Persistence Characteristics of Floods and Droughts of the Ganges-Brahmaputra-Meghna Basins Using Flood Duration Curve and Drought Duration Curve

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***Abstract*-The Ganges-Brahmaputra-Meghna river basin is a unique basin in the world in terms of diversified climate. Climatic extremes specifically, floods and droughts are very common here. This study investigated the hydrological persistence characteristics of floods and droughts using Flood Duration Curve (FDC) and Drought Duration Curve (DDC). Duration curves are drawn for precipitation and streamflow at outlets. The curves indicate annual variation of annual maxima (FDC) and minima (DDC) of moving averages of precipitation and streamflow over various time lengths. It was found that those (except FDC of precipitation) of the Meghnashow larger departures from the long-termaverageamong three basins. Significantly distinct characteristics in persistence structure have been identified, which can be utilized for flood control, reservoir design and operation, and other implications on policy making for water resources management both in flood and drought.**

Keywords-Flood; Drought; Ganges-Brahmaputra-Meghna basin; Flood Duration Curve (FDC); Drought Duration Curve (DDC); Duration curve

I. INTRODUCTION

The Ganges-Brahmaputra-Meghna (GBM) river system with a total area of about 1.7 million km^2 is shared by India (64%), China (18%), Nepal (9%), Bangladesh (7%) and Bhutan (3%). It is the world third largest freshwater outlet to the oceans [1]. During the extreme floods, over 138700 m^3 s^{-1} of water flows into the Bay of Bengal through a single outlet, which is the world largest intensity even exceeding that of the Amazon discharges by about 1.5 times [2]. Three rivers of this system have distinct characteristics and flow through very different regions for most of their lengths.Its diversified climate also makes it a unique basin in the world. The Ganges basin is characterized by low precipitation (760–1020 mm year^{-1}) in the northwest upper region and high precipitation (1520–2540 mm year^{-1}) along the coastal areas. The Ganges is a snowmelt-fed river, which is regulated by 75 artificial dams[3]constructedby upstream countries. The Brahmaputra basin is characterized by high precipitation, large volume of snow in the upstream, that provide huge volume of discharge in the river. It is a snow-fed braided river with mean discharge of about 20000 m^{3}s^{-1}[4]. On the other hand, in the Meghna basin, world's top two highest precipitation (about 12000 mm year^{-1}) areas (Mawsynram and Cherrapunji) are situated. The Meghna River is a comparatively smaller, rain-fed, and relatively flashier river. Climatic extremes specifically, floods and droughts are very common in these three basins.

Floods and droughts have enormous environmental, social and economic consequences, which continue to present dynamic challenges worldwide. There is an increasing need of understanding characteristics of these climatic extremes for prediction, prevention, preparedness, mitigation and risk management to protect our life, property, economy and environment. Many studies have been conducted to understand characteristics of floods and now floods can be predicted successfully with lead-time ranging from several days to even up to a season. However, on the other hand, the properties of severe droughts are not well understood yet, and presently not able to predict these droughts. Drought studies have been suffering from not only the lack of regional data sets but also the lack of consistent methods for drought analysis [5]. Yevjevich (1967) presented threshold level method, where droughts are defined in terms of low flow duration (flow below a certain threshold level) and deficit volume (severity). This method is suitable for reservoir analysis where deficit volume is used to determine the required storage capacity, for analysing the physical factors causing severe regional droughts. However, he didn't define the threshold limit and gives no advice how to determine its value [6]. After that, based on the typical drought characteristics (water deficit and duration) and threshold levels, many researchers proposed different approaches to define drought [7-10].

The relationship between the frequency and magnitude of streamflow can be expressed by flow duration curve, a commonly used method in the field of water resource engineering [11]. It is a graphical representation of the frequency, or the fraction of time during which a specified magnitude of flow equalled or exceeded. It has a complete signature of streamflow variability with time [12]. However, this flow duration curve can be presented in an alternative way which termed as Flood Duration Curve (FDC) and Drought Duration Curve (DDC). Kikkawa& Takeuchi [13, 14] first defined a DDC with mathematical expression and proposed it as a tool for regional hydrological characterization and for reservoir design and operation. Takeuchi [15] applied DDC to develop real-time reservoir operation rule. After that Takeuchi [16] extended it to both FDC and DDC and investigated the hydrological persistence characteristics of floods and droughts in different basins. In

