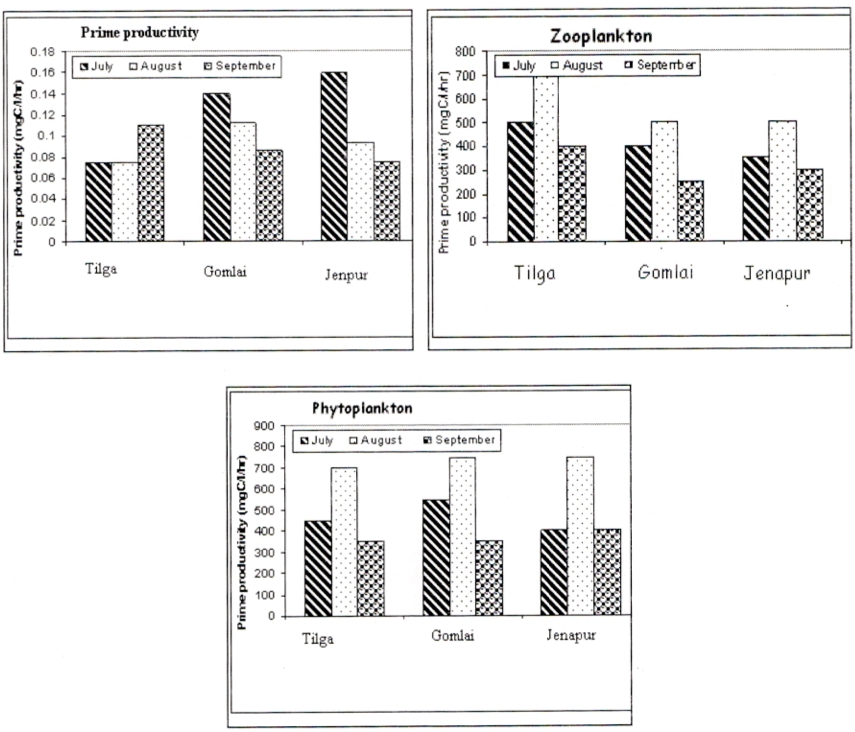


Fig. 7 Ecological parameters at different location

Table 5: Environmental flows water quality improvement

Sampling station	Environmental flows for self purification capacity and water quality improvement			
	Class-B to Class-A		Class-C to Class -A	
	Flow rate (m^3/sec)	Flow Volume (Mcum)	Flow rate (m^3/sec)	Flow Volume (Mcum)
Up to Tilga	1.5	47.30	3.0	94.61
Tilga- Gomlai	19.2	605.49	28.5	898.78
Gomlai- Jenapur	27.8	876.70	40.1	1264.59

Sediment transportation and flushing

In this study, based on the analysis of river load movement (Song et al. 2006), it is pointed out that environmental flows should be required to maintain a balanced state of erosion and deposition. Equation 2 has been used for the analysis. Table 6 provides the estimates of water requirement for sediment flushing.

Table 6: Environmental flows for sediment transport and flushing

Station	Average sediment transport capacity(Kg/m^3)	Sediment yield (Kg/sec)	EF for sediment transport and flushing	
			Flow rate (m^3/sec)	Flow Volume (Mcum)
up to Tilga	0.6	77	128.60	4055.53
Tilga-Gomlai	0.37	280	749.14	23624.88
Gomlai-Jenapur	0.26	276	1062.20	33497.54

Seepage Losses

Equation 3 has been used to estimate the seepage losses and the flow requirement for seepage losses. The results obtained are shown in Table 7. It has been observed that the seepage losses are prominent in upper reaches of river Brahmani.

Table 7: Environmental flows for seepage losses

Station	Hydraulic conductivity (m/sec)	Hydraulic gradient	Cross-sectional area of stream (m^2)	EF for Seepage losses	
				Flow rate (m^3/sec)	Flow Volume (Mcum)
up to Tilga	0.3	0.02	62	0.62	11.73
Tilga-Gomlai	0.1	0.01	130	0.16	4.1
Gomlai-Jenapur	0.1	0.005	320	0.16	5.05

Evaporation Losses

It is important to keep channel evaporation to maintain good climatic environment for the river basin and ecological function of the river system. Equation 4 has been used to estimate the evaporation losses and the results are shown in Table 8. It is interesting to note that the evaporation losses are more than seepage losses in lower reaches of the Brahmani river basin.

