



# Hydrological alteration and its effect on the eco-hydrological state in Tangon river traversing Bangladesh and India

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## Abstract

The present study highlighted the multi-temporal behavior of hydrological alteration (HA) of a river mainly triggered by damming over the Tangon river of India and Bangladesh in 1989 and its impact on eco-hydrological health. For measuring hydrological alteration, hydrological variability at month scale, diurnal flow change using histogram comparison approach (HCA), degree of alteration using a heat map, and periodicity analysis using wavelet transformation method were used. The present study used hydro-ecological matrices like the range of variability approach (RVA), eco-deficit/eco-surplus, and degree of impact (ImHA) using 33 indicators of HA (IHA) for hydro-ecological assessment. Apart from this, the present study endorsed a new approach (integrated degree of impact due to HA (IImHA)) for accounting for integrated hydro-ecological impact in an altered river. The results following hydrological and eco-hydrological alterations were derived in the post-dam period: (1) monthly water level (WL) was attenuated by 1.5–3.0 m, (2) monthly variability of flow increased by 10%, (3) degree of negative HA ranged from 10 to 23% with high during non-monsoon months, (4) statistically significant periodicity (5% level) in flow spectrum was identified after the dam, (5) HCA revealed that diurnal flow distribution turned from positive to negatively skewed pattern (6) RVA-based monthly failure rate ranges from 13.95 to 25.58%, (7) ImHA of different IHA groups ranged from 0.46 to 0.56 signifying poor to moderate impact, and (8) proposed IImHA value accounted (0.406) moderate degree of ecological impact. The study recommends to apply IImHA in such similar works for making the study effective and instrumental. The findings of this study would be effective for the policymakers specially for the restoration of flow and ecological health.

**Keywords** Flow alteration · Flow variability · Degree of change · Histogram comparison approach · Ecological threshold · Flow failure · Eco-deficit · Integrated degree of impact

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## 1 Introduction

Water is a very useful natural resource for continuing natural and anthropogenic systems (Khan & Zhao, 2019; Momb Blanch et al., 2019). From the beginning of civilization, water played a significant role in long-term social development. Climate change and anthropogenic activities are important factors that alter the natural flow, negatively impacting natural ecosystem function and biodiversity deterioration (Alifujiang et al., 2021; Li et al., 2017; Pirnia et al., 2019; Shahid et al., 2018). River flow modification and quantitative and qualitative change of riparian eco-hydrological state triggered by artificial control such as dams and barrages are crucial issues to environmental scientists. The artificial control modified the downstream flow regime concerning the total water volume, magnitude, timing, changing rate, duration, flooding intensity, as well as water quality (Yan, 2010; Pal et al., 2019; Pal et al., 2020). Flow regime alteration controls the ecological dynamics of the river as well as riparian habitat directly and indirectly (Ge et al., 2018; Palmer & Ruhi, 2019; Tonkin et al., 2018). Therefore, the accurate estimation of flow regime alteration is very important to the design suitable plan for ecosystem sustainability and restoration (Kuriqi et al., 2019; Pal & Talukdar, 2020; Suwal et al., 2020). Hydrological modification and its effects on rivers and riparian ecological units have been widely investigated with the help of different statistical tools and techniques (Vollmer et al., 2018; Zeiringer et al., 2018; Peñas et al., 2019). DeHaan et al. (2012) reported that the dam over the Mississippi River in the USA reduced peak flood discharge by 15%. Li et al. (2017) reported that 82% reduction in mean flow from 1991 to 2009 in the Mekong River of Southeast Asia. Hecht et al. (2019) showed that hydropower reservoirs over the Mekong River basin reduced ~2% the mean annual flow in 2008 to ~20% in 2025 in the downstream segment. Pal (2016), Pal and Saha (2017) reported that the Rubber dam over the Atrayee river in Indo-Bangladesh has been reduced by 56% average flow and 84% maximum flow. Talukdar and Pal (2017) reported that in the Punarhaba river, the natural flow was reduced by 36% due to damming. Damming is often a consequence of increased water availability in the upper catchment as well as reduced water availability in the downstream river catchment. (Xu et al., 2020; Yang et al., 2021). The upper catchment's economic and ecological benefits become a burden to the lower catchment due to the hydrological transformation (Xu et al., 2020). Consequently, aquatic biodiversity was disturbed, and other economic activities were highly affected (Rideout et al., 2021). Hydrological transformation often causes reduced flood frequency, magnitude, and environmental or natural flow to the river and associated wetlands (Pal & Sarda, 2020; Talukdar & Pal, 2017; Zheng et al., 2019). In this perspective, measuring the hydrological alteration in the river due to damming is a very important task for maintaining the supply of ecosystem services of the river and riparian ecological units for human well-being.

Daily, monthly, seasonal to yearly levels, hydrological data analysis can provide a good analytical framework for hydrological modification. Analysis of mean flow, minimum flow, peak flow, variability of flow, instability of flow, degree of flow alteration, periodicity of flow, histogram matching of diurnal flow, etc. can provide multifaceted views of flow alteration. Previous literature focuses on the subset of such methods. Among these approaches, flow volume alteration is very common and widely applied by many researchers (Kumar and Jayakumar, 2018; Tonkin et al., 2018; Pokhrel et al., 2018; Ali et al., 2019a, 2019b; Jia et al., 2021) across different rivers of the world. Diurnal flow analysis pursuing damming is less common, however, conducted by Pal (2016) in the Atrayee river of India and Bangladesh. The degree of flow alteration using heat map techniques was presented by

Pal and Talukdar (2020) in the case of the Punarbhaba river in India and Bangladesh. The heat map shows the degree of change between expected and observed flow data in reference to time and therefore comprehensively presents a wide range of data within a single viewer. The wavelet transformation method is a powerful mathematical signal processing technique that was widely used for long-term time series, trend, and periodicity analysis (Rhif et al., 2019; Khazaee et al., 2019; Pal & Talukdar, 2020; Kambalimath and Deka, 2021). This method also solves both time and frequency information from both stationary and non-stationary data sets (Pal & Talukdar, 2020; Santos et al., 2019). Therefore, the wavelet transformation methods can be applied to the hydro-metrological time series data because of their non-stationary data character. If flow data are considered a continuous wave signal, its periodicity can be judged using this method. Any significant break in flow can be detected in this method.

Hydrological modification of a river is strongly associated with the ecological condition of the river. Indicators of hydrological alteration (Richter et al., 1996), ecological limit of hydrological alteration (ELOHA) (Poff et al., 2010), entropy-based multi-criteria approach (Kim & Singh, 2014), histogram matching approach (HMA) (Shiau & Wu, 2008), range of variability approach (RVA) (Daiechini et al., 2020; Pal & Sarda, 2020), revised range of variability approach (RRVA) (Ge et al., 2018; Yang et al., 2014), improved range of variability approach (IRVA) (Singh & Jain, 2021), and set pair analysis (Zhang et al., 2019) are some well-established approaches for estimating the eco-hydrological alteration of a river basin. These approaches were successfully applied by many researchers globally. Despite their merits and shortcomings, each method has some advantages and disadvantages. IHA and RVA are the effective measures of hydrological and eco-hydrological transformation, which incorporate 33 IHA parameters under five hydrological groups (Richter et al., 1996) such as (i) magnitude of monthly streamflow, (ii) magnitude and duration of annual extreme flow, (iii) timing of yearly extreme flow, (iv) frequency and duration of high and low pulses, and (v) rate and frequency of flow transformation (Mathews & Richter, 2007). Many researchers used this method successfully for exploring the degree of eco-hydrological modification. Guo et al. (2012) reported a high degree of hydrological transformation in the middle and lower reaches of the Yangtze River due to the construction of the Three Gorges Dam. Pal (2016), Talukdar and Pal (2018a, 2018b), Pal and Sarda (2020) demarcated the same condition in the Mayurakshi River of India and the Punarbhaba and Atrayee river basins of India and Bangladesh. Apart from them, Ali et al., (2019a, 2019b), Pal et al. (2019), Ren et al. (2019), Pal et al. (2019), George et al. (2021), Pal and Sarda (2021) also successfully identified the hydrological transformation using IHA approach in many rivers globally. The Flow Duration Curve (FDC) is a popular method for calculating environmental flow (Ge et al., 2018). A typical flow duration curve represents the proportion of flow exceeded for a particular time in the river section. Based on this flow exceedance curve, the minimum threshold is defined to preserve the ecological integrity of rivers.

