Water Policy 22 (2020) 70–84

Hydrological assessment for the availability of water for off-stream uses of Karatoa-Atrai River in Bangladesh

Sara Nowreen[a,]*, Preetha Haque[b], M. Shahjahan Mondal[a] and Rashed Uz Zzaman[a]

[a]*Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh*
**Corresponding author. E-mail: snowreen@iwfm.buet.ac.bd*
[b]*Ryerson University, Environmental Engineering, Toronto, Canada*

Abstract

Explicit consideration of in-stream flow requirement (IFR) has now become almost mandatory in many rivers before irrigation withdrawal is made. Thereby, the primary objective was to evaluate the IFR through hydrological approaches and compare the condition with current flow variability and trends. Flow records were collected from five discharge stations for IFR estimation. Performance of the river was also judged with respect to nine hydraulic cross-sectional data and stage data of ten water-level monitoring stations of Bangladesh Water Development Board (BWDB). Results show that since 2000, the upper Karatoa was able to meet IFR, but the lowest part of the river experienced severe deterioration in addressing its dry season functionality. Also, the decreasing trend in off-stream availability is recognized as a threat to the Singra site resulting from severe aggradations of the river beds. Attention to the less off-stream availability at Singra raises concerns over sustaining the river from drying out. It is now evident that a hydrological approach of IFR is more than just an initial rough estimate. Such a precautionary method works well to provide quick technical support and decision reference for a complex system, in particular, to find specific drying out parts of a river of concern.

Keywords: Flow characteristics; Indicators of hydrologic alteration; In-stream flow; Non-parametric trends and statistics

Introduction

Being in the Indian sub-continent, Bangladesh is branded as a riverine country. Flood management and irrigation development are top priorities among water practitioners for water resource management in Bangladesh. Generally, floods in Bangladesh are visibly more damaging than hydrological low-flow events. In fact, low-flow management does not get much attention. On the other hand, ever-increasing human needs are progressively modifying river flows through the structures of flood control,

doi: 10.2166/wp.2020.034

abstractions for irrigation, urban supply and upstream storage. Consequently, many rivers in Bangladesh are subjected to a stressed situation during the dry season (November–May) (WARPO, 2000). Drastic reduction in the discharge of rivers, siltation, drying of water channels and falling groundwater tables are common characteristics of this dry period. Out of about 310 large and medium rivers flowing through Bangladesh, most rivers have deteriorated severely in the past several decades. For example, 13 rivers have been lost from Bangladesh's topography while seven more are on the verge of death. Dozens of others are drying up gradually. The receding water flow has been steadily reducing these rivers to mere canals. Numerous chars (i.e., river islands formed from sedimentation) have emerged in some main rivers. Since the 1980s, navigable routes have been reduced from 5,200 km to about 3,800 km during the lean-flow period (World Bank, 2006). Many regional rivers have lost their connections with their parent (perennial) water sources. Also, rivers are experiencing significantly increased temporal variability of flows leading to large fluctuation between monsoon and lean-period flow rates. On the one hand, rivers are causing aggravated floods and river erosion during the monsoon and, on the other hand, there are widespread siltation and dry river bed conditions during the lean period. This gives rise to an element of uncertainty in the quantity of water available from the surface water system. In many cases, these alterations in the natural (variability of) flow have adversely affected the ecological and environmental conditions of rivers. Such modifications, in turn, have increased the vulnerability of the people, especially the poor, who are the subsistence users of the river resources.

If this situation continues, it will be hard for the people of Bangladesh to utilize the advantages of the rivers. Irrigation schemes in Bangladesh have always been river-centric as rivers are central to many farmers' lives. A recurring problem in river-flow management is the conflict between water demand and water availability during periods of low-flow. Conflicts between in-stream and off-stream uses of water continue to increase as human water needs increase (Tharme, 2003). There is now a growing recognition that modification to river flows needs to be balanced with the maintenance of essential ecological functions and values. For sustainable use of water resources, it is, therefore, imperative to quantify explicitly what amount of water can be withdrawn for our purposes without permanently losing the river. Most of the surface water is already appropriated by humans, and this is projected to increase with time. Furthermore, global warming can lead to increased evapotranspiration or changes in rainfall pattern, resulting in lower river flow. It is, therefore, imperative to analyse the long history of surface water inflows and predict future surface water availability for Bangladesh. With this backdrop, this research intends to assess the surface water availability after meeting in-stream needs of the Karatoa-Atrai River in Bangladesh. The specific objectives are: to assess in-stream flow requirements; to estimate water resource availability for off-stream uses; and to evaluate the river condition based on existing flow variabilities and trends.

This paper begins with a brief depiction of the study site, followed by the background of the research setting and then a description of the data collection and analysis methods. We then describe our results in relation to the requirement of the Karatoa-Atrai River itself and discuss availability in the context of a sustainable withdrawal policy.

The study site

The Karatoa-Atrai River is a trans-boundary river in Bangladesh that was one of the main branches of the old course of the Teesta River before the great earthquake and flood of 1787. After the Teesta had abandoned its old route, Karatoa-Atrai gradually degraded and was entirely cut off from the original

Teesta. At present, the Karatoa-Atrai originates in a beel, or depressed area, of Baikunthapur in India and initially enters into Bangladesh (latitude 26°28′ and longitude 88°36′) at Bardeshwari in Panchagarh district. It runs towards the south up to Sahamjhiaghat before entering India again and running for 50 km within India. The river re-enters Bangladesh (latitude 25°10′ and longitude 88°46′) at Naogaon, flows southward, meets the Little Jamuna (this Jamuna is not the Brahmaputra-Jamuna, it is another river flowing through the district of Naoga) near Rasulpur, and ultimately falls at Hurasagar. This is a long river with a total length of about 455 km. For the present analysis, the river has been divided into two reaches, namely, Karatoa and Atrai. The upper reach is considered to be Karatoa, which extends from Panchagarh to Dinajpur before entering into India, and the lower reach is considered to be Atrai, when it re-enters into Bangladesh from Naogaon and flows up to its outfalls at Hurasagar River. The river is the main system draining a large part of the north-west region of Bangladesh. There are 14 water level and five discharge measurement stations on this river. Water level measuring stations are located at Bardeswari, Panchagarh, Debiganj, Khansama, Bushirbandar, Sahamjhiaghat, Chak Hariharpur, Mohadebpur, Atrai, Singara, Astamanisha, Gumani, Dohakoladanga and Baghabari. Discharge stations are at Panchagarh, Bushirbanqar, Mohadebpur, Atrai and Singara. Figure 1 shows the location of the measuring stations. The highest recorded flow measured at Panchagarh (Station ID: SW140) was 1,630 m^3/s in 1968. Notably, the 95th percentile and 5th percentile discharges for the same station show 3.62 m^3/s and 206 m^3/s flow. Moreover, the same gauge station reports 67.08 mPWD (unit in metre concerning public works datum) and 69.88 mPWD water level for the 95th and 5th percentiles, respectively.