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general, FDC and DDC present the extreme (lowest or highest) average of a hydrological quantity (precipitation or streamflow) over different duration periods with different probability of occurrences. In other words, the curves indicate annual variation of annual maxima (FDC) and minima (DDC) of moving averages of precipitation and streamflow over various time lengths. They contain information that has direct implications on water resources management both in floods and droughts. However, regardless of its unique potential of applicability, this innovative way of expressing duration curves have been followed by very few hydrologists[17, 18]. In this study, FDCs and DDCs are plotted for basin-averaged precipitation over the Ganges, Brahmaputra and Meghna basins and streamflow at their three outlets. The aim of this study is to investigate the hydrological persistence characteristics of floods and droughts in these basins using FDC and DDC. Significant characteristics can be identified from these curves, which can be considered in risk management, planning for prevention, mitigation of these climate extremes and in formulating polices for water resources management.

II. DATA

Table 1 presents some basic statistics and Fig. 1 presents the seasonal cycles of precipitation and streamflow with box-and whisker plot indicating its variations.

TABLE 1 BASIC STATISTICS OF BASINS AND ANALYSED DATA

Item		Brahmaputra	Ganges	Meghna
Outlet station		Bahadurabad	Hardinge Bridge	Bhairab Bazar
Basin area (km^2) [a]		583 000	907 000	65 000
River length (km) [a]		1 800	2 000	946
Precipitation [b]	Mean (mm $year^{-1}$)	1 611	1 149	3 195
	Monthly SD (mm)	120	113	246
	Annual SD (mm)	151	105	499
	Monthly CV	0.006	0.008	0.006
	Annual CV	0.094	0.092	0.156
Streamflow [c]	Mean ($m^3 s^{-1}$)	23 148	13 880	5 142
	Monthly SD ($m^3 s^{-1}$)	17 172	15 957	4 647
	Annual SD ($m^3 s^{-1}$)	5 229	5 074	1 304
	Monthly CV	0.74	1.15	0.90
	Annual CV	0.226	0.367	0.254

[a]Nishat and Faisal (2000)
[b] EstimatedfromWFD precipitation dataset (1980-2001)
[c] Estimated from observed data from BWDB [20]

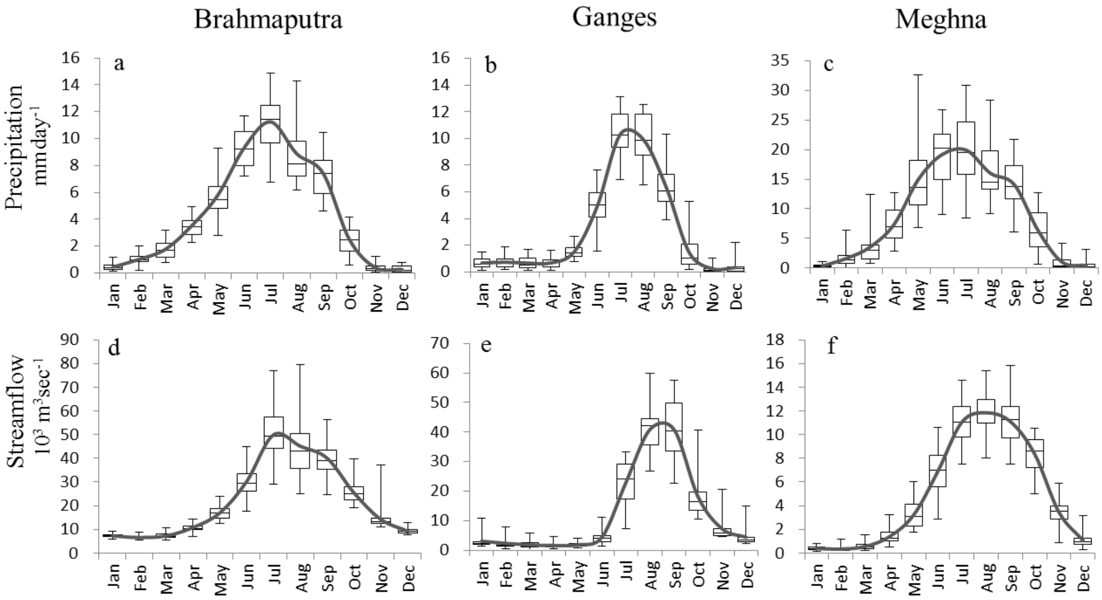

Fig.1 Seasonal cycle of precipitation and streamflow for three basins. Box-and-whisker plots indicate minimum and maximum (whiskers), 25th and 75th percentiles (box ends), and median (black solid middle bar). Solid curve line represents the interannual average value.

