



Quantifying flood events in Bangladesh with a daily-step flood monitoring index based on the concept of daily effective precipitation

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Abstract

Bangladesh, located in the Bay of Bengal, is a developing nation that is prone to devastating flood events that cause loss of lives and several other forms of humanitarian disasters. Identifying, developing and validating new scientific techniques that can be used for flood-risk warning and regular monitoring, including flood risk mitigation and adaptation, can help reduce the catastrophic effect of floods in Bangladesh and other developing countries. In this study, a daily Flood Index (I_F) based on daily effective precipitation (P_E) is utilized for quantifying floods for two cites in Bangladesh: Dhaka (23.7° N, 90.38° E) and Bogra (24.51° N; 89.22° E), where flooding is a common phenomenon. Based on total daily precipitation (P) data, in this study the I_F is determined by calculating the P_E using an exponentially decaying time-reduction function, which considers the gradual depletion of water resources over time. P_E per day is normalized and compared with the average and standard deviation of yearly maximums, within the considered hydrological period. The start of a flood event is identified for $I_F \geq 0$. Subsequently, the I_F severity (I_F^{acc}) as consecutively positive I_F , duration (D_F) as number of days with positive I_F , and peak danger (I_F^{max}) as maximum I_F are estimated for identified flood events, using the run-sum theory. The analysis carried out has accurately identified historical flood events at Dhaka station in 1984 and 2007 as having the largest I_F^{acc} value (i.e., greatest severity). Flood severity (I_F^{acc}) and peak danger (I_F^{max}) parameters have been verified by accumulated precipitation corresponding to the same period. For Bogra station, the 1998 and 1979 events were found to be the most intense. Seasonality analysis of the flood index shows most floods happened during the summer monsoon, although for the Dhaka station, flood events occurred between early June and November, and in Bogra, from late June to October. A rational study of effective precipitation provides a useful severity and danger indicator. The results indicate the practicality of daily I_F for flood-risk assessments where the severity, peak danger, and duration need to be considered as a unified index for flood-risk monitoring. The proposed daily flood index can be useful for hydrologists for the purpose of daily operational flood monitoring in high flood-risk nations.

Nomenclature

AWRI	Available Water Resources Index
AWRI ^{max}	Annual maximum daily AWRI
AWRI ^{tot}	Annual total daily AWRI
d	Day
D_F	Duration of summation for P_E
D_F	Flood duration
$\sum D_F$	Cumulative distribution of D_F

I_F	Daily Flood Index
I_F^{acc}	Accumulated I_F (\equiv flood severity)
I_F^{max}	Maximum daily I_F (\equiv flood danger)
P_E	Effective precipitation
Q_1	Lower quartile
Q_2	Median
Q_3	Upper quartile
P	Daily precipitation

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$\overline{P_E^{p.a.}}$	Mean daily effective precipitation over 1-year period
P_m	Rainfall on day m (mm)
$\frac{1971}{2013} \overline{P_E^{\max}}$	Mean of annual maximum daily P_E for monitoring period 1971–2013
$\sigma\left(\frac{1971}{2013} E_p^{\max}\right)$	Standard deviation of annual maximum daily P_E for monitoring period 1971–2013
SPI	Standardized Precipitation Index
t_{onset}	Onset day of flood event, first day when the I_F is greater than 0 (inclusive)
t_{end}	Termination day of flood event, last day when the I_F is greater than 0 (inclusive)
W	Weighting factor, as exponentially decaying time-dependent reduction function

1 Introduction

Bangladesh is geographically situated on the Ganges Delta, which is made up of tributaries flowing into the Bay of Bengal. Seventy-five percent of the country is less than 10 m above sea level and 80% is on a flood plain (Rahman 2010). Mean annual rainfall across the country varies from 1250 to 5700 mm, with significant fluctuations in different years. Bangladesh is very vulnerable to torrential rainfall and potential flooding (Tingsanchali and Karim 2005), which are detrimental to the country's economy, infrastructures, ecosystems, and population. Scientific techniques for monitoring, progressive development, and assessing potential impacts of flood events based on water-intensive properties are valuable tools for flood vulnerability studies and disaster-risk assessment and management.

As much as 20% of Bangladesh experiences normal annual flooding while more than 50% of the country has been inundated by historical catastrophic flood events (Ali 2007; Chowdhury 2000). Exceptionally, the devastating floods of 1987, 1988, and 1998 inundated more than 60% of the nation, with serious casualties. The 1998 flood caused 1100 deaths, inundated 100,000 km² of land, rendered 30 million people homeless, and damaged 500,000 homes. In 2004, another flood inundated 38% of the country (Rahman 2010). The nature of flood distribution is not uniform throughout the country: heavy monsoonal rain and flooding is the norm in the north and north-eastern parts, but is uncommon in the dryer (drought prone) southwestern districts of Jessore, Satkhira, Khulna, Magura, and Chuadanga. In the southwest region, the average precipitation during the monsoon months (July–October) is 1500 mm (compared to 2500–3000 mm in the northeast) that usually leaves these districts flood free. However, in October and November 2000, and September 2004, the southwestern districts experienced unusual flooding that affected over five million people (Ali 2007). Thus, addressing issues of floods based on the objective quantification of flood possibilities is important for flood-prone nations like Bangladesh.

Flood events are unavoidable, occur spontaneously with short warning times and a high concentration of precipitation on a specific spatial domain, and are extremely difficult to predict or monitor. Scientists have developed monitoring indices for detection, analysis, and prediction of these natural events, including the widely used Standardized Precipitation Index (SPI) for flood as well as drought monitoring (McKee et al. 1993). However, the SPI determines only the general flood and drought situation of a long period (e.g., several months or years) and cannot be used for short-term assessments (e.g., 1 week or less) (Lu 2009), mainly because the index is calculated on a monthly basis. Despite this, many studies have used SPI as an assessment tool. For example, Du et al. (2013) used this index to investigate the spatiotemporal variation of dry/wet conditions and their annual/seasonal trends in Hunan Basin. To verify the usefulness of SPI for drought/flood monitoring, the correlation between river discharge and SPI at multiple scales, and the relation between extreme SPI and occurrence of historical drought/flood events was explored. Interestingly, a strong correlation was found between average river discharge rates and SPI time-series based on rainfall, with the maximum correlation at a 2-month time scale. Seiler et al. (2002) used SPI for analyses of recurrent floods in southern Cordoba Province (Argentina), and indicated that the SPI could satisfactorily explain the development of conditions leading up to three flood events in the region in the previous 25 years. Thus, these studies support the prospect of applying the SPI as a valuable tool for flood and risk monitoring.

Despite its potential, there are limitations to the SPI approach for flood analysis. SPI uses raw values of precipitation without considering how daily water resources vary over the passage of time due to hydrological processes such as run-off, evaporation, infiltration, etc. That is, it does not consider the effects of antecedent precipitation for flood analysis of the current day. Because SPI is based on historical precipitation norms, using it to determine a flood event of three consecutive days, for example, may indicate a flood event as per climatology even if there was no actual precipitation in the preceding days. However, if there is very strong precipitation just before this period, then the recent days may still be in a flood state (Lu 2009).

Clearly, the use of total rainfall without consideration of precipitation during the previous days is a limitation of the SPI. Furthermore, operational monitoring and decision-making for flood assessment require an index to measure daily or weekly flood extents, so that a better assessment of short-term events can be performed. With a daily flood monitoring index, the start, duration, and strength of flood event(s) in any given month or year can be determined (Nosrati et al. 2011). Rather than limiting flood information to a monthly basis, a daily flood index can provide more accurate results for short-term inundations. Also, if the flood index takes into account both current and antecedent precipitation by considering the receding influence caused by the “demands” of water balance processes such as runoff,

evapotranspiration, groundwater flow, and percolation, on recent precipitation, a more scientifically strategic assessment of a flood situation is possible (Lu 2009; Ma et al. 2014).

