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Establishing environmental flows for intermittent tropical rivers: Why hydrological methods are not adequate?

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Abstract

Effective river restoration and management programs require an understanding of the river's variable flow regimes as well as the physical and ecological perspective of the catchments. Several hydrological methods have been applied in different basins of the world to provide simple and conservative estimates of environmental flows (e-flows) based upon long-term discharge data. The climatic, geological, and hydrological variability, as well as habitat diversity, decides the suitability and application of these methods. In this study, five hydrological methods have been used to estimate e-flows for a plain-fed tropical river (Gomti River, a tributary of the Ganges, India). Long-term flow data were collected from the Central Water Commission, India, from 1978 to 2015. The comparison of e-flows estimates derived from hydrological methods with long-term hydrographs and two environmental categories, namely habitat health classes and environmental management classes, highlights the shortcomings of the hydrological methods in justifying the variable flow requirements of a tropical river. These methods have limitations of integrating diverse aquatic ecosystems, riparian vegetation, fluvial geomorphology, and groundwater contribution in overall flow allocation. This study concludes that for a robust and holistic assessment of e-flows, there is a need for refinement of existing methods. The future studies on e-flows estimation should incorporate: (i) multiple needs of aquatic-riparian habitat during high-flow floods and low-flow droughts, (ii) surface–groundwater interactions to account for baseflows in maintaining lean flows, and (iii) water quality to check the effect of pollution loading and water abstraction on the riverine ecosystems.

Keywords Baseflow · Environmental flows assessment · Hydrological methodologies · River ecosystem · Tropical river

Introduction

River ecosystems have become fragile in the wake of strong structural controls and ever-increasing demands of freshwater from urban, economic, and industrial sectors. Large-scale modifications in the catchments resulted in altered river functions and compromised the resilience of aquatic ecosystems (Dynesius and Nilsson 1994; Pedersen 2010; Grumbine and Pandit 2013; Johansson 2013; McCluney et al. 2014; Hartson et al. 2014; Larned et al. 2010; Stubbington et al. 2018). The problem of impaired river ecosystems and river eco-hydrology

started with rapid urbanization and expansion of the dam-building practices in the developed countries, followed by the similar trends in developing countries (Karr 1991; Dynesius and Nilsson 1994; Poole 2010; Vörösmarty et al. 2010; Arthington 2012; Grumbine and Pandit 2013; McCluney et al. 2014). The conventional river management approach was dominated by structural controls that resulted in diminishing levels of river functions (Bandyopadhyay 2011). The growing recognition of diverse ecological functions, services, and values associated with riverine environments led to the application of simple hydrological models to recommend environmental flows (e-flows) for a river or river stretch. Various studies were undertaken in different parts of the world involving applications of techniques from diverse fields such as geomorphology, hydrology, ecology, fisheries, and environmental studies to assess e-flows in the wake of altered ecosystem functions and riverine services. Some notable studies are from the USA (Bunn and Arthington 2002; Richter and Thomas 2007; Poff and Matthews 2013), Australia (Richardson 1986; Arthington

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et al. 1992; Arthington and Lloyd 1998), South Africa (Acreman et al. 2000; Brown and King 2003; Acreman and Dunbar 2004; Acreman et al. 2014), and Europe (Dunbar et al. 1998; Dakova et al. 2000; Bernardova and Mrazek 1998). The earlier attempts to characterize e-flows were focused on developing static minimum flows, which had recently shifted to measuring dynamic flow components rooted in adaptive management principles. The concept of e-flows evolved firstly from 'minimum flow,' and now includes a more holistic term such as 'ecological flows'—the contours and implications of which are still undergoing expansion (Williams et al. 2019; Wohl 2018). The advancement in scientific understanding of the fragile river ecosystems and understanding of complex interactions among physical, ecological, and social processes has led to the development of the holistic frameworks for the assessment of e-flows. Thus, a broader 'riverine ecosystem' perspective on assessment of in-stream ecology came up, which gradually evolved to more inclusive terms such as 'environmental water allocation' or 'ecological flows' (Moore 2004; Song et al. 2003). The first-ever definition of e-flows was given during Brisbane Declaration held in 2007, which stated e-flows as 'the quality, quantity, and timing of water flows required to sustain freshwater, estuarine ecosystem and the human livelihoods' well-being that depend on these ecosystems' (Brisbane Declaration 2007). The definition was further modified in 2018 to include social and cultural dimensions of e-flow management (Arthington et al. 2018). The revised 2018 Declaration includes the following definition: 'Environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being.' The process of e-flows assessment started with an objective to restore the distorted river flow regimes to the natural or nominal flow regimes (Annear et al. 2004; Brown and King 2003; Acreman 2003; Poff 2014). The European Commission (2015) defines 'ecological flows' in terms of 'hydrological regimes' to counter the ecological deterioration of aquatic systems and achieve good ecological status.

The basis of environmental flows assessment (EFA) methodologies is rooted in the study of relationships between natural flow regimes, alteration to flows, and their ecological responses. The e-flows estimation requires the study of multiple factors such as hydrologic, hydraulic, biodiversity, habitat performance, socio-economic, cultural, and water quality. In the development and application of EFA methodologies, there is a difficulty of integrating all these factors in the model-based framework that are required to maintain multiple ecosystem components. The holistic methods used worldwide overlook the significance of water quality in e-flows estimations. Recently, a few studies have incorporated the water quantity component in the existing holistic E-flow frameworks (Acreman et al. 2014; Dhanya and Kumar 2015; King et al. 2010; Malan and Day 2003; Overton et al.

2014). Some other studies either incorporated the water quality assessment of a few specific stretches or have used water quality parameters to categorize the rivers only; however, Opdyke et al. (2014), Paredes-Arquiola et al. (2014), and Walling et al. (2017) have developed a water quality-based modeling approach to estimate e-flows requirements.

The tropical rivers experience a sequence of variable flow throughout the year, i.e., flood (overbank) flows to maintain abundant riffles, connected and disconnected pools, subsurface flow (interflow), and dry period of flow. It makes these rivers to have a combination of both aquatic and terrestrial habitats (Prat et al. 2014), and the associated aquatic communities are well adapted to this variability (Datry et al. 2014; Stubbington et al. 2018). Tropical rivers have more diverse and unique communities (Stubbington et al. 2018) for which the use of model-based frameworks lacks in incorporating the requirements of flow-sensitive aquatic communities (Bernardo and Alves 1999; Bogan et al. 2017; Theodoropoulos et al. 2019; Chakona et al. 2008; Bêche et al. 2009; Bogan et al. 2015). The tropical countries have distinctive arid and semiarid regions that harbor many intermittent rivers where baseflow plays a critical role in maintaining adequate flows during lean-flow periods (Theodoropoulos et al. 2019).

Some of the perennial rivers of Southeast Asia are experiencing intermittent flows due to increasing demands from domestic, industrial, and agriculture sectors. The central part of the Ganga River basin is characterized by high population density and high water footprints. The over-allocation of water, construction of dams, and diversion projects have severely affected the natural flow regimes of most of the rivers. In India, the first regulation on leaving the minimum flow for rivers was made for Yamuna River, a tributary of Ganges, in 1995 by the Government of India. The minimum flow recommended for improving the water quality of the Yamuna River was estimated to be 10 m^3/sec (MoWR 1994). A few other attempts have been made to evaluate the environmental flow requirements (EFR) of Indian river systems during past few years (Durbude 2014; WWF-India 2012; Bhattacharjee and Jha 2014; Jha et al. 2008; WWF-India 2013; Jha et al. 2014; Babu and Kumara 2009). However, the integrated river basin management plans are still lacking in incorporating the EFA methodologies in the planning processes. Most of these methods are based on arithmetic averages of flow which fail to justify the 'periodicity of flow' and 'flow-habitat suitability'. The EFA methodologies can be categorized based on the modeling framework (Tharme 2003) or a chronological basis (Sharma et al. 2015). For Indian rivers, due to lack of long-term reliable data, and lack of studies on eco-hydrological linkages, river–aquifer interactions, pollution-related aspects, lack of valuation of ecosystem services, and deep-rooted societal–cultural value of rivers, correct reflection of e-flows is a challenging task (Smakhtin et al. 2007; Jain and Kumar 2014; Datry et al. 2017; Stubbington et al. 2018).