A. Precipitation

Precipitation data was taken from the WATCH Forcing Data set (WFD) [21]. WFD is a gridded data set, considered as one of the best available global climate forcing datasets to provide accurate representation of meteorological events, synoptic activity, seasonal cycles and climate trends [21]. Lucas-Picher, *et al.* [22] and Siderius, *et al.* [23] found that for the South Asia

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and the Ganges, respectively, the WFD rainfall is consistent with the observed APHRODITE data [24], a gridded (0.25˚) rainfall product based on a large number of rain gauge data. Masood, *et al.* [25] also could reproduce efficiently the daily time series of streamflow at three outlets of the Brahamaputra, Ganges and Meghna by a calibrated hydrologic model driven by meteorological forcing of WFD dataset. Detailed information on the WFD, can be found from Weedon, Gomes, Viterbo, Shuttleworth, Blyth, Osterle, Adam, Bellouin, Boucher and Best [21] and Weedon, *et al.* [26]. For this analysis, monthly time series of basin-averaged precipitation (1980 to 2001) over three basins at their outlets have been calculated from the gridded daily dataset of WFD.

B. Streamflow

Observational hydrological data (river water level and streamflow) were collected from the Hydrology Division, Bangladesh Water Development Board (BWDB). River water level data are available in daily scale, however, streamflow data are available in weekly scale with few gaps. In the Meghna river streamflow measurements are made once per month during the dry season [1] because of its tidal influence. Therefore, for this study daily streamflow data series have been constructed from daily river water level data series by using rating equations developed by the Institute of Water Modelling (IWM) [27] for the Ganges and Brahmaputra and by Masood, Yeh, Hanasaki and Takeuchi [25] for the Meghna river. Streamflow data from 1980 to 2009 at Bahadurabad,Hardinge Bridge and from 1984 to 2009 at Bhairab Bazar, three outlets of the Brahmaputra, Ganges and Meghna, respectively, are used for this analysis.

III. METHODOLOGY

Duration curves are drawn for basin-averaged monthly precipitation and for daily streamflow at Bahadurabad, Hardinge Bridge and Bhairab Bazar, outlets of three basins; the Brahmaputra, Ganges and Meghna, respectively. These curves present the extreme values of precipitation and streamflow, estimated from m-period (days or months) moving averages of observed time series data (x_t). m has been varied from 1 to 1095 days and from 1 to 36 months to draw duration curves for streamflow and precipitation, respectively. Equation 1 and 2 show the annual maxima series, $x_j(m)$ and the annual minima series, $x_j'(m)$, respectively for m-period moving averages of data series. Generalized Extreme Value (GEV) distribution Type-1 which is called Gumbel distribution [28], has been applied on these two series to estimate extreme values for 5, 10, 20 and 50-years return periods (T) (shown by lines with different colours). Because, for flood frequency analyses, the Gumbel distribution has been recommended for the major rivers in Bangladesh [29] as well as it is also suitable for relatively smaller data sample [30].

$$x_j(m) = \max_{t_1 \epsilon j\text{th year}} \frac{1}{m} \sum_{t=t_1}^{t_1+m-1} (x_t) \quad (1)$$

$$x_j'(m) = \min_{t_1 \epsilon j\text{th year}} \frac{1}{m} \sum_{t=t_1}^{t_1+m-1} (x_t) \quad (2)$$

where $\frac{1}{m}\sum_{t=t_1}^{t_1+m-1}(x_t)$ is the average of m consecutive values between time t_1 and time $t_1 + m - 1$. $j = 1, \ldots,$ NwhereN is number of years for which all moving averages starting from any date are available. Nis different for different durations of moving averages concerned.

Figure 2 shows a typical duration curves with its basic terminology that are need to explain the characteristics of flood and drought. The following properties from the figure are identified and explained by Takeuchi [16].

