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Thresholds of hydrologic flow regime of a river and investigation of climate change impact – the case of the Lower Brahmaputra river Basin

Animesh K. Gain*, Heiko Apel, Fabrice G. Renaud, Carlo Giupponi

A. K. Gain
Department of Economics
Ca' Foscari University of Venice,
Cannaregio, 873, 30121 Venice, Italy.
Email: animesh.gain@gmail.com

H. Apel
GFZ German Research Centre for Geoscience
Section 5.4, Hydrology,
Telegrafenberg 14473 Potsdam, Germany
Email: hapel@gfz-potsdam.de

F. G. Renaud
United Nations University,
Institute for Environment and Human Security, UNU-EHS
Hermann-Ehlers-Strasse 10, 53113 Bonn, Germany
Email: renaud@ehs.unu.edu

C. Giupponi
Department of Economics
Ca' Foscari University of Venice,
Cannaregio, 873, 30121 Venice, Italy.
Email: cgiupponi@unive.it

*Corresponding author. Tel.: +39 041 234 9109; Fax: +39 041 2349176
E-mail address: animesh.gain@gmail.com (A.K. Gain)

Abstract

The sustainability of social-ecological systems depends on river flows being maintained within a range to which those systems are adapted. In order to determine the extent of this natural range of variation, we assess ecological flow thresholds and the occurrence of potentially damaging flood events to society in the context of the Lower Brahmaputra river basin. The ecological flow threshold was calculated using twenty-two 'Range of Variability (RVA)' parameters, considering the range between ± 1 standard deviation from the mean of the natural flow. Damaging flood events were calculated using flood frequency analysis of Annual Maxima series and using the flood classification of Bangladesh. The climate change impacts on future river flow were calculated by using a weighted ensemble analysis of twelve global circulation models (GCMs) outputs driving a large-scale hydrologic model. The simulated climate change induced altered flow regime of the Lower Brahmaputra River Basin was then investigated and compared with the calculated threshold flows. The results demonstrate that various parameters including the monthly mean of low flow (January, February and March) and high flow (June, July and August) periods, the 7-day average minimum flow, and the yearly maximum flow will exceed the threshold conditions by 1956-1995 under the business-as-usual A1B and A2 future scenarios. The results have a number of policy level implications for government agencies of the Lower Brahmaputra River Basin, specifically for Bangladesh. The calculated thresholds may be used as a good basis for negotiations with other riparian countries of the basin. The methodological approach presented in this study can be applied to other river basins and provide a useful basis for transboundary water resources management.
Keywords: *Ecological flow threshold; Climate Change; Riverflow; Range of variability (RVA); Brahmaputra*

1 Introduction

A social-ecological system (SES) is defined as a system that includes societal and ecological subsystems in mutual interaction (Gallopín 2006), and that links organization, resilience and dynamics (Gunderson et al. 1995). Dynamic flow patterns of a river must be maintained within a natural range of variation to promote the integrity and sustainability of not only ecological systems (Sanz et al. 2005), but also social systems. Natural flow variability creates and maintains the dynamics of in-channel and floodplain conditions and habitats that play a fundamental role for the functioning of aquatic and riparian species (Poff et al. 1997). High flows of different frequencies are important for channel maintenance, bird breeding, wetland flooding and maintenance of riparian vegetation. Floods distribute and deposit river sediments over large areas of land that can replenish nutrients in top soils and make agricultural lands more fertile. As periodic flooding makes the land more fertile and productive, the populations of many ancient civilizations concentrated along the floodplains of many rivers, e.g. the Nile, the Tigris and the Yellow River (Tockner and Stanford 2002). Similarly, periods of low flow are important for water quality maintenance through algae control (Smakhtin et al. 2006). Low flows can also provide recruitment opportunities for riparian plant species in regions where floodplains are frequently inundated (Wharton et al. 1981).

However, determining thresholds of flow variability of a river SES is a complex procedure and very few studies have been conducted in this area (Richter et al. 1997, 2011). Based on ecological flow regime characteristics (i.e. magnitude, frequency, duration, timing and rate of change of flow) identified by Richter et al. (1996), Richter et al. (1997) proposed the 'Range of Variability Approach' (RVA) for determining thresholds of ecological flow. Besides determining the thresholds of ecological flow, it is equally important to determine the flow regimes that affect the social system (e.g., maximum allowable flood that society can cope with and minimum allowable flow that is required for livelihoods and navigation).

