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Environmental in-Stream Flow Requirements for the Brahmani River, Orissa, India

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ABSTRACT: In-stream flows are essential determinants of channel morphology, riparian and aquatic flora and fauna, water quality estuarine inflow and stream load transport. The ecological and environmental in-stream flow requirements should be estimated to make the exploitation and utilization of water resources in a highly efficient and sustainable way and maintain the river ecosystem good health. River Brahmani in Orissa, India is an important river having high socio-economic values. It plays a great role in the development of eastern states of India and the health of the ecosystem of the region. The objective of this study is to estimate the environmental in-stream flow requirements for improving the Brahmani River's ecological and environmental condition and develop the river healthily. Concerning the main ecological and environmental functions of the Brahmani River, the environmental in-stream flow requirements for each sampling station including minimum In-stream Flow Requirements (IFR) for aquicolous biotopes maintenance and stream self-purification were estimated in this paper. The methods to estimate the in-stream flow requirements for stream self-purification and in-stream flow requirements for sediment transportation has been tested for its applicability in Brahmani river. The results mainly include in-stream flow requirements for self-purification and sediment transportation in each typical year.

INTRODUCTION

A river system is one of the most important natural ecosystem resources and has a quite intimate relationship with human beings. Influx of pollutants in rivers without prior treatment and construction of water resources structures with no flow release at the down-stream have significant impact on riverine functionalities. To make the exploitation and utilization of water resources highly efficient and sustainable and maintain the river ecosystem in a state of good health, the environmental in-stream flow requirements in rivers systems needs to be estimated. Although this issue has recently been gaining proper recognition and adequate importance in water resource management globally (Vladimirov and Rao *et al*., 1992; Jorde and Schneider, 1998; King and Louw, 1998; Strange and others 1999; Li and Zheng, 2000; Hughes, 2001; Brismar 2002; Liu *et al*., 2002; Ni *et al*., 2002; Shields and Good 2002; Stewart and Harper 2002; Tharme, 2003; Smakhtin *et al*., 2006), many of the policy and planning documents have remained more or less silent over the issue of EWD in developing countries including India.

In the present work, most commonly used global techniques were applied to estimate the environmental in-stream flow requirements for each sampling station including minimum In-stream Flow Requirements (IFR) for aquicolous biotopes maintenance and stream self-purification.

STUDY AREA AND DATA COLLECTION

The Brahmani River is the 2nd largest river in the state of Orissa, covering a drainage area of 39,116 sq. km. (Figure 1). The geology of the Brahmani basin covers (i) northern plateau with cratonic blocks of earth's crust comprising granite complex with associated meta-sedimentary rocks, (ii) southern part with granulitic rocks of eastern ghat group with superposed depositions of meta basic sediments of iron ore group, and (iii) central part with unclassified granites and gneiss with interspersed residual hillocks made up of harder granite gneiss and quartzite.

The annual average rainfall in the basin is 1359.70 mm. The daily maximum temperature of the region rises to as high as 47°C in May and the minimum temperature falls to as low as 4°C in December. The water resource, i.e., the virgin flow of the entire Brahmani up to the delta head at Jenapur, on average and at 75% dependability on an annual basis, comes out to be 19088.61 mm^3 (532.61 mm) and 14447.11 mm^3 (403.01 mm), respectively. For the analysis, daily flow data of Tilga, Gomlai, and Jenapur were collected as shown in Figure 2.