This study utilizes the Flood Index (I_F) (Byun and Jung 1998; Byun and Wilhite 1999; Deo et al. 2015; Nosrati et al. 2011) for flood analysis in the Bangladesh case, where floods occur quite frequently. In this study, the daily time-series of the I_F is deduced from the weighted sum of daily precipitation, hereafter referred to as “effective precipitation, (P_E).” P_E is used to measure the relative extent of a flood event based on current day rainfall, superimposed onto antecedent rainfall amounts. Basically, the I_F is derived from daily P_E using the weighted sum of P over an annual cycle (i.e., 365 days or more) where each day’s P_E is based on a time-dependent reduction function that places greater emphasis on recent (vs. older) rainfall. In accordance with previous studies (An and Kim 1998; Lee 1998), the time-dependent reduction function for P_E concurs with rainfall-runoff model results where the depletion factor accounts for loss of water resources due to hydrological processes (e.g., run-off, evaporation, and infiltration).

The I_F is a standardized metric that represents the deficit or the surplus of water resources per day from the view point of flood occurrences. In case of a flood, the I_F exhibits a peak that corresponds to an elevated value of P_E , adopted as the Available Water Resources Index (AWRI) by earlier studies (e.g., Byun and Lee (2002), Han and Byun (2006), and Park et al. (2014)). Thus, its application in Bangladesh is a novel contribution to scientific insights on floods.

The main objectives of this investigation are:

- To evaluate the usefulness of I_F in detecting flood danger using daily rainfall data from the Dhaka (1976–2013) and Bogra (1971–2013) weather stations.
- To perform statistical analysis of individual events in order to quantify flood onset (t_{onset}) and end (t_{end}) dates, and the severity (I_F^{acc}), peak danger (I_F^{max}), and duration (D_F) of flood events using run-sum approaches (e.g., Yevjevich 1967). This allows for a check of the dynamical behavior of rainfall vs. flood danger within the flood period.
- To perform a seasonal analysis of flood events over the period of study.
- To demonstrate the ability of I_F for ranking floods based on water-intensive properties and analysis of individual events in the period of study.

The remainder of the paper is structured as follows: In the next section, characteristics of the precipitation data, study area, and the two weather stations are described and the calculation of daily I_F is detailed. In Section 3, the findings are presented to demonstrate the usefulness of the I_F in quantifying flood events for the period of study. In Section 4, it is concluded that the I_F is a useful scientific tool for quantification of floods, particularly for identifying flood properties (severity, peak danger, and durations) and collating statistical information on the seasonality of floods.

2 Materials and methods

2.1 Study area

Bangladesh occupies an area of 147,570 km² between 20.5° N and 26.5° N and 88° E and 92° E (Dewan et al. 2003). Since the Dhaka and Bogra locations are spatially vulnerable to flood events (Ali 2007; Dewan et al. 2003; Shamsuzzoha et al. 2011; Tingsanchali and Karim 2005), these stations were selected as the primary study areas. Hence, the two weather stations under study are located in the flood-prone cities of Dhaka (23.7° N, 90.38° E) and Bogra (24.51° N; 89.22° E) (Fig. 1). The larger city, Dhaka, is also the capital of Bangladesh, with an area of 258.78 km² and situated at an elevation of 75 ft above sea level. Dhaka has a tropical monsoon climate with four seasons: pre-monsoon (March to May), monsoon (June to September), post-monsoon (October to November), and dry season (December to February). The annual rainfall is approximately 2000 mm with 80% of this occurring during the summer monsoon season. The second study region, Bogra, is located in the northwestern region of Bangladesh, and has an area of 71.56 km² and an elevation of 85 ft above sea level. The mean annual rainfall at Bogra is 1847 mm (Shamsuzzoha et al. 2011). The city has a tropical monsoon climate, characterized by moderately warm temperatures and a rainy monsoon season mainly from June through mid-October. More than 80% of the annual rainfall normally occurs during this period. These two cities have been subjected to numerous severe floods in the past (e.g., (Rahman 2010)), and the potential application of the Flood Index to analyze flood events is considered a novel contribution in the study regions.

2.2 Climate data and computation of flood index

Precipitation data for flood analysis were acquired from the Climate Division of the Bangladesh Meteorological Department, Agargaon, Dhaka-1207, and included daily rainfall (mm) from Dhaka and Bogra stations in the periods 1976–2013 and 1971–2013, respectively. Table 1 shows the characteristics of the study sites. After replacing missing data with the respective calendar mean, the precipitation data were analyzed using flood detection and analysis software (<http://atmos.pknu.ac.kr/~intra3/>) developed by Byun and Wilhite (1999). For reasons of space, only a concise description of the I_F methodology is provided here, but readers are referred to Byun and Wilhite (1999) for more details.

Consistent with recent research work on floods (e.g., (Lu 2009; Ma et al. 2014)), the danger of a flood on any day is assessed by superimposing the current day’s P on previous days’ possibility of flooding based on P during these days. I_F was derived from effective precipitation (P_E), the summed value of rainfall for the current and previous days, determined

Fig. 1 A map of Bangladesh showing the studied weather stations (i.e. Dhaka and Bogra)



by a time-dependent reduction function (Byun and Jung 1998). If P_m was the total rainfall recorded on any given day m ($1 \leq m \leq 365$), and N was the duration of the summation of the preceding period, then the P_{E_i} for that (current i th) day was given by:

$$P_{E_i} = \sum_{N=1}^D \left[\frac{\sum_{m=1}^N P_m}{N} \right] \tag{1a}$$

$$= P_1 + \frac{P_1 + P_2}{2} + \frac{P_1 + P_2 + P_3}{3} + \dots + \frac{P_1 + P_2 + P_3 + \dots + P_{365}}{365} \tag{1b}$$

$$= P_1 \left(1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{365} \right) + P_2 \left(\frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{365} \right) + \dots + P_{365} \left(\frac{1}{365} \right) \tag{1c}$$

Table 1 Description of the study sites used to monitor flood events. Data source: Climate Division of the Bangladesh Meteorological Department, Agargaon, Dhaka-1207

ID	Station	Location	Elevation (m)	Data length	Precipitation, P (mm year ⁻¹)		
					Average	Max	Min
Weather stations							
01	Dhaka	23.7° N, 90.38° E	23	(1971–2013)	1875	8895 (2007)	4934 (2003)
02	Bogra	24.51° N; 9.22° E	26	(1976–2013)	1847	2248 (1995)	1432 (1974)

$$\approx P_1 + 0.85P_2 + 0.77P_3 + \dots + 4.23 \times 10^{-4}P_{365} \tag{1d}$$

Note that Eqs. (1a–d) define the degree by which daily P_m has been converted into the daily P_E for i th day. More importantly, this mathematical model considers the P of previous days with reduced weightings and therefore uses the rationale of Lu (2009) that the previous day’s rainfall tends to decay with time, and the current day’s rainfall has the greatest influence on flood extent. That is, P_E accumulates 100% of the precipitation received 1 day before, approximately 85% of that 2 days before, approximately 77% of that 3 days before, and so on, including a total of $\approx 0.0423\%$ of precipitation 365 days before the i th day.