- Average line: Values in the y-axis are normalized by dividing by its long-term mean. Therefore, the average line (*y*-axis value=1, shown by thick black line) corresponds to the long-term mean (written in the figures) and acts as the separator of FDC (above the line) and DDC.
- Departure: The departure of duration curves from the average line refers the intensity of seasonal variation around long-term mean. Large departure means large seasonal variation and vice versa. In general, DDCs show steeper gradient and wider departure from the average line than those of FDCs. Especially, in desert areas DDCs show a sharp drop-off, because in those areas there are considerable periods during which no precipitation occurs.
- Angle: The angle between FCD and DDC refers the degree of recovery from an extreme event. However, the angle is different at different m, which reflects local gradient of the curves. A steeper gradient of the curve represents a situation when the extreme event lasts for a shorter duration and the average situation recovers quickly as the duration becomes longer.
- Variation: This refers to the variation of duration curves due to different mean recurrence intervals or probability years. Higher variation refers larger year to year variation of the process. In general, variation is large in DDCs and small in FDCs. Small probabilistic variations in high precipitation and large variations in low precipitation are very significant both from the climatological and water resource point of view. It may imply that the wet duration is constrained by the time scale of global meteorological circulation and moisture supply from the ocean.

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- Oscillation: Oscillating shapes of the curves at right-hand side correspond the degree of seasonality. Usually it starts from about *m*=1 year when both FDCs and DDCs are nearly symmetrically situated above and below the average line. These oscillations represent strong seasonal variation of hydrological quantities (precipitation, streamflow etc.). It is typically absent where seasonality is very week.

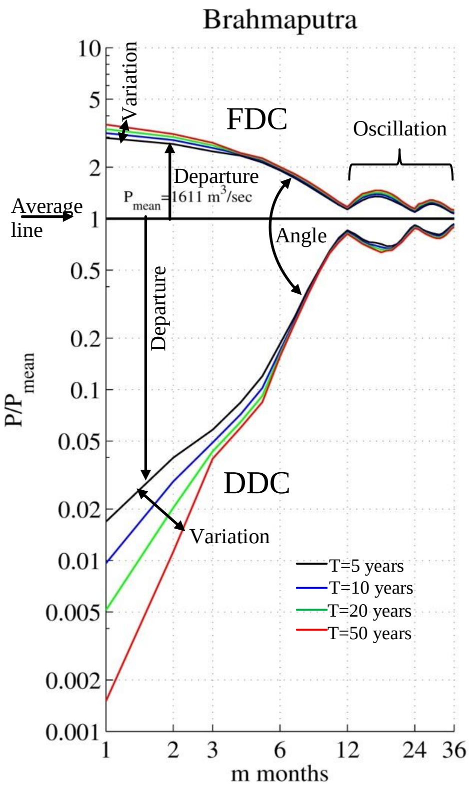

Fig.1 A typical Flood Duration Curve (FDC) and Drought Duration Curve (DDC) of monthly precipitation series and its basic terminologies.

The duration curves drawn here are in log-log paper. Because, it is possible to show both curves in a single figure. However, it should be noted that the logarithmic scale distorted the absolute scale. Therefore, regardless of the relative appearance of the curves in a logarithmic paper, differences in absolute values are much larger in FDCs than in DDCs.

IV. RESULTS AND DISCUSSIONS

A. Duration characteristics of precipitation

It is important to note that the duration curve of both precipitation and streamflow are termed as Flood Duration Curve and Drought Duration Curve. However, for precipitation, instead of Flood Duration Curve, high precipitation duration curve might sound more grammatically reasonable. But for simplicity a common term is used here and which is also following the original usage by Takeuchi [16]. Figure 3 presents duration curves of basin-averaged monthly precipitation for three basins. All sub-plots are shown on the same scale and every pair can be directly compared with the other. The following characteristics can be pointed out from these figures:

(1) FDCs decrease as duration *m* increases, whereas DDCs increase. This is because both curves approach the long-term mean (toward the average line) as the duration becomes longer. In other words, both floods and droughts may be extreme in a short time but if averages are considered, they become less severe over a longer interval.