Data and method

Preparation of data

According to the data availability of at least 25 years of record, five discharge measurement stations and ten water level measurement stations of Bangladesh Water Development Board (BWDB) were selected for the study. The selected gauging stations are listed in Table 1 with the available record length. The record length varies considerably. The smallest record length is 25 years and the largest is 50 years. The average record length is 33 years and the standard deviation is 9.1 years. In addition to the measured fortnightly discharge dataset, daily (generated) mean discharge data (up to 2006/07) that are stored at BWDB were also collected. The analysis is also supplemented by nine nearby cross-section site records mentioned in Table 1.

As BWDB does not measure discharge daily but measures daily river stages, MDD (mean daily discharge) was obtained from the rating curve using the corresponding observed daily water level. Power type equations were selected separately for wet (June–October) and dry (November–May) seasons for establishing rating curves. The statistical tests used in this paper are of the non-parametric type, which avoids hypothesis regarding the essential distribution. Anomalous data for each gauging station were marked using both graphical plots and box plots of R statistical package (R Core Team, 2016) and were removed from the datasets applying judgement. Initially, the data were screened to get a temporally uniform, continuous dataset over all the selected locations ($n > 5,500$, Figure 1) for each year. In order to get error-free estimates, water level values beyond the range of the 95th percentile of the selected locations of each year were omitted from further analyses, resulting in at least ~4,500 locations for each year. A plot of each of the data series was made in conjunction with looking at the history of

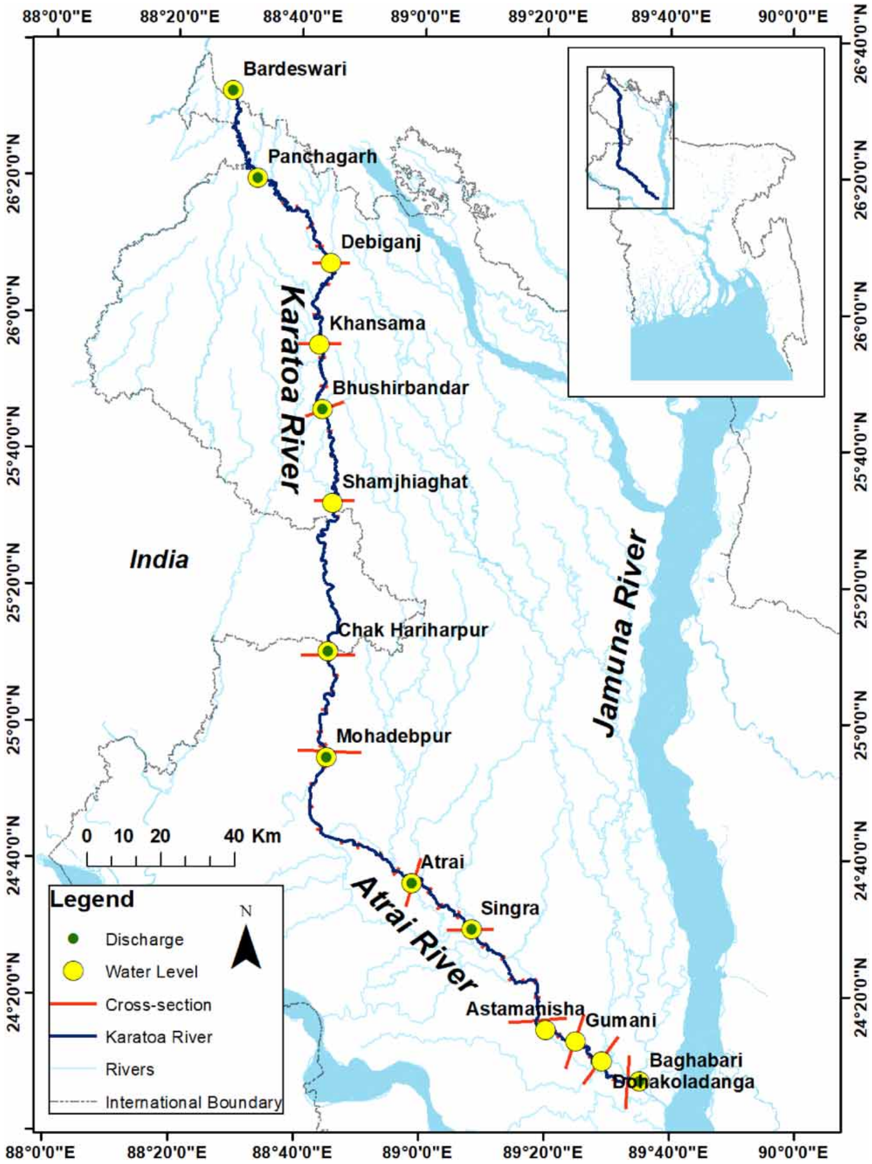

Fig. 1. Karatoa-Atrai River, Bangladesh with locations of its hydrological stations.

the data series to form a subjective judgement. The plots of the data series under study were not found to show any instability in mean low-flow value.

Method

There is no widely accepted single flow value or threshold level that will better characterize low flows concerning the conservation of natural morphology and ecosystem or aquatic organisms. Therefore, threshold level selection of an in-stream flow is critical. The value is dictated by a function of the

Table 1. Selected gauging stations and their corresponding dataset used for the hydrological assessment of Karatoa-Atrai.

		Data period			
River	Station ID (station name)	Water level (mPWD)	Mean daily discharge (m^3/s)	Fortnightly discharge (m^3/s)	Nearby cross-section station ID (data period)
Karatoa	SW 140 (Panchagarh)	1981–2014	1964–2006	2007–2015	–
	SW 141 (Debiganj)	1985–2014	–	–	RMKAG5 (1994–2013, total 6 measurements)
	SW142 (Khansama)	1985–2014	–	–	RMKAG8 (1994–2013, total 7 measurements)
	SW 142.1 (Bhushirbandar)	1981–2014	1964–2006	2007–2015	RMKAG12 (1994–2014, total 6 measurements)
	SW 143 (Shamjhiaghat)	1985–2014	–	–	RMKAG15 (1994–2014, total 6 measurements)
Atrai	SW 145 (Mahadebpur)	1985–2009	1973–2006	2007–2014	RMKAG22 (1994–2013, total 5 measurements)
	SW 147 (Atrai)	1981–2009	1964–1994	2007–2014	RMKAG31 (1994–2014, total 5 measurements)
	SW 147.5 (Singara)	1983–2006	1983–2006	2008–2014	RMKAG35 (1994–2014, total 5 measurements)
	SW 149 (Astamanisha)	1981–2014	–	–	RMBG9 (1973–2001, total 7 measurements)
	SW 150 (Dohakoladanga)	1981–2010	–	–	RMBG4 (1973–1996, total 6 measurements)

