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Research Article

ENVIRONMENTAL FLOWS ALLOCATION IN TWO MAIN DISTRIBUTARIES OF MAHANADI RIVER

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ABSTRACT
The environmental flows concept mainly recognizes, needs of fresh water system to maintain the ecological integrity and provide goods and services to society &dependent communities. In the Mahanadi river basin the environmental flow method was first introduced in Chilika Lagoon, downstream of Naraj Barrage, Odisha by World Bank Environment Department. In 2002 the EFA project was successed to integrate key water quality concern, particularly salinity within the lagoon, for functioning the lagoon ecosystem while it was not successed to influence in operation of the Barrage at Naraj. The river system attains zero and very low flows in low flow period due to construction of hydropower generating structures, water retaining structure and withdrawal of water by water users, which possesses a tremendous threat to the environment, ecology & aquatic life. Therefore, a need arises to regulate the reservoirs and barrages for releasing the adequate water in the river throughout the year. Thus, environmental flows assessment is done in Lower Mahanadi sub-basin and its two main distributaries for providing the Environmental Flow Requirements (EFRs), with a range of Low Flow Requirements (LFRs) and High Flow Requirements (HFRs) to be ensured at any circumstances to avoid any degradation of river ecosystem. The paper analyse the applicability of several desktop hydrology-based environmental flow assessment methods such as Tennant, Tessman, Variable monthly flow (VMF), Range of variability Approach(RVA), FDC shifting technique using GEFC software. In this approach daily discharge data of Mahanadi River are used to assess Environmental flows in percentage of Mean Annual Flow (MAF) and range of flow in percentage of mean Low flow and mean High flow respectively. The comparative results indicate that a minimum flow i.e. 624m^3/sec (equivalent to 40%of MAF) for main stream of Mahanadi river, 203m^3/sec (equivalent to 26% of MAF) for Kathajodi river and 23m^3/sec (equivalent to 33.5% of MAF) for Birupa river respectively. This paper also promote the requirement of environmental water allocation in planning of water resources development project in Mahanadi river system.

Keywords: *EFR, GIS, Tennant, Tessman, VMF, Smakhtin Method, RVA and GEFC Software*

INTRODUCTION
Environmental flow refers to water provide within a river, wetland or coastal zone to maintain ecosystems and the social benefits, which they provide for people.
Environmental flows is may be termed as "ecological water demand" similar to agricultural or Industrial water demands and it is effectively a balance between Water Resources Development & the need to protect freshwater-dependant ecosystem.
Fresh water ecosystems provide many important goods and services includes clean water, Ground water recharge, food sources for fish & invertebrates, opportunities for harvesting fuel wood & grazing on riverine corridors, cropping on flood plain, Biodiversity conservation, flood protection, Removal of wastes through biogeochemical process, recretional opportunities and cultural, asthetic & religious benefits. Environmental flows are central to supporting sustainable development and adressing poverty allevation. Investment in water resources infrastructure like multipurpose dams or barrages have been essential for economic development including hydropower generation, irrigation, industrial & urban water supply and flood & drought mitigation, but they can cause problem for downstream ecosystem & communities, when they are improperly planned, designed & operated on the basis of volume, pattern & quality of flow.

There are many methods suggested by environmental researchers from very simple to the very complex for estimating environmental flow requirements. The process of estimating environmental flow requirements, for maintaining aquatic ecosystem referred to as Environmental Flow Assessment (EFA). The water quality, sediment, food-supply & biotic interactions are the important determinant of aquatic ecosystem.

In mid of 1990, the World Bank environment Department were taken seventeen case studies for the advance understanding & integration in operational terms of environmental water allocation into integrated water resources management. One case study was from India i.e. restoration of Chilika Lagoon, located at downstream of Naraj Barrage, Mahanadi river basin, Odisha. Chilika Lagoon is the largest brackish Lagoon in Asia, is located in the state of Odisha.

The Lagoon is a biodiversity hotspot, especially for of water birds & other aquatic species. Over 2millions individuals of 160 species water birds are found at the peak migratory times. The Chilika Lagoon ecosystem provides income for about 200,000 people, who are directly or indirectly dependent upon the fish, crab & prawn catch.

In this case study it was incorporated that the EFA project was success to integrated key water quality concerns particularly salinity within the lagoon as it is an important parameter for functioning the lagoon ecosystem, while it was not able to successed in influencing the operation of the Barrage at Naraj. However the World Bank assistance provided training and improved the understanding of Environmental Flows Assessment (EFA) procedures within the State Government agencies (Hirji and Davis, 2009a).

Environmental Flows Adoption and Methods

Many environmental methods were designed to protect a single species to address a single issue. However, the managing flows for single species may not result in robust aquatic ecosystems and also may even fail to preserve the target species, because their dependence on a wide range of ecosystem functions such as food webs & habitat.

The wide range of methods provides a choice of suitable technique to suit various time tables, budgets and purposes. There is no simple figure can be suggested for the environmental flow requirement of rivers; as it is related to a number of factors including: (a) the size of the river; (b) its natural state; (c) combination of the desired state of the river; (d) in practice, the uses to which it is put (Acreman and Dunbar, 2004).

Methods for Determining Instream Flow Requirements

The instream flow may be defined as the amount of water flowing past a given point within a stream channel during one second. The instream flow requirements mostly have been based on the habitat requirements for some species or groups of fish, historically these requirements have been expressed in terms of some minimum flow.

Water is taken out of the stream for a variety uses, such as irrigation purposes, municipal and industrial. But "minimum flow" or "low flow" means that amount of water must be left in the stream for the fish. In addition minimum flows were now a day established for water supply, navigation and protective of aquatic life.

Quantification of Environmental Flow Requirements (EFRs)

The quantification of Environmental flow requirements can be approached in two ways i.e. bottom-up and top-down. In "bottom-up" approach, the environmental flow regimes are built up by flows requested for specific purposes from a starting point of zero flows.

Whereas in "top-down" approach the environmental flow regime built up by determining the maximum acceptable departure from natural condition. The bottom-up approaches are commonly used, including Building Block Methodology (Holistic approach) and Instream Flow Incremental Methodology (IFIM). The bottom-up approach is dependent on the knowledge of the participants in the process & availability of reliable data of stream and it would examine the environmental flow regime is likely to one to natural regime.

In top-down approach the degree of departure from the natural regime under various management scenario, which are quantified in relation to key indicator and then examine the acceptable deviation to natural regime. The top-down approach was developed by Queensland Department of Natural. The top down based on key indicator statistics tied to geomorphological and ecological outcomes.

In bottom-up approaches generally two to three flow bands are considered, such as low flows, medium flows and high flows.

Low flows: The low flow requirements are generally based on ecological consideration, i.e. the availability or suitability of instream habitat for target species. Medium flows: Particularly medium flow requirements are important in sand bed rivers, which often capable of entraining and transporting sand. High flows: Generally high flows are emphasised in geomorphological assessments of Environmental flow requirements, due to following objectives: (i) to maintain channel size and form, (ii) to limit vegetation encroachment, (iii) to remove fine sediment build ups from the stream bed. High flows also termed as flushing flows or "channel maintenance flows" (Stewardson & Gippel, 1997).