The empirical model places greater weighting on present day rainfall, whereas the antecedent days’ contribution decreases gradually up to the maximum duration of an annual cycle ($N = 365$ days, ignoring the additional day in a leap year for simplicity). Unlike rainfall-runoff models that are highly complex in their data input requirements, this empirical model uses only P data, and requires no parameter estimation. The reduced size of weighting over time signifies the loss of water resources due to hydrological processes and the decay value of the water resources is expected to peak a few days after a rainfall event (An and Kim 1998; Lee 1998; Lu 2009). From this standpoint, the danger of a flood is expected to be greatly influenced by recent downpours, but cumulative (or lesser) effects of antecedent rainfall is also considered objectively in the proposed methodology.

Based on daily P_E , the Available Water Resources Index (AWRI) (Byun and Lee 2002; Kim et al. 2009) (Byun and Lee 2002; Kim et al. 2009), which is attributable to the accumulated P summed over an annual cycle, was determined as follows:

$$AWRI = \frac{P_E}{W} \tag{2}$$

$$W = \sum_{n=1}^{n=D} \frac{1}{n} \tag{3}$$

where W is a weighting factor applied as an exponential decay time-dependent reduction function to the accumulation of daily precipitation. This concurs with the physical reasoning of decline in water resources as in the case of rainfall-runoff models (e.g., Jakeman and Hornberger 1993; Lee and Huang 2013) and recent studies of flood detection using daily data (e.g., Lu 2009; Lu 2012). However, this equation is far less complex than rainfall-runoff models and is advantageous for assessing the surplus or deficit of water reserves that are likely to trigger a flood situation. In general, if the AWRI is larger in magnitude than that in the normal period, the water resources are considered to be relatively abundant, thus indicating the possibility of a flood event (Han and Byun 2006).

Finally, the Flood Index (I_F), a standardized metric, is denoted as follows:

$$I_F = \frac{P_E - \overline{P_E^{max}}}{\sigma(P_E^{max})} \tag{4}$$

where $\overline{P_E^{max}}$ is the mean of the annual maximum daily P_E for the monitoring period 1971–2013 and $\overline{P_E^{max}}$ is the standard deviation (1971–2013 was used for Bogra, and 1976–2013 for Dhaka due to shortage of data).

Based on this, the danger of flooding on any given day can be identified using the criterion of daily I_F being greater than zero. The severity of a flood event, I_F^{acc} , is the sum of positive I_F values from the flood’s onset [t_{onset} , i.e., first day when $I_F > 0$ or daily P_E exceeds the norm ($\overline{P_E^{max}}$)] to its end (t_{end} , last day $I_F > 0$, before dropping below 0, or the day before P_E drops to less than the norm); the peak danger of a flood event, I_F^{max} , is the maximum value of I_F between t_{onset} and t_{end} ; while the duration of the flood situation, D_F , is the number of days between t_{onset} and t_{end} of the flood event. Importantly, various forms of flood event characteristics can be calculated (Eqs. 5–7) and analyzed using a simple running-sum approach (e.g., Yevjevich (1967):

$$I_F^{acc} = \sum_{t=t_{onset}}^{t=t_{end}} I_{F_t} \text{ where } I_{F_t} > 0 \tag{5}$$

$$I_F^{max} = \max(I_F)_{t_{onset}-t_{end}} \tag{6}$$

$$D_F = t_{end} - t_{onset} \text{ (days)} \tag{7}$$

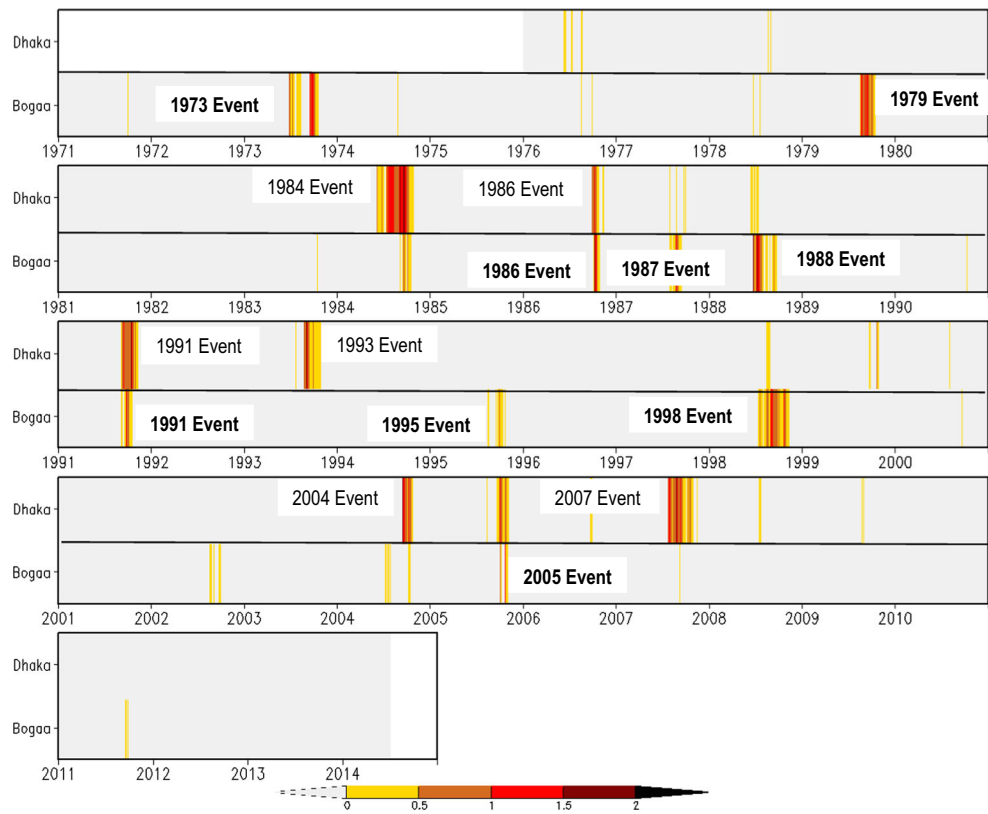
where I_{F_t} is the index of a flood for day t during a period of flooding, i.e., when $I_F > 0$ and $t_{onset} \leq t \leq t_{end}$.

For any given flood event in the study period, the daily I_F is a time-varying signal where the significantly high (or low) rainfall will yield a positive (or negative) value of the index (Byun and Wilhite 1999; Kim and Byun 2009; Nosrati et al. 2011). Consequently, a positive I_F is taken as a flood period and the properties of the flood event are analyzed in this flood window.

3 Results and discussion

Based on the I_F time-series for the study sites, a long-term flood map of Dhaka and Bogra was prepared, where periods with $I_F > 0$ were identified as flood events. Figure 2 shows the flood map for 1971–2013 (Bogra) and 1976–2013 (Dhaka). In this spatiotemporal flood map, only the positive value of the I_F in each yearly bracket was considered in order to reflect flood periods in respective years. A comparison of the historical flood events allowed for the identification of the spatiotemporal distribution of floods at a glance for the period of study.