The use of hydrological methodologies is easy to use and requires less time as well as in data and information-deficient conditions it provides indicative e-flow estimates (Durbude 2014; Bhattacharjee and Jha 2014; Dubey et al. 2013; Jha et al. 2008; Jha et al. 2014; Babu and Kumar 2009). Further, for intermittent tropical rivers which are primarily fed by rain and groundwater, for example plain-fed tributaries of Ganges, the hydrological methods are not able to address the broad spectrum of variable flow regimes and geomorphological variability of the fluvial systems (Costigan et al. 2017; Cid et al. 2017; Skoulikidis et al. 2017). Therefore, there is a need for refinement of the existing hydrological methods to adequately address the requirements of intermittent tropical rivers (Costigan et al. 2017; Theodoropoulos et al. 2019). The successful attempt to estimate e-flows will further advance efforts to conserve and restore fluvial resources using integrative and interdisciplinary sciences.

In this study, five hydrological methods were used to recommend e-flows for Gomti River, a tributary of the Ganges, India. Long-term flow data for the period of 1978–2015 have been used to compute e-flows estimates from five hydrological methods. The estimates are then compared with long-term hydrographs and two environmental categories, namely habitat health classes (HHC) and environmental management classes (EMC). The findings highlight the shortcomings of the hydrological methodologies in justifying the variable flow requirements of an intermittent tropical river. These methods have limitations of integrating diverse aquatic ecosystems, riparian vegetation, fluvial geomorphology, and groundwater contribution in overall flow allocation. This study suggests the need for developing environmental flow categories suitable for the aquatic biodiversity of tropical rivers to recommend ecological water requirements of the river. This study highlighted the long-term and seasonal water quality scenarios observed at the studied sites. Studies have shown that water quality-based e-flows estimations are not able to quantify the flow requirements. As in heavily polluted areas, the e-flows requirements will surpass the natural flow availability of a river. Water quality is a crucial component to maintain the riverine ecosystem and the social well-being of the riparian inhabitants. However, this can be best addressed by treating pollution before entering the river. The study was conducted for the entire river basin during 2013–2017.

Study area

The study area is the Gomti River basin (GRB) in Uttar Pradesh (UP), India, which is a sub-basin of Ganges (Fig. 1). River Gomti originates from 'Fulhar Jheel' (Gomat Taal) situated about 55 km south of the Himalayan foothills at an elevation of 200 m amsl (above mean sea level) (28°34′ N– 80°07′ E) in MadhoTanda village of the Pilibhit District

in UP (Dutta et al. 2015). It travels about 942 km from its origin and joins River Ganga at an elevation of 62 m amsl at Kaithi in Ghazipur District. The basin contributes 12% of the total geographical area of the state of UP and 3.53% of the Ganga basin (NIH 1998). It is a rain- and groundwater-fed meandering river (Dutta et al. 2011). The river has sluggish flow throughout the year except for the monsoon period, when it receives high discharge due to rainwater runoff. The river turns intermittent at some places due to a shortage of flow in the summer months (April–June), while in monsoons, it does flood occasionally. The e-flows assessment for this study considers three sites of River Gomti, namely Neemsar, Lucknow, and Maighat, based on the availability of long-term data from CWC stations. This river is home to a vast biodiversity of flora and fauna.

Materials and methods

The methodology developed for this study includes the selection of three sites on river Gomti based on the availability of long-term data, namely Neemsar (upstream), Lucknow (midstream), and Maighat (downstream). Further, based on satellite images and flow data, major morphometric and hydraulic parameters were estimated to get the baseline information on the GRB. The e-flows estimates were made using five EFA methodologies, namely—Tennant method, Tessman method, Smakhtin method, Q90–Q50 method, and variable monthly flow (VMF) method. The recommended e-flows derived from these five hydrological methods were compared with the long-term hydrographs to see how recommended e-flows fit the existing variable flow regime of the river. Due to the unavailability of specially devised environmental flow categories for Indian rivers, HHC derived from instream flow regimes (Tennant 1976) and EMCs, as developed by IWMI (2006), were used to compare the results of the five hydrological methods used in this study. The following section provides a short description of the methodology followed in this study.

Morphometric analysis

SRTM-90 m Digital Elevation Database (Shuttle Radar Topography Mission) was acquired from the Consortium of International Agricultural Research Centers-Consortium for Spatial Information (CGIAR-CSI 2017) for the year 2007 at 90 m resolution. RESOURCESAT-1/RESOURCESAT-2: LISS III Satellite images were acquired from Bhuvan for the year 2014 (Bhuvan 2017). The basin area is 31,009 Km^2 with basin length and perimeter of 476.8 km and 1844 km, respectively. The elongation ratio of 0.416 indicates moderate relief and slope for GRB. The elongation ratio varies from 0.6 to 1 for most of the basin, wherein a value less
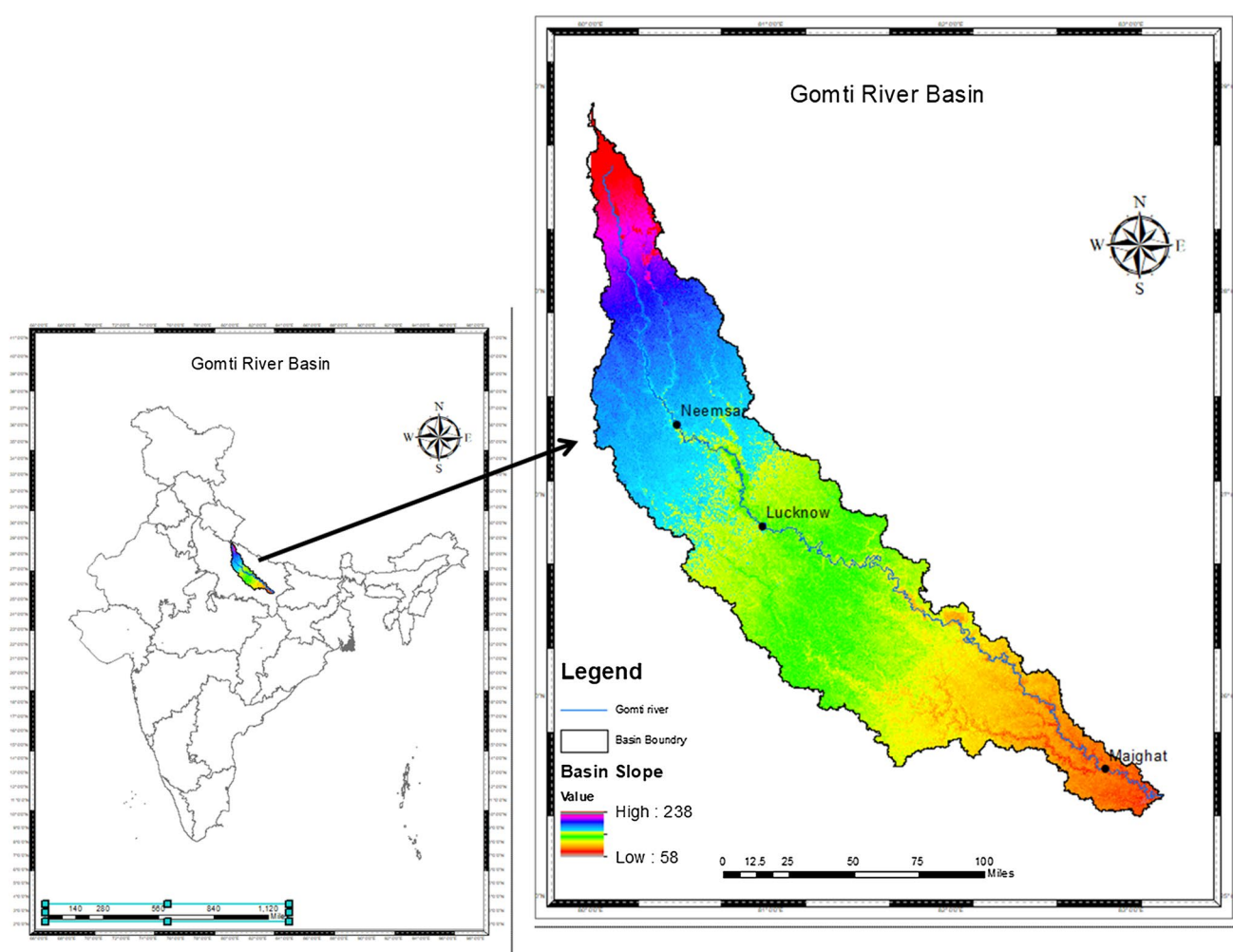
Fig. 1 Gomti River basin showing study sites and basin slope