Review of Environmental Flows Assessment Methods

Before the 1990's the water management was limited to water quality standards and minimum flow requirements.

In the last two decades it has changed towards managing river to achieve more natural flow regime, capturing the seasonal and inter annual flow variability as well as the magnitude, timing & frequency of different flow condition.

In a comprehensive study of Environmental flow methodologies, Tharme (2003) documented the existence of more than 207 significantly Environmental Flow Methods (EFMs) implemented in 44 countries within 6 regions of the World which can be classified into four broad categories: hydrological methods; hydraulic rating methods; habitat simulation methodologies; holistic methodologies (Tharme, 2003; Acreman and Dunbar, 2004; Dyson *et al.,* 2008).

These methods were mainly developed after studies have been conducted for rivers, wetlands, estuaries, forest and grassland ecosystem.

Hydrologic Index (Desktop) Methods**:** These methods analyze the historical hydrology to identify natural flow conditions and prescribed flow recommendation. Hydrological approaches have been developed for broad scale planning & which are fully dependent on the historical flow records. The hydrologic index methods are simple, inexpensive and use as a flow indicator of the biological condition. The method assumes a relationship between flow and specific biological parameters. In this method the long-term time series data (usually20-50 years) of the river flows is used and the minimum flow expressed as the percentage of natural flow values. Tennant method, Tessman method, Range of variability approach, Desktop reserve model, FDC analysis method, Hydrologic Assessment Tool (HAT) are some examples of Hydrologic Index method.

Hydraulic Rating Methods**:** These types of method relates to the hydrodynamics of the river with its morphology to design adequate habitat for the environment.

Hydraulic rating methods assume a relationship between discharge and some hydraulic measure of a stream across river cross-section. In this method the flow estimation based on surveyed cross section relates to various parameters of stream geometry such as width, depth, wetted perimeter and discharge rates (Jowett, 1989).

The minimum or optimal flows, usually for fish spawning and maximum production by benthic invertebrates are generally identified from a discharge near the break point of the wetted perimeter-discharge curve. Wetted perimeter method and R_2 cross method are the two examples of Hydraulic rating methods. These methods are used to compute minimum flow and correlate the available habitat areas based on river channel geometry. Hydraulic methods are not suitable for the assessment of seasonal flow requirement.

Habitat Simulation Methodologies**:** Habitat model is an extension of Hydraulic rating methods, which determine flow requirements using hydraulic condition to meet specific requirement of biota. These models are generally complex and data intensive.

In this method a variety of models is used to establish a relationship between flow regimes and the amount & quality of physical habitat for various species as well as with other environmental aspects such as sediment transport, water quality and fish passage. In-stream flow Incremental methodology (IFIM) is the example of habitat model.

The In-stream Flow Incremental method (IFIM) relates different flows with habitat changes using predetermined preferences for specific fish species. The IFIM is a software system which is used to integrate micro-habitat (depth, velocity, substrate, cover) suitability and macro- habitat (basin, network, river segments) suitability into habitat units that are then related to flow over time.

***Holistic Methodologies*:** In this type of methods Multidisciplinary (from many disciplines of natural & social sciences and engineering and participation of stake holders) experts are required to define a flow regime intended to achieve a particular objective or to determine acceptable degrees of departure from the natural flow regime.

The holistic method consider whole riverine ecosystem. In this approach the environmental flow requirement is assessed for all biotic and abiotic components of the river ecosystem, including the wetlands, ground water & estuaries as well as physical features and organisms. Holistic approaches are also based on the premise modified flow regimes are similar to the historical flow regimes in their spatial and temporal variability, required to sustain stream morphology, habitats and all kinds of organisms (Arthington, 1998; King *et al.,* 2003). The basis of the Holistic approach is the systematic construction of a modified flow regime through a bottom-up or a top-down process (King *et al.,* 2003). A process of interaction and consensus building allows integration of data and knowledge to achieve a mutually agreed upon description of a flow regime, which is required to maintain a specified river condition. Building Block Methodology (BBM), Downstream Response to Imposed Flow Transformation (DRIFT), Catchment Abstraction Management Strategies (CAMS) and Expert Pannel Assessment (EPA) are the example of Holistic methodology.

MATERIALS AND METHODS

Study Area

The Mahanadi river is the second major peninsular river in India after Godavari, is located in East Central India within geographical co-ordinates 80° 28´ to 86° 43´ East longitude &19° 8´ to 23° 32´ North latitude.

The Mahanadi is extend over five states i.e. Chhatisgarh (52.42%), Odisha (47.14%, approximately the catchment area of 65847 Sq Km & length 494 Km) & smaller portion of Jharkhand, Maharashtra & M.P. The total length of the Mahanadi river basin is 851 Km from origin to Bay of Bengal with have maximum length 587 Km & width have 400 Km comprising the total catchment area of 139681.51 Sq Km (GIS based) respectively.

The Mahanadi is the largest river in Odisha originates from a fall of Pharasiya village, Dhamtari district of Chhatisgarh at an elevation of 442m above m.s.l. The basin is broadly divided into three sub basin i.e. Mahanadi upper sub basin, Mahanadi middle sub basin, Mahanadi lower sub basin. The lower Mahanadi sub-basin comprising a catchment area of 57958 Sq Km, lying in Odisha extending within geographical co-ordinates 82° to 86° East longitude &19° 30´ to 21° 30´ North latitude approximately has been considered in the present work. The thematic map of lower Mahanadi sub-basin and its sub-watersheds (Figure 1) are generated using Arc GIS 10.2.2 software.

During the traverse a no. of tributaries join the river and out of those the principal tributaries are Ib, Ong, Tel. The Ib join at the upstream of dam, whereas Ong & Tel are join at the downstream of the dam respectively.

The Ib river flowing into the reservoir (created by the Hirakud Dam of 4800m length) which is located across Mahanadi 10 Km from Sambalpur city. Below Sambalpur the Mahanadi enters the Bolangir district and after flowing 45Km it reaches Sonepur. After flowing 11Km of Sonepur, the Ong and Tel join the Mahanadi from right.

After flowing a distance of 23Km, the river flows through the extremely narrow Satkosia Gorge. The Tikarapara village is about 6Km below the start of the Gorge. The 64Km long Satkosia Gorge ends at Barmul. Below Barmul the river widers again and takes sharp turn to the left & ends at Mundali (4.8 Km from upstream of Naraj barrage) and finally emerge into the delta at Naraj, which is 11 Km far away from Cuttack. In 1993 a barrage of 1353 m has been constructed in place of old weir at Mundali to regulate the undivided Mahanadi river flow.