objectives pursued. Notably, an extensive amount of literature exists on the selection of approaches to determine in-stream (or environmental) flow requirement of rivers (Baghel *et al.*, 2018; Sharma, 2019). These are called in-stream flow methods because they deal with flows ‘in the stream’. There is no single technique or combination of techniques that satisfy all conditions of rivers. In a review of the status for determining environmental flows, Tharme (2003) recognized the existence of 207 individual methodologies, recorded in 44 countries around the world. These methodologies are broadly categorized into four major distinct methods (as shown in the Supplementary material, Table S1): hydrological, hydraulic rating, habitat simulation and holistic/integrated methodologies (Zeiringer *et al.*, 2018). Some methods (i.e., hydrological, hydraulic and habitat) are quantitative by nature, focusing on flow records but leaving the river-ecosystem functions largely implicit. On the other hand, the holistic method tries to include all the functions of the river-ecosystem, but is commonly based on expert decision and thereby difficult to reproduce. Each method has its strengths and weaknesses and differs in its data requirements, procedures for selecting flow requirements, ecological assumptions and effects on river hydraulics. This raises the problem of which technique is appropriate in a certain context. It should be noted that the hydrological method, often regarded as the simplest approach, is the most widely used around the globe (Tharme, 2003). In particular, this method can be applied rapidly at a large number of sites as a first estimate of the likely quantities of the in-stream requirement. However, this assessment may provide an initial ‘low confidence’ estimate. Hence, based on data availability as well as time and budgetary constraints, the hydrological approach was selected as a suitable initial stage of research method to examine in-stream flow for the Karatoa-Atrai River. In this study, three methods of hydrological approach were used for assessing monthly in-stream flow: (i) Tennant or mean annual flow (MAF) method, (ii) flow duration curve (FDC) method and (iii) constant yield (CY) method. Although these methods were designed for rivers in North America and fish, engineers in Bangladesh have been using these approaches for recommendations about the amount and timing of water flows needed to support ecosystem health (e.g., Rahman, 1998; Hossain & Hosasin, 2011). Side by side, to date, a large number of hydrological indices have been commonly taken to quantify river flow conditions using IHA (indicators of hydrologic alternation) method (e.g., Mathews & Richter, 2007; Aguilar & Polo, 2016; Rahman *et al*., 2017). The IHA tool has also been widely used to analyse hydrological alterations in a large number of areas, like the Yellow River in China (Zhang *et al*., 2018), the Nakdong River in Korea (Lee *et al*., 2014) and rivers in Europe (e.g., Peres & Cancelliere, 2016; Pfeiffer & Ionita, 2017). Therefore, several low-flow indicators of IHA were used to determine low-flow thresholds for annual as well as for high-flow seasons (Zhang *et al*., 2015; Liu *et al*., 2017). The selected hydrological methods are explained below.

The Tennant method, also known as mean annual flow (MAF) method, is the most widely known and is recognized by 16 US states. A flow recommendation was specified by selecting the desired classification, e.g., 10% for poor quality habitat (survival), 30% for moderate quality habitat (satisfactory) and 60% for excellent quality habitat; and multiplying MAF by the corresponding percentage. The FDC method includes the provision to eliminate abnormal events, after which the recommended flow for in-stream protection is set at the 90th percentile (defined here as the flow $\geq$90% of the time) for low-flow months and the 50th percentile during high-flow months. In this case study of Bangladesh, June to October was considered the high-flow months and November to May the low-flow months. The constant yield method uses a combination of the median flows for each month in two different ways. In the first method, the median flow of each month was computed considering the entire period of the available record. In the second method, median monthly flow for each month of each year was computed separately, and then the median of these values was taken as the median for the given month over the entire period of the record. The IHA tool consists of a total of 67 statistical parameters, subdivided into two groups, 33 IHA parameters and 34 environmental flow component (EFC) parameters. In this study, historical changes to river flow were quantified and characterized using non-parametric (percentile) statistics. Such distribution-free tests were chosen because they are based on fewer assumptions (e.g., they do not assume the output data to be normally distributed).

Next, the difference between estimated monthly in-stream flow and the corresponding IHA indices (e.g., monthly medians; 1-, 7-, 30- and 90-day minimum flow; extreme low peak; extreme low-flow threshold) were compared. These comparative studies helped to produce the flow value that was available monthly for off-stream use. In addition to that, both the lowest river stage and the corresponding lowest discharge trends (i.e., Sen's slopes) were compared to identify whether the river was silting up or not. Apart from the desktop calculations, some stakeholder consultations were carried out in five locations (i.e., discharge observation points) through field studies to achieve meaningful outcomes on determining the adequacy of river stages required for the sustainability for irrigation and the protection of aquatic life in the northwest region of Bangladesh.

Past studies in Bangladesh

As far as low-flow studies of Bangladesh are concerned, several important works have estimated the in-stream flow of several rivers, namely, the Surma, Kushiyara (Bari & Marchand, 2006), Teesta (Mullick *et al*., 2013), Gorai (Moly *et al*., 2015; Rahman *et al*., 2017), Dudhkumar (Hossain & Hosasin, 2011), Halda (Akter & Ali, 2012), Turag (Rahman *et al.*, 2013), Ganges (Gain *et al.*, 2011), etc. The National Water Management Plan (NWMP) of Bangladesh reported month-wise dependable flows for major and regional rivers assessed by frequency analysis of monthly flow data (WARPO, 2000). The NWMP also considered the minimum flow requirement of the Lower Meghna River, studied by Chowdhury & Haque (1990). Decade-wise changes in discharge were reported for the Gumti River (Chowdhury, 1979), Ganges and Brahmaputra (Chowdhury & Hossain, 2003; Mondal *et al.*, 2010). However, in general, discharge measurements are rarely precise in the low-flow range. The lack of available (quality) data is generally a problem, especially in low-flow analyses. Regionalized methods are often used for transferring information about low-flow, especially to ungauged basins as depicted by Blöschl (2013), Laaha *et al.* (2013), and Salinas *et al.* (2013). Furthermore, low-flow frequency analyses and FDC methods were mostly performed through various distribution statistics for different regions of Bangladesh, namely, studies by Bari & Islam (2006) and Bari & Sadek (2002).