than 0.5 indicates a more elongated basin. The elongated basin is efficient in the discharge of runoff, and watershed retains water for a more extended period in the basin. The form factor is 0.136, which is a dimensionless quantitative expression of a drainage basin. The low value of the form factor indicates that basin will have a flatter peak of flow for a longer duration. The sinuosity index of the river is 1.97, which indicates a meandering river.

Environmental flows assessment methodologies

For the assessment of e-flows, the mean monthly discharge data and mean monthly water level data were obtained from the Central Water Commission (CWC), India, from 1978 to 2015. The hydrological indicators studied for the selected sites are summarized in Table 1, namely baseflow index (BFI), hydrological variability index (HVI), mean annual flow (MAF), and the number of high- and low-flow months for each site, respectively. For the calculation of baseflow,

the BFI + model of Hydro-office was used (Gregor 2010a). There are multiple methods for the baseflow separation, such as graphical separation methods, filtering separation methods, frequency analysis methods, and recession analysis methods (Rutledge and Mesko 1996; Cheng et al. 2014; Thomas et al. 2015; Jung et al. 2016). For this study sliding interval method, a sub-type of filtering separation method was used for the baseflow separation. In this method, the lowest discharge in half of the interval minus one day [$0.5(2 N* - 1)$ days] is taken before and after the day being considered and assigns this value to that day. The discharge at the point of intersection is assigned to the median day in the interval, and then, bar slides over next day value, and the same process is repeated (Gregor 2010a). These values are connected to give baseflow hydrograph. Flow duration curves (FDCs) were prepared by FDC 2.1 tool of Hydro-office (Gregor 2010b). HVI was calculated based on the FDC method, using HVI = [(Q25–Q75)/Q50], where Q25, Q75, and Q50 are the percentage of flow exceeded

Table 1 Hydrological indicators of selected study sites in Gomti River basin

Study sites	Geographical location	MAF (m³/sec)	Low flow–High flow range (m³/sec)	BFI (Hydro-office computed) Sliding interval method	HVI [(Q25-Q75)/Q50]	No. of LF months, i.e., MMF < 0.4 MAF	No. of HF months, i.e., MMF > 0.8 MAF	Number of intermediate-flow months
Neemsar	27°20′ 46″/ 80°28′ 40″	30.787	1.73–320.57	0.78	0.89	1(May)	4 (July, Aug, Sep, Oct)	6 (Nov, Dec, Jan, Feb, Mar, Apr, Jun)
Lucknow	26°50′ 00″/ 80°57′ 00″	67.46	3.85–916.96	0.76	1.20	2 (Apr, May)	4 (July, Aug, Sep, Oct)	6 (Nov, Dec, Jan, Feb, Mar, Jun)
Maighat	25°38′ 17″/ 82°51′ 47″	234.71	20.83–3545.73	0.69	1.46	4 (Mar, Apr, May, Jun)	5 (July, Aug, Sep, Oct, Nov)	3 (Dec, Jan, Feb)

or equaled to 75%, 50%, 25% of the flow for the period of record, respectively. The higher the variability index, the greater the variable flow regimes.

The hydrological methods selected for conducting this study were the Tennant method, Q90–Q50 method, Smakhtin method, Tessman method, and VMF method. These hydrological methods considered three hydrological seasons to recommend flows, i.e., low-flow requirements (LFRs), high-flow requirements (HFRs), and intermediate-flow requirements (IFRs). Tennant (1976) recommended a portion of MAF as e-flows to maintain the biological integrity of a river ecosystem. A constant percentage of MAF is recommended for low and high flows for different seasons, respectively. This method recommends 20% of MAF as LFRs and 40% of MAF as HFRs to maintain the minimum flow in the stream. This method also recommends a periodic flushing flow of 200% during the monsoon season. Tessman (1980) modified the Tennant's method and included the monthly variations in recommending the e-flows. Each month is assigned one of the three pre-defined categories of monthly flows in the ratio of mean monthly flow (MMF) or MAF (Tessman 1980). This method recommends MMF as the flow to meet the LFRs, 40% of MMF is recommended for HFRs, and 40% of MAF is recommended to maintain the IFRs in the river stream. Smakhtin and Anupthas (2006) developed a method based on the FDC shifting method, where the EFs were recommended based on four pre-defined conditions in terms of percentage of mean annual runoff (MAR). The environmental LFR was assumed to be equal to Q90 (the monthly flow, which is exceeded 90 percent of the time on average throughout a year). The FDCs were constructed using long-term discharge data acquired from CWC, and the tool used was FDC 2.1 tool developed by Hydro-office (Gregor 2010b). FDC is constructed by ranking all the flows recorded from higher to the lowest and assigning the probability or percentage of exceedance to each flow in the rank series. The thumb rules followed in Smakhtin method are as follows: For a basin with highly variable flow, where Q90 < 10 percent of MAR, HFR was set at 20 percent of

MAR. For rivers with a stable flow, where Q90 is higher than 30 percent of MAR, HFR was considered to be equal to zero. Finally, for rivers with Q90 ranging from 10 to 20 percent and 20 to 30 percent of MAR, HFR levels were set at 15 percent and 7 percent of MAR, respectively. The Q90–Q50 method (Pastor et al. 2014) is grounded on the annual flow quantiles which are used to recommend the minimum instream flow for high- and low-flow seasons. In this method, Q90 is considered as the LFRs, and Q50 is considered as the HFRs for the river. FDC software (a tool by Hydro-office) was used to draw FDCs (Gregor 2010b). The Q90 is the minimum flow threshold for low-flow seasons, and Q50 is the threshold for the high-flow season. The VMF method is a parametric method that recommends the EFs requirements based on average monthly flow (AMF) (Pastor et al. 2014). Along with low and high-flow ecological flow requirements, this method also suggests the intermediate-flow requirements to protect the freshwater ecosystems. As per this method, 60% of MMF is recommended as LFRs, 30% of MMF is recommended as HFRs, and 45% of MMF is recommended as IFRs for the river stream.