From Naraj the Mahanadi River throws its first limb known as Kathajodi. In 2005 a barrage of 940 m has been constructed in place of old weir at Naraj, to regulate the river flow of the Kathajodi. Then it branches into Serua, Biluakhai, Devi, Kandal and Taunla and finally it fall into the Bay of Bengal, named as Devi river mouth. Another sub-distributary branches off from Kathajodi named as Kuakhai, and it bifurcated into Kushabhadra, Bhargavi and Daya.

The Kushabhadra has an indepedent mouth to the Bay of Bengal, where as Bhargavi & Daya reunite & discharge into Chilika Lake. The coastal plain stretching from Naraj to Devi mouth around 101 Km & covering the Delta plain area of 9063SqKm. The estuarine part of the river covers a length of 40Km and has a basin area 9SqKm.

Similarly another distributary Birupa has bifurcated into Genguti & these two branches finally join to the Brahmani River and enters to the Bay of Bengal at Dhamra.

In 1991 a barrage of 203 m has been constructed in place of old Birupa weir at Jagatpur, to regulate the river flow of the Birupa.

Other distributaries of Mahanadi include Chitrotpala, Luna, Paika and it finally fall into Bay of Bengal named as Mahanadi Mouth.

In 1991 a longest barrage of 1928 m length has been constructed in place of 60 m far away from old anicut at Jobra, to regulate the river flow of the downstream of Mahanadi.

Physiographically the basin divided into four regions, i.e. Northern plateau, Eastern Ghat, the Coastal plain and the erosional plains of central table land. The coastal plain stretching from Naraj to Devi mouth around 101 Km & covering the Delta plain area of 9063Sq Km. The estuarine part of the river covers a length of 40 Km and has a basin area 9Sq Km. The Mahanadi Basin receive an average annual precipitation around 1450 mm.

In the period of July to September the basin received the precipitation of 800 mm to 1600 mm, while less than 50 mm precipitation received in rest of the months. As per CWC (2009) the temperature variation in Mahanadi basin is from 7^0C to 45.5^0C. In winter the mean daily minimum temperature varies from 4^0C to 12^0C and in summer the mean daily maximum temp varies from 38^0C to 45.5^0C. May is the hottest month in the Odisha, where the mean maximum temperature ranges from 38^0 C to 43^0C over the hills & plains respectively.

***Selection of EF Sites for Environmental Flows Assessment in Lower Mahanadi Sub-Basin*:** The Mahanadi basin comprising a lot of multipurpose Water resources development project and it is important to know what amount of water will be release from dam or weir/barrage to downstream in order to protect and maintain aquatic life in stream.

Accordingly the study was carried out to determine the environmental flow amount for lower reach of Mahanadi river basin and its distributaries. The features of the sites along with name, geographical location and period of hydrologic data sets are illustrated in the table 1.

***Description of the Hydraulic Features of Study Area*:** For the assessment of Environmental flows, the daily discharge data of Mahanadi River has been used in this study. The flow regimes of the study area were analysed using several hydrological indicators i.e. Base Flow Index (BFI) = $((Q_{90})/$ MAF) & Hydrological Variability Index (HVI) = $((Q_{25}-Q_{75}) / Q_{50})$. Where, Q_{90}, Q_{75}, Q_{50}, Q_{25} are the annual flows equalled or exceeded for 90%, 75%, 50%, 25% of the time respectively. MAF = Mean annual flow and MMF= Mean monthly flow. These all rivers have strong Base Flow Index more than 20% and a Hydrological Variability Index less than 1 (table 2).

Method

In worldwide various methods have been developed to determine a minimum stream flows requirement for protection of habitat.

Out of these six methods that have been applied widely were selected for comparison in this report. These methods include the

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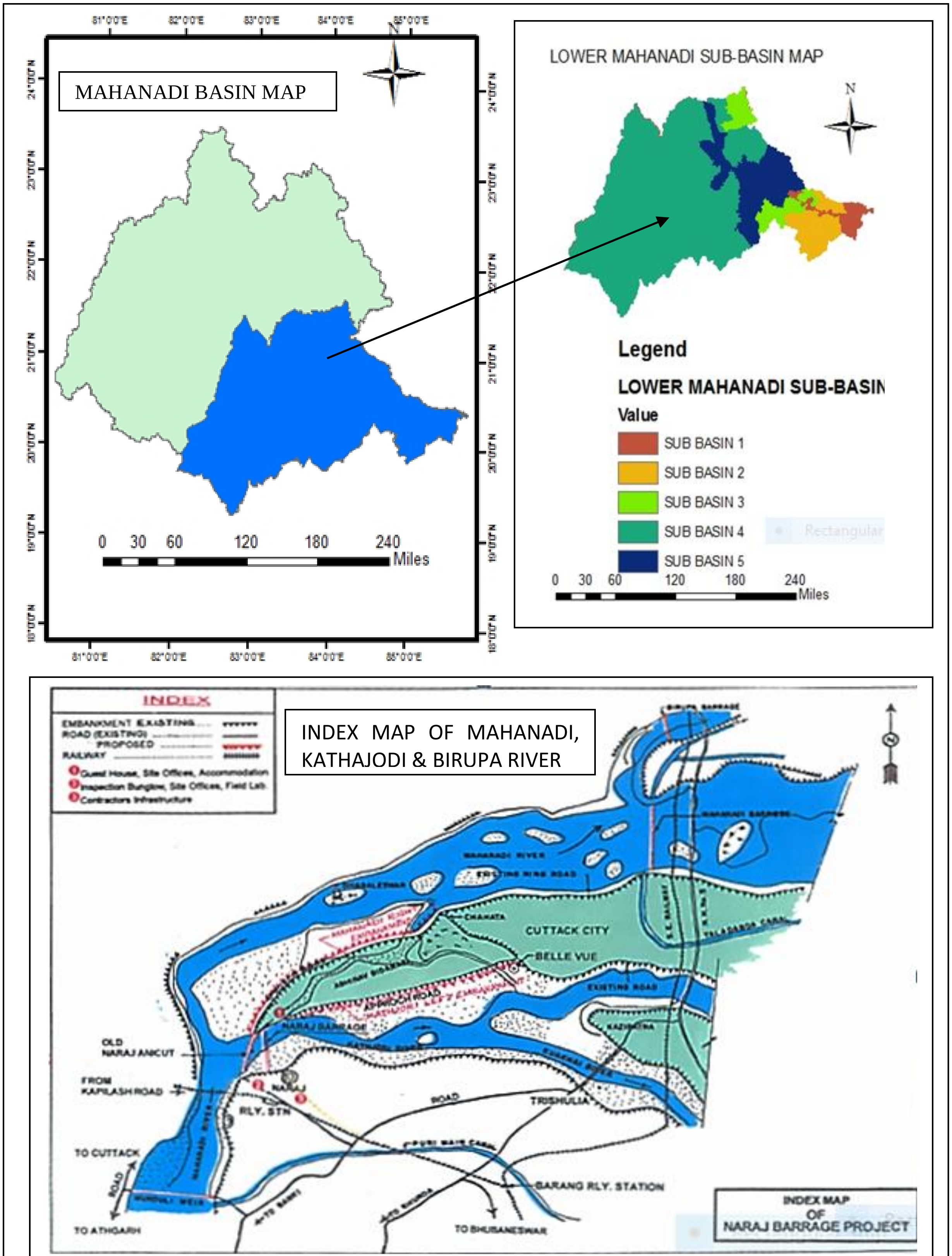