Fig. 2 Chronological flood map for Dhaka (1976–2013) and Bogra (1971–2013) weather stations based on daily values of the Flood Index (I_F). Note that major flood events are identified for each station and only positive values of I_F (flood cases) are shown to display major flood periods



It was observed that the years 1973, 1979, 1986, 1987, 1988, 1991, 1995, 1998, and 2005 exhibited the worst flood events in Bogra. In Dhaka, the pattern of flooding is different, with the years 1984, 1986, 1991, 1993, 2004, and 2007 having the worst flooding. Interestingly, the major flood events at the two stations did not occur simultaneously except in the year 1986 when an I_F greater than 1.5 was recorded. The most

extreme flood event occurred in 1984 at the Dhaka station and in 1998 at the Bogra station. In recent years (2008–2013), neither station recorded an intense flood period. There has not been a major flood since 2007, possibly related to the recent decreasing trend in summer monsoon rainfall over the middle to southwestern regions of Bangladesh (Ahasan et al. 2010). Overall, the spatiotemporal flood map

Fig. 3 A time-series plot of **a** the severity of the annual flood event defined by accumulated Flood Index (left axis), I_F^{acc} and total precipitation, P (right axis), and **b** the peak danger, I_F^{max} (left axis) and the duration, D_F (right axis) of flood events for the Dhaka weather station. Each bar has been plotted at the onset date in the yearly bracket

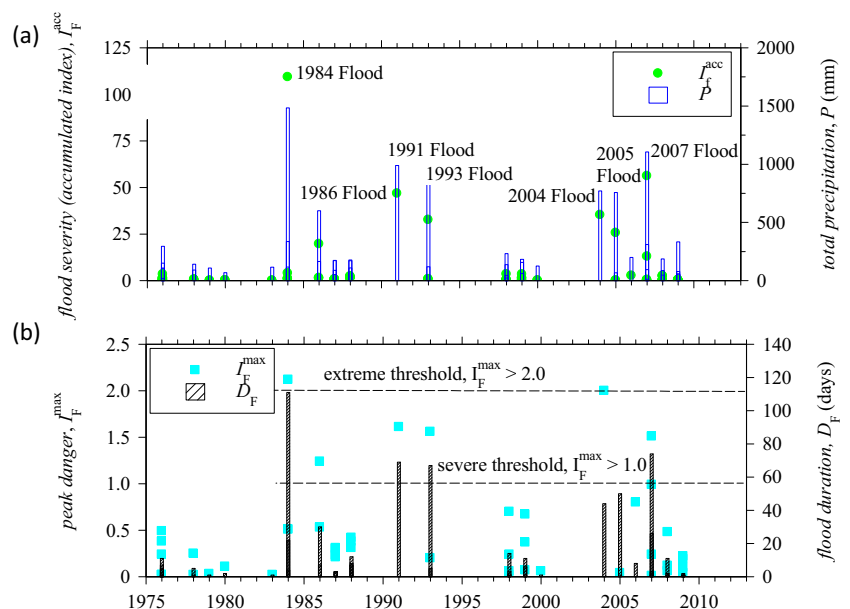


Fig. 4 The daily flood monitoring based on the Flood Index, I_F , and its corresponding precipitation value, P , used for the assessment of flood danger at Dhaka weather station during the July 1984 flood event

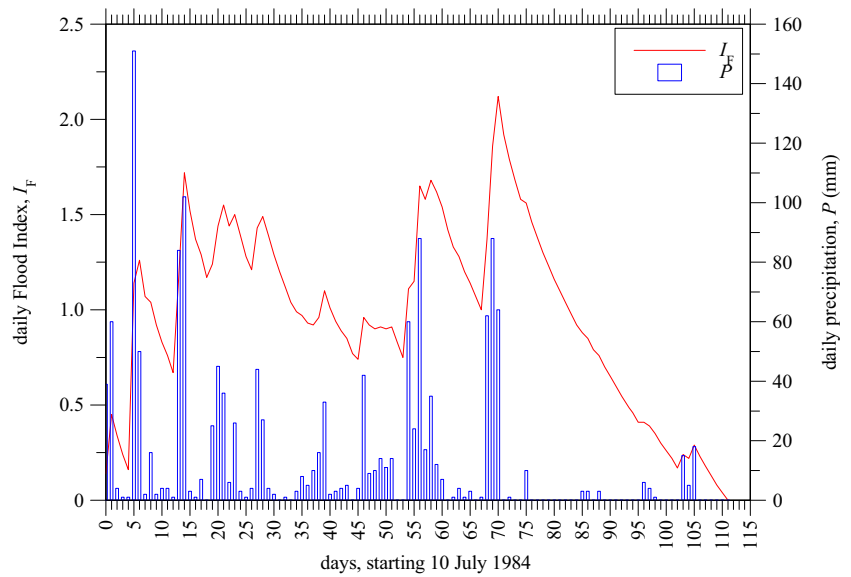


Table 2 Rank of the ten most severe floods based on Flood Index (I_F) according to severity, I_F^{acc} (accumulated I_F); peak flood danger, I_F^{max} (maximum I_F) and the duration of flood event, D_F for (a) Dhaka (1971–2013) and (b) Bogra (1976–2013) weather stations. Note: the danger of

the flood event was quantified using start date (t_{onset}) with $I_F > 0$, and for each event, the water-intensive properties are $AWR^{tot} \equiv$ total Available Water Resources Index; $PCN^{tot} \equiv$ total precipitation and $AWR^{max} \equiv$ maximum Available Water Resources Index

Rank	Onset date	Flood properties			Water intensive properties		
		Severity I_F^{acc}	Peak danger I_F^{max}	Duration D_F (days)	AWR^{tot} (mm)	Precip. PCN^{tot} (mm)	AWR^{max} (mm day ⁻¹)
(a) Dhaka weather station							
1	10-Jul-1984	109.31	2.12	111	80,895	1485	891
2	23-Jul-2007	56.22	1.51	74	51,562	1105	804
3	05-May-1991	46.78	1.61	69	47,276	989	818
4	14-Sept-2004	35.27	2.00	44	30,923	771	873
5	24-Aug-1993	32.67	1.56	67	44,084	839	810
6	20-Sept-2005	25.63	1.18	50	33,083	757	757
7	27-Sept-1986	19.67	1.24	30	20,459	601	766
8	08-Aug-2007	13	0.99	26	17,155	310	729
9	12 Jun-1984	3.98	0.51	22	13,518	336	661
10	18-Aug-1998	3.49	0.70	14	8742	232	689
(b) Bogra weather station							
1	05-Aug-1998	59.12	1.72	99	62,599	1157	775
2	16-Aug-1979	49.96	1.63	63	41,403	974	764
3	24-Jun-1988	36.68	1.71	43	28,589	779	774
4	17-Sept-1973	26.55	1.72	35	22,846	498	775
5	06-Oct-1986	19.06	1.99	25	16,331	440	809
6	12-Aug-1987	17.87	1.20	37	22,851	521	709
7	19-Sept-1991	16.82	1.58	33	20,500	428	757
8	28-Jun-1973	9.33	0.98	20	12,313	413	681
9	15-Sep-1984	7.19	0.91	16	9816	229	672
10	26-Sep-1995	7.06	1.00	19	11,471	249	683

appears to be a useful resource from a historical point of view for comparative analysis of flood events at the two stations.

Next, the time-series of annual flood events defined by the accumulated Flood Index, I_F^{acc} , total precipitation, P , peak danger, I_F^{max} , and duration, D_F , of events at the Dhaka weather station are considered. The severity of each flood event was analyzed using I_F^{acc} (the sum of positive I_F values from the flood's onset to its end date), and P . Figure 3 shows the results from 1976 to 2013. Some years have multiple flood events indicated by the overlapped bars with corresponding I_F^{acc} symbols. The highest precipitation accumulation

(1500 mm) occurred in 1984 due to heavy rains, which indicated the greatest flooding possibility (Fig. 3a). Therefore, 1984 appeared to be the most severe flood year for the Dhaka weather station among all the years of flood events. Other severe cases were recorded in 1991, 1993, 2005, and 2007, where the flood severity parameter corresponded very well with large amounts of accumulated precipitation. This result for Dhaka can be verified by the temporal flood map (Fig. 2).