Environmental categories are defined to reflect specific e-flows needed to maintain ecosystems. Each class specifies an environmental flow scenario from natural unregulated flow conditions. Two environmental categories were considered to conduct this study: first proposed by Tennant (1976) and second by the International Water Management Institute (IWMI) (as described by DWAF 1997). The Tennant's Instream flow regimes recommended e-flows for two periods, which are appropriate for temperate countries. Tennant's recommendations were modified as per Indian monsoon cycle, i.e., the e-flows estimates for April–September as suggested by Tennant were considered for monsoon season in India (June to September), whereas estimates for October–March were considered for non-monsoon season (October to May), and named as HHC, as shown in Table 2.

Another environmental category referred to was given by the IWMI. The Global Environmental Flow Calculator (GEFC) software was used to get the flow estimates

of EMCs.' This software calculates the shifting FDC to estimate the EMCs by 'reducing' the natural hydrological regime on a proportional basis at specific thresholds that indicate specific degrees of ecological disturbance, which could be high, moderate, or low (IWMI 2006). It has six management classes starting from natural (A) to critically modified (F). Class A or 'natural' status of rivers denotes minor modification in the instream and riparian habitat of the river system. Class B denotes 'slightly modified' status mainly due to water resource development and basin modification. Even after modifications, class B rivers have unharmed biodiversity and habitats. Class C depicts a 'moderately modified' category wherein the natural habitat and dynamics of the river biota are disturbed; however, the basic ecosystem functions are still intact. Sensitive species disappear or reduce in the modified extent, and invasive alien species appear. Class D represents the 'largely modified' category in which natural habitat, biota, and basic ecological functioning of the river is highly disturbed. Species richness is lower than expected, intolerant species are negligible, and invasive species flourish well. Class E is designated as 'seriously modified' category in which availability of habitat and its diversity decline; species richness is critically lower, and only robust species flourish. Class F represents 'critically modified' category, which is the extreme level of modifications by anthropogenic actions in an ecosystem and its functions. There is an almost total loss of natural biota and habitat. In some worst cases, irreversible destruction occurs in river ecosystem functions.

The recommended e-flow from HHC and EMC was used to compare the e-flow estimates from five hydrological methods used in this study. The Tennant, Q90–Q50, and Smakhtin methods were compared with the environmental classes as they recommend for two periods only that are low flows and high flows. However, VMF and Tessman methods recommend variable flows; thus, a range was considered to compare results obtained from these two methods. To develop this range, the highest flow and the lowest flow for both the lean-flow and monsoon periods were considered to state the specific class of flow these methods were recommending.

Physicochemical analysis of water

For the physicochemical analysis of river water quality, sampling was performed at the similar sites studied for e-flows assessment. Sampling was performed in the year 2016 and 2017 at Neemsar (upstream), Lucknow (midstream), and Maighat (downstream) during pre-monsoon and post-monsoon seasons. To study the long-term scenario of water quality in River Gomti, secondary data on water quality were obtained from the CWC for the years 2013 to 2015. All the physicochemical parameters were analyzed by following the standard methods, as described in APHA (1998). The physicochemical analysis was performed to understand the water quality status of the river. The water quality prevalent in the river was compared to the Central Pollution Control Board (CPCB) water quality criteria for using the river water for various purposes. The parameters taken into consideration were pH, electrical conductivity, total dissolved solids, temperature, turbidity, biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO). As per the CPCB standards, rivers based on water quality can be categorized in different classes where in the first class (A), the DO of river water should be more than or equal to 6 mg/L and BOD should be less than or equal to 2 mg/L. This water source can be used for drinking purposes without conventional treatment just after disinfection. In the second class (B), DO should be more than or equal to 5 mg/L, and BOD should be less than or equal to 3 mg/L. This water source can be used for organized outdoor bathing. In the third class (C), DO should be more than or equal to 4 mg/L, and BOD should be less than or equal to 3 mg/L. This water source can be used for public water supply after giving appropriate primary, secondary, and tertiary water treatments. In the fourth class (D), DO should be more than or equal to 4 mg/L. This water source is suitable for propagation of wildlife and fisheries. In the fifth and last class (E), the river water source meets none of the above-listed conditions as discussed in class A to D. This water source can be used for irrigation, industrial cooling, and controlled waste disposal purposes. For maintaining good ecological conditions, the optimum range of temperature, turbidity, electrical conductivity, and total dissolved solids is between 22 to 23, 26.5 to 30.5, 300 to 350, and 250 to 300, respectively (Dutta et al. 2017).

Table 2 HHC modified from Tennant's Instream flow regimes in relation to the Indian monsoon cycle. *Source*: Modified from Tennant's Instream flow regimes (Tennant 1976)

Habitat health classes	% of MAF	
	October–March (non-monsoon)	June–September (monsoon)
Flushing or maximum	200	200
Optimum	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	10	30
Poor	10	10
Severe degradation	< 10	< 10

Results and discussion

Recommended E-flows using hydrological methodologies

The results of recommended e-flows by five hydrological methods showed the potential e-flows for River Gomti at three sites. Site-wise estimation is done to consider river variability. The graphs of FDCs prepared to estimate the Q90–Q50 discharge are presented in Fig. 2 for each site. The results of the recommended e-flows by different methods used in this study are shown in Table 3.

The FDC has been shown to illustrate discharge versus percent of time that a particular discharge has equaled or exceeded. The area under the FDC with arithmetic scales gives the average daily flow, and the blue line represents the median daily flow which is the 50% value. Q95 represents the flow rate equaled or exceeded for 95% of the time in a year. Flow rates between Q0 and Q10 are considered high-flow rates with flooding events, flows from Q10 to Q70 are the 'medium' range of flows, while flow rates from Q70 to Q100 are the 'low flows' that characterize the sluggish flow. As the flow rates move from Q95 toward Q100, the lean-flow or drought events follow.

The results of hydrological methods were compared with long-term hydrograph for each site to know how the recommended e-flows fit in the existing long-term flow regimes (Fig. 3a–c). Out of all the methods used, Tessman method gives the highest e-flows recommendations followed, by variable monthly flow, Q90–Q50, Tennant, and Smakhtin method, respectively, for all the sites. Results clearly show that none of the methods used recommends adequate flow to address the flow requirements during the monsoon season. Tables 4 and 5 represent the e-flows requirements to maintain a specific environmental category as estimated by HHC and EMC, respectively. These categories based on ecological water allocation were further compared with the recommended e-flows by the hydrological methods used.

Comparison of recommended e-flows with environmental categories

The comparisons of the results of hydrological methods with the HHCs and EMCs for all the sites show the Smakhtin method recommends e-flows in the 'poor' category, and the Tennant method recommends in the 'good' category. Q90–Q50 recommends different categories at different sites. The Tessman method and VMF method recommend flow between fair and excellent categories. The comparison of the results of hydrological methods with EMCs shows that both

Tennant and Smakhtin methods recommend very low EMC, other three methods Q90–Q50, Tessman, and VMF recommend the higher class for monsoon period respectively, but all these methods recommend low EMCs for the non-monsoon period.

## Physicochemical status of river water

The water quality is an important component in maintaining the healthy ecological conditions of the aquatic ecosystem. The water quality analysis of the river water indicates that the three stretches studied fall under different quality classes in different seasons. In the pre-monsoon season, at Neemsar (upstream region of River Gomti), water quality is found to be falling in-between 'D' and 'E' classes. DO is recorded in the range of 'A' and 'B' class, but BOD demand is recorded high for this region. Thus, this water source is not fit for direct drinking and outdoor bathing, but could be used for public supply after proper treatment. Moving downwards to Lucknow (midstream region), water quality falls in the 'E' class as per the recorded values of both DO and BOD. Water in the middle stretch is highly polluted. In Maighat (lower stretch), the water quality slightly improves as DO concentration improves to class 'A,' but BOD is still in higher concentration falling between classes 'D' and 'E.' In the post-monsoon season in the Neemsar region, water quality has improved to the class 'B' and above, whereas in midstream and downstream region, DO concentration has improved to class 'A,' but the BOD has increased, bringing water quality to class 'D' and below. Other water quality parameters checked for the suitability of water for ecological needs in pre-monsoon and post-monsoon season are shown in Fig. 4a–h.