Until now, the methods for determining threshold flows were applied for investigating the impact of dam construction, reservoir operation and other human induced alterations. However, it is also important to investigate the impact of climate change on threshold flow that affects SESs like the Lower Brahmaputra River Basin (LBRB), where population pressure is very high and the main economic activity is agriculture. The population is therefore highly dependent on a few ecosystem services such as provisioning services from soil and water for their direct livelihoods, and the flow regime can have direct and indirect positive or negative impacts on these livelihoods. Climate change increases the already high variability in the temporal distribution of water, which creates floods during the rainy season and water scarcity due to very limited rainfall during the dry season (Gupta et al. 2005). In the medium term, projected climate change impacts in the upstream Himalayas will likely cause substantial cascading effects on biodiversity, local livelihoods, downstream water availability and global feedbacks (Xu et al. 2009).

The objectives of this study were (1) to determine thresholds of natural flow regime for a social (through flood categories) and ecological system (through RVA parameters), in parallel and (2) to investigate climate change effects on the determined thresholds for the Lower Brahmaputra River Basin. The analysis allowed us to provide insights on the expected impacts of climate change on the hydrologic regime of studied river basin, which can be later useful for a broader assessment of impacts on local SESs. Moreover, the calculated thresholds may be used as a good basis for negotiation with other riparian countries in the Brahmaputra River Basin.

In determining threshold flows, the consideration of both ecological (i.e., application of RVA method) and social system (i.e., identification of damaging flood event to society) is a novel approach, as well as the estimation of climate change impacts on the determined threshold flows.

2 Study area

The Brahmaputra is a major transboundary river which drains an area of around 530,000 km^2 and crosses four different countries: China (50.5% of total catchment area), India (33.6%), Bangladesh (8.1%) and Bhutan (7.8%). Immerzeel (2008) categorized the Brahmaputra basin into three different physiographic zones: Tibetan Plateau (TP), Himalayan belt (HB), and the floodplain (FP). The area with an elevation of less than 100 m a.s.l. is considered as FP and comprises about 27% of the entire basin. This study focuses on river flow in the lower Brahmaputra River Basin which belongs to the FP (Fig. S1 of online supplementary materials), where the hydrological impact of climate change is expected to be particularly strong because of glacier melt, extreme monsoon rainfall and sea level rise (Gain et al. 2011; Immerzeel et al. 2010). The major discharge measuring station of the lower Brahmaputra is in Bahadurabad (Bangladesh) for which long-term observed records are available through the Bangladesh Water Development Board. The data are of high quality and used in most hydrological studies for flood forecasting and other planning purposes (Gain et al. 2011). Therefore, long-term observed records from this station are used in this study.

3 Methods

To investigate the impact of climate change on the threshold of hydrologic flow regime, we first analyze trends and the independence of observed discharge time series. We then calculate thresholds for both ecological flow as well as different extent of floods. The investigated methods are illustrated in Fig. S2 (of supplementary material) and are discussed below.

3.1 Testing natural condition of discharge for the observation period

Daily discharge data are collected from the Bahadurabad station, for the observation period of 49 years from 1956 to 2004. However, in the data series, some data related to the dry season period were missing from 1996 to 2004. Therefore, ecological flow thresholds were calculated using the daily data series covering a period of 40 years (1956-1995). However, flood frequency analysis was carried out using the yearly maximum data (or Annual Maximum Series, AMS) covering a period of 49 years (1956-2004), as continuous data were found for high flow seasons. The first step to determine thresholds was to test for trends in the observed data. For this, we used a linear trend analysis following Gain et al. (2008), applied to annual maximum, average and minimum (7 day average) data series. The result of the trend tests indicates that all the series are trend free as the calculated value of trend statistics, T_c for each series is lower than critical value (2.02) at 5% significance level. For testing stochasticity, an independence test was then carried out. The result of independence test also showed that the calculated statistics of independence did not exceed the critical value (2.093) of the Student distribution (5% significance level). Therefore, all the data series can be considered trend free and independent, and thus can represent natural conditions of observed flow.