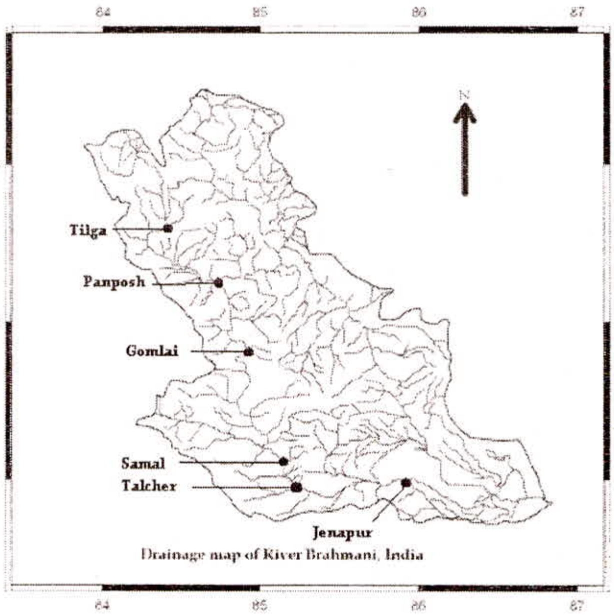

Fig. 1: Brahmani River system in Orissa, India

METHODOLOGY

Minimum In-Stream Flow Requirements (IFR) for Aquicolous Biotopes Maintenance

Minimum in-stream flow for the protection and maintenance of aquatic life considers riverine fishes, macro-invertebrate, underwater vegetation and aquatic microorganisms as primary target species. Flow is required during critical periods in the life stages of these species and for the maintenance of the natural stream flow pattern. That is why some volumes of in-stream flows are needed to maintain these processes.

In the present work the Flow Duration Curves (FDC) technique, which is the second most widely used method (Smakhtin, 2001; Tharme, 2003), were tested and applied to estimate 7-day 10-year flow (7Q10) FDC (Singh and Stall, 1974; Chiang and Johnson, 1976) in Brahmani River. In the analysis, virgin or present-day historical flow records were analyzed over specific durations to produce curves displaying the relationship between the range of discharges and the percentage of time that each of them was equaled or exceeded (Gordon *et al.*, 1992). A flow duration curve of each water year was constructed by plotting and arranging the daily discharge values in descending order. The flow duration curve for various return periods were developed using the characteristics of distribution of probability plots of stream, calculated by the Weibull plotting formula, at suitable time intervals from 0 to 100 percent on the time axis. The developed FDCs were used to evaluate the severity of high, ordinary, and low flow regimes of Brahmani River. The procedure followed to obtain FDCs of various return periods is given below (Sugiyama *et al.*, 2003):

1. After construction of an FDC for each year, read values of daily discharge at every 5% probability of exceedance.
2. Make separate table for each year discharge versus probability of exceeedance.
3. Rank discharge values in ascending order and read from each flow duration curve of a given N year term.
4. 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,

$$P = \frac{m}{(n+1)} \times 100 \qquad \dots (1)$$

   where P is the probability of an event less than or equal to a given discharge value, m is the rank of the event, and n is the number of events in the record.
5. Visually fit a straight line through the estimated values.
6. Using a straight line equation, obtain the discharge value from the best fit line for the chosen probability value for a return period of 10 years.
7. 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%).
8. Plot probabilities of daily discharge values read at suitable intervals and draw a smooth FDC of a return period of 10 years.

Discharges representing specific flow percentiles were calculated from the curves, and then used to produce environmental water demands. The value of probability of exceedance equal to 90% (Q90) was used as EWD to maintain aquatic life in the Brahmani River system.

Stream Self-purification

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, the self purification capacity of Brahmani River is decreasing with time.

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 ($o\text{-}PO_3$), 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.

Phase 1

In phase 1, physically based water quality models developed for Indian river systems for conservative pollutants (BOD, DO, nitrate, phosphate, sulphate, potassium) and non-conservative pollutants (chromium, aluminum and iron) were used to estimate the pollution level in different reaches of Brahmani River after the influx of pollutant discharges either from point sources and/or non-point sources. From observed data it was found that BOD, DO, chromium, aluminum, and iron were mainly discharged from point sources, whereas nitrate, phosphate, sulphate, and potassium were mostly discharged from non-point sources. The governing equations and their solutions used to estimate conservative and non-conservative pollutants values in the downstream reaches after the influx of pollutants can be expressed as follows:

Governing Equation for Conservative Pollutants

The chemical mass balance equation based on the conservation of mass has been used largely for indirect measurement of the sum of point and non-point loads of conservative water quality constituents in the receiving river water from upstream-downstream measurements (Plummer and Back, 1980; Christopherson and Wright, 1981). The equation used to estimate pollution loads, such as Chromium, Aluminum and Iron, in Brahmani River can be written as (Jain, 1996),

$$Q_d C_d = Q_u C_u + \sum_{i=1}^{n} L_i \quad \ldots (2)$$

where Q_u and Q_d are the upstream and downstream flow (m^3/sec), respectively; C_u and C_d are the upstream and downstream concentrations (g/m^3), respectively; and $\sum_{i=1}^{n} L_i$ is the sum of individual loadings, including the effect of any loss or generation within the water body.