Results and discussion

Analyses of nine selected water level stations indicate that there exists stations with significant (2) increasing, (3) decreasing and (2) no change trends in lowest water levels. Among five discharge stations, three stations were indicative of increasing in minimum discharge and two stations had no change in minimum discharge. A brief summary of these analyses is shown in the Supplementary material, Table S2. A comparison of both the lowest water levels and minimum discharge in Karatoa-Atrai River indicated that many parts of the river were either being scoured or silted up. For example, the upper most part of the river (at Panchagarh) showed a decreasing trend in the lowest water level and increasing trend in minimum discharge. This reflects severe scouring occurring at this (Panchagarh) station. Supplementary material Table S1 shows that among the three stations with the lowest water level trend decreasing, two stations were being scoured because minimum discharge showed no trend. In the Singara station, while maximum discharge was showing a decreasing trend, the highest water level was increasing. This is an indicator of siltation occurrence. Again, the same station showed no trend in lowest water level and a decreasing trend in minimum discharge, reflecting siltation. Notably, this station did not have the data of the recent 10 years to indicate the new river bed condition. Evidence from the historical cross-section changes (as seen in Supplementary material Figure S1) in the Karatoa-Atrai River channel also indicate lowering of the highest bed level supporting siltation of the river bed for four stations and deepening or scouring of the highest bed level for three stations. A summary of the plots is provided in the Supplementary material Table S1.

In general, April is the driest month in the long time-series showing the lowest river flow. On the other hand, July and August are the highest flow months for the Karatoa and the Atrai, respectively. On average, 100–350 m^3/s median flow was observed during the wet months (June–October) with sharp peak flows rising up to 1,200 m^3/s. As presented in Table 2, extreme low-flow events (e.g., $Q_{min\text{-}1}$, $Q_{min\text{-}3}$, $Q_{min\text{-}7}$) were always less than that in the poor condition (i.e., 10% mean annual flow) of the river system. Therefore, according to Tennant's formula, the river is in less than poor conditions during the dry period. In contrast, July, August and September showed more flow than the flushing flow (200% of average flow) except for the Atrai station (see Figure 2). This implies that Tennant's formula either overestimated (underestimated) the low-flow (high-flow) or the river was in extreme condition. The latter condition could be due to too much low-flow in the dry period and too much high-flow in the wet period. Figure 2

Table 2. Low-flow indicators that are estimated for the low-flow months (November to May) including in-river flows estimated through different hydrological IFR methods.

In-stream flow (Nov-May)	Description	Panchagarh SW140	Bhushirbandar SW142.1	Mohadebpur SW145	Atrai SW147	Singra SW147.5
Flow duration curve	90th percentile	6–27	13–75	**10–**63	**10–**211	55–224
Constant yield (method 1)	Median flow (w.r.t. annual time series)	6–15	13–33	**10**–40	**10**–103	12–131
Constant yield (method 2)	Median flow (w.r.t. long-term time series)	6–14	14–34	**10**–40	**10**–105	**8**–138
Tennant method	30% MAF (fair or degrading)	15	33	39	45	39
or	10% MAF (poor)	5	11	13	15	13
Mean annual flow (MAF)	<10% MAF (severe degradation)	≤**5**	≤**11**	<13	<15	<13
Low-flow observations	Env. low-flow = median values of low flows of each month	7–14	15–31	15–39	16–99	26–135
	10th percentile	**3–**8	**7–**16	**4–**26	**1**–43	**6–**79
	25th percentile	**4–**12	**9–**22	**7–**33	**4–**63	**17–90**
	$Q_{min\text{-}1}$ = annual minima, 1-day mean	**4**	**10**	**7**	**2**	**5**
	$Q_{min\text{-}3}$ = annual minima, 3-day means	**4**	**10**	**7**	**3**	**6**
	$Q_{min\text{-}7}$ = annual minima, 7-day means	5	**10**	**7**	**4**	**7**
	Q_{min-30} = annual minima, 30-day means	5	12	**9**	**7**	16
	$Q_{min\text{-}90}$ = annual minima, 90-day means	6	14	13	12	23
	Extreme low peak = median values of extreme low flow event	**3**	**8**	**7**	**5**	**4**
	Extreme low-flow threshold = an initial low flow below 10th percentile of daily flows for the period	5	10	10	10	11

Underlined values with bold font show annual lowest threshold rate and bold values point towards the flows that were underneath the threshold flow.

also shows monthly medians and different percentages of flow along with different in-stream flow requirements (IFR) estimated under different IFR methods. Finally, in-stream discharge is considered the average of all hydrological methods during the dry-flow months. However, for the high-flow months, the environmental low-flow that has been calculated by the IHA software is considered the in-stream flow.

Traditionally, a single IFR value was used as the minimum flow, below which no human influence should take place. With time, attention was shifted towards methods that consider the flow regime with some degree of variability to maintain the natural morphology, ecosystem and socio-cultural dimensions (Acreman & Dunbar, 2004; Taylor *et al.*, 2016; Magdaleno, 2018; Anderson *et al.*, 2019). Considering June to October as high-flow months and other months as low-flow, estimated values of IFR thresholds and medians along with coefficient of dispersions and trends (i.e., Sen's slope) are provided in Table 3 for each month of the river. The existing flow pattern (as seen in Table 3) of the river proves that the in-stream flow requirement was not met during the low-flow months with the exception of April and May at the upper part of the Karatoa River. Fortunately, low-flow medians showed increasing trends for the river with an exception in the lower parts of the Atrai. Particularly, November at the Atrai station, and November–January and May at Singara station show a decreasing trend during the low-flow period.