Fig.1. Location of the study area map: (a) Mahanadi basin(b)Lower Mahanadi sub-Basin(c)Index map of Mahanadi, Kathajodi and Birupa river

Table 1: Geographical Location of the Study Area and their Hydrological Data Sets

Gauge Station/Name of the River	Station ID	Geographical Location	Daily Flow Data of Hydrological Year Used in this Study
Tikarapara, Mahanadi river	EF1	$20^0$36'N,$84^0$45'36''E	Natural flow data (1990-2012) No flow regulation
Naraj, Kathajodi river	EF2	$20^0$28'N,$85^0$47'E	Historical data(2005-2015) Regulated flow at barrage
Jagatpur, Birupa river	EF3	$20^0$30'36''N,$85^0$55'12''E	Historical data(1992-2015) Regulated flow at barrage

Table 2: Hydraulic Features of Flow of the Study Area

Station ID	MAF (m^3/sec)	Range of L.F-H.F (m^3/sec)	Average L.F - H.F (m^3/sec)	BFI (%)	HVI	No. of L.F Months	No. of H.F Months	No. of I.F Months
EF1	1552	347.2-5476.7	453.4-3748.7	49.6	0.42	6	4	2
EF2	782	23.7-3645	127-2746	60.6	0.28	8	4	
EF3	69	17.8-197	33-140	29.8	1	4	4	4

L .F=Low Flow average (when MMF>MAF) and H. F=High Flow average (when MMF≤MAF).

Tennant Method **(Tennant, 1976):** Known as Montana method, which is developed specifically for the needs of fish. Tennant assumed a proportion of the mean flow which is needed to maintain a healthy stream environment in his 17 years of experience on hundreds of streams and testing in the field on 11 streams (58 cross section, 38 different flows) in Montana. He observed in his case study, the stream width, water velocity and depth increased from no flow to 10% of the mean flow and decreased thereafter. Then he considered the suitability of the physical habitat that was only related to the flow. He considered an average depth of 0.3m & velocity 0.25m/sec for short term survival and an average depth of 0.45 to 0.6m and velocity 0.45 to 0.6m/sec to be optimal for fish. These two parameters were obtained at 10% &30% of the mean annual discharge (Q_{MA}) respectively. In general, with 30% of $Q_{MA,}$ the most of the stream substrate is submerged &with 10% of $Q_{MA,}$ half or more of the stream substrate is exposed. Hence, many researchers have considered in their study the 40% of MAF for High Flow season and 20% of MAF for Low Flow season is required for good habitat condition.

Tessman Method**:** looking into the importance of the flow variability in the river system, the constant allowance for environmental flow based on the mean annual flow (MAF) will be not adequate for the Indian River system which has a large variation in the flow during the monsoon and non-monsoon periods. Hence, Tessman (1980) determine the flow thresholds by considering natural variations in flow on a monthly basis. He recommends minimum flow guidelines by considering the following rule:
(a) MMF, if MMF<40% MAF;
(b) 40% of MAF, if 40% MAF<MMF<100%MAF;
(c) 40% of MMF, if MMF>MAF. Further a 14 days period of 200%MAF is required for channel maintenance during the month of highest flow.

Variable Monthly Flow (VMF) Method**:** The Variable monthly flow (VMF) method was developed by Paster *et al.*, (2014) for accounting environmental flow requirements in global water assessments. The monthly flow is used to calculate EFRs and it follows the natural variability of discharge. This method is used to develop the increase in the protection of fresh water ecosystems during the low flow season with a reserve of 60% of the MMF & a minimum flow of 30% of MMF during the high flow season. This

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method also allows water users such as industry and irrigation sector to withdraw water upto 40% of the MMF during the low flow season. In this method the Low flow, Intermediate flow and High flow seasons with different algorithm defined. Accordingly they recommends minimum flow guidelines by considering the following rule:
(a) 60% MMF, if MMF < 40% MAF;
(b) 45% of MMF, if 40% MAF<MMF<80%MAF;
(c) 30% MMF, if MMF> 80% MAF**.**

Shifting FDC Technique**:** Smakhtin and Anuptha (2006) has been proposed a variant of the FDC method for data-deficient situation. In India, practically all river discharge data are either classified or restricted due to variety of reasons and also ecological data on river biota are very poor. This method relies on a reference FDC based on the monthly discharge time series and calculates how much the flow can be modified for a specified desired condition of the river. The FDC are then generated corresponding to the 17 fixed percentage points such as 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 & 99.99 to cover the entire range of flow. The desired condition of the river is referred to as "Environmental Management Class" such as EMC A, B, C, D, E & F are described here (table: 3) & corresponding default levels of EWR is defined. Two additional classes E & F may describe present ecological status but not a target. Higher EMC requires more water for ecosystem maintenance or conservation. These classes are purely conceptual and not based on any emprical relationship between flow and ecological condition. The rivers are placed into different EMCs by expert judgement using a scoring system. The environmental Water Requirement (EWR) is then estimated for all or any of the EMCs corresponding to Mean Annual Run off (MAR) and then the best one feasible under the given existing and future conditions is choosen.

Table 3: Description of Default EMCs

EMCs	**Description (Management Perspective)**
EMC A	Negligible modification from natural condition and negligible risk to sensitive species. (No new water projects are allowed).
EMC B	Slight modification from natural condition and slight risk to intolerant biota. (Water supply scheme or irrigation developments are allowed).
EMC C	Moderate modification from natural condition and especially intolerant biota may be reduced in number & extent.(Multiple disturbances associated with the need for socio economic development).
EMC D	High degree of modification from natural conditions and intolerant biota unlikely to be present. (Clearly visible Disturbances associated with basin water resources development like dam, diversion etc).

The FDC for each EMC is determined by shifting the reference FDC to the left gradually. For class A river the default environmental FDC is determined by shifting the reference FDC by one step (flow which was exceeded 99.99 percent of the time in the original FDC will be exceeded 99.9 percent of the time), for class B shifting the reference FDC by two steps (flow at 99.9 percent becomes the flow at 99 percent) and so on. Then a linear extrapolation is used to define the "new low flows".

Global Environmental Flow Calculator Software**:** Global Environmental Flow Calculator (GEFC) is a software package which is developed by International Water Management Institute (IWMI, 2006). The GEFC uses the shifting technique to estimate EF. The calculator uses monthly flow data and is built around a flow duration curve (FDC), subsequently a non-linear transformation procedure converts into flow time series of environmental flow. The curve is calculated for Environmental flow for several categories of aquatic ecosystem protection from "largely natural" to severely modified" (Smakhtin & Eriyagama, 2008). In the GEFC, four steps are involved in the estimation procedure of Environmental flows. (1) Select a data source (user defined File):- which provides to carry out EF calculations for own time series. (2) In display of hydrological characteristics such as original monthly time series, annual time series, monthly flow distribution, FDC of whole period of record & flow statistics. (3) Calculating EF with simulating reference hydrological conditions with 17 fixed percentage probabilities are 0.01%, 0.1%, 1%, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, 99.9%, 99.99% for each default EMCs. (4) Select the most suitable EMC for the desired river with expert judgement and the display time series will generate monthly Environmental time series corresponding to FDC.