Governing Equation for Non-conservative Pollutants

Biochemical Oxygen Demand (BOD_5) and Dissolved Oxygen (DO) are found to be major contributing non-conservative pollutants in Brahmani River. The equations used to estimate the pollution level in the downstream reaches of Brahmani River after the influx of pollutant discharges from point sources can be expressed as (Jha *et al.*, 2007),

$$L = L_0 e^{-(K_1+K_3)t} + \frac{L_d ql\left(1-e^{-(K_1+K_3)t}\right)}{(K_1+K_3)(Q_u+ql)} + \frac{BQ_u\left(1-e^{-(K_1+K_3)t}\right)}{(K_1+K_3)(Q_u+ql)} \quad \ldots (3)$$

$$\begin{aligned} D = {} & D_0 e^{-K_2 t} + \frac{K_1 Q_u L_0\left(e^{-(K_1+K_3)t} - e^{-K_2 t}\right)}{(K_2-(K_1+K_3))(Q_u+ql)} + \frac{K_1 Q_u L_d ql\left(1-e^{-K_2 t}\right)}{K_2(K_1+K_3)(Q_u+ql)^2} \\ & + \frac{K_1 Q_u\left(e^{-(K_1+K_3)t} - e^{-K_2 t}\right)L_d ql}{(K_2-(K_1+K_3))(K_1+K_3)(Q_u+ql)^2} + \frac{K_1 Q_u^2 B\left(1-e^{-K_2 t}\right)}{K_2(K_1+K_3)(Q_u+ql)^2} \\ & - \frac{K_1 Q_u^2 B\left(e^{-(K_1+K_3)t} - e^{-K_2 t}\right)}{(K_2-(K_1+K_3))(K_1+K_3)(Q_u+ql)^2} + \frac{D_d ql\left(1-e^{-K_2 t}\right)}{K_2(Q_u+ql)} - \frac{(P-R)Q_u\left(1-e^{-K_2 t}\right)}{K_2(Q_u+ql)} \end{aligned} \quad \ldots (4)$$

where L is the BOD in water (g/m^3), L_0 is the initial BOD in water (g/m^3), K_1 is the rate coefficient of biochemical decomposition of organic matter (1/day), K_3 is the rate coefficient of BOD removal by sedimentation (1/day), L_d is the concentration of BOD in the lateral inflow to the stream (g/m^3), Q_u is the rate of flow at the beginning of the river reach (m^3/sec), q is the lateral inflow rate (m^2/sec), B is the benthic oxygen demand (g/m^3), l is the distance downstream along the river (m), and t is the travel time (day).

Nitrate (NO_3), ortho-Phosphate ($o\text{-}PO_3$), Sulphate (SO_4) and Potassium (K) are also found in Brahmani River mainly due to the influx from non-point source pollution. The equation used to estimate the pollution level in the downstream reaches of Brahmani River after the influx of pollutant discharges from non-point sources can be expressed as (Jha *et al.*, 2005),

$$\text{Total}-\text{Load}=Q_uC_ue^{-kt}+C_{npx}\left[\frac{(Q_d-Q_u)}{l}x\right]e^{-kt_{npx}}+C_{np2x}\left[\frac{(Q_d-Q_u)}{l}x\right]e^{-kt_{np2x}}+\ldots+C_{np(l-x)}\left[\frac{(Q_d-Q_u)}{l}x\right]e^{-kt_{np(l-x)}}+C_{npl}\left[\frac{(Q_d-Q_u)}{l}x\right] \quad \ldots (5)$$

Here C_{np} is the non-point source concentration (g/m^3), k is the rate of attenuation/decay coefficient (day^{-1}), and t is the travel time (day).

Phase 2

In phase 2, knowing the water quality at different locations, the volume of flow required to maintain river water quality within permissible ranges (Class-C to Class-A and Class-B to Class-A) were estimated from equations (2), (3), (4), and (5) using the Newton-Raphson iteration technique. This is known as EWD for self purification capacity and water quality improvement (EWD$_{\text{water quality}}$). All the parameters used for the analysis in these equations were collected by extensive field surveys and empirical equations developed in the recent past.

RESULTS

Minimum In-Stream Flow Requirements (IFR)

The flow duration curves (7-day mean-10 year return period) for each gaging station were developed using the methodology discussed earlier. Using 7Q10 –FDC of all the sampling stations, the values of different flow indices were computed (Table 1). As explained earlier, the flow indices Q90 was found most suitable as minimum environmental in-stream flow for maintenance of aquatic life, therefore, their values were computed. Moreover, the flow volumes required for the maintenance of aquatic life were also computed.