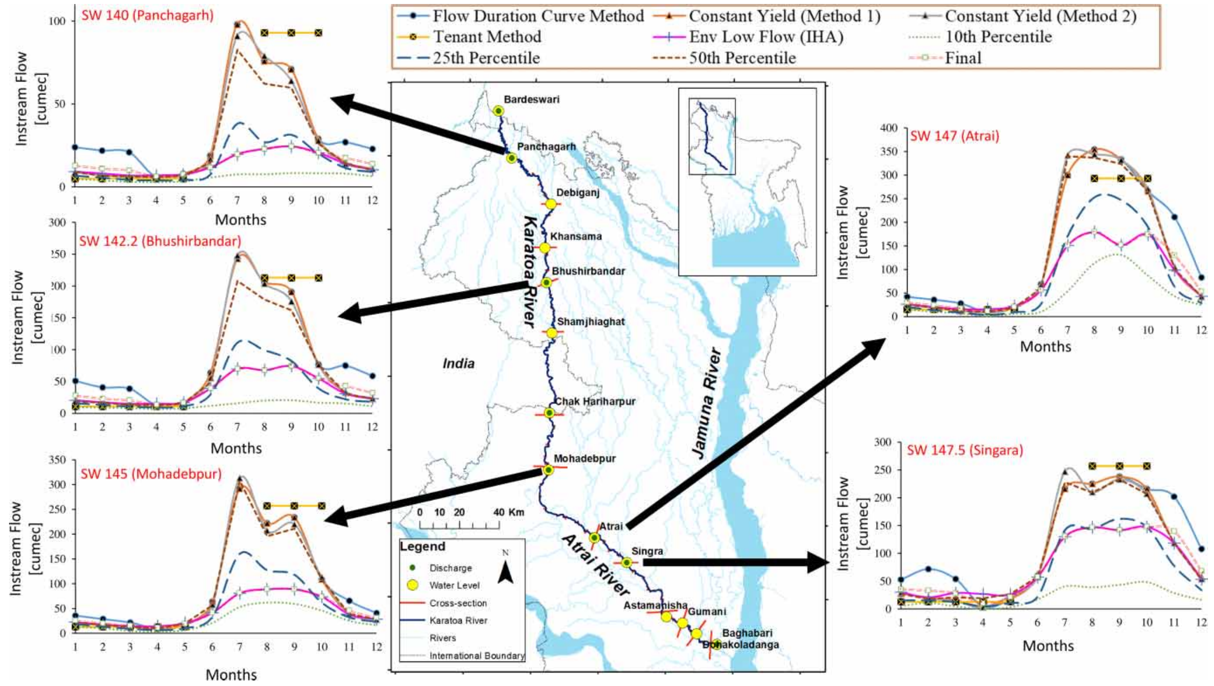

Fig. 2. Monthly low-flow characteristics for the selected five monitoring stations, namely, Panchagar, Bhushirbandar, Mohadebpur, Atrai and Singara of the Karatoa-Atrai River, respectively.

December at Atrai station and February in Singara showed no change over the time. On the other hand, July to October months can be characterized as excessive high-flow showing downward trends with exceptions at Panchagarh station, June and August at Bhusirbandar station, October in Mahadebpur and June–July at Atrai station. The lowest part of the Atrai (at Singara station) was mostly in a critical condition. Notably, dry season satellite (i.e., Google earth) images also showed heavy sedimentation narrowing down the river width, particularly in the lowest Atrai portion.

In general, the dry period off-stream water showed almost invariably negative values in the time series plots in Figure 3. An implicit assumption in this inference is that huge volumes were abstracted for irrigation or too many structural interventions, e.g., small scale road bridges, have altered the flow. Field visits also confirmed that abstraction occurred by constructing several local cross-dams at 1–2 km upstream for the Chalaan Beel irrigation. A pattern of abundant flow year followed by several years of scarce (or decreasing) flows was also visible from the annual time series plots for the lowest part of the Atrai (Figure 3). In contrast, scarcities during the wet season are rarely observed at the same station, e.g., Singara (Figure 4).

The ranges of the computed off-stream flows are summarized in Table 4 along with the field visit comments. Scarcity for the upstream stations, namely, Panchagarh and Bhushirbandar continued until the shift occurred in 2000. Since then, only a little amount of abundance in the flow has occurred. However, the cross section at Bhusirbandar (Supplementary material, Figure S1) does not show any change between 1999 and 2002 in support of such alteration behaviour. As per consultation with local stakeholders of the Panchagarh (SW140) site, illegal sand mining and stone lifting is the leading cause behind the deepening of the river bed, although timeline analysis confirmed the reduced water flow from upstream in recent years. A field visit at Bhusidbandar (SW142.2) found that this site has been

Table 3. Existing flow characteristics and computed in-stream flow.

			Monthly discharge (cumec)											
			LF months					HF months					LF months	
River	Station name (ID)	General statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Karatoa	Panchagarh (SW140)	IFR	13	11	10	6	8	12	20	23	24	21	18	14
		Median	**9**	**7**	**6**	6	7	17	91	79	64	28	**14**	**11**
		CD	4	4	3	5	4	14	64	47	43	9	4	3
		Sen's slope	0.2	0.2	0.2	0.2	0.2	0.3	0.9	0.8	0.1	0.1	0.2	0.2
	Bhushir-bandar (SW142.1)	IFR	28	23	21	14	17	39	70	68	74	55	43	32
		Median	**20**	**17**	**14**	14	17	56	248	204	176	77	**35**	**24**
		CD	7	6	4	6	8	42	132	105	116	48	14	9
		Sen's slope	0.3	0.3	0.2	0.3	0.3	0.8	−2.3	1.1	−1.0	−0.1	0.2	0.2
	Mahadebpur (SW145)	IFR	26	20	16	11	19	42	81	89	89	74	46	31
		Median	**22**	**17**	**13**	**10**	19	58	313	207	220	113	**40**	**28**
		CD	7	6	5	4	11	46	164	115	156	77	13	6
		Sen's slope	0.6	0.3	0.1	0.2	0.1	−0.4	−9.7	−2.7	−4.3	0.3	0.6	0.5
Atrai	Atrai (SW147)	IFR	30	24	17	11	21	56	151	179	152	174	129	53
		Median	**26**	**20**	**12**	**10**	**20**	68	342	344	332	270	**105**	**43**
		CD	8	7	7	9	13	60	187	135	128	89	62	21
		Sen's slope	0.2	0.4	0.1	0.1	0.3	0.5	1.1	−4.0	−2.5	−2.4	−0.8	0.0
	Singara (SW147.5)	IFR	40	36	40	17	39	77	147	180	171	177	155	79
		Median	**30**	**19**	**14**	**3**	**24**	**58**	247	210	233	207	**119**	**54**
		CD	12	11	18	5	22	55	69	104	137	89	49	33
		Sen's slope	−1.8	0.0	0.2	0.6	−0.7	−1.6	−2.3	−5.0	−7.0	−3.8	−3.5	−2.5

Underlined values with bold font point towards the flows that were underneath the in-stream flow requirement (IFR).

LF, low-flow; HF, high-flow; CD, coefficient of dispersion.