Range of Variability Approach (RVA): The Range of Variability Approach (RVA) was developed by the Richter *et al.*, (1997) for the estimation of an environmentally acceptable flow regime. RVA is an excellent technique, where the role of hydrological variability in structuring and maintenance of a fresh water dependent ecosystem. In this method Richter *et al.*, identified 32 ecologically-important hydrological parameters later changed into 33 hydrological characteristics divided into 5groups (magnitude, timing, frequency, duration and rate of change) of the annual flow regime. This approach sets appropriate measures of variability for the monthly flow values either 1standard deviation from the mean flow or within the 25^{th}& 75^{th} percentile of the monthly mean flow. Non parametric measures the 25^{th}&75^{th} percentile of the mean flow were used in this study because hydrologic data are often skewed (Armstrong *et al.*, 1999; Babel *et al.*, 2012). Richter (1997) point out that the targeted range will not be attained every year due to natural flow variability, but he suggested that it should be attained at the same frequency as the natural flow regime or pre development flow regime.

***Smakhtin Method*:** The Smakhtin method was developed by Smakhtin *et al.*, (2004) for environmental water requirements in a global water resources assessment. In basin with highly variable flow regimes a largely proportion of the total annual flow occur in wet period (usually one to three months), but in dry period of the year, such rivers may either go completely dry or have very low discharge. Accordingly to this Environmental Low flow requirements was assumed to be equal to the monthly flow, which is exceeded 90% of time (Q_{90}), on average throughout a year & is normally estimated from FDC. A "steep" FDC is indication of as variable flow regime, where a flat slope is indication of stable flow regime. For rivers with highly variable flow regimes, in case of Krishna river Q_{90} may be equal to zero or very small (Smakhtin *et al.*, 2004).

After many studies on low flow hydrology, Smakhtin (2001) suggested that Q90 varies in the range of 0-50% of MAR & it would be account for only smaller part of total annual base flow. But with existing experience with setting HFR, Hughes and Hannart, (2003) suggested that HFR may vary in the approximate range of 5-20% of MAR, depending on the type of flow regime & the objective of the environmental flow management. Hence, it is decided for basin with: (a) High variable flow regime: HFR=20% of MAR, where Q90<10% of MAR; (b) Stable flow regime: HFR=0, where Q90>30% of MAR; (c) HFR=15% of MAR, where Q90 ranging from 10% to 20% of MAR; (d) HFR= 7% of MAR, where Q90 ranging from 20% to 30% of MAR and the total annual Environmental Water Requirements (EWRs) calculated as sum of Low flow requirements (LFR) & High flow requirements (HFR).

RESULTS AND DISCUSSION

The Environmental flow requirements computed by standard methods for determining a minimum flow for Mahanadi River and its distributaries were compared, which are illustrated in the table 4 and Figure 2 &3. Using a combination of the six EF methods, on an average the EFRs is recommended 624.50 m^3/sec (equivalent to 40.24% of MAR), along with Low flow requirements (LFRs) & High flow requirements (HFRs) are 397.80 m^3/sec (equivalent to 88% of mean annual LF) & 1077.50m^3/sec (equivalent to 28.75% of mean annual HF) respectively for Tikarapada gauge station, main stream of Mahanadi river. The RVA method provided highest EFRs i.e. 873.80 m^3/sec (equivalent to 56.30 % of MAR), where Tennant method provided lowest result 413.80 m^3/sec (equivalent to 26.70% of MAR) respectively. Similarly, on an average the EFRs is recommended 203.30 m^3/sec (equivalent to 26 % of MAR), along with LFRs & HFRs are 92.20m^3/sec (equivalent to 72.56% of mean annual LF) & 536.70m^3/sec (equivalent to 19.55% of mean annual HF) respectively to be released at Naraj Barrage, Kathajodi river. The Tessman method provided highest EFR i.e. 333 m^3/sec (equivalent to 42.60 % of MAR), where

GEFC software provided lowest result 76.62 m^3/sec (equivalent to 9.80 % of MAR) respectively. On an average the EFR is recommended 23.07 m^3/sec (equivalent to 33.61 % of MAR), along with Low flow requirements (LFRs) & High flow requirements (HFRs) are 15m^3/sec (equivalent to 45.50% of mean annual LF) & 39.20m^3/sec (equivalent to 28% of mean annual HF) respectively to be released at Birupa Barrage, for maintaining the ecosystem in Birupa river. The Tessman method provided highest EFRs i.e. 35.75 m^3/sec (equivalent to 52.10% of MAR), where Smakhtin method provided lowest result 15.21 m^3/sec (equivalent to 22.17% of MAR) respectively. The Low-flow requirements are usually higher than high -flow requirements relative to MAR, as the low flow season is higher than four months at Tikarapada gauge staion (Mahanadi River) & Birupa River and five months higher than at Kathajodi River respectively.

There is a specialization in case of GEFC software, it developed the FDCs and displays the natural and environmental monthly flow time series corresponding to different EMCs of river for each class i.e. EMC A, B, C, D, E, F are shown in Figure 4. The software estimates the long term Environmental Flows in % of Natural MAR for different EMCs of the rivers, which are illustrated in Table 5. It is cleared that the corresponding Environmental flows decreases progressively as ecosystem protection decreases & for higher the EMC more water needs for ecosystem. On average the annual EF allocation 623 m^3/sec (equivalent to 39.7% of MAR) for EMC B of Mahanadi river, 76.62 m^3/sec (equivalent to 11% of MAR) for EMC C of Kathajodi river and 20.55 m^3/sec (equivalent to 28.9% of MAR) for EMC C of Birupa river i.e. water released from the Tikarapada gauge station, Naraj barrage, & Birupa barrage respectively to maintain the D/S stretch of the river to keep the basic ecosystem function intact.