In flood analysis, peak danger and approximate duration of events are very important to assess impacts on vulnerable

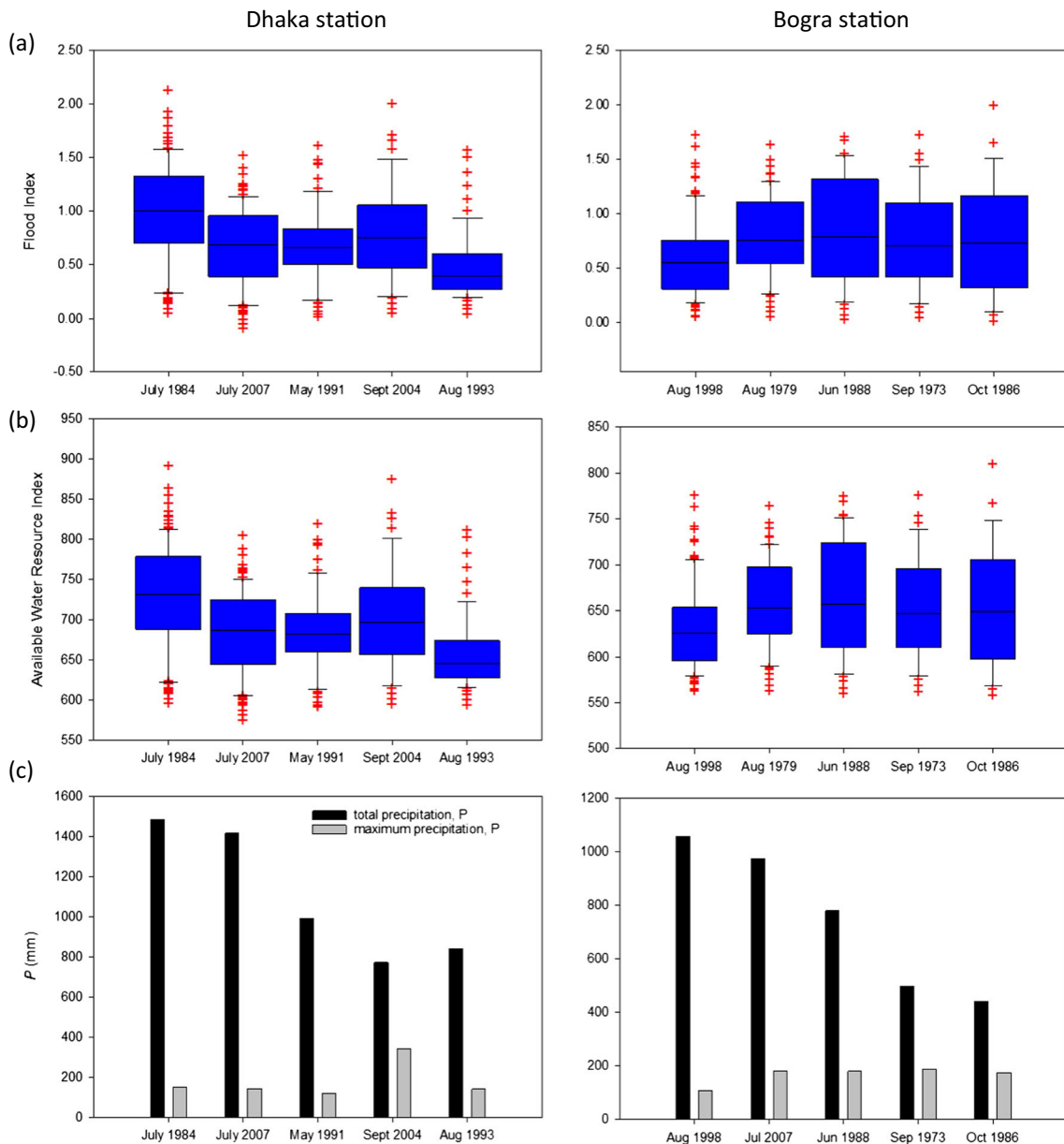


Fig. 5 Boxplots of **a** the distribution of daily Flood Index, I_F , **b** distribution of Available Water Resources Index, AWRI and bar graphs of **c** total accumulated precipitation, P , and maximum precipitation for top 5 severe floods in Dhaka and Bogra over the period 1975–2012. Note that

the points of extremity are indicated as outliers (red); period of floods was derived from Table 2, and order of bars from left to right on abscissa of bar graph shows the rank (severity) of each flood event based on accumulated Flood Index, I_F^{acc}

Table 3 Distribution statistics of flood event parameters (precipitation, P , Flood Index, I_F) for the five worst flood events at the Dhaka station extracted from the time-series of I_F for each flood period based on flood onset (t_{onset}) and duration in Table 2

Distribution statistic	Five worst flood events				
	1984	2007	1991	2004	1993
Daily precipitation, P (mm)					
Upper quartile, Q_3	13.0	10.5	16.0	14.8	14.0
Median, Q_2	3.0	1.0	0.0	0.0	2.0
Lower quartile, Q_1	0.0	0.0	0.0	0.0	0.0
Standard deviation, P_σ	25.1	27.5	25.7	53.4	25.0
Mean, \bar{P}	13.4	13.7	14.3	17.5	12.5
Daily Flood Index, I_F					
Upper quartile, Q_3	1.32	0.96	0.84	1.06	0.60
Median, Q_2	1.00	0.69	0.66	0.76	0.40
Lower quartile, Q_1	0.72	0.41	0.51	0.50	0.28
Standard deviation, $I_{F\sigma}$	0.67	1.17	2.10	3.49	2.59
Mean, \bar{I}_F	0.98	0.67	0.68	0.80	0.49

regions. Figure 3b shows the yearly changes in peak danger of floods (I_F^{max}) and flood duration (D_F) for all identified flood cases in Dhaka. The flood event in 1984 attained an I_F^{max} value that exceeded the extreme threshold category denoted by $I_F^{max} > 2.0$ with a duration of almost 111 days, the longest flood in the historical period. I_F^{acc} and P (Fig. 3a) exhibited distinct peaks for this event, indicating internal consistency among the data and the capability of the methodology to quantify multiple properties of flood events. Based on Fig. 3a, b, the year 1984 appears to have been the most dangerous flood year for the Dhaka weather station.

From an operational viewpoint, a significant benefit of the daily I_F for short-term monitoring is its ability to demonstrate the gradual or episodic progression of flood potential and how it changes in the corresponding value of daily precipitation; P can be used to assess an oncoming event. Figure 4 shows changes in I_F and P for the Dhaka weather station during the severe flood of 1984 where the maximum amount of precipitation (151 mm) occurred on July 15. As a result of this high precipitation, the magnitude of the index increased from 1.14 (day 5/July 15) to 1.26 (day 6/July 16). Additionally, the AWRI registered large values of 750.7 and 767.2 mm, respectively (not shown here), reflecting significant danger of flooding on these two days.

Figure 4 also shows a gradual decline in the magnitude of I_F as the precipitation dropped from July 15 (Day 5) to July 22 (day 12). However, on 23–24 (day 13–14) July, the precipitation amount increased swiftly (84 and 102 mm, respectively), causing the flood index to rise from $I_F = 1.18$ to 1.72. The highest I_F reflects the abundance of daily water resources, with an AWRI of 833.98 mm that exceeded the value of AWRI on 15 July. One may therefore conclude that the greatest

possibility of flooding was on 24 July 1984 at the Dhaka weather station (Table 2).

A comparison of the flood properties (I_F^{acc} , D_F , and I_F^{max}) measured for the study locations enabled us to rank the severity of all flood events based on their progressive phases and the water-intensive properties such as the total Available Water Resources Index (AWRI^{tot}), total recorded precipitation (PCN^{tot}), and maximum Available Water Resources Index (AWRI^{max}). Table 2 displays the severity (I_F^{acc}) ranking of all flood events. Flood severity, duration, and peak danger properties accord very well with the water-intensive properties in terms of their magnitudes to denote overall flood risk at the two stations.