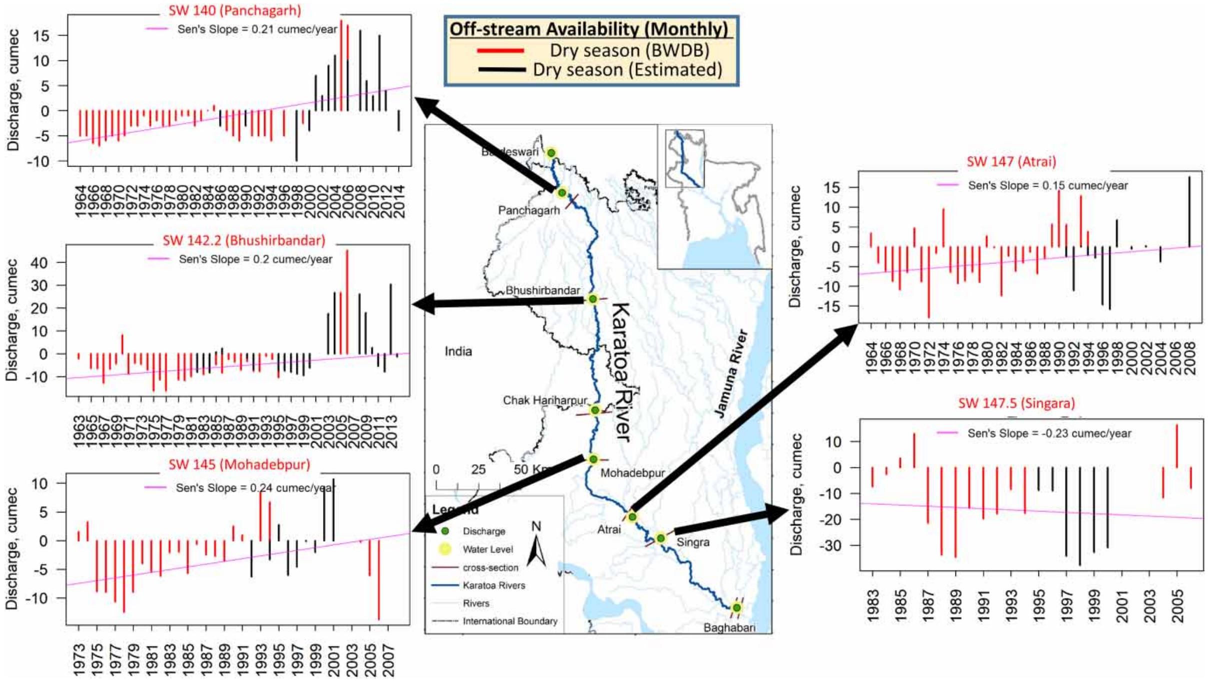

Fig. 3. Estimated dry season (November–May) off-stream water that was available at Karatoa-Atrai River. Here, off-stream availability denotes low-flow months' uses that were calculated by subtracting the in-stream flow requirement presented in Table 3.

receiving inflows from a few local springs nearby resulting in higher water availability compared to Panchagarh (SW140) during the dry period. At Mahadebpur (SW145) site, local stakeholders were blaming upstream withdrawal for the condition of the existing lower flow of the river. April was the critical month, and farmers had already switched to groundwater irrigation due to the reduction of the river water level. Notably, water quality deterioration also compelled local users to abandon river water even for any domestic use since dead fish had started floating in this (SW145) area. As per the consultation meetings with the stakeholders of the lower part of the river, both the Atrai (SW147) and the Singra (SW147.5) experienced increased temporal variation in flows leading to large fluctuations between monsoon (June–October) and dry season (November–May) flow rates. This caused aggravated floods and river erosion, on the one hand, and widespread siltation and dry bed conditions, on the other hand, in many parts along the river course in the dry season. In particular, local stakeholders found water availability at the Atrai station (SW147) satisfactory, but for Singra station (SW147.5), overdraft of upstream water for the Chalan Beel irrigation through the construction of local cross-dams caused April to be the most critical month. An indication of river deterioration at the downstream stations of Mohadebpur (SW145) and Singra (SW147.5) is also supported by the hydrological analyses summary shown in Table 4.

Here, the upper part of Karatoa River, particularly the Panchagarh and Bushirbandar gauging stations, showed acceptable dry season discharge values that were greater than the annual low-flow thresholds (ranging between 5 and 11 m^3/s) to meet the in-stream requirement. These were especially true for the flows after 2000. However, the recommended monthly IFRs for the same upstream stations were exactly the same as the median flow during the critical months (i.e., April and May) but less for the rest of the dry months. On the other hand, the lowest part of the river experienced severe deterioration

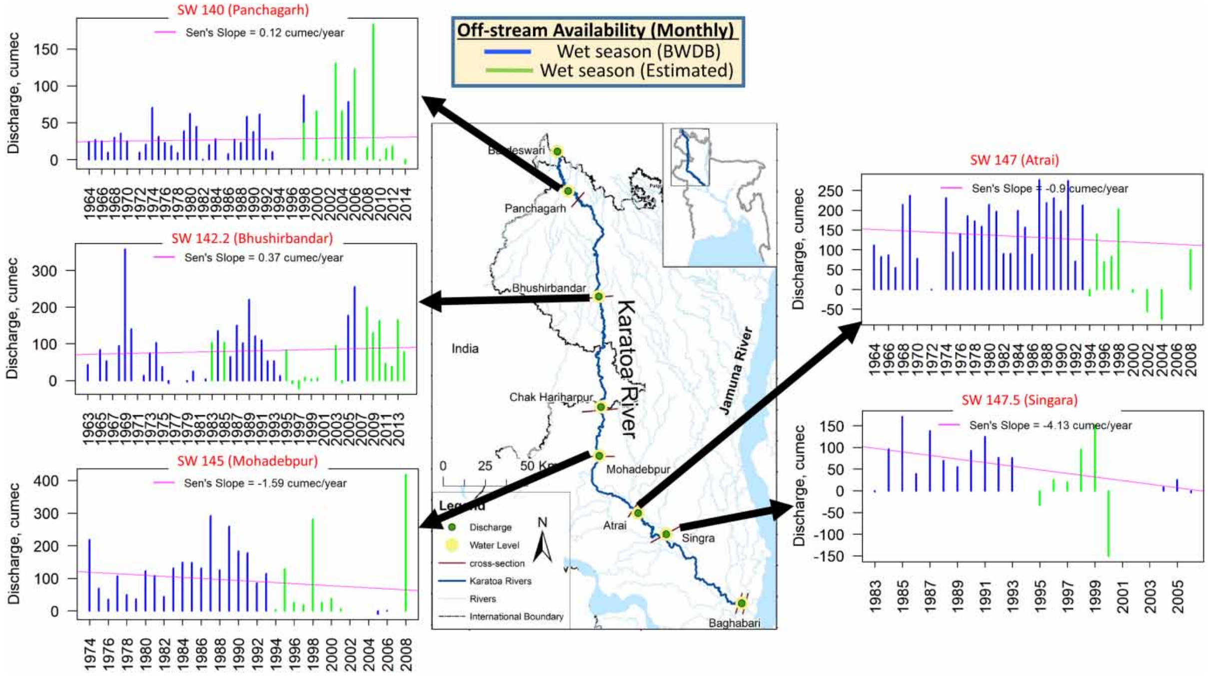

Fig. 4. Estimated wet season (June–October) off-stream water that was available at Karatoa-Atrai River. Here, off-stream availability denotes high-flow months' uses that were calculated by subtracting the in-stream flow requirement presented in Table 3.

Table 4. Summary status of estimated off-stream flow that was calculated by subtracting in-stream flow requirement presented in Table 3.