Discussion

The hydrological methods, when compared with long-term hydrograph, showed the Tessman method is allocating 100% of MMF during the lean period of flow as e-flows. Thus, it will be an unrealistic situation as no water will be there for other requirements such as domestic, agricultural, and industrial purposes (Pastor et al. 2014). This method will also create the situation of flooding during the low-flow season, thus increasing the risk of invasive species (O'Keeffe 2009). VMF is recommending between 30% and 60% of MMF, which is high for the low-flow season and low for the monsoon season (Bond et al. 2008). It is not suitable for intermittent Indian river systems. During the high-flow season, the VMF method allocates 30% of MMF, and the Tessman method allocates 40% of MMF. Thus, the allocation
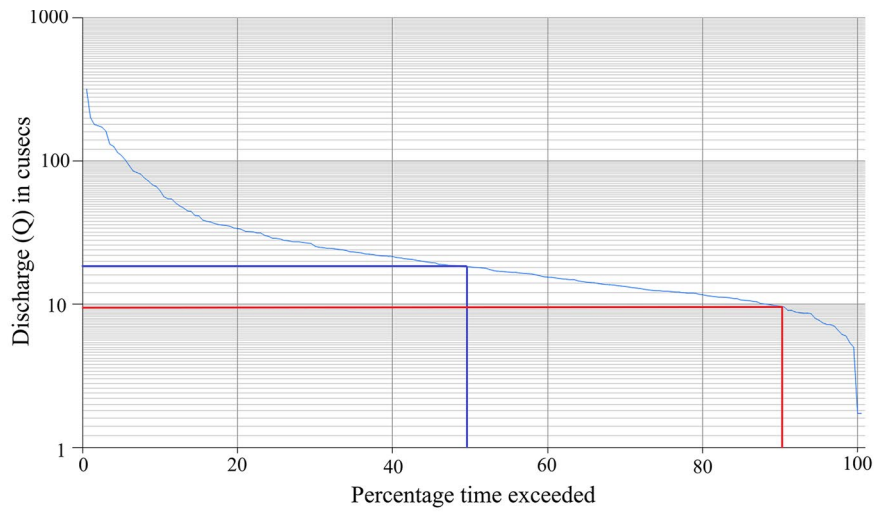
(a) Neemsar
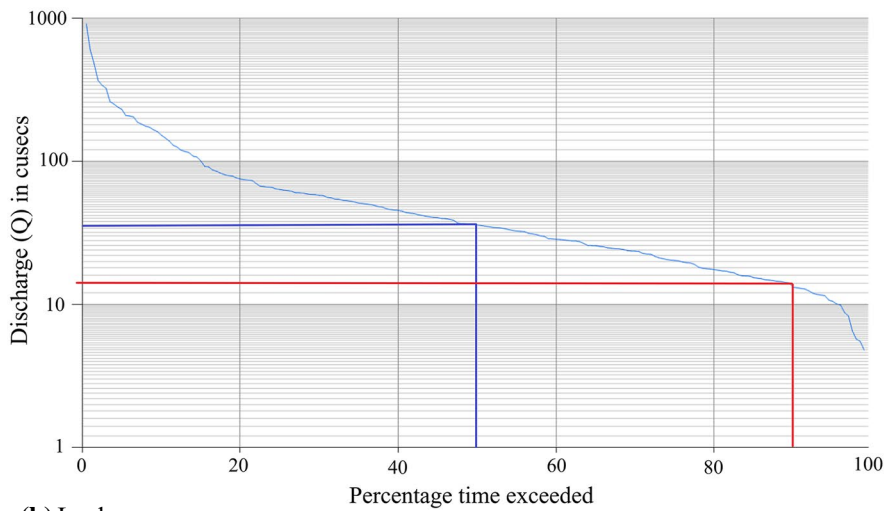
(b) Lucknow
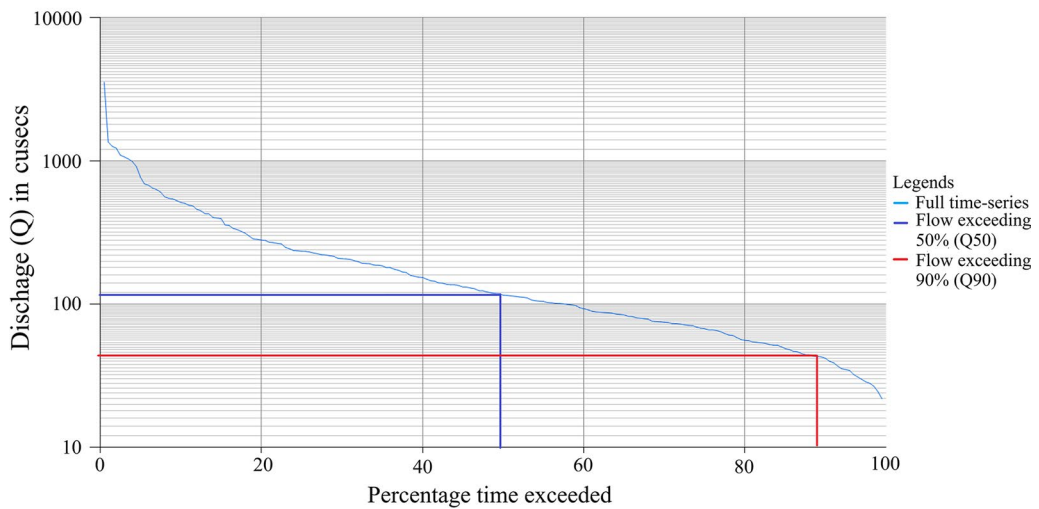
(c) Maighat

◄**Fig. 2** Flow duration curves (FDCs) for three sites **a** Neemsar, **b** Lucknow, and **c** Maighat where red and blue line indicates Q90 and Q50 (Q90 and Q50 are the flow exceeding 90% and 50%, respectively, during the period of record 1978–2015)

for high flow does not differ significantly between VMF and Tessman methods (Pastor et al. 2014). Therefore, both the hydrological methodologies are lacking in recommending the flushing flow requirements of the Indian river in the monsoon season. The variability of Indian rivers plays an important

Table 3 Estimation of the e-flows requirements for Gomti River basin using five hydrological methods