3.2 Calculation of ecological flow threshold

Once the natural condition of flow was tested, the ecological flow thresholds of natural variability were analyzed. Reflecting different aspects of flow variability (magnitude, frequency, duration and timing of flows), Richter et al. (1997) proposed the 'range of variability approach' (RVA) which considers thirty-two hydrological parameters. However, many parameters that are used in the original RVA method are likely to be correlated with each other, as significant redundancy (multicollinearity) exists between many hydrologic parameters (Olden and Poff 2003). Monk et al. (2007) suggested a refined number of clearly defined hydrological parameters, where known duplication of hydrological information has been removed/minimized using hydrological understanding. Smakhtin et al. (2006) reduced the number of RVA flow parameters to sixteen. For assessing maximum and minimum flow, Smakhtin et al. (2006) considered only 1-day and 90-day average flows. However, maximum and minimum flows of 3-, 7- and 90-day average can capture different extent of droughts and floods information. Therefore, for assessing ecological flow thresholds, we considered twenty-two flow parameters of which twelve represent the mean flow value for each calendar month that can jointly capture the seasonal flow distribution, and the remaining ten parameters (1-, 3-, 7-, 30- and 90-day maxima; 1-, 3-, 7-, 30- and 90-day minima) reflect the variability of maximum and minimum range and their different duration (Table S1 of online supplementary materials).

In an altered flow regime (by means of climate change or human perturbation), those parameters should be maintained within the limits of their natural variability, which should be based on extensive ecological information, taking into account the ecological consequences of different flow regimes. However, setting flow targets based on ecological information is very difficult to achieve.

In the absence of extensive ecological information, Richter et al. (1997) suggested several measures of dispersion (e.g., ±1 or 2 standard deviation, twentieth and eightieth percentile, etc) to use in setting initial threshold flows. The choice of the most appropriate measure of dispersion should be based on whether each parameter follows normal or skewed distribution and in the case of normal distribution one could use the standard deviation (SD) from the mean value as initial threshold flow. In order to select an appropriate measure of dispersion, we tested the distribution of each of the 22 RVA parameters and we found that all the parameters follow normal distribution. Therefore, values at ± 1 SD from the mean were selected as thresholds for each of the twenty-two RVA parameters. Any considered parameter should thus stay in the limits

(mean – SD) ≤ mean ≤ (mean + SD)

Exceedance of these limits by a particular parameter may lead to considerable ecosystem stress over long time periods. We used this approach for setting initial flow thresholds in this study.

3.3 Flood frequency analysis and determination of damaging flood events

For determining damaging flood events to society, we test different flood classifications that are used in Bangladesh and are based on the extent of inundation, respective return periods and the level of physical damage (Mirza 2002) as shown in Table S2 (supplementary material). During a normal flood (when probability of occurrence is more than 0.5 or equivalent return period is less than 2 years, cf. Table S2), about 21% of total land (in Bangladesh) is inundated and alluvial organic matter is deposited with beneficial effects on monsoon crops (Hofer and Messerli 2006). Similarly, moderate flood extent (with a probability of occurrence of 0.3 or return period of 3.33 years) is also beneficial for increasing soil fertility and local communities can easily cope with the disturbance. But for a severe flood event (return period of 10 years, cf. Table S2), economic losses are higher and evacuation measures are required. Other lower probability floods are even more damaging. People can cope with potential impacts with no external support until waters reach a level of 'moderate extent flood', a flood with a return period of 3.33 years (Table S2). Therefore, we can consider 'severe flood' as a damaging flood event with return period of 10 years.

In order to determine the different extent of damaging flood events, flood frequency analysis of the annual maximum series (AMS or yearly maximum flow) was carried out. For determining AMS, maximum discharge of each hydrological year (from 1st April to 31st March of the following year) was considered. In this study, the uncertainty of distribution functions was considered. Different distribution functions that are widely used in flood frequency analysis were fitted to the AMS: 3-Parameter Log Normal (LN3), Generalized Extreme Value (GEV), Generalized Logistic (GL), Pearson type III (PE3), and Gumbel. The parameters of the distributions were estimated by the methods of L-moments similar to Hosking and Wallis (1997). A composite distribution was then computed using the maximum likelihood weights of the functions (Apel et al. 2006). Using different distribution functions, flood volumes for different return periods were calculated.