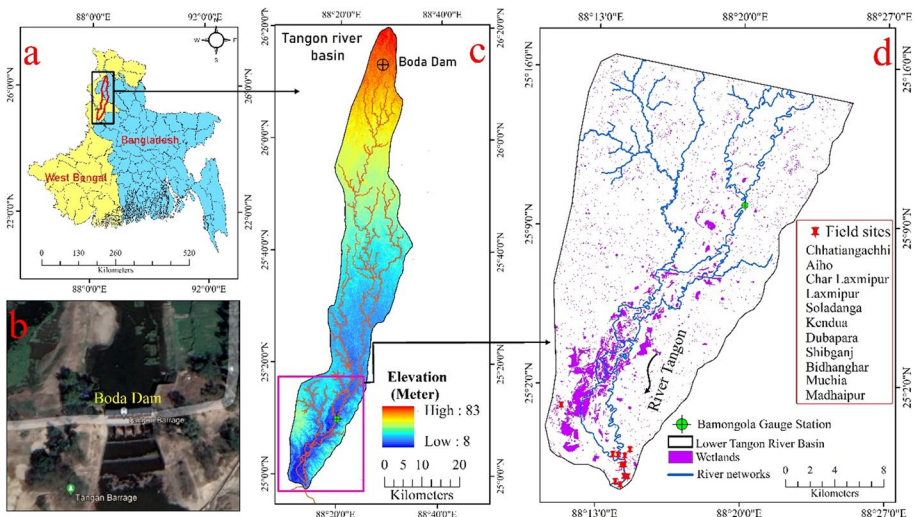
The issues of flow alteration due to damming are not any new topic. Many researchers tried to explain hydrological modification based on different parameters. A group of researchers highlighted focusing on hydrological aspects (Mezger et al., 2021; Peñas & Barquín, 2019), and another group focused on eco-hydrological aspects (Khatun et al., 2021; Wang et al., 2019). Moreover, while dealing with hydrological modification, researchers used eco-hydrological measures like flow failure rate, and eco-deficit/eco-surplus in order to present the impact of eco-hydrological alteration. As far the knowledge is concerned, no such attempt was taken integrating different eco-hydrological aspects like failure rate, eco-deficit/eco-surplus, flow variability, and degree of hydrological alteration. In fact, such analysis is essential for understanding the possible ecological alteration and

formulating as well as implementing restoration measures. The present study attempted to account for hydrological alteration in a diurnal to year scale and develop a new integrated eco-hydrological index including important hydrological and ecological aspects in order to account for the integrated degree of impact of hydrological alteration. Since the Tangon river between India and Bangladesh was intervened by damming in its upper reach and lower reach, it witnessed significant problems related to water scarcity, and this river was taken as a case in order to explore the impact of hydrological alteration on the eco-hydrological state of the downstream river course.

## 2 Materials and methods

### 2.1 Study area

The Tangon River (267 km) basin is located in India and Bangladesh (Fig. 1), traversing the older alluvium Barind tract. In 1989, a dam was built over it for irrigation purposes, which creates extensive hydrological changes over the lower catchment. Consequently, this flow volume declined significantly, leading to rapid hydrological transformation in riparian wetlands since the wetlands are majorly fed by rain and floodwater (Pal & Singha, 2022; Singha & Pal, 2023a). Seasonal rainfall disparity is a significant reason behind the hydrological and morphological dynamics of the wetland (Khatun & Pal, 2021; Kundu et al., 2022; Pal et al., 2019). Since, out of the total annual average rainfall (1257–1508 mm), 80% happens during monsoon season (June–September), seasonally inundated wetlands expand maximally during monsoon time and squeeze maximally during pre-monsoon season (March–May) due to rain scarcity. Agriculture and fishing are the main economic activities in this study region and more than 70% of people are engaged in these sectors (Singha & Pal, 2023b).



**Fig. 1** Study area maps show the location of the Tangon river basin in a broader geographical area (a), the location of Boda dam (b), the river basin with elevation (c), and wetland dominated lower part of the river basin (d). Case study sites were also mentioned over the lower basin

## 2.2 Hydrological data collection and preprocessing

Three hours interval water level (WL) data from 1978 to 2020 were collected from the Bamangola gauge (88°20'6" E and 25°9'57" N) station (under the Irrigation and Waterways Department of the Government of West Bengal) for hydrological transformation analysis. A Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM) of the United States Geological Survey (USGS) (30 m spatial resolution) and Google earth maps were used for base map preparation. A village survey and focused group discussion were carried out for case-specific analysis of the nature of hydrological modification and its impact. Some missing flow data between 1978 and 2020 was predicted using artificial neural network (ANN)-based forecasting techniques. Before conducting any analysis based on flow data, an outlier analysis was conducted and a few abnormal data were replaced with the average flow of previous and successive flow data.

## 2.3 Measuring hydrological alteration

### 2.3.1 Methods of hydrological alteration variability, trend and instability analysis

Hydrological variability (average and maximum flow levels) during the post-dam period was attempted to focus separately on three major seasons e.g., pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–December). For annual variability analysis of all the hydrological parameters, standard deviation (SD) and coefficient of variation (CV) are used. Instability of flow was also measured for the same seasons following the method of Cuddy and Della Vale (1978) (Eq. 1). High CV refers to high variability in time series flow levels.

$$IF = CV \times \sqrt{1 - R^2} \quad (1)$$

where  $R^2$ =coefficient of determination, CV=coefficient of variation of selected time series water levels, and less IF value indicates less instability and vice versa.

Box plots of monthly flow data of monsoon and non-monsoon seasons were plotted, showing the inter-quartile range (IQR), maximum, minimum, median flow, and outlier data (if any). This method is very effective to display the descriptive nature of the flow data.

### 2.3.2 Flood frequency and magnitude analysis

Flood frequency and magnitude were analyzed based on maximum flow level data. Maximum flow data of different years were presented in reference to danger level (DL) and extreme danger level (EDL). The peak flow above EDL indicates flood year. Flow level above DL also signifies flood threats. Average and minimum flow level data are also presented in the same frame in order to know the position of average flow level in reference to DL. Flow level above EDL signifies higher flood magnitude (Ghosh & Guchhait, 2016; Talukdar & Pal, 2018a, 2018b).

### 2.3.3 Periodicity analysis using wavelet transformation

Wavelet transformation analysis is a technique for studying multi-scale frequency characteristics in time series. The wavelet transformation solved the time series data in different scales as well as solved the main variability pattern, frequency, and frequency change over time. Worldwide, wavelet analysis was widely used in different environmental science fields, especially in geophysics and remote sensing (Chou et al., 2022; Torrence & Compo, 1998; Zheng et al., 2017) and signal analysis (Morlet et al., 1982). Wavelet analysis is capable of dealing with non-stationary changes in different frequencies better than Fourier transformation (Morlet et al., 1982; Grinsted et al., 2004). The wavelet function is effective for dealing with the rapidly changing area of non-stationary signals (Yin et al., 2022). The data with local stationary characteristics of the signal were solved using this system and obtained periodic changes under a specific ratio. Due to the time–frequency characteristics of wavelets, wavelets are mainly used for time–frequency and timescale analysis. Wavelet transformation can be classified into two categories, such as continuous wavelet transformation (CWT) and discrete wavelet transformation (DWT). The CWT provides better signal feature extraction ability, so it was widely used for different environmental research to estimate the periodic change of wavelets (Morlet et al., 1982; Grinsted et al., 2004). The Morlet wavelet transformation provides the sinusoidal signal from the time series data, both sudden and constant. So, in this study, CWT with the Morlet wavelet was used for identifying the periodic change in water levels (Eq. 2).