(2) Probabilistic variations (variation due to different return periods) decrease with the increase of *m* both for FDCs and DDCs. This is because interannual variations of extremes (both high and low precipitation) are larger for shorter interval (in case of smaller *m*) but if averages are considered over a longer interval, variations reduce as the average converges to the long term mean. Note that variations are prominently visible in the DDCs, which is simplybecause of its logarithmic depiction in vertical axis.

(3) Among three basins, the probabilistic variation in the FDCs of the Ganges is the smallest. That means,interannual variation of annual maxima of moving averages of precipitation is lower in the Ganges basin than that in other two basins. It may reflect the fact that the Ganges is the largest basin among the three and the spatial average cancels out the extremes and that compared with Brahmaputra, the heterogeneity in hydro-climatic phenomena is less. On the other hand, the

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probabilistic variation in the DDCs of the Ganges is much larger (up to *m*=7 months) than that in the other two basins, which indicates the larger variation of prolonged droughts in the basin.

(4) The Meghna has larger probabilistic variation in both FDCs and DDCs, which refers to the larger annual variation of both high-precipitation and low-precipitation in the basin. Meghna's annual coefficient of variation (CV) of precipitation is also the largest among three basins (Table 1), which is closely connected to the probabilistic variation.

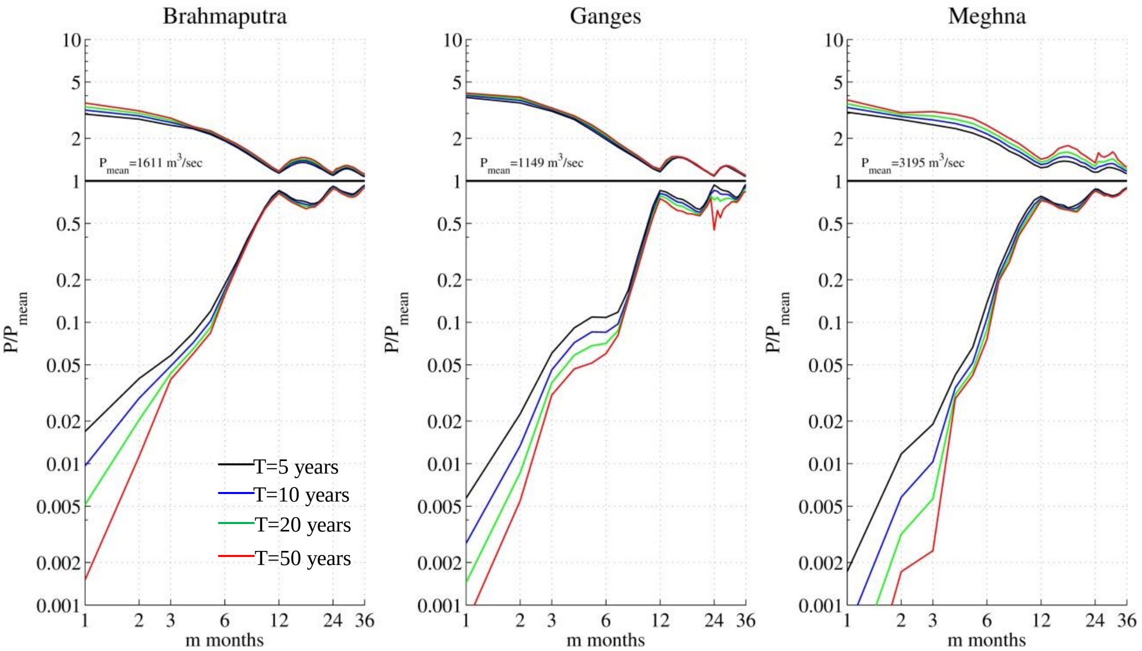

Fig. 2 Flood and drought duration curves of basin-averaged monthly precipitation (P) series of the Brahmaputra, Ganges and Meghna.

B. *Duration characteristics of streamflow*

Figure 4 shows the FDCs and DDCs of daily streamflow series. Compared to duration curves of precipitations, those of streamflow are quite different. Some of the most significant differences are as follows:

(1) DDCs are very different from FDCs. For all *m*, the departure of DDCs from the average line is smaller for streamflow than that for precipitation. This is due to having natural storage of water in the river, which reduces the seasonal variation of streamflow.