3.4 Investigation of climate change impacts

For investigating the possible climate change effects on future river flow, a multi-model ensemble analysis carried out by Gain et al. (2011) was used in this study. Multiple outputs of twelve global circulation models (GCMs) for the control period (1961-1990) and the SRES scenarios A1B and A2 (2071-2100) of the IPCC were used to force the global hydrological model PCR-GLOBWB (van Beek and Bierkens 2009). The short names for the selected GCMs are MICRO, GFDL, GISS, CCCMA, CGCM, BCCR, HADGEM, NCAR, ECHAM, CSIRO, ECHO, and IPSL. A1B and A2 scenarios were selected because they assume business-as-usual emissions of greenhouse gases and aerosol levels, best reflecting the currently observed trends. PCR-GLOBWB calculates the water storage for each grid cell ($0.5° \times 0.5°$ globally) and for each time step (daily). The model considers canopy interception, snow storage and melting. Snow accumulation and melt is modeled by a temperature degree-day approach as in Bergström (1976). The snow module also considers the storage of melted water in the snow pack, and possible refreezing and evaporation of melt water. For glacier melt a similar degree-day approach is applied, but with different threshold values for melting. The structure and parameterization of the global hydrological model PCR-GLOBWB are described in van Beek and Bierkens (2008). Multi-model ensemble discharge was calculated using a weighting factor on each of 12-model simulated discharge. The weight for each model was determined based on the similarity of mean monthly value of observed discharge with the model simulated discharge for the overlapping period (1973-1995). A constant weight was then applied for the entire time series and the approach was validated by comparing the flow duration curve of the observations with the modeled discharge. For both the A1B and A2 scenarios, the results of multi-model weighted variation (i.e., uncertainty estimation) of discharge are shown in Fig. S3 (online Supplementary Material) that represents seasonal average flows of four time slices (reference period 1980-99; 2011-30; 2046-65; 2080-99). Seasonal average flows were obtained by first calculating cumulative frequency distributions per GCM and then constructing a weighted cumulative frequency distribution by weighting values belonging to the same quantile. The statistics in the box plots are thus based on the weighted cumulative frequency distribution. For a detailed description of future river flow assessment considered in this study, see Gain et al. (2011).

Due to climate change, flow regime of future periods can be altered and exceed the RVA threshold range (± 1 SD from mean values). For investigating the effects of climate change induced altered flow regime on determined thresholds, the percentage of altered flow regime years not meeting the RVA target was calculated for each of the twenty-two parameters.

4 Results

4.1 Ecological flow threshold

After characterizing and testing natural conditions of the observed data series, we determined ecological flow thresholds of twenty-two RVA parameters, reflecting different aspects of flow variability (magnitude, frequency, duration and timing of flows), as shown in Table S1 (supplementary materials). For assessing mean and standard deviation values of each parameter (column 2 and column 3 of Table S1, respectively), we analyzed daily mean discharge series for a 40 years period (1956-1995). Minimum threshold (mean - 1 SD) and maximum threshold (mean + 1 SD) values for each parameter is shown in column 4 and column 5 of Table S1, respectively. During the reference period (1956-1995), about one-third of the total number of years exceeds the criteria of threshold, as the distribution is normal.

4.2 Damaging flood events

Based on the flood classification by Mirza (2002), we can classify the return periods of different floods. In order to determine different classes of floods, we need to analyze flood frequency based on the annual maximum series for the available 49 year record period (1956-2004). However, different statistical distributions are typically used for flood frequency analysis often leading to different results. For a certain design value the cumulative distribution function of annual failure probability (AFP) of yearly maximum flow can be derived for each considered distribution function. Fig. 1 shows the five distribution functions and the observed data. Using different distribution functions, river flow is computed for floods of different return periods according to the Bangladesh flood classification (Table S3, supplementary materials). For the Bahadurabad station, Fig. 1 shows that the effect of distribution uncertainty on AFP is very low.

4.3 Investigation of climate change effects on flows

In order to investigate climate change impacts for both A1B and A2 scenario of the IPCC, we categorized future periods into three time intervals (i.e., 2011-30, 2046-65, and 2080-99). These time intervals split the 21st century into three parts, i.e., early century (2011-2030), mid century (2046-2065) and late century (2080-2099) as described in IPCC Fourth Assessment Report (Meehl et al. 2007). The rate of exceedance of RVA threshold values for the reference period and for the future years was calculated by counting the number of years that would have failed to meet the threshold conditions and the calculation was carried out for both A1B and A2 scenarios (Table 1). As an example, results indicated that for the month of January 35% of the next 20 years (period 2011-30) in the A1B scenario would have passed the upper or lower limit of the thresholds. Similarly, for the periods 2046-65 and 2080-99, thresholds for A1B scenario are exceeded in 50% and 85% of the cases, respectively and for A2 scenario, in 70% and 80%, respectively.