Month	Tennant method	Q90-Q50 Method	Smakhtin method	Tessman	Variable monthly flow
Neemsar	e-flows in cusec				
Jan	6.15	9.61	9.61	12.37	9.63
Feb	6.15	9.61	9.61	12.37	7.53
Mar	6.15	9.61	9.61	12.37	6.60
Apr	6.15	9.61	9.61	12.35	7.41
May	6.15	9.61	9.61	11.78	7.07
June	6.15	9.61	9.61	12.37	6.38
Jul	12.31	18.13	0[a]	16.60	12.45
Aug	12.31	18.13	0[a]	18.75	14.06
Sep	12.31	18.13	0[a]	37.76	28.32
Oct	12.31	18.13	0[a]	20.84	15.63
Nov	6.15	9.61	9.61	12.37	10.66
Dec	6.15	9.61	9.61	12.37	8.72
Lucknow	e-flows in cusec				
Jan	13.49	13.08	13.08	26.88	15.02
Feb	13.49	13.08	13.08	26.88	13.99
Mar	13.49	13.08	13.08	26.88	12.54
Apr	13.49	13.08	13.08	24.96	14.98
May	13.49	13.08	13.08	22.81	13.69
June	13.49	13.08	13.08	26.63	13.33
Jul	26.88	35.67	10.12	36.40	27.58
Aug	26.88	35.67	10.12	55.40	41.61
Sep	26.88	35.67	10.12	83.20	62.61
Oct	26.88	35.67	10.12	41.97	31.48
Nov	13.49	13.08	13.08	26.88	22.80
Dec	13.49	13.08	13.08	26.88	17.96
Maighat	e-flows in cusec				
Jan	46.7	39.89	39.89	94.37	61.20
Feb	46.7	39.89	39.89	94.37	51.75
Mar	46.7	39.89	39.89	86.00	51.60
Apr	46.7	39.89	39.89	62.00	37.20
May	46.7	39.89	39.89	47.00	28.20
June	46.7	39.89	39.89	87.00	52.20
Jul	93.82	115.12	35.39	131.60	98.70
Aug	93.82	115.12	35.39	218.40	163.80
Sep	93.82	115.12	35.39	274.40	205.80
Oct	93.82	115.12	35.39	163.60	122.70
Nov	46.7	39.89	39.89	94.370	81.45
Dec	46.7	39.89	39.89	94.370	66.60

[a]At Neemsar site, the Q90 for the month of July–October is higher than 30% of MAF; therefore, according to Smakhtin method, the recommended HFR is zero for that area

Fig. 3 **a–c** The comparison of results of five hydrological e-flows methods along with long-term hydrograph for three sites **a** Neemsar, **b** Lucknow, and **c** Maighat

(a) Neemsar

(b) Lucknow

(c) Maighat
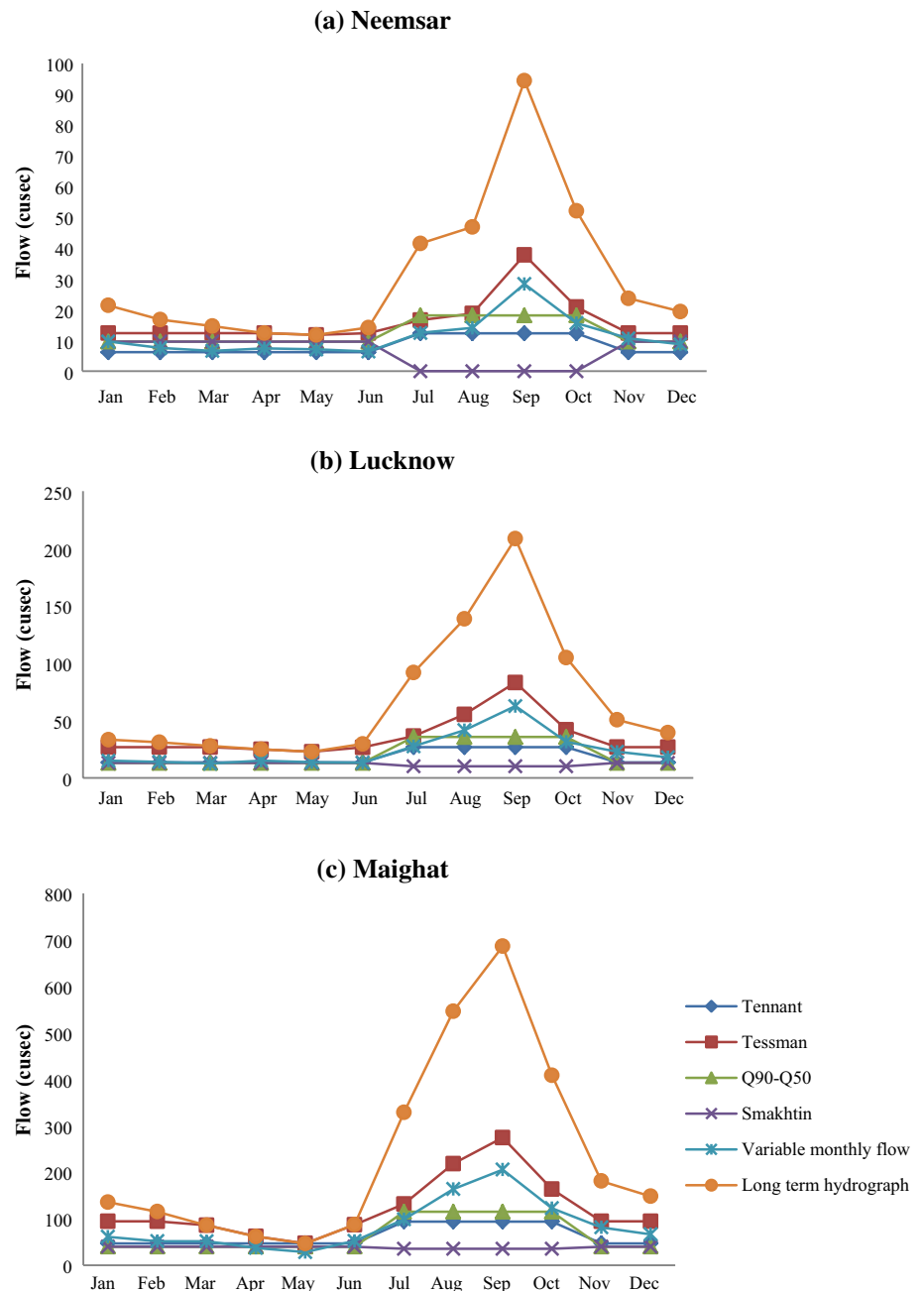
role in maintaining the aquatic ecosystem integrity and shaping the natural flow paradigm (Kale 2002). Remaining three methods, i.e., Q90–Q50, Tennant, and Smakhtin methods, recommend flow for two periods, only constant high flow of 4 months (June to September) and constant low flow of 8 months (October to May). These methods lack in addressing the seasonal flood pulse and lean flow of tropical rivers. This variability influences the ecology of the river, as the movement of water, sediment, nutrient, and organisms from the channel toward the floodplains during the flooding season

and vice-versa in low-flow or baseflow periods is directly dependent on it (Wohl 2018). Variable flow is a master variable in maintaining the aquatic habitat, river morphology, biotic life, river connectivity, and water quality (Karr 1991; Bunn and Arthington 2002; Jain 2015; Joshi 2017). In this comparison, Smakhtin method gives the lowest flows for the monsoon period which is impractical and not suitable for Indian rivers. All the five methods used are not able to address the variable flow requirements of the river studied.

The highlights of the shortcomings of these methods in application to tropical rivers like Gomti are listed in Table 6.

The river water quality recorded at the three studied sites was found poorest in the midstream region in comparison with the upstream and downstream regions. The urbanization and morphometric changes in this stretch have resulted in the degradation of the river water quality in past years (Iqbal et al. 2019). The improvement in the water quality in the downstream region indicates the ability of water to replenish itself as it moves away from the pollution sources (McColl 1974). Water quality has been defined as an essential component of e-flows in all the definitions given so far. However, e-flows assessment methods principally focus on the quantity of water required to maintain ecosystem integrity, whereas very few studies have been developed considering water quality implications (Scherman et al. 2003; Chen et al. 2013; Chaudhary et al. 2019). One approach integrating water quality involves the practice of protective water quality guidelines to recommend a level of resource protection and has never been linked to e-flows (Palmer et al. 2007). A few researchers have considered developing environmental flow requirements (EFR) of a river based on combined quantity–quality-EFR (Liu et al. 2016). These studies have recommended reducing pollution load and meeting both quantitative and qualitative requirements to estimate the e-flows for healthy riverine ecosystems. The drawback of water quality-based e-flows assessment methodologies is that these methods assume the initial river water quality conditions to be constant and do not consider the actual water quality conditions, which could also sharply change both spatially and temporally due to natural and anthropogenic interferences. The water quality-based frameworks can provide recommendations to dilute the pollution load of the river through additional flow augmentation by reducing the allocation for canals. However, for highly polluted river in the urban stretches, the water quality-based e-flow estimates would surpass the flow augmentation possibilities and natural flow available in the river (Chaudhary et al. 2019).