River name	Station ID	Data period	Off-stream flow availability		Field comments on dry season availability
			Dry	Wet	
Karatoa	SW 140 (Panchagarh)	1964–2014	Scarce (till 2000) to abundance	Abundance with no trend	Artificial sand mining attributed to deepening of the river bed
	SW 142.1 (Bhushirbandar)	1964–2014	Scarce (till 2000) to abundance	Abundance with increasing trend (0.4 $m^3/s/yr$)	Inclusion of neighbouring springs to this point increases stage flow
	SW 145 (Mahadebpur)	1973–2008	Mostly scarce	Abundance with decreasing trend (−1.6 cumec/yr)	Deterioration started through river widening with thalweg lowering
Atrai	SW 147 (Atrai)	1964–2008	Scarce	Abundance with decreasing trend (−0.9 $m^3/s/yr$)	But recent trends show increase in water availability
	SW 147.5 (Singara)	1983–2007	Mostly scarce with depleting trend	Abundance with decreasing trend (−3.3 $m^3/s/yr$)	Tendency to die out due to upstream water withdrawal (using cross-dams) + critical in April

in addressing its entire dry period functionality, both in terms of satisfying annual as well as monthly IFR demands. Also, severe aggradations of the river beds with less water discharge/carrying capacity at Singra resulted in a scarcity of water availability. Finally, the decreasing trend (-3.3 $m^3/s/yr$) in off-stream water availability in the Singra indicated existing excessive abstraction from the river, extracted via minor irrigation and farm-level water uses. It is evident that river sites, where IFR was not met, are subjected to permanently losing their river functionalities. Hence, a simple single hydrological approach works well to identify specific drying out parts of a river of concern.

Conclusion

The most common characterization of the adequacy of river health focuses on in-stream flow. Provision for in-stream uses was also explicitly recognized by the Bangladesh Water Act, 2013 and National Water Policy, 1999. However, in-stream flow assessment is a complicated process and needs both consultation and technical assessment. The large numbers of in-stream flow requirement (IFR) methods have been categorized in different ways, and there is no universally accepted method for all rivers. Any one method cannot provide all that IFR needs, and minimum flow assessments are always subjected to re-evaluation with changing demands for different indicators. On the other hand, the classical method used for a minimum (or low) flow estimation focuses on the analyses of hydrologic data that are useful for assessing various characteristics of minimums in rivers. Hence, as a part of reconnaissance level assessments, the hydrological approach was chosen to evaluate the Karatoa-Atrai River condition because it is inexpensive and rapid with simple data requirements; and later results can be upgraded by further local input and/or professional judgement. Additionally, a variable IFR threshold was chosen along the river considering the seasonal patterns of the flow. This is because there is no single threshold level that is preferable, and the selection of a specific threshold level always remains a subjective decision. Drawing on discussions in IFR, this research finally explores the historical off-stream water availability for the Kartoa-Atrai River located in the northwest of Bangladesh over the last 50 years. Ultimately, the study identified the urgent need of introducing measures to increase the water discharge capacity of the lowest part of the river so that the continuous lowering of the river water during the dry months can be reduced. Otherwise, the river might lose its perennial characteristics.

As previously mentioned, the IFR results, presented in Table 3, are of a preliminary nature largely due to the single hydrological approach to assess seasonal flow needs. These results can provide preliminary estimates of in-stream flow before undertaking any detailed, expensive and time-consuming analyses. Such look-up table approaches lack ecological support, give low confidence answers and have a danger in extrapolation to different unsuitable regions (O'Keeffe, 2009). Yet, results of hydrological studies are expected to be useful for water resource practitioners in Bangladesh, like the Institute of Water Modeling (IWM) and the Center for Environmental and Geographic Information Services (CEGIS) for sustainable and safeguard subsistence use of river resources. In other words, the output of this study can be helpful to decision-makers in undertaking river restoration and resuscitation tasks, e.g., the Water Resources Planning Organization (WARPO) and BWDB in allocating water for different uses. However, it is essential to conduct further work to improve the accuracy based on other specific flow requirements for the Karatoa-Atrai River. The output provided by the study was only a small part of the data necessary for effective policy making and management of river resources. One and only information (i.e., flow), by itself, is usually insufficient for the formulation of recommendations regarding accurate off-stream flow use. Additional information (e.g., biological, socio-political) and associated analyses need to be conducted to address the specific habitat/water issues within this river. However, it is now evident from this study that the hydrological approach of IFR is more than just an initial rough estimate. This single process works satisfactorily to find specific drying out parts of a river of concern. In particular, where budget and time are the constraints, the findings of hydrological IFR can at least be used to find the specific location of a river in need of extra/immediate attention by the water organizations and practitioners in planning, regulation and maintenance.

Supplementary material

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wp.2020.034.

References

Acreman, M. C. & Dunbar, M. J. (2004). Defining environmental river flow requirements? a review. *Hydrol. Earth Syst. Sci. Discuss. 8*(5), 861–876.

Aguilar, C. & Polo, M. J. (2016). Assessing minimum environmental flows in nonpermanent rivers: the choice of thresholds. *Environ. Modell. Software 79*, 120–134.

Akter, A. & Ali, M. H. (2012). Environmental flow requirements assessment in the Halda River, Bangladesh. *Hydrol. Sci. J. 57*, 326–343.

Anderson, E. P., Jackson, S., Tharme, R. E., Douglas, M., Flotemersch, J. E., Zwarteveen, M., Lokgariwar, C., Montoya, M., Wali, A., Tipa, G. T., Jardine, T. D., Olden, J. D., Cheng, L., Conallin, J., Cosens, B., Dickens, C., Garrick, D., Groenfeldt, D., Kabogo, J., Roux, D. J. & Arthington, A. H. (2019). Understanding rivers and their social relations: a critical step to advance environmental water management. *Wiley Interdiscip. Rev. Water 6*(6), e1381. doi:10.1002/wat2.1381.

Baghel, D. S., Gaur, A., Karthik, M. & Dohare, D. (2018). Global trends in environmental flow assessment: an overview. *J. Inst. Eng. India Ser. A 100*, 191–197.

Bari, M. F. & Islam, K. M. S. (2006). Stochastic model of flow duration curves for selected rivers in Bangladesh. In: *Climate Variability and Change–Hydrological Impacts*. Proceedings of the Fifth FRIEND World Conference. Havana, Cuba, IAHS Publ. 308, pp. 99–104.

Bari, M. F. & Marchand, M. (2006). *Introducing Environmental Flow Assessment in Bangladesh: Multidisciplinary Collaborative Approach. BUET-DUT Linkage Project, Ph-III*. Dhaka, Bangladesh.

Bari, M. F. & Sadek, S. (2002). Regionalization of low-flow frequency estimates for rivers in northwest Bangladesh. In *FRIEND 2002–Regional Hydrology: Bridging the Gap Between Research and Practice*. Fourth International FRIEND Conference, Cape Town, South Africa, pp. 257–263.