The results also demonstrate that during low flow (January, February and March) and high flow (June, July and August) periods, the rate of exceedance is very high for both the A1B and A2 scenarios. In Fig. S4 (supplementary materials), monthly means for January (Fig. S4a), February (Fig. S4b) and March (Fig. S4c) are plotted for the Brahmaputra River, whereas, Fig. S5 represents the monthly average flow of June (Fig. S5a), July (Fig. S5b), and August (Fig. S5c). In some other months (October, November, December, and May) the exceedance rate of threshold values is very low. This is mainly due to the fact that in contrast to normal flow periods, the impact of climate change is very high in extreme low and high flow seasons.

Seven-day average yearly minimum flow for both A1B and A2 scenario are plotted for three different time periods and compared with the calculated low and high threshold values (Fig. 2a). Similarly, yearly maximum flows for both scenarios are also plotted in Fig. 2b.

For the observation period (1956-2004), the different extreme floods were classified and identified in section 3.3. We compared yearly maximum river flow with the different classes of floods. The rate of exceedance of different types of flood levels that is expected to occur under future climatic conditions is shown in Table 2. Simulated results indicate that in the near future (2011-30), 45% and 40% of the total years would have exceeded the 100-yr flood (calculated in the observation period) for A1B and A2 respectively. For the period 2080-99, the rate of exceedance is 100% for both scenarios.

5 Discussion

In climate predictions, a multi-model ensemble tends to give more reliable results than single model simulation (Gleckler et al. 2008; Knutti 2008). Unweighted multi-model means are often used to develop model ensembles, as in the Fourth IPCC Assessment Report (Meehl et al. 2007). However, results of several studies showed that more reliable results are obtained by using projections of a cluster of better performing models or calculating a weighted ensemble average (Sperna Weiland et al. 2012). In the weighted ensemble analysis, the individual GCM weights were derived from model performance and future ensemble convergence (Giorgi and Mearns 2002; Murphy et al. 2004; Räisänen et al. 2010). In this study, weights were determined by using the model performance, i.e., historical relationship between model outputs and observations. Although model agreement with observations is a necessary pre-condition for a model to be considered, it does not definitely prove that the model is accurate for the right reason (Tebaldi and Knutti 2007). In the presented case, Fig. S6 and Fig. S7 (of supplementary materials) confirm that the weighted ensemble mean outperforms un-weighted means. Therefore, we argue that the use of the weighed ensemble mean is an appropriate choice to investigate climate change impacts.

Calculated ecological flow threshold values for the Lower Brahmaputra river basin (LBRB) suggest that exceedance rate of any of the RVA threshold parameters was less than 33% during the reference period (1956-1995). The different exceedance rate of stream flow for dry and wet months of the reference period can be considered as natural range of variation which is necessary to sustain the full native biodiversity and integrity of aquatic ecosystems, and ultimately to provide multiple services to the people living in the region. Through modeling, we investigated the effects of climate change on the flow regime. This revealed that compared to the reference period by 1956-1995, the ecological thresholds were more frequently exceeded for the RVA parameters of average flow of January, February, June, July, August and yearly maximum flow for both IPCC scenarios A1B and A2 by the weighted ensemble mean.

Due to climate change, the increased exceedence of the hydrologic parameters has important implications for stream processes and patterns (Poff et al. 1996). According to Poff and Ward (1990), the more a modified hydrological regime deviates from the historical norm, the greater the inferred ecological consequences. Aquatic ecosystems are highly sensitive to such modifications, as climate change induced altered flow regimes potentially interfere with the reproduction of many aquatic species, which eventually affect species composition and ecosystem productivity (Poff et al. 2002). Hydrologic modifications due to climatic changes affect the abiotic factors (river gradient, depth of water and river flow) of the Brahmaputra River and this has a strong bearing on its hydrobiology (Boruah and Biswas 2002). As a consequence, the population of about 200 species including the most spectacular animal, the river dolphin (*Platanista gangetica*) are expected to steadily decline from the basin (Biswas and Boruah 2000).