(2) For all basins, FDCs for streamflow have larger probabilistic variation (variation due to probability years) than that for precipitation. This is because streamflow curves show more regional variation than of precipitation curves. This reflects the fact that the streamflow duration characteristics are influenced by precipitation, evaporation, basin geology and many other regional factors.

(3) Probabilistic variations of FDCs are similar, however, that of DDCs are quite different among three basins. The Ganges has the largest variation whereas the Brahmaputra has the lowest variation. Those probabilistic variations are not proportional to FDC-DDC angles nor departure from the average line.

(4) Larger probabilistic variation in the DDCs of Ganges refers to the larger year to year variation in annual minima of moving averages of streamflow in the river. In addition to natural variations, high anthropogenic water use in that basin would be acting as a major role in the low-flow variations because the streamflow time series under analysis are the observations intervened by human activities.

(5) Lower variations in DDCs of the Brahmaputra indicate its consistent pattern of low flows during dry periods though its mean flow is the largest among three rivers. This is due to having its large volume of snow in the upstream which may act as reservoir to ensure consistent supply of flow even in extreme dry periods

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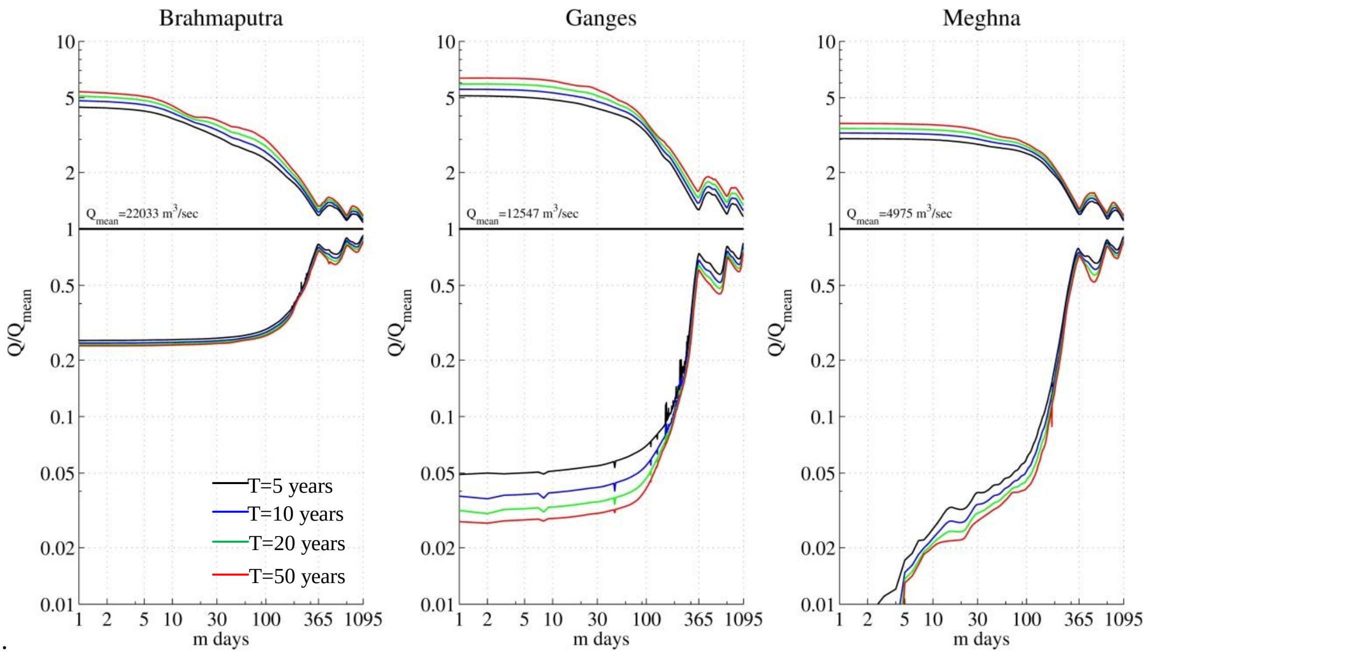

Fig.4 Flood and drought duration curves of daily streamflow (Q) series of the Brahmaputra, Ganges and Meghna at three outlets; Bahadurabad, Hardinge Bridge and Bhairab Bazar, respectively.