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi * \left[ \frac{(n' - n)\delta t}{s} \right] \quad (2)$$

where  $W_n$  = power spectra,  $x_n$  = time series,  $\psi$  = mother wavelet (Morlet wavelet),  $n'$  = transitional value,  $n$  = total time index,  $n$  = local time index,  $s$  = wavelet scale,  $*$  = complex conjugation,  $N$  = time index, and  $\delta t$  = sampling interval.

### 2.3.4 Diurnal flow analysis using histogram comparison approach

Daily flow data of different seasons between pre- and post-dam periods in percentage were compared using the histogram comparison approach (HCA) (Huang et al., 2017; Pal & Sarda, 2021). Three flow level classes were developed and the percentage of days within each class was computed for pre- and post-dam periods. The same was presented in a comparative histogram in order to show the daily flow level changes.

### 2.3.5 Measuring the degree of flow alteration

Monthly water level (WL) alteration due to damming was successfully presented using a heat map based on the time series data from 1978 to 2020. It represents the percentage of change in the observed flow level from the expected flow level. The degree of WL alteration was estimated using the expected and observed flow data (Eq. 3) (Saha et al., 2022). Water level data were also presented using a heat map.

$$\text{DFA (\%)} = \frac{O_{wl} - E_{wl}}{E_{wl}} \times 100 \quad (3)$$

where  $DFA$  = degree of flow alteration,  $O_{wl}$  = observed water level, and  $E_{wl}$  = expected water level.

The status of the degree of hydrological alteration falls into three categories it may be positive or negative, or zero. A positive alteration means that the observed value remains above the expected flow level, whereas a negative alteration means that the observed value remains below the expected level. A zero alteration means there are no differences between observed and expected values.

## 2.4 Eco-hydrological measures

### 2.4.1 Indicator of hydrological alteration

The indicator of hydrological alteration is one of the most popular tools developed (Richter et al., 1996) for measuring the eco-hydrological alteration of a river. IHA is commonly used in hydrological science to estimate hydrological alteration due to anthropogenic stressors and climate change. Overall, IHA consists of 67 indicators, out of which 33 are used for analyzing hydrological alteration, while 34 are used for eco-flow component assessment. The hydrologic regime of a river can be categorized into five main elements: (a) magnitude (volume of water that circulates through a point per unit of time), (2) frequency (number of times that a flow condition occurs during a time interval), (3) duration (period of time associated with the flow condition), (4) timing or predictability (measure of the regularity of the flow condition), and (5) rate of change (pointer of the velocity of change between distinct flow conditions) (Richter et al., 1996). In IHA, the parameters are logical and have a strong relation to the river ecosystem, and reflect human interventions by the construction of artificial structures, such as dams, barrages, and water diversion (Gao et al., 2009; Mathews & Richter, 2007). The details of these indicators are given in Table 1.

### 2.4.2 Measuring the hydro-ecological state

Eco-deficit and eco-surplus are the two measures that exhibit the overall impact of river flow alteration. Vogel et al. (2007) successfully applied non-dimensional metrics of eco-deficit and eco-surplus based on the flow duration curve (FDC). A flow duration curve, typically constructed from historical field records, provides a convenient, simple, and powerful technique for analyzing the flow regime characteristics in a river basin under natural and anthropogenic changes. This is a simple method that involves the magnitude and frequency of historical flow data over a specific period and identifies a synoptic view of the eco-hydrological process of a river basin (Langat et al., 2019). This method was widely applied in water resource engineering, planning, and management (Burgan & Aksoy, 2022; Pal et al., 2019). The effect of climate change and artificial control over a river system for two non-overlapping periods is often difficult to understand simply by studying long-term stream flow hydrographs (Girihagama et al., 2022). However, FDC analysis is a very useful method that successfully detects the flow magnitude and frequency of rivers under this condition. Vogel et al. (2007), Talukdar and Pal (2019) also successfully developed eco-deficit and eco-surplus methods for identifying the ecological state such as habitat suitability. According to them FDC of the unregulated condition of a river, when remains above the regulated condition are called eco-surplus and reverse condition signifies eco-deficit. The eco-deficit condition often causes ecological stress to the species living in the river.



**Table 1** Hydrologic alteration indicators used in the indicators of hydrologic alteration approach adopted after Richter et al. (1996)

IHA group	Flow regime characteristics	Indicators of hydrologic alteration, IHA
1. Magnitude of monthly water conditions	Magnitude/timing	IHA <sub>1</sub> to IHA <sub>12</sub> The mean value for each calendar month
2. Magnitude and duration of annual extreme water conditions	Magnitude/duration	IHA <sub>13</sub> Annual minimum, 1-day mean
		IHA <sub>14</sub> Annual minimum, 3-day means
3. Timing of annual extreme water conditions	Timing	IHA <sub>15</sub> Annual minimum, 7-day means
		IHA <sub>16</sub> Annual minimum, 30-day means
		IHA <sub>17</sub> Annual minimum, 90-day means
		IHA <sub>18</sub> Annual maximum, 1-day mean
		IHA <sub>19</sub> Annual maximum, 3-day means
		IHA <sub>20</sub> Annual maximum, 7-day means
		IHA <sub>21</sub> Annual maximum, 30-day means
		IHA <sub>22</sub> Annual maximum, 90-day means
		IHA <sub>23</sub> Number of zero-flow days
		IHA <sub>24</sub> Base flow index
		IHA <sub>25</sub> Julian date of each annual 1-day minimum
4. Frequency and duration of high/low pulses	Magnitude/frequency/duration	IHA <sub>26</sub> Julian date of each annual 1-day maximum
		IHA <sub>27</sub> Number of low pulses
5. Rate and frequency of water condition changes	Frequency/rate of change	IHA <sub>28</sub> Mean duration of low pulses (days)
		IHA <sub>29</sub> Number of high pulses
		IHA <sub>30</sub> Mean duration of high pulses (days)
		IHA <sub>31</sub> Rise rates
		IHA <sub>32</sub> Fall rates
		IHA <sub>33</sub> Number of hydrologic reversals



### 2.4.3 Ecological flow and flow failure rate computation

Ecological flow assessment of a river is a very essential task for water resources management. Various methods, such as the twentieth and eightieth percentile, 1 standard deviation (SD), and 2SD, were widely used by researchers for ecological flow estimation (Richter et al., 1997). Laub et al. (2012), Pal and Sarda (2020), Pal and Talukdar (2020), Pal and Sarda (2021), Zheng et al. (2021), Khatun et al. (2021) successfully applied this method for river flow assessment. The range of variability approach (RVA) approach was developed by Richter et al. (1997) to estimate the ecological flow status of a river basin. To compute the higher and lower threshold limit of streamflow  $\text{Mean} \pm 1\text{SD}$  was used for the present purpose. Flow within  $\text{Mean} \pm 1\text{SD}$  denotes the natural eco-hydrological condition, the flow greater than  $\text{Mean} \pm 1\text{SD}$  can be treated as an eco-hydrologically affluent state and less than  $\text{Mean} - 1\text{SD}$  can be treated as an eco-hydrologically stress condition. Flow failure rate (FFR) was computed based on the above-mentioned classes. It was examined whether individual flow falls within the RVA threshold (range of natural flow) or beyond the RVA threshold. Flow frequency in percentage that remains beyond a threshold can be termed as FFR. FFR was computed considering time periods of both pre- and post-dam periods (Eq. 4) (Pal, 2016).

$$\text{FFR} = \left( \frac{F_{\text{RVA}}}{T_{\text{FO}}} \right) \times 100\% \tag{4}$$

where  $F_{\text{RVA}}$  is the frequency of flow beyond RVA and  $T_{\text{FO}}$  is the total number of flow occurrences considered.