Further, the water quality of the river plays a vital role in defining the habitat suitability to recommend the e-flows for endangered and keystone species. In this case, the two environmental categories used to compare the recommended e-flows, namely HHC and EMC, could not satisfy the e-flows requirements for the river. The Tennant's ecological classes, even after modification, recommend very low e-flows and do not satisfy the ecological flow needs in the study area. The EMCs recommend high e-flows in comparison with HHCs, but they are also lacking in meeting the particular needs of the study area and individual sites. Despite the shortcomings mentioned above in the hydrological methods, there are several factors which

Table 4 Recommended e-flows for fish, wildlife recreation, and related environmental resources using HHCs

% of MAF as per Habitat health classes	e-flows in % of MAF (cusec)		
	Neemsar	Lucknow	Maighat
200	61.56	134.92	469.65
100	30.79	67.46	234.71
60	18.47	40.48	131.0
50	15.39	33.7334	117.5
40	12.31	26.88	93.82
30	9.23	20.24	70.5
20	6.15	13.4	46.7
10	3.08	6.75	23.5

should be considered while establishing e-flows for intermittent tropical rivers, which are summarized as follows:

1. *Requirements during dry periods* The dry period requirements should be calculated based upon the variety of drivers such as endangered species, iconic species, keystone species, and distinct ecosystems present in the study area (Acreman et al. 2014; Theodoropoulos et al. 2019). Baseflow plays an important role in maintaining the integrity of the riverine ecosystems in the low-flow or lean-flow periods. Its contributions sustain the flow in the rivers during low-flow periods. Thus, it is recommended to have adequate inland water storages in the form of ponds, lakes, and small check dams to facilitate the groundwater recharge especially for intermittent rivers. This study emphasizes on bottom-up approach where tributaries can be managed first, and subsequently, the larger river can be approached.

2. *The flow magnitude to maintain the flow variability* The extreme and unpredictable dry and monsoon periods may occur in tropical rivers. The extreme dry period will increase evapotranspiration and off-stream water demands, which may lead to over-abstraction of groundwater (Rossouw et al. 2005; Ivkovic et al. 2009; McDonough et al. 2011). In monsoons, few days have the highest rainfall resulting in floods, which might be followed by days with no or less rainfall. In this case, it is recommended to study the surface and groundwater interactions to measure baseflow as it is an essential component in maintaining the e-flows for tropical rivers (Gardner 1999; Theodoropoulos et al. 2019). Suitable rainwater harvesting sites should be identified to increase the groundwater recharge in the river basin. Also, the water flow velocity in the rapid flowing streams can be reduced by constructing multiple small check dams on lower-

Table 5 Computation of e-flows at selected sites using various EMCs

Environmental management classes	e-flows in % of MAF (Discharge in cusec)					
	Neemsar		Lucknow		Maighat	
	% of MAF (%)	Discharge	% of MAF (%)	Discharge	% of MAF (%)	Discharge
A	66.9	20.68	62.5	42.16	62.9	148.39
B	48.8	15.08	43.1	29.08	43.7	103.10
C	37.7	11.65	31.5	21.25	32.2	75.97
D	29.8	9.21	24	16.19	24.9	58.74
E	23.6	7.29	18.5	12.48	19.7	46.48
F	18.4	5.69	14.2	9.58	15.8	37.28

Fig. 4 a–h Physicochemical analysis of river water for three sites Neemsar, Lucknow, Maighat, respectively, during pre- and post-monsoon seasons for the year 2013 to 2017
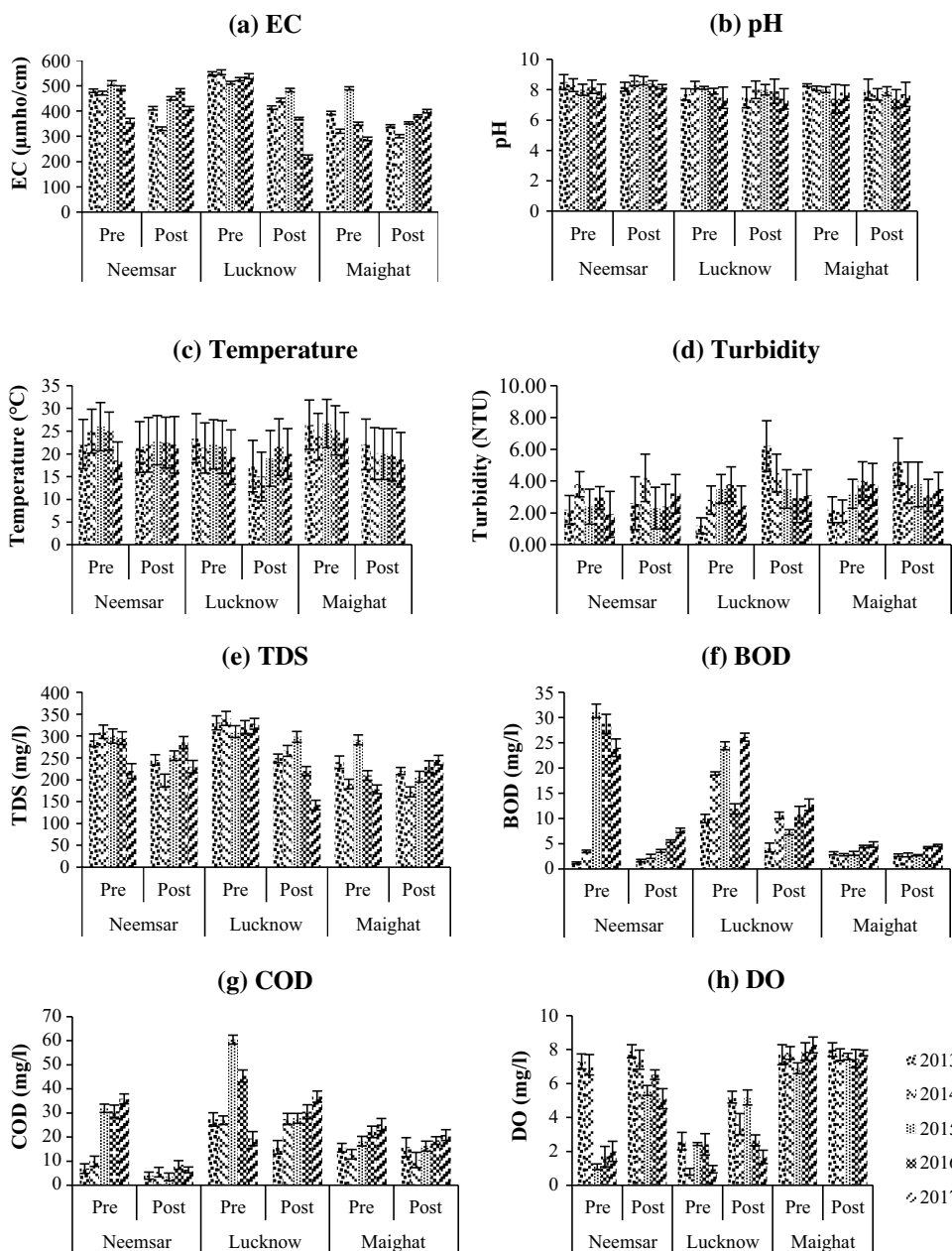
Table 6 Major shortcomings of the hydrological methods used to evaluate the e-flows for Gomti River