It is clear that the extent of the floods at the two stations is significantly different in terms of temporal onset and end dates. For the Dhaka weather station, the 1984 event, which started on 10 July and lasted 111 days, was the worst case with an $I_F^{acc} = 109.31$ and $I_F^{max} = 2.12$ (Table 2). The flood properties were also consistent with the highest magnitude of the total available water resources and precipitation (80,895 and

Table 4 Comparison of two severe floods (July 1984 and September 2004) in accordance with cumulative frequency (%) of the daily Flood Index (I_F) in various thresholds based on start (t_{onset}) and end (t_{end}) dates of each event

Flood severity category	1984 Flood	2004 Flood
$0 \leq I_F < 0.5$	19.8	25.0
$0.5 \leq I_F < 1.0$ [moderate]	29.7	45.5
$1.0 \leq I_F < 2.0$ [severe]	49.5	27.3
$I_F \geq 2.0$ [extreme]	0.9	2.3

1485 mm, respectively), and the highest maximum recorded AWRI (891 mm/day). The next most severe flood commenced on 23 July 2007, although the accumulated magnitude of the I_F for this event was only 50% that of the July 1984 flood event.

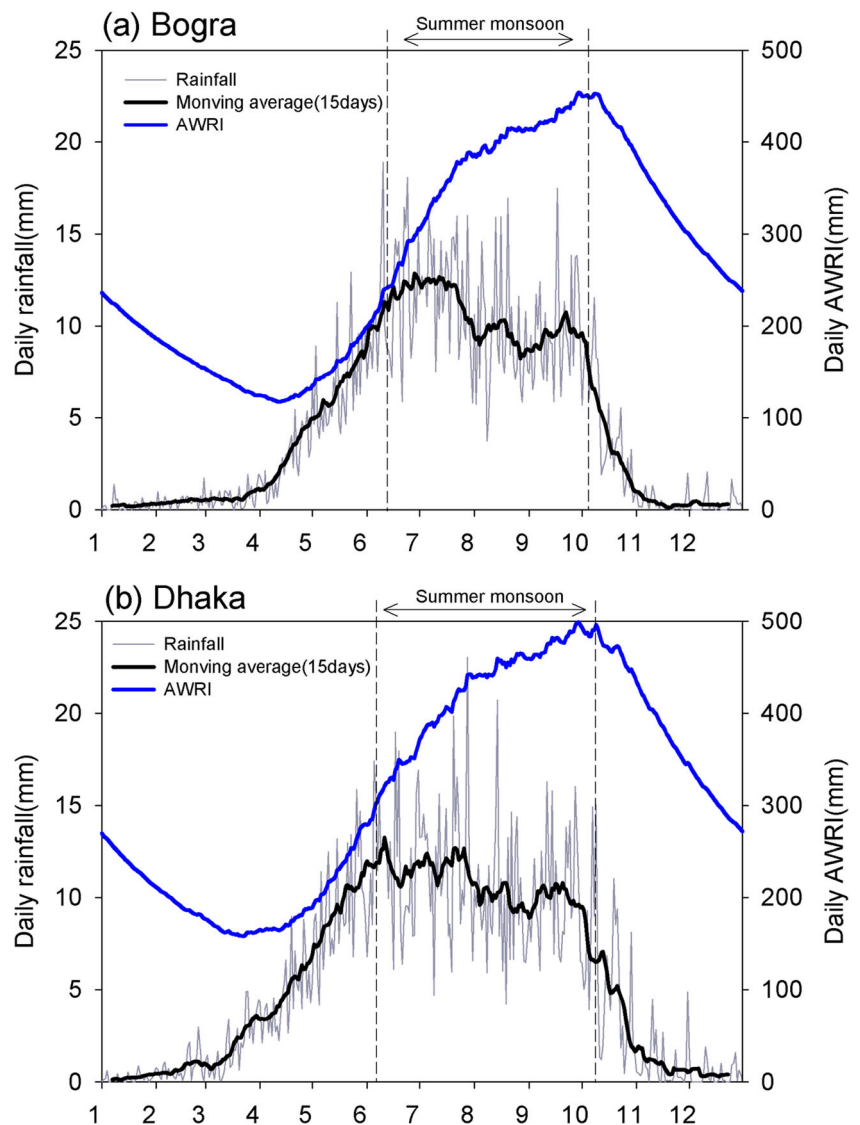
Flood analysis for the Bogra weather station data indicates that the worst event started on 05 August 1998 with $I_F^{acc} = 59.12$ and $I_F^{max} = 1.72$ (Table 2). Although the flood severity and peak danger were much smaller in magnitude than the worst event at the Dhaka station, the flood duration was 99 days, connoting that flooding impact can persist for a long period. This is perhaps attributable to the relatively large value of $AWRI^{tot}$ (62,599 mm) and PCN^{tot} (1157 mm), which were only 34% less than that of Dhaka's worst event. This also indicates that the gradual decline in water resources at Bogra is slower relative to Dhaka, and therefore the flood status is retained for a long period of time. The two stations exhibit

variations in flood and water-intensive properties that reflect their different geography.

Using the five worst floods from Table 2, we plot the distribution of I_F , AWRI, and total accumulated and maximum precipitation for Dhaka and Bogra, as shown in Fig. 5. For both weather stations, the points of extremity for the I_F and AWRI are quite consistent, whereby the worst events, represented by large I_F , are reflected in the elevated magnitude of the AWRI. Both parameters are also consistent with the magnitude of total precipitation (Fig. 5c).

The flood distribution statistics of flood parameters (P , I_F) for the five worst flood events are compared for Dhaka (Table 3). These statistics are extracted from the time-series of I_F for each flood period based on flood onset (t_{onset}) and end (t_{end}) dates shown in Table 2. Interestingly, the median of both the P and I_F values are the highest for the 1984 event despite the upper quartile of the P values being less than that of the

Fig. 6 Climatological seasonal cycles of rainfall and the Available Water Resource Index (AWRI) for **a** Bogra and **b** Dhaka. Daily values were averaged from 1971 (Bogra) and 1976 (Dhaka) to 2013. Onset and withdrawal dates of the summer monsoon were indicated by dash lines, which were also reported by Ahasan et al. (2010)



1994, 2001, and 1993 flood events. The standard deviation of the I_F is the highest for the 2004 flood event (3.49), indicating that the I_F exhibits much larger fluctuation in its magnitude than other floods. Therefore, the flood situation during the 2004 event was highly dynamic at the Dhaka weather station.

Table 4 compares the two worst events that occurred in Dhaka in July 1984 and September 2004, by categorizing cumulative days (%) with I_F values in different thresholds based on flood start (t_{onset}) and end (t_{end}) dates. The percentage of days that fell in the extreme flood category, ($I_F \geq 2.0$), for the 2004 event exceeded that of the 1984 event by more than 2.5-fold. This indicates that there were a greater number of days when flood danger was very high for the 2004 event despite the D_F and I_F^{acc} being relatively smaller (Table 2). However, the September 2004 event had an $I_F^{max} \approx 2.0$ similar to ≈ 2.14 for the 1984 event. Almost 50% of the days during the 1984 flood event were in the severe flood category ($1.0 \leq I_F < 2.0$) compared to only 27% during the 2004 event. The trend for days that exhibited the moderate category of flooding ($0.5 \leq I_F < 1.0$) was the opposite; approximately 46% of all days for the 2004 event compared to less than 30% for the 1984 event. The proportion of days in the three categories of flood severity for the two events were highly disparate, thus showing the importance of seasonality for the flood events.