### 2.4.4 Measuring the degree of impact

For showing the integrated impact of hydrological alteration, the Euclidian distance of each individual IHA was measured and combined (Eq. 5) (Pal, 2016). The high distance between natural and regulated flow shows a high degree of impact and reverse in case of low distance.

$$\text{ImHA} = \sqrt{\left[ \frac{1}{n} \sum_n (I_i)^2 \right]} \forall_j \tag{5}$$

where ImHA (indicator of hydrological alteration) is the overall degree of impact  $j$ ,  $i$  refers to the percentage change of  $i$ th IHA, and  $n$  refers to the total number of IHA considered. ImHA value varies from 0 to 1. Here, ‘0’ signifies the situation is almost identical to the natural flow, and therefore, no impact could be considered. Contrarily, the value near 1 signifies a high impacted river. For impacted river, IHA takes a value close to 1, with highly impacted sites showing scores greater than 1.

### 2.4.5 Integrated degree of impact due to hydrological alteration

Apart from the above-mentioned approaches, the present work also tried to develop a new index for measuring the integrated degree of impact of hydrological alteration (IImHA). For this, four measures were initially done i.e. (1) variability of flow using CV, (2) flow failure rate, (3) degree of impact of hydrological alteration (ImHA)

based on IHA, and (4) net hydro-ecological deficit/surplus (NED/S). The methods for computing CV, FFR, and ImHA were already discussed in the previous section. After computing all these measures, CV, and FFR were normalized using Eq. 6. NED/S was computed based on computing the ratio between the gap between FDCs of natural and regulated flows and the total area within FDC of the pre-dam period (Eq. 7). For computing an area within FDC of the pre-dam period, the base flow line was considered. Non-weighted compositing and averaging were done after normalizing all indices (Eq. 8). The value of the degree of impact, in this case, will range from 0 to 1, where 0 signifies no impact and 1 signifies a high degree of impact.

$$X_{\text{Nor}} = \frac{X - X_{\text{Min}}}{X_{\text{Max}} - X_{\text{Min}}} \quad (6)$$

where  $X_{\text{Nor}}$  = normalized observation,  $X$  = actual observation,  $X_{\text{Max}}$  = maximum observation, and  $X_{\text{Min}}$  = minimum observation

$$\text{NED/S} = (\Delta\text{FDC}/\text{FDC}_N) \quad (7)$$

where NED/S = net eco-deficit/eco-surplus,  $\Delta\text{FDC}$  = Gap of flow between natural and regulated flow, and  $\text{FDC}_N$  = Area under natural FDC.

$$\text{IImHA} = \frac{(\text{CV} + \text{FFR} + \text{ImHA} + \text{NED/S})}{N} \quad (8)$$

where IImHA = integrated degree of impact of hydrological alteration and  $N$  = the total number of indices considered (here four).

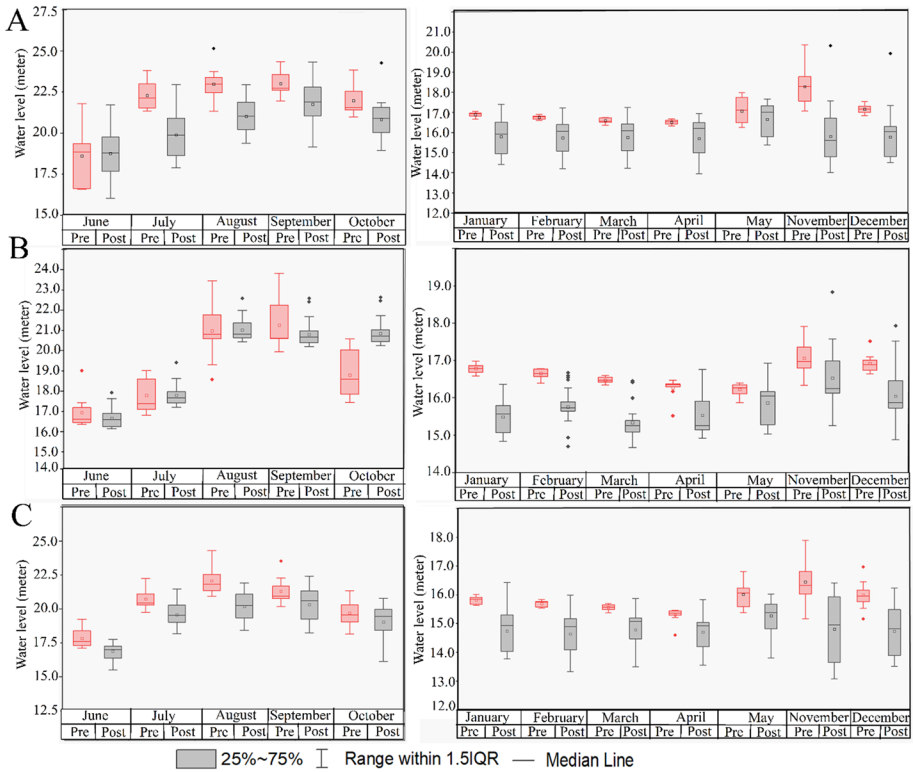
## 3 Results

### 3.1 Hydrological alteration

#### 3.1.1 Hydrological variability

The comparative variation of maximum, minimum, and average water levels (WL) was represented in the box plot (Fig. 2) for pre-dam and post-dam phases focusing on monsoon and non-monsoon months. From the graph, it is evident that monsoon months show higher maximum (25.18 m), minimum (23.39 m), and average (24.42 m) water levels as usually than the non-monsoon months. Some extreme WL conditions were also identified in both monsoon and non-monsoon months; however, it was infrequent during the post-dam period. Inter-quartile range clarified that maximum, average, and minimum WL dispersion was considerably enhanced in the post-hydrological period indicating increasing uncertainty of flow.

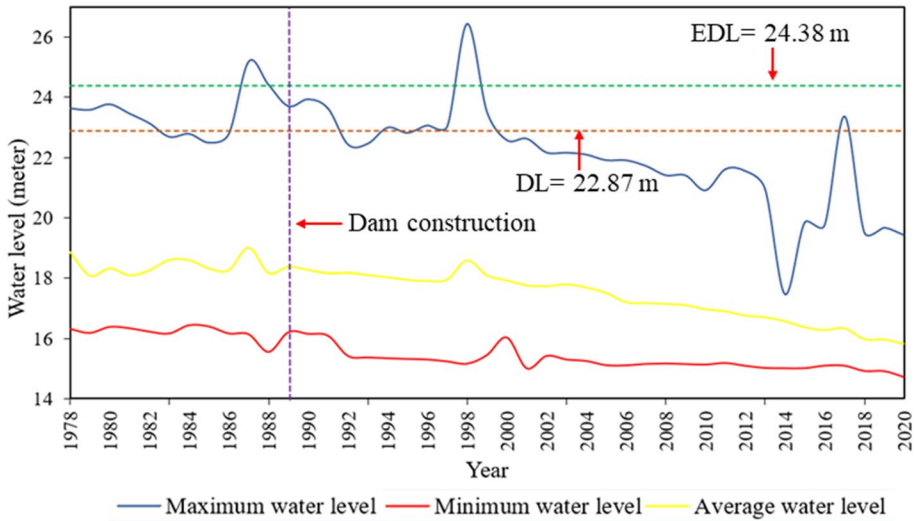
There is a reduction in the mean flow level after damming, but flow variability was increased, sufficing the dispersion analysis. Monthly discharge variability was between 0.59 and 8.68%, with an average of 3.58 during pre-dam and 10.38 to 19.94, within 13.25 during the post-dam period (Table 2).