Furthermore, the results obtained were checked for implementation at Jenapur. At the upstream of Jenapur, Rengali dam has been constructed and regulated flow appears in the river downstream of the dam. Mean monthly flows were found to be higher than the flows prior to the construction of Rengali dam (Figure 2). This indicates a positive impact of a water resources project constructed in the Brahmani basin.

Table 1: Results of Flow Indices in the Brahmani River System

Flow Indices	*Tilga*		*Gomlai*		*Jenapur*	
	Flow Rate (m^3/sec)	*Flow Volume (Mcum)*	*Flow Rate (m^3/sec)*	*Flow Volume (Mcum)*	*Flow Rate (m^3/sec)*	*Flow Volume (Mcum)*
Q90	0.8	25.23	10.3	324.80	16.5	520.35

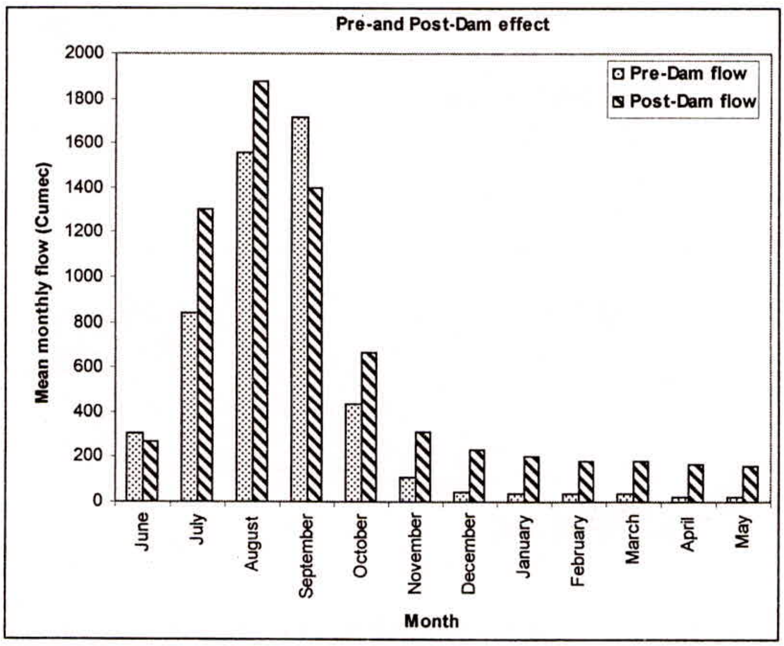

Fig. 2: Mean monthly flow (pre- and post-Dam construction) at Jenapur

Stream Self-Purification

Nine water quality variables, namely Bio-chemical Oxygen Demand (BOD_5), Dissolved Oxygen (DO), Nitrate (NO_3), ortho-Phosphate ($o\text{-}PO_3$), Sulphate (SO_4), Potassium (K), Chromium (Cr), Aluminum (Al) and Iron (Fe), were found to be present at all the sampling locations in Brahmani River. Analysis of water quality samples indicates that the industrial waste water constituents about 8 to 15% and domestic waste water constituents about 80% of the total waste water. In Orissa, since the use of fertilizers and pesticides is at low level compared to other states, the pollution level is not alarming at the present stage. The major problem constituents for the water quality at all stretches seem to be of organic (BOD_5) nature, whereas all other water quality variables were found in the permissible range. Flow-concentration (Q-c) graphs developed for BOD_5, DO and electrical conductivity are shown in Figure 3. It is found that, in the present scenario, the available water is sufficient for self purification and water quality improvement, if the water continues to be used as Class-B and Class-C quality.