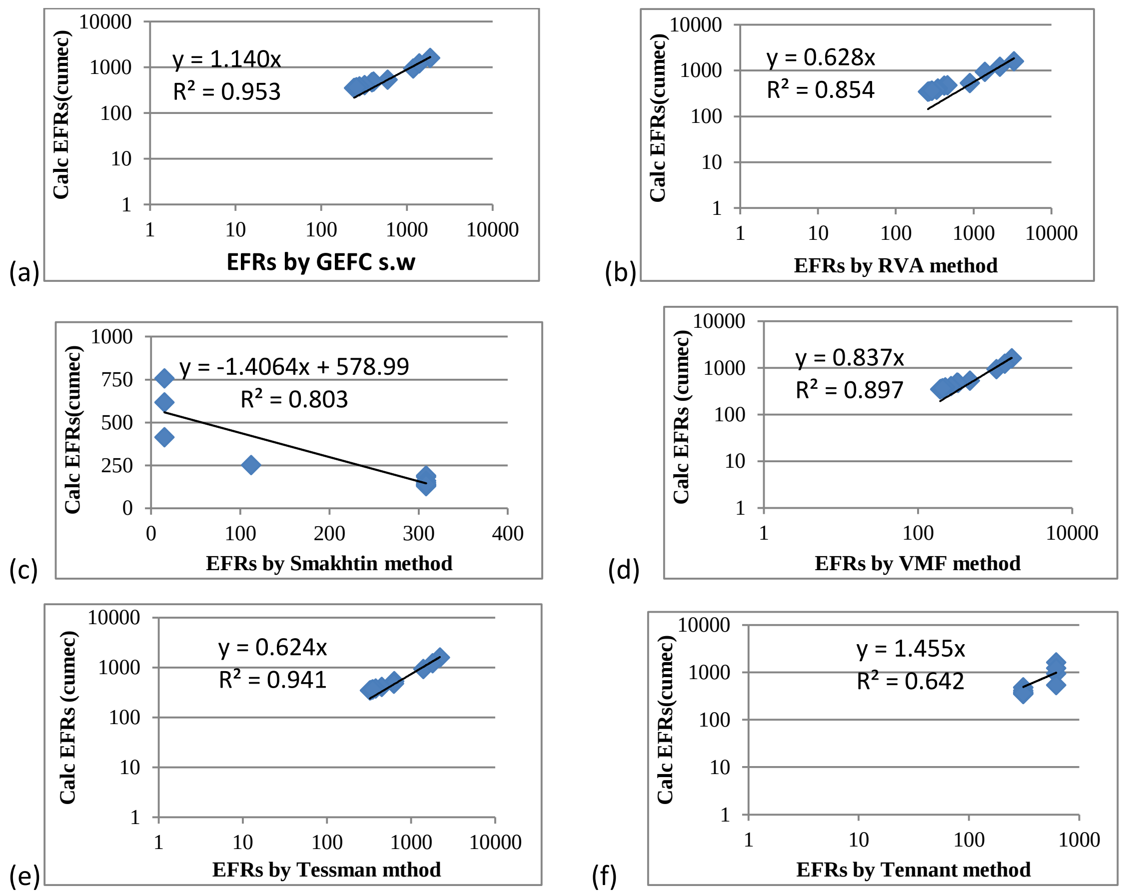

Figure 5: Establish Correlation between the Monthly EFRs by Several Methods and the Calculated EFRs of Mahanadi River and its Distributaries such as Kathajodi River and Birupa River

Table 4: Computation of Annual Average Environmental Flow Requirements (EFRs) by various Methods Corresponding to Study Area

Name of EF Site/River	Hydrologic-al Season	GEFC S.W.	RVA Method	Smakhtin Method	VMF Method	Tessman Method	Tennant Method	Calc EFRs
Tikarapada, Mahanadi river (EF1)	EFRs (LFRs-HFRs) in m^3/sec	623 (301-1267)	874 (334-1953)	513 (769-0)	538 (245-1125)	785 (427-1500)	414 (310-621)	624 (398-1078)
	% of MAR % of (LF-HF)	40 (66.4-34)	56 (73.7-52)	33 (169.7-0)	35.7 (54-30)	50.5 (94.2-40)	26.7 (68.5-16.6)	40.2 (87.7-29)
Naraj, Kathajodi river (EF2)	EFRs (LFRs-HFRs) in m^3/sec	76.6 (15-261.5)	208.4 (55-669)	162.2 (198-54.7)	244.2 (51-824)	333 (78-1098)	195.4 (156.3-312.7)	203.3 (92.2-537)
	% of MAR % of (LF-HF)	9.8 (11.8-9.5)	26.7 (43.2-24.4)	20.75 (155.9-2)	31.25 (40.2-30)	42.6 (61.3-40)	25 (123-11.4)	26 (72.6-20)
Jagatpur, Birupa river (EF3)	EFRs (LFRs-HFRs) in m^3/sec	20.6 (9.8-42.2)	23.5 (3.8-62.8)	15.2 (20.4-4.8)	25.1 (16.6-42)	35.8 (25.6-56)	18.3 (13.7-27.5)	23.1 (15-39.2)
	% of MAR % of (LF-HF)	30 (29.7-30)	34.2 (11.7-44.8)	22.2 (62-3.4)	36.5 (50.4-30)	52.1 (77.8-40)	26.7 (41.7-19.6)	33.6 (45.5-28)
Average	% of MAR % of (LF-HF)	27 (36-25)	39 (43-40)	25 (129-2)	34 (48-30)	48 (78-40)	26 (78-16)	33 (69-25)

The EFR, LFR, & HFR are expressed as a percentage of mean annual flow of river in natural condition, mean annual low-flow & mean annual high-flow

Table 5: Estimation of EF in Percent of MAR for Different EMCs using the FDC Shifting Technique (GEFC Software) in Mahanadi River, Kathajodi River and Birupa River

Name of Site	Natural MAR (m^3/sec)	EF at EMC A (%MAR)	EF at EMC B (%MAR)	EF at EMC C (%MAR)	EF at EMC D (%MAR)	EF at EMC E (%MAR)	EF at EMC F (%MAR)
EF1	1551.81	62	39.7	27.2	20.8	17.3	15.2
EF2	781.71	53.7	26.3	11	4.4	2.1	1.3
EF3	68.64	65.6	43.5	28.9	18.8	12.1	8

The correlation between the EFRs determined with the six selected methods and the calculated EFR results shown in Figure 5. Among the EF methods used in this study, all the simulated EFRs are highly correlated with calculated EFR results. The FDC shifting technique (GEFC software), Tessman method recorded the highest correlation (R^2) is 0.94 above, the RVA and VMF method showed a correlation (R^2) of 0.86 above, while the Smakhtin method and Tennant method showed a correlation (R^2) of 0.8 and 0.64 respectively.

Conclusion

In the present study the three gauge stations were choosen for determining the minimum stream flow requirements are estimated to support of aquatic habitat by means of Tennant, Tessman, Variable Monthly Flow (VMF), Smakhtin, Shifting FDC technique (GEFC software) method and Range of Variability Approach (RVA) along with common flow statistics in the distributaries of Mahanadi river. The EFRs determined at the three EF sites (gauge station) by averaging the stream flow requirements from the Tennant for good habitat condition, Tessman, Variable Monthly Flow (VMF), Smakhtin, Shifting FDC technique (GEFC software) method and Range of Variability Approach (RVA). On an average the EFRs of 624.40m3/sec (equivalent to 40% of MAR) and the range of LFRs of 398 m3/sec (87.75% of mean annual Low Flow) & HFRs of 1078 m3/sec (28.75% of mean annual High Flow) respectively with no withdrawal, is recommended for Tikarapada gauge station (main stream of Mahanadi river).