Methodology	Shortcomings
Tennant	The HHC based on in-stream flow recommendations was not suitable for tropical countries due to different monsoon patterns from temperate countries
	Flow recommended for two periods, only, i.e., high- and low-flow, and no intermediate-flow requirements were taken into consideration
Q90–Q50	Unilateral prescription of e-flows. Recommends flow for two periods, only, i.e., high- and low-flow, no intermediate-flow requirements were taken into consideration
	It allocates high e-flows for perennial rivers and low in the case of Indian rivers
Smakhtin	Recommends flow for two periods, only, i.e., high- and low-flow, no intermediate-flow requirements were taken into consideration
	It allocates lower in the case of Indian rivers
	It allocates 100% of MAF for Arctic North Pole Rivers, 40–60% of MAF in regions of tropics, and 0–40% of MAF in other parts of the world
	It recommends low flow during monsoon season in comparison with the non-monsoon season for Indian rivers
Tessman	It allocates 100% of MMF available during the lean-flow period; thus, water withdrawal is not possible during the low-flow period
	Though it takes an intermediate period of flow into consideration, a single constant value of flow has been recommended for intermediate flow from November to March
VMF	In this method, the variable peaks are less than the actual natural flow. Thus, the natural variable regimes will be disturbed. It recommends between 30 and 60% of MMF as e-flows, about 60% of MMF is recommended in low flows, whereas 30% of MMF is recommended for monsoon period and 45% of MMF as intermediate flow

order stream which could help in retaining the water in the basin for extended dry periods.

3. *High-flow pulses, small, and large floods* In tropical rivers, floods play an important role in nutrient and sediment transportation. These rivers need high-flow pulses as well as small and large floods for specific timing and duration to maintain its ecosystem (O'Keeffe and Quesne 2009). The specific climatic conditions and geological settings should be taken into consideration while recommending e-flows for intermittent tropical rivers. The prediction of magnitude, timing, and duration of the flow requirements should be incorporated with detailed aquatic biota and riparian vegetation studies (O'Keeffe and Quesne 2009; Rivaes et al. 2017).

4. *Prevention of riparian corridor encroachment* Riparian corridors play an essential role in maintaining the riverine ecosystems (Wohl 2018). Thus, the encroachment and degradation of the riparian corridors should be prevented. Also, there is a need to conduct a detailed study on assessing and maintaining the riparian corridor width along the river channel from the origin of the river to its mouth. After a successful estimation of the required width of the river corridor, the land falling inside the corridors should be registered in the name of the river to prevent any encroachments.

5. *Water quality as a component of e-flows* It will be beneficial to incorporate the water quality-based e-flows estimates to explore the flow augmentation possibilities. It will also facilitate the estimation of the timing and quantity of the required flows during lean-flow periods

to dilute pollution in the urban segment of the river (Chaudhary et al. 2019). Quality-based e-flow recommendations might be useful for maintaining the river reaches present below regulated diversions and storages.

6. *Site-specific environmental categories* The site-specific ecological flow requirements can be addressed through the conduction of extensive studies on the flow requirements of all the associated ecosystems. Multiple studies have been done to assess the habitat suitability index for various species (Moore 2004; Song et al. 2003). However, in developing nations, e-flows recommendations still lack in incorporating the extensive ecological surveys and habitat suitability assessments. The e-flows estimates based upon the short duration flow data cannot handle extreme events as well as large-scale variability due to climate change appropriately (Shenton et al. 2012). The habitat suitability should be assessed to express the entire range of the population of aquatic species.

7. *Future scenarios and broader geographical scales* The e-flow projections based on historical flow data underestimate potential risks of future abstractions and overallocations. The future projections on the water requirements and required management works should be taken into consideration (Dutta et al. 2020). The climatic and geological settings of a river substantially affect the overall frequency, timing, and duration of flow between snow-melt-dominated rivers and rain-fed-dominated river systems, thus harboring different ecological and

evolutionary constraints. In different segments of the rivers in tropical countries, significant variation is present in the biophysical and ecological processes, even more than that have been explored so far. The shortcomings of hydrological methods should be addressed to develop a robust framework for integrating water quality, flow, and ecological components into the e-flows estimation processes for tropical rivers.

Conclusion

The structural control and ever-increasing freshwater demands are resulting in altered river functions and compromised resilience of aquatic ecosystems. Intermittent tropical rivers which are primarily dependent upon groundwater are under pressure to maintain the various ecosystem services due to diminishing flows resulting from rapid decline in groundwater table and increased abstraction for drinking water supply and irrigation projects. Many researchers have attempted to quantify the 'minimum flow' that a river should be having based upon various hydrological methods. However, such methods disregard flow-habitat linkages and do not have rooms for ecological understanding of river systems. In the early phase of e-flows assessment methodologies, the focus was to recommend 'static minimum flows,' but with the refinement of EFA methodologies, more holistic methods were integrated. With a further increase in understanding of diverse ecological functions, services, and values associated with riverine ecosystem, new methods emerged in the literature. However, most of the methods which are in practice for e-flows assessment were developed for temperate rivers that are characterized by more or less uniform flow throughout the year. Researchers in developing countries are still using hydrological methodologies due to the unavailability of real-time data, and these methods are easy to use. All the five methods used in this study are not able to address the variable flow requirements of an intermittent tropical river. Due to variability in climatic conditions, high variability in flow regimes, and high ecological diversity, the hydrological methods fail to recommend the adequate e-flows to address the needs of intermittent rivers as these methods recommend flow to maintain nearly constant water discharge in the river stream for several months of the year. It is important to mention here that e-flows which are generally arrived arithmetically are based on 'averages' and would not be able to restore the ecological integrity of the fluvial systems. For example, a river system has a periodic flushing flow requirement to carry sediment loads and re-establish the ecology. The current approach sets aside certain percentage of flow, say 25% of the annual flow with the assumption that the remaining 75% of the flow can be abstracted from the river without ecological damages. The abstraction may ignore the damages done to the fluvial ecosystems—such as those occurring from alterations in the baseflows or groundwater recharge. Thus, there is much room for refinement of existing methods and the addition of extra steps to make them suitable for intermittent tropical rivers.

The incorporation of water quality as a component in e-flows estimates would be beneficial in incorporating the timing of the allocation of flow during lean-flow periods to dilute pollution. Also, the Indian subcontinent is home to a variety of flora and fauna, thus calling for the development of region-specific ecological categories, which could represent the flow requirements of a river's biodiversity. The refinements in the EFA methods should take the rainfall cycle into consideration to address the variability of flow based on monthly and daily flow regimes. Also, the methodology should adequately address the ground and surface water interactions, importance of inland water bodies in maintaining the flow for extended dry periods, and the importance of adequate width of riparian corridors for rivers. The methodological framework should also balance the water requirements of domestic, agricultural, and industrial needs while fulfilling the ecological needs. The identification of potential groundwater recharge sites and ways to control over-abstraction of groundwater to maintain the baseflow during the lean-flow seasons should be adequately addressed. Appropriate assessments of e-flows can only be made when entire range of ecosystem processes and services carried out by a river—such as sediment transport, movement, and growth of specific fish species, maintenance of baseflows, etc., are clearly identified and incorporated in the assessment. The e-flows should establish the 'periodicity' of the flows as well as different 'flow-regimes' characteristic of a tropical river to justify the flow-habitat suitability. River Gomti is a major tributary of River Ganges, and by restoring its flow, a holistic river basin management plan can be made.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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