**Fig. 2** Box plot showing comparative dispersion of **A** maximum, **B** minimum, and **C** average water level in pre- and post-dam periods in monsoon and non-monsoon season (note: Pre=Pre-dam period and post=post-dam period)

**Table 2** Change of variability of IHA parameters in two periods

Months	Pre-dam period (1979–1988)			Post-dam period (1990–2020)		
	Mean	Std. deviation	CV (%)	Mean	Std. deviation	CV (%)
January	16.88	0.13	0.77	15.34	1.60	10.41
February	16.75	0.10	0.62	15.06	1.66	11.01
March	16.59	0.10	0.59	14.51	1.75	12.05
April	16.30	0.36	2.22	14.17	1.82	12.87
May	16.68	0.36	2.15	14.75	2.01	13.60
June	17.70	1.20	6.79	15.97	2.27	14.24
July	19.54	0.57	2.93	17.28	2.18	12.59
August	21.69	1.75	8.07	18.38	3.48	18.96
September	21.64	1.88	8.68	18.75	3.74	19.94
October	19.72	0.99	5.03	17.45	2.21	12.69
November	17.70	0.66	3.71	15.97	1.64	10.27
December	17.02	0.26	1.50	15.40	1.60	10.38



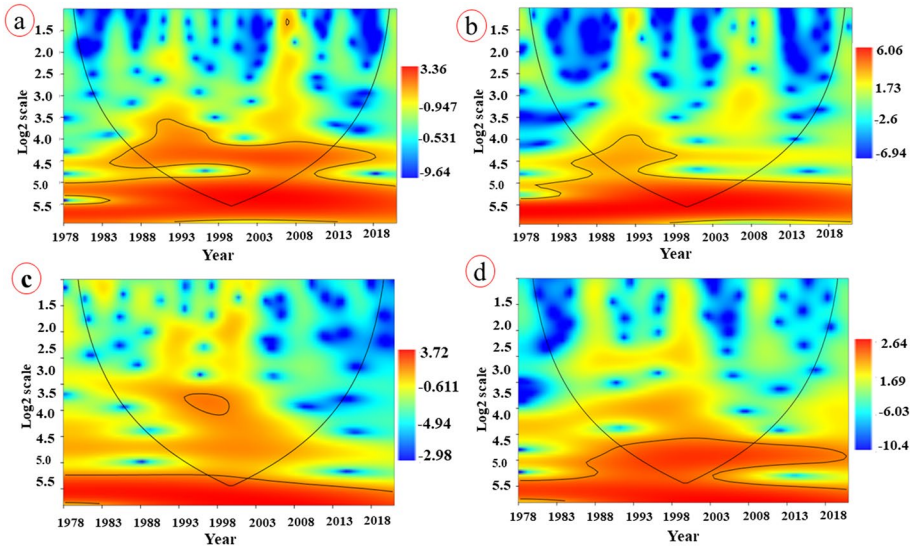
**Fig. 3** Yearly stage hydrographs from 1978 to 2020 show maximum, minimum, and average water levels (m) above DL (danger level) and EDL (extreme danger level)

### 3.1.2 Flood frequency and magnitude analysis

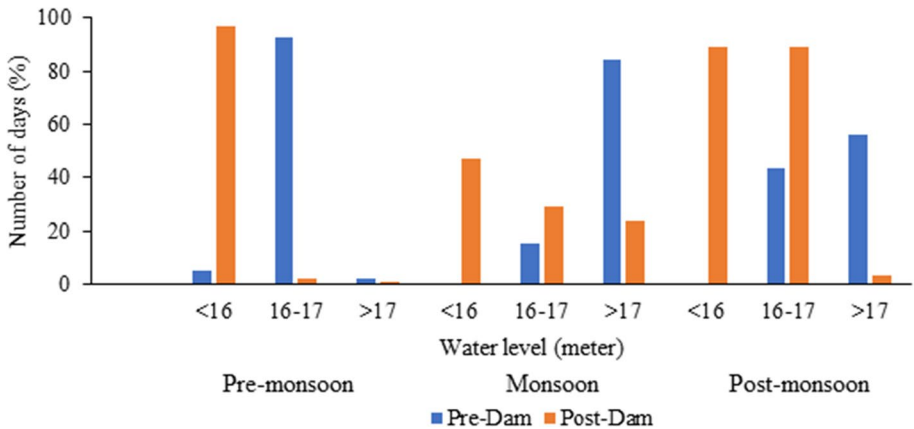
Figure 3 shows that in the post-dam period, except for two years (1998 and 2017), within 22 years, the water level was below the extreme danger level (DL and EDL). In the pre-dam period, six floods occurred within ten years. However, in terms of the magnitude of the flood, the flood of 1998 was the largest ever seen. Inhabitants in the river basin also reported that overflow during 2017 was the second largest flood. In the graph, its magnitude was not reported as high, and it may be due to the breaching of the embankment astride river at many places during this time. Flood stagnation day of flood 2017 was also longer than that of 1998. According to the views of local people, flood frequency was reduced, but its suddenness and devastation significantly increased after damming. The variability of the difference between the maximum and average WL also justifies their views (Fig. 3).

### 3.1.3 Flow periodicity analysis

Figure 4 presents the continuous wavelet transformation of average water level in the pre-monsoon, monsoon, post-monsoon, and winter seasons from 1978 to 2020. After damming (1989), significant periodicity (at a 5% level) in the wavelet power spectrum was identified in bands 3–4 years in different seasons. However, it was found to be more prominent from 1989 to 2007 during the pre-monsoon, monsoon, and winter seasons. A weaker power spectrum was seen in the lower spectrum zone (<3 years band). In the post-monsoon season, a significant power spectrum was only noticed from 1997 to 2001.



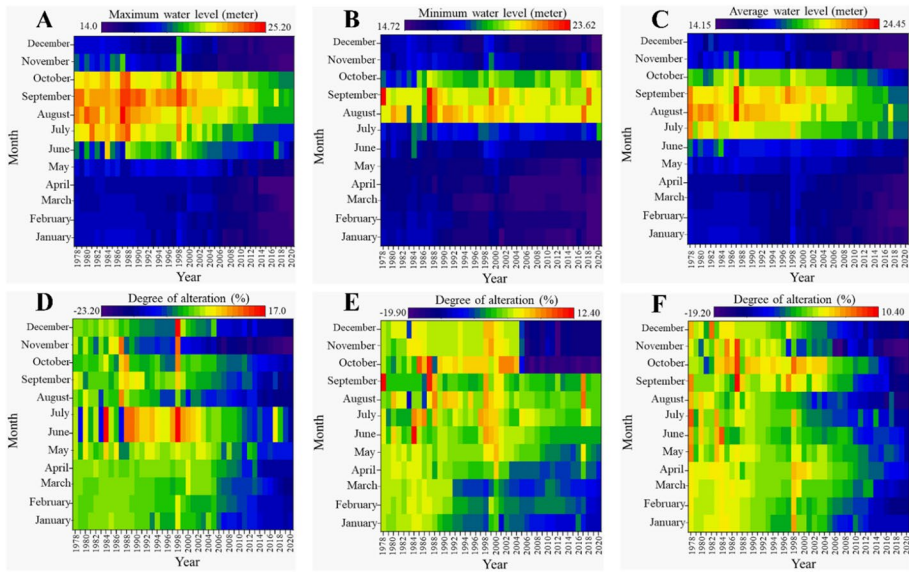
**Fig. 4** Continuous wavelet power spectrum of average flow data from 1978 to 2020 was recorded at Baman-gola gauge station over the Tangon river basin for **a** pre-monsoon, **b** monsoon, **c** post-monsoon, and **d** winter season. Red and blue colors indicate stronger and weaker powers, respectively. A thick black contour line indicates a 5% significance level against the red noise. The conic concave area shows the cone of interest within which significance could be judged