Flood frequency analysis revealed that in the LBRB, more frequent and more intense floods are expected to occur in future years, which has both social and ecological implications for the lower part of the basin in Bangladesh. Roughly 30 per cent of the total flood related damages are accounted for by loss of agricultural crops in Bangladesh. Rice is the main crop, which is highly dependent on the onset, retreat and magnitude of monsoon precipitation (Brammer et al. 1996). In particular, high-yielding ‘aman rice’ varieties are highly susceptible to floods as the flood peaks in August–September may affect sowing of the crop (Mirza 2002). Floods are also detrimental to monsoon vegetables and other crop varieties. Yearly crop damage could be about 0.5 million tons, but during an exceptional flood (with a return period greater than 20 years), damages could be much more detrimental. As an example, crop damage for the flood years of 1987, 1988, and 1998 was estimated at 1.32, 2.10, and 3.0 million tons, respectively (Ahmed 2001). Damage due to floods has many more implications including direct loss in agricultural employment and indirect effects on the society, depending on local and institutional adaptive capacity (e.g. Renaud et al 2010). Crop damage by floods and consequently food security can be considered a serious problem, even in a normal year in Bangladesh, with half of its population living below the poverty line.

Our results have a number of policy level implications for government agencies of the LBRB. First, calculated threshold flow of twenty-two RVA parameters can be used as initial targets for water resource, flood risk and ecosystem management in Bangladesh. The Bangladesh government could consider allowing human perturbation and development activities within these ranges. These criteria can also be used for water allocation to meet household, agriculture and industrial water demands. In trans-boundary river basin management, thresholds of flow variability can be used as a basis for negotiation with other riparian countries for regional flood management through up-stream and down-stream data sharing, establishment of early warning system and regulation of low flows through appropriate upstream reservoirs operation. Second, the government may consider damaging flood events when flow exceeds a 10-yr return period at Bahadurabad station, and can prepare planning and management activities for different flooding extents accordingly. Third, the results of climate change impact show that for both A1B and A2 SRES scenarios, most of the considered periods may fail to meet the RVA threshold criteria, which means that significant changes in social-ecological system is expected to occur. Major species may not adapt to such changes, which will require planned adaptation, requiring the consolidation of relevant institutional mechanisms at various governance scales. Because of the high frequency of the threshold exceedance, planned adaptation strategies and targets need to be jointly discussed by the policy makers and river basin management authority of the region. The methodological approach for examining the impact of climate change on flow variability and social-ecological systems presented in this study may also prove to be useful in other river basins.

6 Conclusion

Our analysis showed that under different scenarios of climate change, the RVA threshold criteria would be exceeded in most future years and more intense and more frequent flooding are expected to occur. The exceedance of threshold conditions is detrimental to aquatic ecosystems and agricultural crops, which eventually affect the social-ecological system of the basin.

The approach of hydrologic thresholds flow confirms its potential for use in planning and management of water resources which have impacts on coupled social-ecological system. In this study, thresholds have been calculated for ecological (i.e. through RVA approach) and social systems (i.e. flood categories) separately. But societal and ecological subsystems remain in mutual interaction and their states, interactions and feedback mechanisms need to be analyzed jointly in future studies, particularly when addressing sustainable development issues (Gallopín 2006).

In setting ecological threshold flows with the RVA approach, the study is mainly based on statistics. However, further research is required investigating the physical impact of hydrologic flow regime on ecosystems in detail (Monk et al. 2007). Similarly, for determining damaging flood events through flood frequency analysis, parameter uncertainty should be considered in future studies.

In this study we focused only on the expected impact of climate change on river flow thresholds. However, in reality, climate change and human induced perturbation (e.g., development of river infrastructure such as dams) happen concomitantly and interactively. Along with climate change, the increasing human activities such as dams in the Himalayan foothills reported by Grumbine and Pandit (2013) might provide both positive as well as negative feedback to downstream regions. The extent of hydrologic perturbation associated with human activities such as dam operations, flow diversion, groundwater pumping, or intensive land-use conversion has already been assessed in several studies (Richter et al. 1996, 1997; Mirza 1998). To investigate the combined impact of climate change and human induced perturbation, future studies are required aiming at a more in-depth understanding of the system, which with respect to ecosystems should also consider water quality issues.