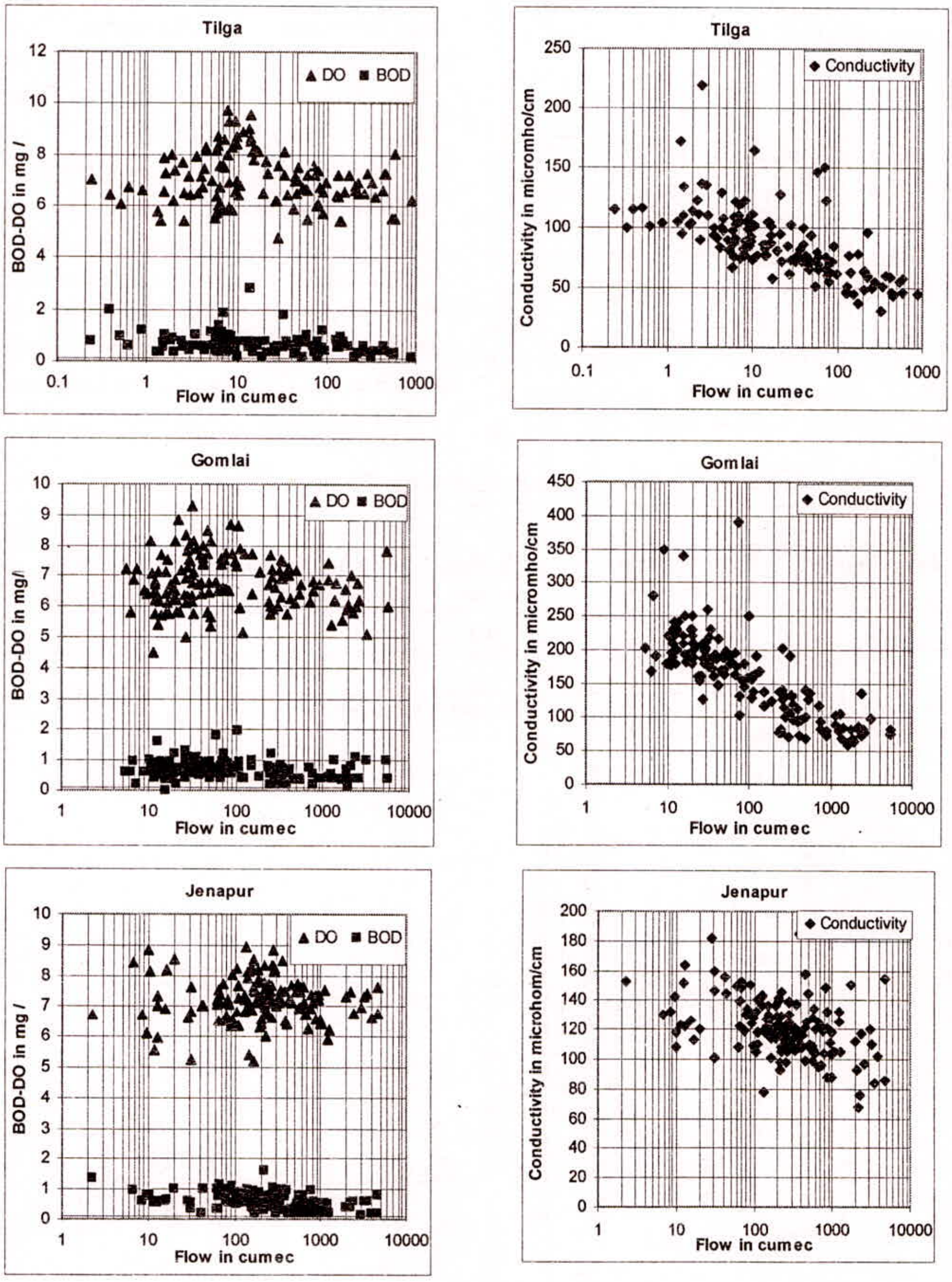

Fig. 3: Flow Vs Water Quality at two Tilga, Gomlai and Jenapur

After computation, the total volume of environmental in-stream flow was estimated as follows:

Table 2: Volume of EWD Required For Different Purposes

Station	*Up to Tilga*	*Tilga-Gomlai*	*EWD $_{total}$*
Minimum In-Stream Flow Requirements (IFR)	25.23 (1.07% MAF)	324.82 (2.38% MAF)	520.34 (2.51% MAF)
Stream self-purification	Nil	Nil	Nil
TOTAL	25.23 (1.07% MAF)	324.82 (2.38% MAF)	520.34 (2.51% MAF)

CONCLUSIONS

Assessment of minimum in-stream flow requirements are essential to maintain aquatic life and ecology. The values were found to be ranging between 1–2.5% of mean annual flow, which is very nominal amount in terms of volume. It is interesting to see that after the construction of Rengali dam, the low flow values at the downstream reaches have increased, which indicates a positive impact of a water resources project. Further, it is found that in the present scenario, the available water is sufficient for self purification and water quality improvement, if the water continues to be used as Class-B and Class-C quality. Water resources planners and decision makers can use these findings as input for the development of new water resources projects in Brahmani River basin.

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