**Fig. 5** Diurnal average flow conditions in the pre-dam and post-dam periods

### 3.1.4 Diurnal flow analysis

HCA of the percentage of days under different water level classes presented in Fig. 5 shows that after implementation of the dam, the frequency of high flow was substantially declined, and contrarily, the frequency of low flow level was enhanced in all the seasons. For instance, during the pre-dam period, the frequency of high flow days

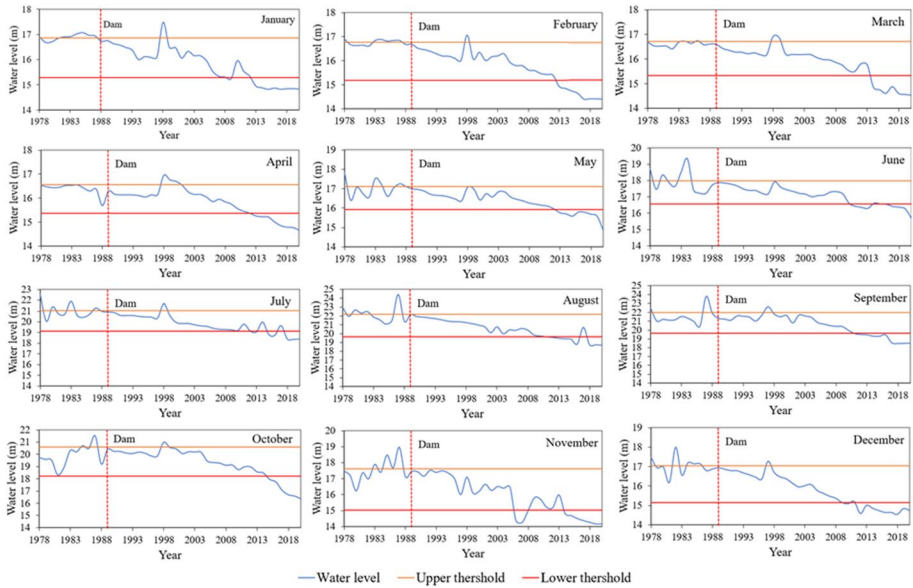


**Fig. 6** Heat map showing water level alteration about absolute maximum, minimum, and average water level (A–C) and maximum, minimum, and average water level change rate (D–F) using Bamangola gauge station data sets. Here, 1989 is the damming year

(> 17 m) in the monsoon season was 84.40%, and it dropped to 23.79% in the post-dam period. Similarly, during the pre-monsoon season, about 95% of days recorded water levels > 16 m, but after damming, 97% of days recorded WL < 16 m. These statistics clarified that the duration of high flow in a year declined after damming, indicating the mounting stress on the river nestled ecosystem and supported livelihood.

### 3.1.5 Measuring the degree of flow alteration

The heat maps show the maximum, minimum, and average water levels and their degree of change in the Tangon river (Fig. 6A–F). Positive anomaly in water level was recorded in pre-dam cases, but after dam construction (1989), negative changes in water level were recorded. The degree of hydrological alteration also reported a negative change in water level after the installation of the dam. In the pre-dam period, many years recorded a positive anomaly of water flow compared to the pre-dam average. However, after damming (1989), all the years recorded significant negative changes in water level (Fig. 6D–F). Hydrological alteration ranged from  $-23.01$  to  $16.90\%$ ,  $-19.83$  to  $12.36\%$ , and  $-19.11$  to  $10.33\%$ , respectively, for maximum, minimum, and average water levels. A negative deviation was found after damming for all the cases (maximum, minimum, and average WL). Only a few years recorded a slight positive change in the post-dam period. All the seasons witnessed negative alteration after damming. The negative alteration was very high during pre-monsoon, post-monsoon, and winter seasons, mainly due to scarcity of rainfall, water diversion, and other direct withdrawal of discharge from the river for different purposes.



**Fig. 7** Monthly average water level condition in reference to lower and upper RVA thresholds

### 3.2 Eco-hydrological conditions

#### 3.2.1 Ecological flow threshold and flow failure rate

River flow eco-hydrological threshold condition for each month (January–December) was categorized into (a) natural and ecological flow state (within 25th and 75th percentile), (b) failure rate which is above upper ecological flow state (above 75th percentile), and (c) failure rate which is below the lower threshold (below 25th percentile). The monthly stream flow state from 1978 to 2020 is presented in Fig. 7 in reference to upper and lower threshold limits. Most of the months clearly recorded that the flow failure state was very high in

**Table 3** Seasonal and average pattern of IHA impact for different flow regime components

Flow regime component	Pre-monsoon	Monsoon	Post-monsoon	Winter	Overall
Group 1: magnitude of monthly water conditions	0.882	0.398	0.393	0.471	0.536
Group 2: magnitude and duration of annual extreme water conditions	0.815	0.452	0.443	0.539	0.562
Group 3: timing of annual extreme water conditions	0.351	0.772	0.551	0.431	0.526
Group 4: frequency and duration of high and low pulses	0.381	0.752	0.641	0.393	0.542
Group 5: rate and frequency of water condition change	0.363	0.561	0.551	0.372	0.462
Overall	0.612	0.555	0.495	0.446	0.526



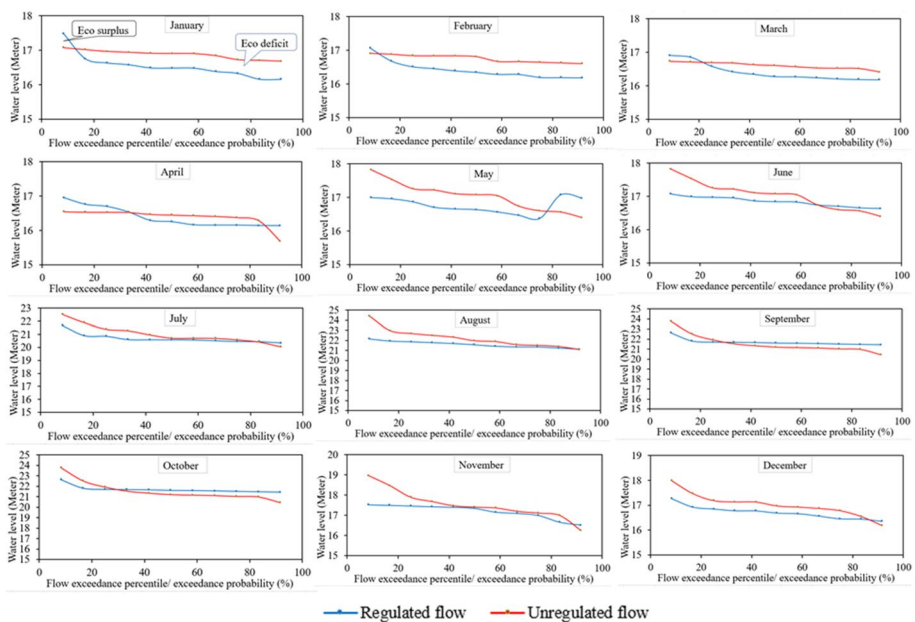
the post-dam period. More clearly, in pre-monsoon, monsoon, and winter months, FFR ranges from 13.95 to 25.58%, respectively.