C. *Inter-basin comparisons*

In order to make inter-basin comparisons easier, duration curves of a single common recurrence interval were plotted in the same figure. Figure 5 and 6 present combinations of duration curves with recurrence interval of 10 and 20 years for precipitation and streamflow, respectively. The following characteristics can be identified from the figure:

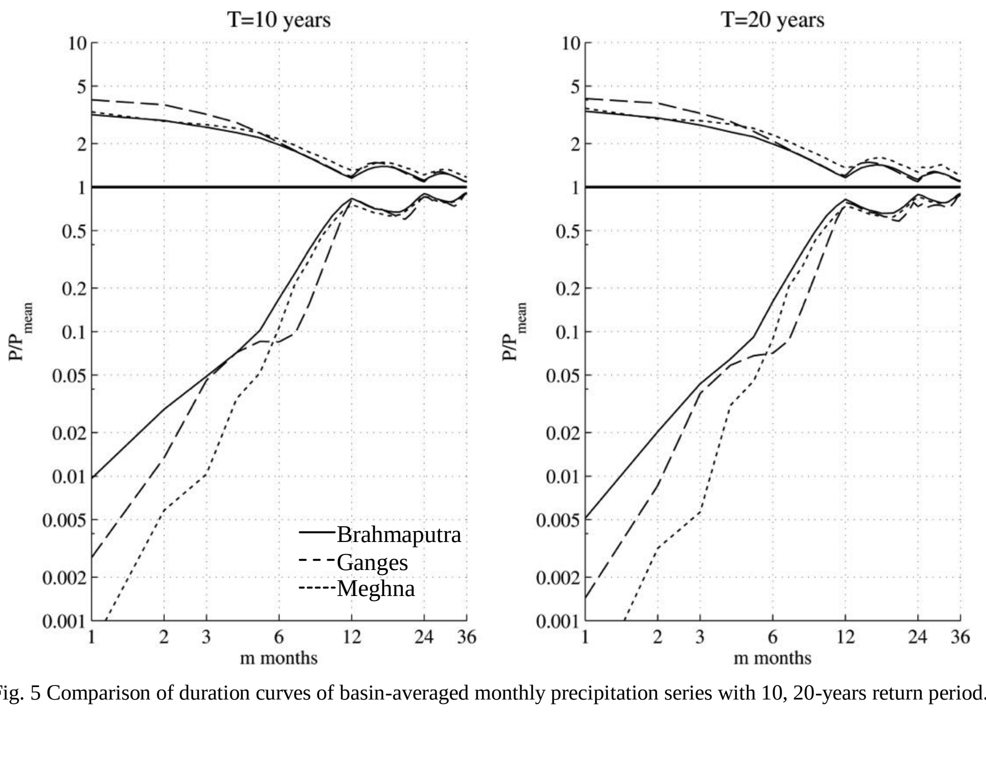

Fig. 5 Comparison of duration curves of basin-averaged monthly precipitation series with 10, 20-years return period.

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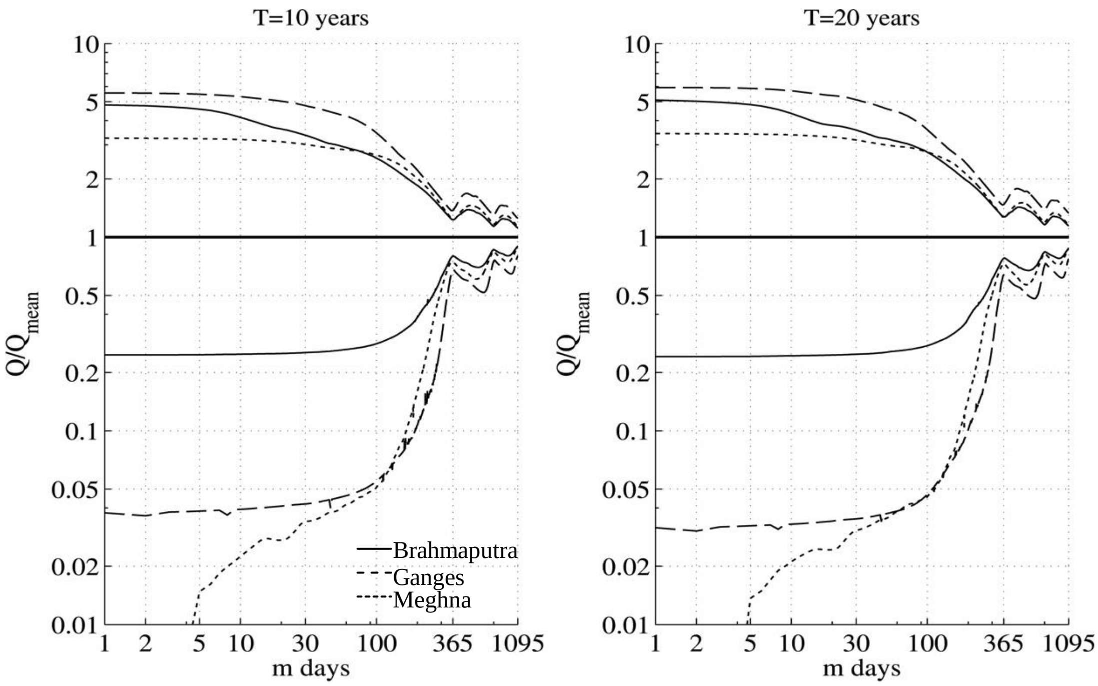