Blöschl, G. (2013). *Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales*. Cambridge University Press, New York, USA.

Chowdhury, J. U. & Haque, A. (1990). Permissible water withdrawal based upon prediction of salt-water intrusion in the Meghna Delta. In: *The Hydrological Basis for Water Resources Management*. Proceedings of the Beijing Symposium. IAHS Publ. 197, pp. 35–40.

Chowdhury, J. U. (1979). A probabilistic approach for forecasting low flow of the Gumati River. *J. Inst. Eng. Bangladesh 7*, 17–22.

Chowdhury, J. U. & Hossain, M. A. (2003). *Probabilistic Model for Dry Season Hydrographs in the Ganges-Jamuna-Padma and Available Water After Meeting in-Stream Requirement*. IWFM, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

Gain, A. K., Immerzeel, W. W., Sperna Weiland, F. C. & Bierkens, M. F. P. (2011). Impact of climate change on the stream flow of the lower Brahmaputra: trends in high and low flows based on discharge-weighted ensemble modelling. *Hydrol. Earth Syst. Sci. 15*, 1537–1545.

Hossain, M. M. & Hosasin, M. J. (2011). Instream flow requirement of Dudhkumar River in Bangladesh. *Asian Trans. Eng. 1*, 42–49.

Laaha, G., Hisdal, H., Kroll, C. N., Van Lanen, H. A. J., Nester, T., Rogger, M., Sauquet, E., Tallaksen, L. M., Woods, R. A. & Young, A. (2013). Prediction of low flows in ungauged basins. In: *Run-off Prediction in Ungauged Basins, Synthesis Across*

Processes, Places and Scales (G., Bloschl, S., Wagener, Th. M., Viglione & H., Savenije, eds). Cambridge University Press, New York, USA, pp. 163–188.

Lee, A., Cho, S., Kang, D. K. & Kim, S. (2014). Analysis of the effect of climate change on the Nakdong river stream flow using indicators of hydrological alteration. *J. Hydro-Environ. Res. 8*, 234–247.

Liu, Y., Cao, S., Yang, Y. & Zhang, X. (2017). Assessment of hydrologic regime considering the distribution of hydrologic parameters. *Water Supply 18*(3), 875–885. doi:10.2166/ws.2017.161.

Magdaleno, F. (2018). Flows, ecology and people: is there room for cultural demands in the assessment of environmental flows? *Water Sci. Technol. 77*(7), 1777–1781. doi:10.2166/wst.2018.075.

Mathews, R. & Richter, B. D. (2007). Application of the indicators of hydrologic alteration software in environmental flow setting. *Journal of the American Water Resources Association 43* (6), 1400–1413.

Moly, S. H., Rahman, M. A. T. & Saadat, A. H. M. (2015). Environmental flow characteristics of the Gorai River, Bangladesh. *Int. J. Sci. Res. Environ. Sci. 3*, 208.

Mondal, M. S., Chowdhury, J. U. & Ferdous, M. R. (2010). Risk-based evaluation for meeting future water demand of the Brahmaputra floodplain within Bangladesh. *Water Resour. Manage. 24*, 853–869.

Mullick, M. R. A., Perret, S. R. & Babel, M. S. (2013). Benefit functions for instream water uses – a case of the Teesta River, Bangladesh. *J. Appl. Water Eng. Res. 1*, 118–128.

O'Keeffe, J. (2009). Sustaining river ecosystems: balancing use and protection. *Progress in Physical Geography: Earth and Environment 33*(3), 339–357. https://doi.org/10.1177/0309133309342645.

Peres, D. J. & Cancelliere, A. (2016). Environmental flow assessment based on different metrics of hydrological alteration. *Water Resour. Manage. 30*(15), 5799–5817. doi:10.1007/s11269-016-1394-7.

Pfeiffer, M. & Ionita, M. (2017). Assessment of hydrologic alterations in Elbe and Rhine Rivers, Germany. *Water 9*(9), 684. doi:10.3390/w9090684.

Rahman, A. (1998). *Hydrologic Determination of Instream Flow Requirement of the Ganges River*. MSc Thesis, BUET, Dhaka, Bangladesh.

Rahman, M. A. T., Moly, S. H. & Saadat, A. H. M. (2013). Environmental flow requirement and comparative study of the Turag River, Bangladesh. *Int. J. Sci. Res. Environ. Sci. 1*, 291.

Rahman, M., Hoque, S. & Saadat, A. (2017). Selection of minimum indicators of hydrologic alteration of the Gorai river, Bangladesh using principal component analysis. *Sustainable Water Resour. Manage. 3*, 13–23.

R Core Team (2016). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Salinas, J. L., Laaha, G., Rogger, M., Parajka, J., Viglione, A., Sivapalan, M. & Blöschl, G. (2013). Comparative assessment of predictions in ungauged basins–Part 2: flood and low flow studies. *Hydrol. Earth Syst. Sci. 17*, 2637–2652.

Sharma, U. (2019). Effective framework for environmental-flows estimation for data deficient Indian rivers. *J. Appl. Nat. Sci. 11*(2), 545–555. https://doi.org/10.31018/jans.v11i2.2116.

Taylor, K., Moggridge, B. & Poelina, A. (2016). Australian indigenous water policy and the impacts of the ever-changing political cycle. *Aust. J. Water Resour. 20*, 132–131. doi: 10.1080/13241583.2017.1348887.

Tharme, R. E. (2003). A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Res. Appl. 19*, 397–441.

WARPO (2000). *Draft Development Strategy, Annex K: Data Management. Ministry of Water Resources*. Government of Bangladesh, Dhaka, Bangladesh.

World Bank (2006). *Bangladesh Country Water Resources Assistance Strategy*. Report No. 32312-BD. Environment and Social Development Unit, Agriculture and Rural Development Unit, Energy and Infrastructure Unit, South Asia Region.

Zeiringer, B., Seliger, C., Greimel, F. & Schmutz, S. (2018). River hydrology, flow alteration, and environmental flow. In: *Riverine Ecosystem Management: Science for Governing Towards A Sustainable Future*. Schmutz, S. & Sendzimir, J. (eds). Springer International Publishing, Cham, Switzerland, pp. 67–89.

Zhang, Q., Gu, X., Singh, V. P. & Chen, X. (2015). Evaluation of ecological instream flow using multiple ecological indicators with consideration of hydrological alterations. *J. Hydrol. 529*, 711–722.

Zhang, Q., Zhang, Z., Shi, P., Singh, V. P. & Gu, X. (2018). Evaluation of ecological instream flow considering hydrological alterations in the Yellow River basin, China. *Global Planet. Change 160*, 61–74.

Received 22 February 2019; accepted in revised form 22 November 2019. Available online 20 January 2020