A closer examination of the onset dates of the ten top floods (Table 2) shows that most of these events occurred between

May and September at both weather stations. In order to check the seasonality of flood events, the climatologically averaged daily value of precipitation and the AWRI are plotted for the Bogra and Dhaka weather stations (Fig. 6). Consistent with Ahasan et al. (2010), the present analysis shows that the summer monsoon season starts around June 6 and then ends around October 11 at the Dhaka weather station. However, at the Bogra weather station, the summer monsoon starts around June 12 and ends around October 4, and is apparently shorter compared to Dhaka. This is especially evident from early summer rainfall peaks that indicated summer monsoon onset occurred between mid-June and mid-July, and were more dominant at the Bogra compared to the Dhaka weather station. Also, the climatological mean value of the AWRI increased rapidly from the ordinate axis when the summer monsoon season commenced and then reached its maximum value immediately before the summer monsoon started to end.

We also investigated the seasonality of flood events based on I_F^{acc} , I_F^{max} , and D_F and plotted against flood onset dates in each monthly bracket (Fig. 7). Consistent with the seasonal climatology pattern (Fig. 6), floodings occurred during the summer monsoon period at both weather stations. However, it is interesting to observe that severe floods are more frequent during the late summer monsoon period (i.e., from late July to October) when the value of the AWRI is climatologically at a

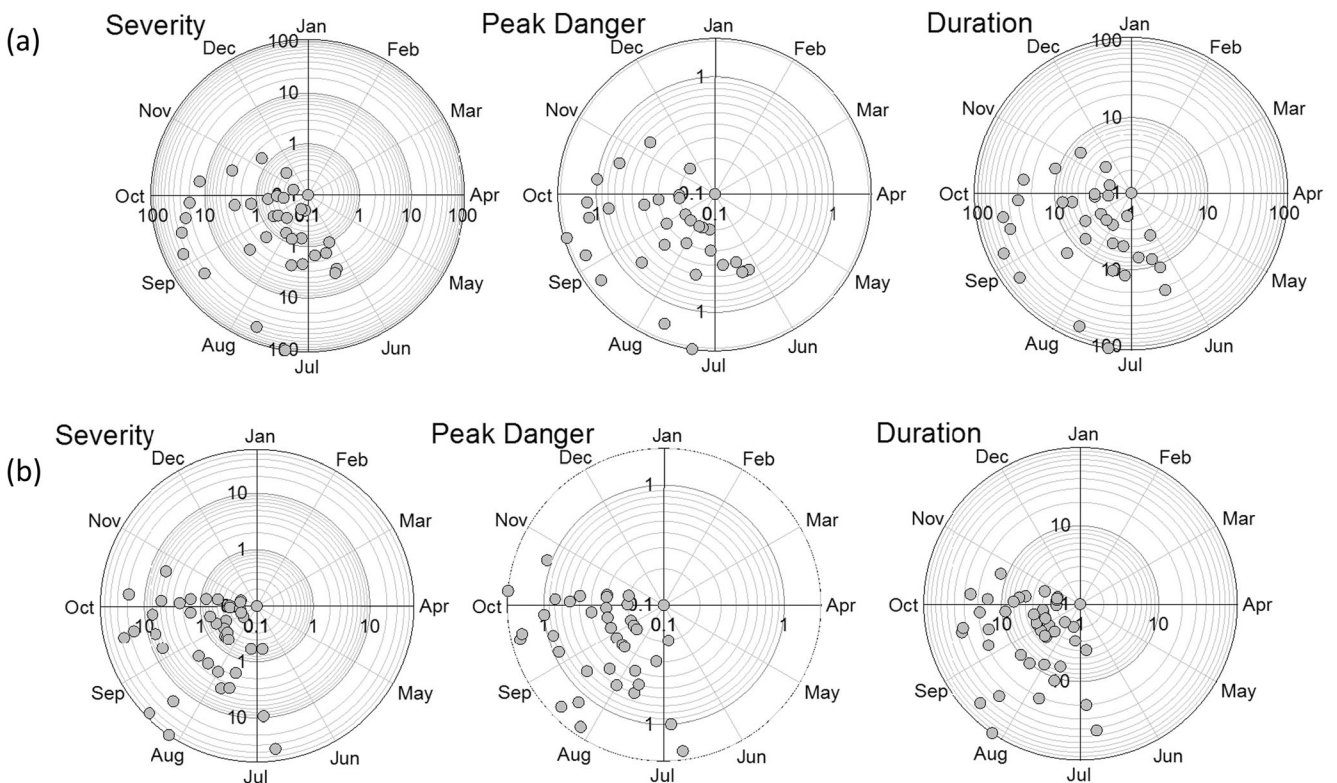
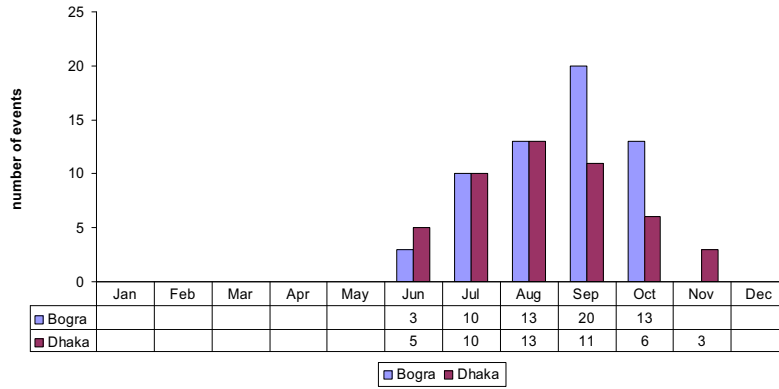
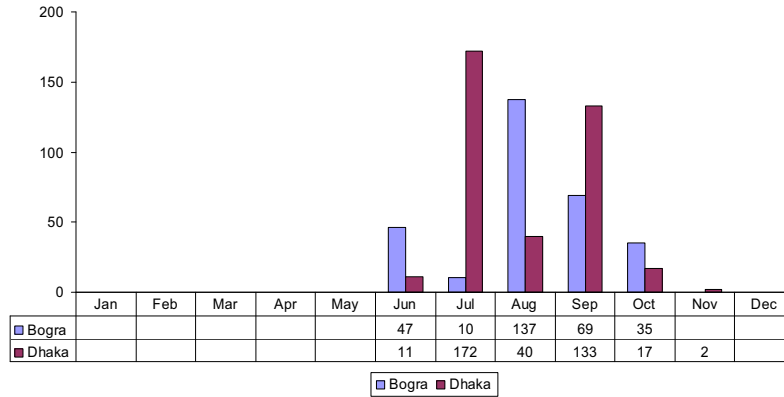


Fig. 7 A polar plot of the accumulated value of the Flood Index (I_F^{acc}), peak danger (I_F^{max}), and flood duration (D_F) against the flood onset dates within each monthly bracket. **a** Dhaka and **b** Bogra. The ordinate axis is shown in the logarithmic scale and each radial value denotes the first day of the month

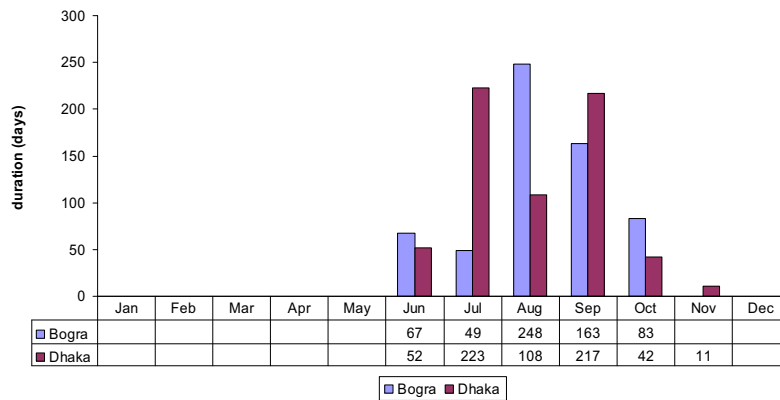
(a) Seasonal frequency (total number) of flood events (n)