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Figures

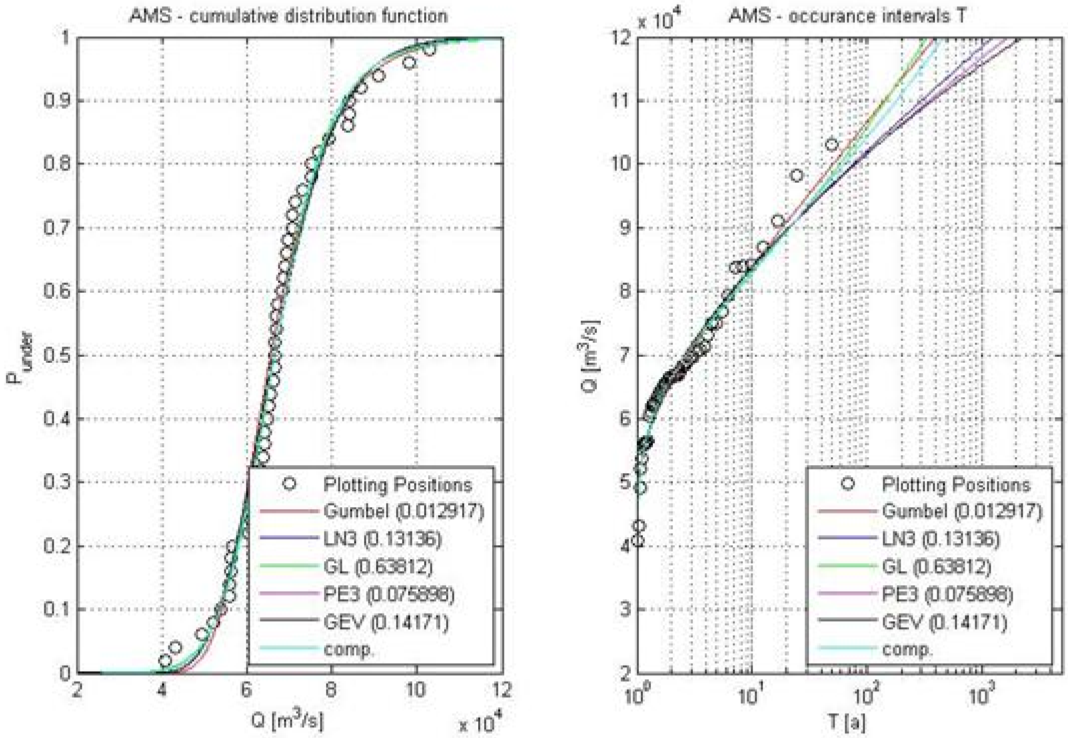

Figure 1. Different distribution functions fitted to the annual maximum flood series 1956-2004 of the gauge Bahadurabad, Brahmaputra River. **a**) cumulative probability (P_{under}) versus computed discharge (Q) of fitted distributions; **b**) computed discharge (Q) of fitted distributions versus return period (T). Comp. refers composite distribution