The EFRs of 203.30m3/sec (equivalent to 26% of MAR) with LFRs & HFRs are 92.20 m^3/sec (equivalent to 72.56% of LF) & 536.70m^3/sec (equivalent to 19.55% of HF) for Naraj Barrage (Kathajodi river); 23.07m3/sec (equivalent to 34% of MAR) with LFRs & HFRs are 15m^3/sec (equivalent to 45.50% LF) &39.20m^3/sec (equivalent to 28% of HF) for Birupa Barrage (Birupa river) respectively with no withdrawal are recommended for maintaining the downstream aquatic ecosystem.

A single average minimum stream flow of 33% of MAF with a range of LFRs of 69% of mean annual Low Flow & HFRs of 25% of mean annual High Flow respectively were determined by averaging these minimum stream flows for each sites, to be released at Mundali Barrage (undivided Mahanadi river basin) to maintain the downstream of Mahanadi river aquatic ecosystem.

In this study, the RVA approach was used to determine monthly mean flows; the VMF and Tessman methods were determined low, intermediate, high-flows; Tennant & Smakhtin method were determined seasonal flows (Low flow & High Flow) and the GEFC software was used to develop FDC & to generate flow requirements corresponding to different levels (such as natural to critically modified) of river ecosystem values.

In this study the EF methods limited to hydrological methods, because of a lack of data on ecosystem response. In defining EFs the biological data, river morphological data and understanding the ecological impacts of flow alternation are necessary, hence, more information should be gather on ecological data and fish communities. The timing and duration of low flows is critical to the health of aquatic ecosystem.

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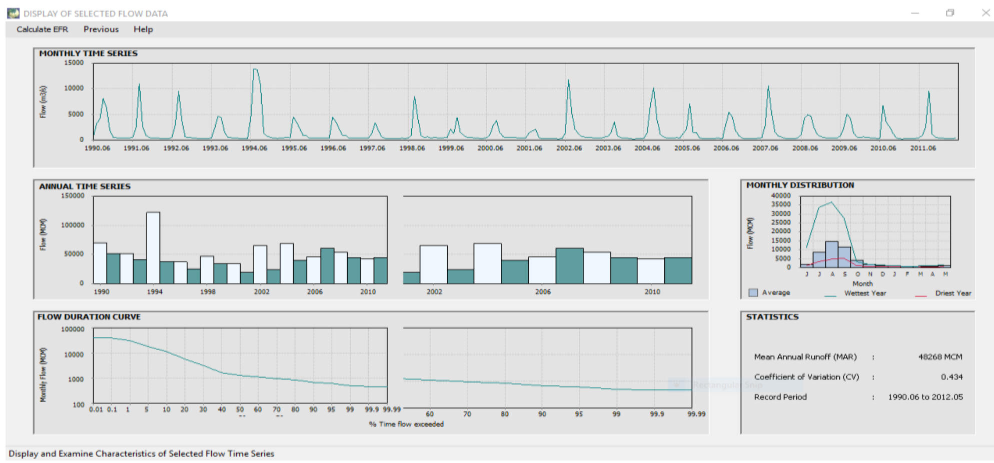
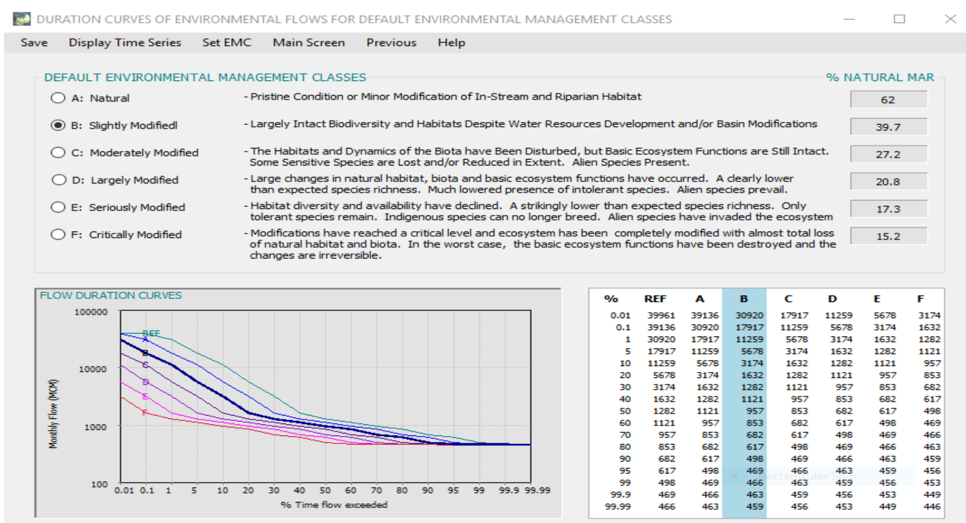
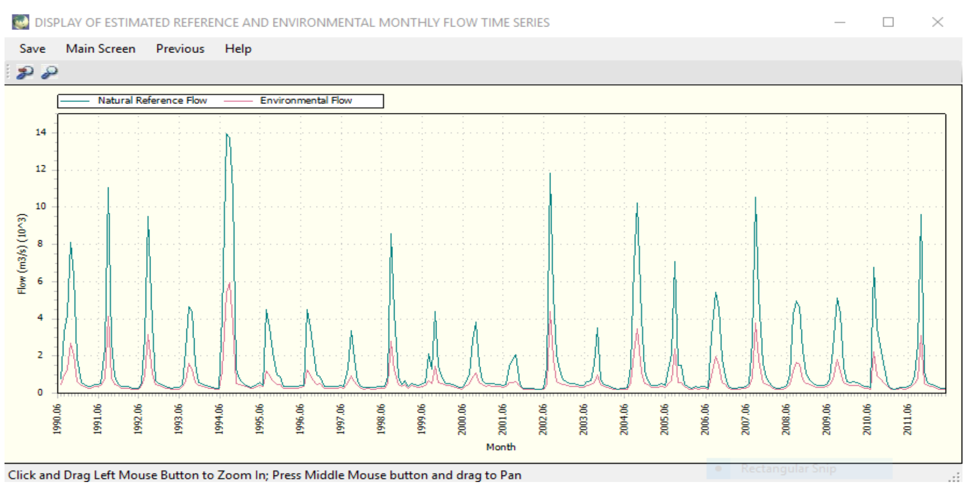


(a)



%	REF	A	B	C	D	E	F
0.01	39961	39136	30920	17917	11259	5678	3174
0.1	39136	30920	17917	11259	5678	3174	1632
1	30920	17917	11259	5678	3174	1632	1282
5	17917	11259	5678	3174	1632	1282	1121
10	11259	5678	3174	1632	1282	1121	957
20	5678	3174	1632	1282	1121	957	853
30	3174	1632	1282	1121	957	853	682
40	1632	1282	1121	957	853	682	617
50	1282	1121	957	853	682	617	498
60	1121	957	853	682	617	498	469
70	957	853	682	617	498	469	466
80	853	682	617	498	469	466	463
90	682	617	498	469	466	463	459
95	617	498	469	466	463	459	456
99	498	469	466	463	459	456	453
99.9	469	466	463	459	456	453	449
99.99	466	463	459	456	453	449	446

(b)



(c)

Figure 4: EFRs Calculation through GEFC Software from Natural to Critical Modified Condition of Mahanadi River at Tikarapada Gauge Station; The involved steps are: (a) discplay of selected flow data; (b) F.D.C.s of Environmental flows for default Environmental Management Classes; (c) Display of estimated reference and Environmental monthly flow time series.