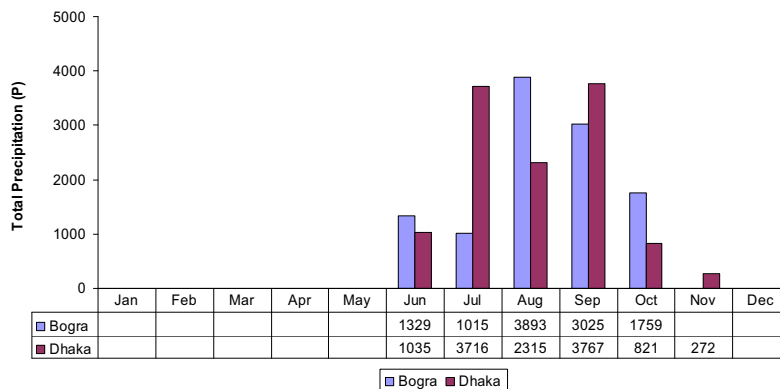
(b) Flood Severity, I_F^{acc}



(c) Flood Duration (D_F), days



(c) Total Precipitation (P), mm



◀ **Fig. 8** An overall seasonality analysis of the flood events detected at the Dhaka (1971–2013) and Bogra (1976–2013) weather stations. **a** Seasonal frequency (total number) of recorded floods, **b** flood severity defined by accumulated value of Flood Index, I_F^{acc} in a flood period, **c** flood duration (D_F), and **d** total accumulated precipitation value, P

peak for the year. It is also noteworthy that at the Dhaka weather station, flood events are distributed more evenly throughout the entire summer monsoon period (June to early October) than at the Bogra weather station. In addition, flood events occurred even during the post-monsoon season (mid-October to November) in Dhaka while in Bogra, floods occurred more intensively during the defined summer monsoon period. However, the flood events during the early summer period (late-June to mid-August) generally lasted for more than 10 days.

A closer seasonal analysis of the flood properties for the Dhaka and Bogra weather stations in terms of the frequency (total number) of recorded floods (n), I_F^{acc} in a flood period, D_F , and P in the corresponding identified flood period is illustrated in Fig. 8. For both stations, the heavy rain starts in June with a gradual increase in flood frequency to a peak value in August for Dhaka and September for Bogra. A near normal distribution was obtained when the two weather stations were analyzed by their climatological total number of flood events (Fig. 8a).

For the Bogra weather station, the possibility of flooding appeared to cease after October, whereas for the Dhaka weather station, a significant number of flood events were recorded in November (Fig. 8a). By contrast, when the severity of flood events was considered by the accumulated magnitude of I_F , this parameter exhibited a bimodal behavior for the Dhaka weather station with the most severe events in July and September. Similarly, bimodal behaviors were also obtained for duration and total precipitation. For the Bogra weather station, the flood severity parameter, flood duration, and maximum precipitation during the flood events yielded the highest values during August (Fig. 8b). Although both stations exhibited flooding during the summer monsoon season, the individual properties of flood events were discernible by their characteristics, thus indicating the possibility of geographically diverse flooding at the two weather stations.

In the present study, the daily flood index was based on the concept of Available Water Resources Index where a gradually decaying function for the remaining water after a rainfall event was considered to study the flood possibility (Byun and Jung 1998; Deo et al. 2015; Deo et al. 2018; Nosrati et al. 2011). With this concept, an exponentially decaying function was employed; however, the current flood monitoring techniques also employ several non-mathematical tools that can provide new ways to compare the efficacy of the present approach. For example, Matgen et al. (2011) designed a new concept based on standardized synthetic aperture radar (SAR)-based monitoring of floods with algorithms that enable an automatic delineation of flooded areas. A further

comparison of the proposed technique could also be made to study spatial extent and temporal pattern of flood inundation from remotely sensed imagery, where NOAA/AVHRR imagery can be used (Sheng et al. 2001).

In addition, a multi-sensor method that uses radar and visible/infrared satellite imagery for mapping the extent of flooded wetland areas (Töyrä et al. 2002) could also provide a spatial evaluation of the flood possibility, and could be used to compare with the present daily index over a much larger study area (e.g., comparisons could be made on hourly scales (Deo et al. 2018)). The proposed daily index could also be compared with those of Memon et al. (2015) in such a way that the Normalized Difference Water Index and Water Index could be used to delineate and map surface water with satellite-based data sources (e.g., moderate resolution imaging spectroradiometer, MODIS) to check for near real-time images and how those compare against the risk evaluated by the daily flood index in this paper, as a follow-up study.

4 Summary and conclusion

A Flood Index (I_F) originally developed by Byun and Jung (1998), modified by Byun and Wilhite (1999), and used recently in two studies: (Nosrati et al. (2011) and Deo et al. (2015)), was applied in this paper for the analysis of flood events in Bangladesh, a flood prone nation. The proposed index relies on the concept of daily effective precipitation with the superposition of current day precipitation onto antecedent precipitation, summed over the entire hydrological cycle. On this basis, flood events were identified at two stations in Bangladesh (Dhaka and Bogra) over the period 1971–2013 (Bogra) and 1976–2012 (Dhaka).

In order to assess the danger of floods in the study regions, the I_F was used to produce a chronological flood map, and formulate flood properties such as the severity (I_F^{acc}), peak danger (I_F^{max}), and duration index (D_F). Additionally, the time-series was employed to investigate the seasonal variability of flood events at the Dhaka and Bogra weather stations. The primary findings of this study were the following:

1. The chronological flood map depicted geographic differences in flood occurrences between the two weather stations, and was able to adequately detect the major flood events that occurred during 1973, 1979, 1986, 1987, 1988, 1992, 1995, 1998 for the Bogra weather station, and 1984, 1986, 1991, 1993, 2004, and 2007 for the Dhaka weather station. However, the magnitude of the I_F indicated different strengths of these flood events at the two stations.
2. Accumulated magnitude of I_F showed that flood event severity was highest during the 1984 flood event in Dhaka, which was well reflected by the highly elevated

total precipitation accumulation and peak danger of flood event determined by the maximum value of the I_F . Interestingly, this event also had the longest duration compared to all other events at this weather station.

3. The distinct seasonality of the 1984 and 2004 flood events as evident by the highest value of the climatological rainfall that occurred from mid-July until October, resulting in the greatest abundance of daily water resources, and therefore, the highest possibility of flooding during this summer monsoon season.
4. In terms of the seasonal frequency of flood events, both the Bogra and Dhaka weather stations exhibited a peak in flood possibility during the heavy rainy season with a peak in September (Bogra) and August (Dhaka). However, the various properties of flood events (e.g., duration or total rainfall accumulation during flood periods) were distinguishable for the two stations, suggesting distinct geographic patterns of individual stations.

Based on the present analysis, it can be concluded that the daily I_F has the scientific potential for an objective monitoring of flood situations, as well as for quantifying the various properties of flood events. However, it may be interesting to compare this approach with rainfall, surface run-off, and flood forecasting models and validate its response using other datasets such as stream or river discharge rates. Furthermore, the newly developed hourly flood monitoring index (Deo et al. 2018), which also operates on a similar principle to the proposed daily flood index, albeit on shorter and more real-time scales, could also be adopted for this study region to explore its ability for short-term monitoring of flood events (i.e., over hourly scales). This would reveal the extent of its operational applicability in geographically diverse terrains where several topographical factors may play crucial roles in how the index is interpreted, reformulated, or utilized for operational usage.

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