### 3.2.2 Degree of Impact owing to the hydrological alteration

Table 3 presents that the overall ImHA, including all the seasons, ranges from 0.462 to 0.562 for all the IHA groups and the average including all the IHA groups is 0.526, which indicates moderate impact in the post-dam period. Among the IHA groups, the degree of impact was maximum in the case of group 2 (magnitude and duration of annual extreme water conditions). The degree of impact for the magnitude of monthly flow condition was maximum (0.882) during the pre-monsoon season and lowest (0.393) during the post-monsoon period. Most of the groups registered high impact during pre-monsoon and monsoon periods. The impact of the timing of annual extreme water conditions was higher in the monsoon (0.772) period and lower in the pre-monsoon (0.351) period. The overall impact is relatively less in the winter season (ImHA: 0.372) compared to other seasons. Such statistics clearly demonstrated that hydrological alteration has a crucial effect on the degree of impact on the ecological milieu of the river ecosystem and dependent aquatic ecosystem.

### 3.2.3 Eco-deficit and eco-surplus analysis

FDC-driven monthly (January to December) eco-deficit and eco-surplus state of the Tangon river is presented in Fig. 8. In all months during the pre-dam period, the FDC of unregulated flow was found above the FDC of regulated flow, signifying the dominance



**Fig. 8** Monthly FDC for ecological surplus and deficit of Tangon river; the blue color line indicates the regulated flow, the red color line indicates the unregulated flow and the gap between regulated and unregulated flow indicates an eco-deficit state

**Table 4** Integrated degree of impact of hydrological alteration

Flow variability (CV)	Flow failure rate (FFR)	Degree of impact of hydrological alteration (ImHA)	Net eco-deficit/eco-surplus (NED/S)	Integrated degree of impact of hydrological alteration (IImHA)
0.527	0.217	0.526	0.355	0.406

of eco-surplus condition. Conversely, the situation became reversed during the post-dam period, indicating the dominance of eco-deficit.

### 3.3 Integrated degree of impact due to hydrological control

IImHA computed using multiple relevant eco-hydrological measures depicted the moderate impact of hydrological alteration in the ecological milieu with an IImHA value of 0.406. In terms of flow variability, it was 0.527, FFR was 0.217, ImHA was 0.526, and NED/S was 0.355 (Table 4). Different individual indexes signified that the degree of impact ranges from poor to moderate. Only in the case of FFR, the poor impact was accounted. If water harvesting from the river grows, the situation may shift beyond control. So, in view of ecological sustainability, a preventive check is highly required.

## 4 Discussion

The continuous decrease in water levels clearly demonstrated the effect of the construction of the dam. During non-monsoon months, flow level attenuation varies from about 10–23%. The dam at Panchagarh district in Bangladesh was constructed in 1989 over the Tangon river basin for irrigation purposes. It causes a continuously decreasing water level downstream of this river basin. Apart from water diversion for irrigation purposes from the dam, growing water harvesting directly from the river through river lift irrigation projects, industrial and municipal purposes also are the discernible causes behind flow attenuation. A similar trend with a varying magnitude of alteration was also reported by Pal and Sarda (2020), Pal and Talukdar (2020) in the Atreyee and Punarbhaba rivers of India and Bangladesh. Ngor et al. (2018); Amenuvor et al. (2020), Talukdar and Pal (2019), Gierszewski et al. (2020), Hecht et al. (2019), Abdelhaleem et al. (2021) in the case of Mekong-3S, Volta, Punarbhaba, lower Vistula, Nile, Mekong rivers across the world mainly due to artificial flow regulation.

Apart from flow attenuation, increasing flow variability was also reported in this river. This result is always not in agreement with the literature of the world. Mohammed et al. (2018), Ali et al., (2019a, 2019b), Gierszewski et al. (2020) reported similar results; however, Pal (2016) in case of the Atreyee river reported narrowing variability. Due to increasing flow variability, the flow has become more uncertain in this river and it is not ecologically viable.

Flood frequency after the dam was recorded to decline; however, two most devastating floods in 1998 and 2017 occurred in the post-dam period. Reducing flood frequency is caused for the non-viable sustenance of riparian ecology, particularly in wetland areas. Wetland astride of this river strongly depends on river water for their survival, ecological, and other service support (Scholte et al., 2016; Pal & Saha, 2018; Talukdar & Pal, 2019). The declining trend of the same withstands against the free-flowing ecological goods and services not only from the river but also from dependent wetlands (Sabater et al., 2018; Larsen et al., 2021). Diurnal flow variation through the histogram comparison approach (HCA) exhibited that the positively skewed distribution of the pre-dam period was turned into a negatively skewed distribution in the post-dam period. On average, about one meter of WL was reduced in > 95% of days of a year in the post-dam period. Although the diurnal level analysis in this manner is less across the world, monthly and seasonal scale studies

conducted by Lu et al. (2018), Hecht et al. (2019), Yang et al. (2019) reported a similar trend.

Morlet's wavelet transformation method is usually used for analyzing the periodicity of flow. It helps to understand whether there is any discontinuity of flow in the entire flow spectrum. In case of the Tangon river, a statistically significant change in the flow regime was identified after 1989. Many researchers (Aladağ, 2021; Dong et al., 2019; Morin, 2019; Mouatadid et al., 2019; Pal & Talukdar, 2020) used wavelet transformation for flow analysis and reported that artificial control on flow was responsible for defining new flow regime.

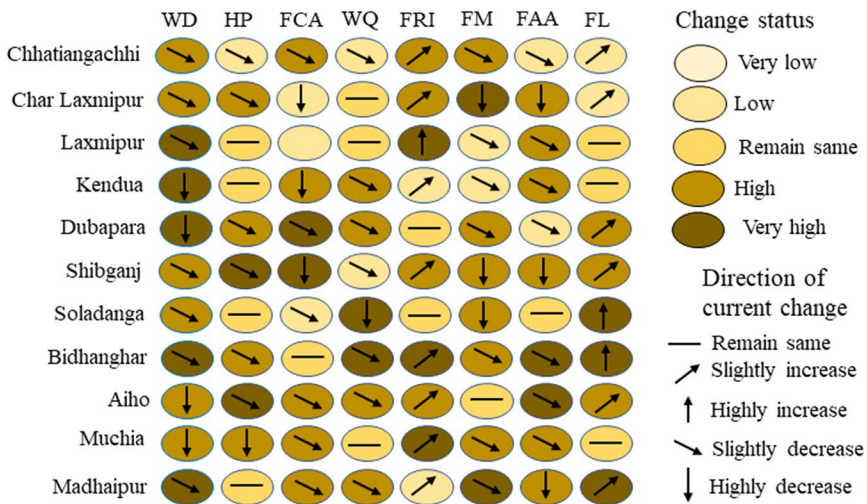
Severe flow alteration often beyond ecological thresholds is caused for an increasing trend of flow failure rate. Enhanced FFR was found in the present work. Similar findings were also recorded by different researchers such as Pal and Sarda (2020), Pal and Talukdar (2020), Nowreen et al. (2020); Cui et al. (2020), Mezger et al. (2021) in different rivers across the world. In the post-dam period, flow failure below the lower RVA threshold is more common in all the months, and this condition is ecologically very stressful. So, it is evident that damming is caused for growing ecological stress in the river ecosystem. The present study reported eco-deficit conditions followed by damming and consequent hydrological alteration which is concomitant with the studies of the previous researchers. Zhang et al. (2018) in the Yellow River, Basheer et al. (2019) in the Tekeze–Atbara River, Chaudhari et al. (2019) in the Amazon River, Roland II and Crowley-Ornelas (2022) in Pearl River, Tang et al. (2021) in the Hongshui River, and Zhang et al. (2021) in Loess plateau watershed reported eco-hydro-deficit in the rivers due to artificial control. It often causes the reduction in the aquatic species diversity, frequency, narrowing of suitable habitats of the aquatic species, breaching and qualitative degradation of breeding grounds, etc. (Gain & Giupponi, 2014; Talukdar & Pal, 2019).