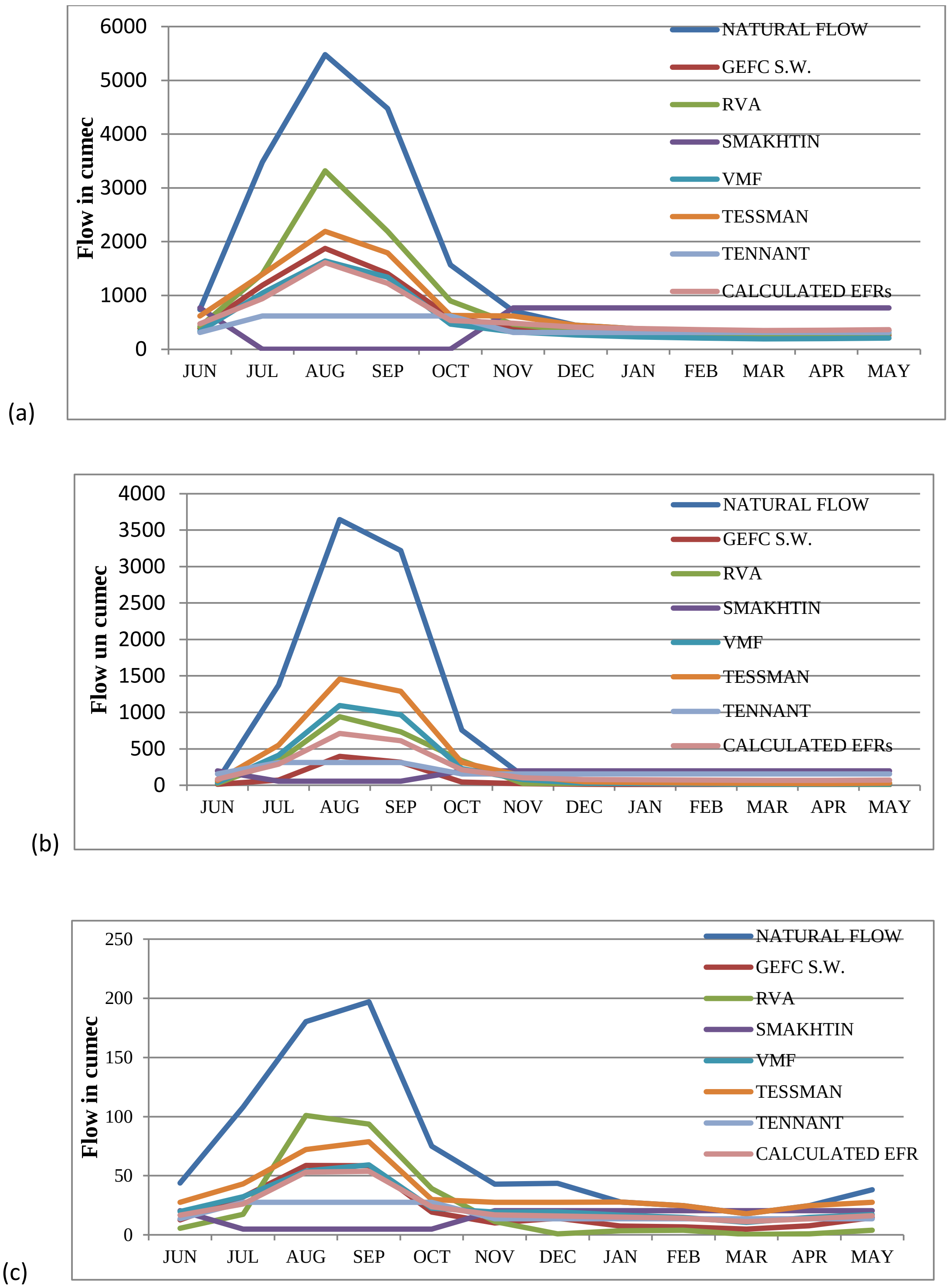


Figure 2: Comparison of EF Methods with Calculated EFRs in Different EF Sites
(a) Tikarapada, Mahanadi River,
(b) Naraj Barrage, Kathajodi River,
(c) Birupa Barrage, Birupa River

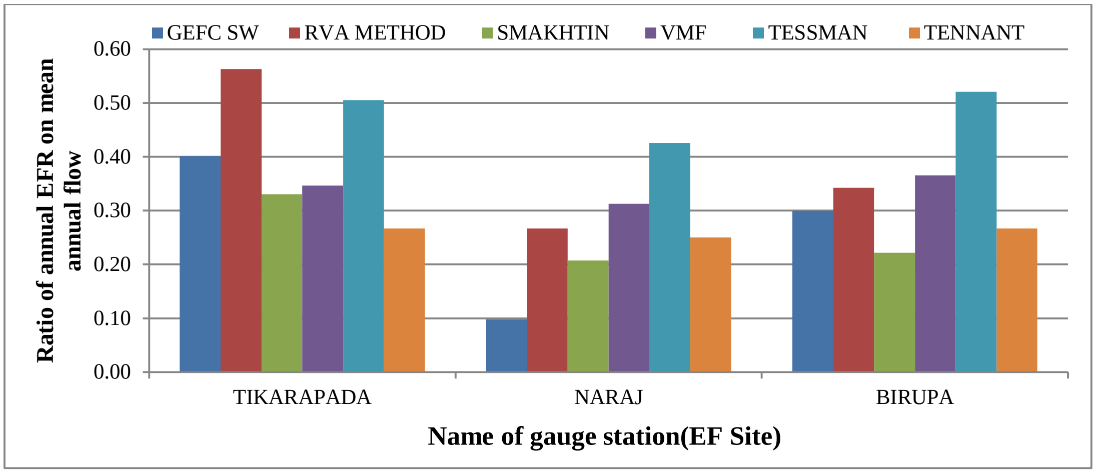


Figure 3: Comparison of the Six Environmental Flow Methods at the Mahanadi, Kathajodi & Birupa River

Hence more study is required for gather information regarding the time periods over which stream flow requirement should be applied.

The main aim of this study is to ensure the minimum value of flow at any circumstances to provide fresh water to maintain ecological integrity and avoid any degradation of river ecosystem. Lastly, if the excess water can be stored, then that can be used for further expansion of irrigation land, in industries, hydropower sector, recreation and many more.

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