Fig. 6 Comparison of duration curves of daily streamflow series with 10, 20-years return period.

(1) As seen in the Fig. 5, FDCs of Brahmaputra and Meghna are very similar, whereas their DDCs are very different from each other. The departures of the Meghna's DDCs are the largest among these three basins. That means, relative to its mean precipitation seasonal variation of low-precipitation in the Meghna is the largest.
(2) The Ganges has the steepest gradient of curves which makes the highest open angle between FDCs and DDCs. Steep gradient of the Ganges implies that the extreme events in the basin will last for a short duration and the recovery rate from that extreme event will also be quicker.
(3) The Brahmaputra has the smallest open angle which means extreme events of the basin last longer than that in other basins.
(4) From the duration curves for streamflow (Fig. 6) it is observed that the Meghna has the lowest departure of FDC and highest departure of DDC from the average line. This would indicate that among three basins, the seasonal variation of high-flow is lowest and the seasonal variation of low-flow is highest for the Meghna. The Brahmaputra's DDC has the lowest departure from the average line which means low-flow variation is the lowest in that basin among these three basins.
(5) A large departure means a large reservoir storage is necessary to adjust the seasonal variation [16]. As seen in the Fig. 6, departure of DDCs of the Ganges and Meghna are much larger than that of the Brahmaputra. That means, relative to its basin size larger reservoirs are necessary to manage drought in the Ganges and Meghna.

V. CONCLUSIONS

The study presents Flood Duration Curves (FDCs) and Drought Duration Curves (DDCs) for basin-averaged monthly precipitation and daily streamflow at three outlets of the Brahmaputra, Ganges and Meghna basins. The aim of this study was to investigate and compare the hydrological persistence characteristics of floods and droughts in these three basins. Significant characteristics have been identified from these curves, which are summarized below:

- DDCs of streamflow are very different from DDCs of precipitation. And for any duration, the departure of DDC curves from the average line is smaller for streamflow than for precipitation due to natural storage in the river.

- For all basins, FDCs for streamflow have larger variation than those for precipitation, because streamflow is influenced by many regional factors especially evapotranspiration which amplifies variation in low-flows.

- For precipitation, the probabilistic variation in the DDCs of the Ganges is the largest and in the FDCs is the smallest, indicating higher annual variation of low-precipitation and lower annual variation of high-precipitation in the Ganges basin. For the Meghna, FDCs with larger probabilistic variation refers to its larger annual variation of high-precipitation.

- The Ganges has highest FDC-DDC angle, which implies that the extreme events in the basin will last for a short duration and the recovery from that extreme event will also be quicker. Whereas the Brahmaputra has the smallest angle which indicates its longer probable extreme events.

It is necessary to note that as the duration curves are plotted in the non-dimensional *y*-axis which is normalised by the long-term mean of hydrological quantity, the interpretations of the shape of curves should also be made relative to their long-term

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mean rather than to their real values. These curves have useful information to understand the hydrological persistence characteristics of both flood and drought. These curves can be used as a tool to design retention pond for flood control and to design and operate reservoir for effective water use during drought. The information contained in these curves has direct implications on policy making for water resources, planning for preparedness, prevention, mitigation and disaster risk management.

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