Table 8: Environmental flows for evaporation losses

Station	Average width of surface water (m)	Length from upper reach to lower reach (Km)	Channel evaporation capacity (mm)	Time (sec)	EF for evaporation losses	
					Flow rate (m^3/sec)	Flow Volume (Mcum)
up to Tilga	10	115	0.10	420	0.27	6.51
Tilga-Gomlai	25	125	0.10	480	0.65	20.50
Gomlai-Jenapur	50	110	0.10	480	1.04	32.79

Estimating Total Environmental Flows Requirement

After computing the Environmental flow requirement for different purposes at different reaches of Brahmani River, the total volume of Environmental flows have been estimated as percentage of mean annual flow. The results are shown in Table 9. This table is very important for water resources planners and policy makers.

Table 9: Volume of Environmental flows required for different purposes

Station	Up to Tilga	Tilga-Gomlai	Gomlai-Jenapur
$EWD_{aquatic}$ (Mcum/year)	25.23 (1.07%MAF)	324.82 (2.38%MAF)	520.34 (2.51%MAF)
$EWD_{water\ quality}$ (Mcum/year)	94.61 (3.99%MAF)	898.78 (6.59%MAF)	1264.59 (6.1%MAF)
$EWD_{sediment}$ (Mcum/year) &	4055.53 (171.23%MAF)	23624.88 (173.14%MAF)	33497.54 (161.64%MAF)
$EWD_{sediment}$ (Mcum/month)	333.33 (14.07%MAF)	1941.77 (14.23%MAF)	2753.22 (13.29%MAF)
$EWD_{seepage}$ (Mcum/year)	11.73 (0.83%MAF)	4.1 (0.09%MAF)	5.05 (0.05%MAF)
$EWD_{evaporation}$ (Mcum/year)	6.51 (0.55%MAF)	20.50 (0.23%MAF)	32.79 (0.26%MAF)

CONCLUSIONS

Numerous methods are available to estimate the environmental flows. Some of them are discussed and used in the present work. IT is understood that the environmental flows are essential to maintain the environment, ecology, river morphology, aquatic life, pollution, and water transfer among surface water and groundwater. It has high socio-economic impact with no revenue losses.

It has been observed that some of the methods used in the present work over estimates the environmental flows. Further, some of the methods are based on few parameters to estimate environmental flows. The modified approach used in the present work provides realistic estimate of environmental flows by considering estimate of seepage and evaporation losses in addition to environmental flow requirements for various purposes. Table 9 provides very useful information for policy makers and decision makers to utilize water for different purposes depending on their requirement and socio-economic considerations.

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INDIAN NATIONAL COMMITTEE ON HYDROLOGY (INCOH)

(IHP National Committee of India for UNESCO)

Constituted by the Ministry of Water Resources in 1982

INCOH Activities Related to UNESCO's IHP-VII Program

India is actively participating in IHP-VII activities and a detailed program has been chalked out in accordance with IHP-VII themes towards preparation of reports, taking up research studies, organisation of seminars/symposia at national and regional level, and promotion of hydrological education in the country. It is envisaged to participate in all the relevant and feasible programs identified under the various focal areas of IHP-VII themes as given below.

India's participation in IHP-VII program

Theme	Selected Focal Area/ Activities to be taken up
1. Global Changes, Water Resources and Aquifers	(i) Water resources management under drought situation (ii) Assessment of water resources under climate change
2. Ecohydrology and Environmental Sustainability	(iii) Real time flood forecasting (iv) Flood inundation zoning for different return periods
3. Water Quality, Human Health and Food Security	(v) International conference on water, environment, energy and society (WEES)

INCOH Publications

Publication of Journal of Hydrological Research and Development

To disseminate information and promote hydrological research in the country, INCOH brings out the 'Journal of Hydrological Research and Development' (earlier known as '*Jalvigyan Sameeksha*' (Hydrology Review Journal). The papers published in the Journal are by invitation only. The Journal is widely circulated amongst major organisations and agencies dealing with water resources.

Publication of State of Art Reports

In pursuance of its objectives to periodically update the research trends in different branches of hydrology, state of art reports authored by experts identified by INCOH from various institutes and organisations in India, are published regularly. These reports are circulated free of cost to central and state government agencies including academic and research organisations.

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