Since the hydrological alteration is highly associated with the ecological transformation of the ecological milieu, the present study also analyzed the eco-hydrological aspects of the river. Range of variability in flow and consequent flow failure rate, degree of impact, eco-deficit/eco-surplus, and finally IImHA were used for quantifying the degree of impact on the eco-hydrological condition. Many studies used the RVA approach and computed FFR for studying the eco-hydrological milieu. However, in this study, a novel index was devised integrating different eco-hydrological measures to examine the overall possible consequence of hydrological alteration. This measure successfully explored the degree of ecological impact due to hydrological alteration. Apart from this particular methodological aspect, this work tried to explore the hydrological alteration at different temporal resolutions focusing diurnal to year scale.

RVA analysis clarified that the flow regime in all the months was within the natural flow limits; however, over the advances of time after the dam, some years were recorded when the flow level was below the lower threshold. Computed FFR ranges from 13.95% to 25.58% with high FFR during monsoon season. IHA analysis also recorded zero flow during the altered situation. This weak spectrum of flow promotes ecological deprivation. Consequently, this eco-deficit was recorded to be more common in the post-dam period. This river computed a moderate degree of impact (0.526) due to hydrological alteration. IImHA accounted for 0.406 and also reported the same trend of impact including different aspects. Pal et al. (2019), Pal and Sarda (2020), Khatun et al. (2021) conducted FFR in the damming rivers and accounted for 58% to 100% failure rate. The present findings on eco-deficit/eco-surplus and degree of impact were supported by some concomitant studies across the world. Wang et al. (2018), Ren et al. (2019), Ali et al. (2019b), Tang et al. (2021) also reported similar types of findings in their study cases.

In consequence of this hydrological alteration, ecological environment and river- and riparian wetland-dependent livelihood witnessed a significant change. Although the present study has not investigated the ecological consequences of hydrological consequences in detail, based on the existing studies, some possible consequences could be mentioned. A few works focused on various such impacts. Pal and Talukdar (2019), Sarda and Pal (2021), Pal et al. (2022), Pal and Khatun (2022) clearly mentioned the decrease in wetland habitat area and quality due to changes in water availability in connected rivers. Adel (2012) figured out that due to dwindling flow in river Padma caused by water diversion through the Farakka feeder canal, the loss of breeding and nesting ground of 109 fishes was lost. Hossain and Haque (2005) reported that 50 more fish had become rare in the same area. Meng et al. (2017) documented the complete breaching of 36 fish in Taihu Lake in China in the last 57 years. Santos et al. (2018), Yoshida et al. (2020), Soukhaphon et al. (2021) state about the loss of breeding grounds, and fish species due to a significant reduction in the natural flow. A decrease in water availability may cause an enhancement in water temperature, turbidity etc. which are causes for ecological hostility in waterbody (Yang et al., 2010). Narrowing flow duration also adversely hampers the life cycle of many species that used to live in water (Figueiredo-Vázquez). Flow modification in the Tangon river may also exert such influence in this river and riparian environment. At the riparian wetland scale some of such effects have been reported by Pal and Khatun (2022), Khatun and Pal (2021), Khatun et al. (2021) in this river basin and surrounding river basins.

Apart from a literature-based analysis of flow modification, a survey (67 respondents to 11 sites) was conducted from eleven riverside villages to explore how far the change has occurred flow environment and its consequences. All the respondents were above 45 years of age. Information regarding water depth, hydro-period, fish catch amount, water quality, flood recurrence interval, flood magnitude, flood-affected area, and the number of fish totally lost were collected. The quantitative and qualitative information received from the



WD=Water depth; HP= Hydro-period; FA=Fish catch amount; WQ=Water quality; FRI=Flood recurrence interval; FM=Flood magnitude; FAA=Flood affected area; FL= Number of fish totally loss

Fig. 9 Some case studies show the nexus between river flow hydrological modification and associated hydrological changes after damming

villagers regarding this issue is shown in Fig. 9. The information received from human perception depicted decreasing rate of water depth, flow duration, and flood magnitude and these are the strong evidence of the hydrological transformation as accounted in data analysis. In a consequence of this, they also reported that it has a crucial impact on fishing activities. The focused group discussion identified that chital (*Notopterus chitala*), shal (*Channa marulius*), and khorikata (*Badis badis*) fishes were found before damming, but these are totally lost in recent times. The fish habitat was quantitatively and qualitatively reduced due to narrowing hydro-period, reducing water depth, decreasing water quality, etc. The amount per net fish catch was reduced by 30–70% as per the view of the fisherman community from different parts of the study unit. Pal and Khatun (2021), Kundu et al., (2022) also reported the same issue in this river basin. Pal and Khatun (2022) explained that hydrological alteration in the river is caused for a squeeze of major suitable fishing areas in the wetland. The fisherman community also reported livelihood insecurity due to flow alteration. Decreasing water availability in the river and increasing the influx of contaminants from different points and nonpoint sources also negatively influence habitat quality.

## 5 Conclusion

The study explored that river flow was significantly reduced maximally by 23% after damming. Non-monsoon months recorded more change than monsoon months. Periodicity was recorded from wavelet transformation analysis. As a consequence of hydrological transformation, increasing FFR was recorded. The eco-deficit condition was found more common in the post-dam period. All these have serious ecological implications. Moderate degree IImHA was recorded and it is a serious threat to the ecological viability of a river and riparian habitat particularly aquatic habitats, more particularly fish habitats. Since the study at a different temporal scale explored the change in flow behavior, it would be an important tool for the eco-hydrological restoration of the river and riparian environment. A large number of inhabitants particularly the fishermen community heavily depend on the river and riparian wetlands for their livelihood. But the decline of flow volume and its negative consequence on the ecological milieu adversely affected the fishing community making their livelihood insecure.

Hence, the issue raised here is very vital and findings would be instrumental for river flow management, conservation and restoration of hydrological health of the river-dependent wetlands, nourishing and amelioration of associated ecosystems, and goods and services received from the river and wetland. Considering the fruitful outcome of the study, the current study recommends using ecological analysis in relation to hydrological alteration. A novel method, IImHA, as proposed could be applied in similar other fields in order to obtain integrated ecological effects of hydrological alteration. Since the hydrological alteration and its ecological effect is not much high in this moment, it is high time to adopt ecologically viable measures to restore the river flow. Ecological flow measurement would be the first step in this regard and the ecological flow should be allowed for the sustainability of river flow and restoring ecological health. Although the study focused only on river flow alteration and associated eco-hydrological issues, there is a further scope to explore the impact of hydrological alteration on biodiversity and other forms of turnover from ecosystem goods and services associated. Livelihood modification in the same consequence would be another scope for further study.

Along with the novelty of the work, as discussed in “Discussion” section, a few limitations are there that need to be mentioned for proving the further scope of development. The entire work is based on time series water level data sets. Discharge data would be more relevant in this analysis. Some missing data were there that were predicted using the ANN-based forecasting method for IHA analysis. The length of time series data taken for the pre-dam period (1978–1989) was quite narrower.

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**Data availability** The data that support to fulfill of this present study are available from the corresponding author, upon reasonable request.

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