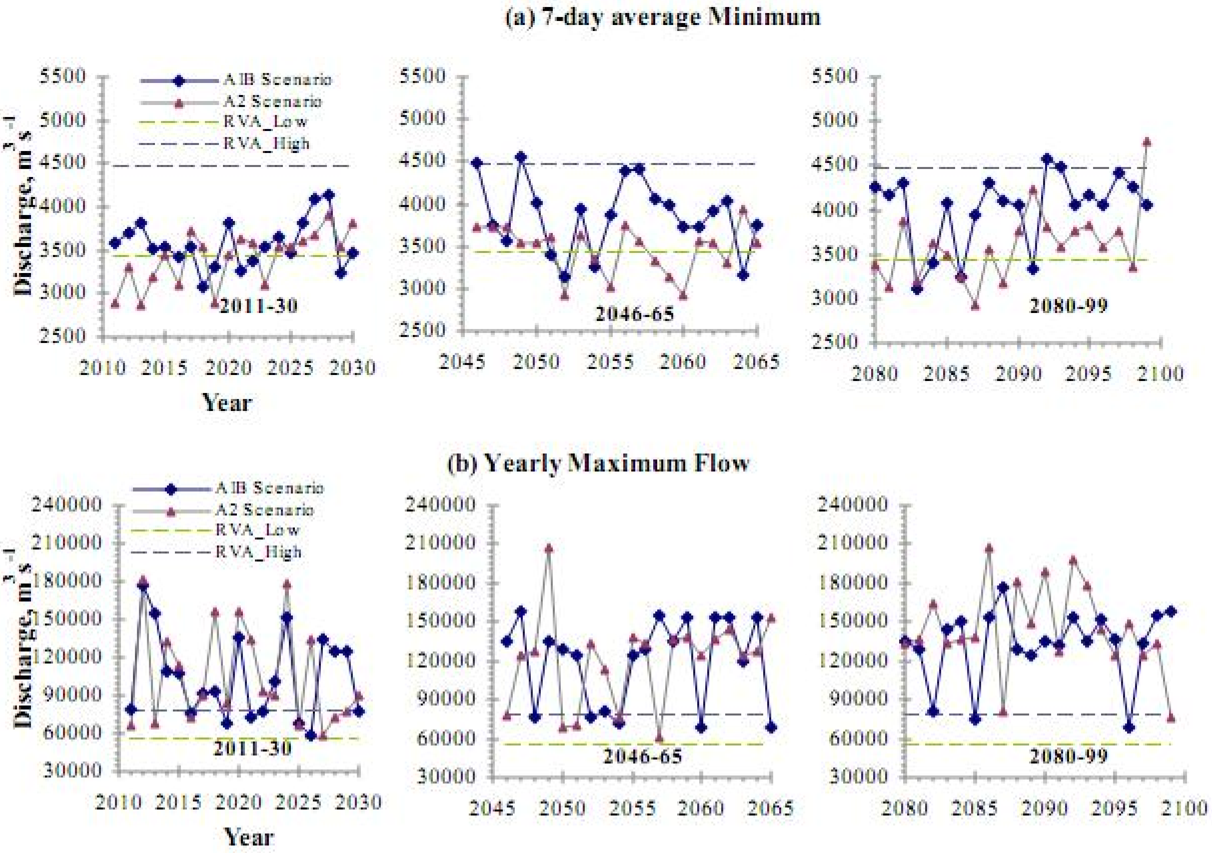

Figure 2. Investigation of thresholds values for future A1B and A2 Scenarios of **a)** 7-day average yearly minimum flow; **b)** yearly maximum flow. RVA_Low denotes minimum threshold limit whereas, RVA_High refers maximum threshold

Table

Table 1. Exceedance of threshold values of different RVA parameters in future climatic condition in percent

	Exceedance of threshold values for different time slices of A1B and A2 scenario (%)					
	2011-2030		2046-2065		2080-2099	
	A1B	A2	A1B	A2	A1B	A2
January	35	40	50	70	85	80
February	50	45	65	55	80	70
March	30	40	35	40	35	55
April	30	40	35	40	35	35
May	30	35	30	35	30	40
June	35	35	35	40	45	45
July	30	45	50	40	75	85
August	55	40	75	75	90	95
September	35	30	40	35	45	40
October	25	30	25	30	30	25
November	25	30	25	30	40	40
December	30	35	50	35	50	40
1- day maximum	65	65	75	80	90	95
3- day maximum	45	45	50	55	70	75
7- day maximum	35	45	40	55	55	65
30- day maximum	35	40	45	55	45	60
90- day maximum	35	40	40	40	45	55
1-day minimum	30	35	35	35	35	35
3- day minimum	35	30	35	30	35	40
7- day minimum	30	35	30	35	30	40
30- day minimum	30	40	35	40	35	35
90- day minimum	30	35	30	35	30	40

Table 2. Percentage of exceedance of computed flow in future climatic condition

Return Period	Different flood classification	Computed discharge, m^3/s (composite distribution)	Exceedance of threshold values (compared to computed flow of observation period) [%]					
			2011-30 (A1B)	2011-30 (A2)	2046-65 (A1B)	2046-65 (A2)	2080-99 (A1B)	2080-99 (A1B)
2	Normal flood	66378	100	90	100	100	100	100
3.33	Moderate flood	72434	95	85	95	100	100	100
10	Severe flood	83123	80	60	95	85	100	100
20	Catastrophic flood	89416	65	45	85	80	100	100
50	Exceptional flood	97710	50	40	85	80	100	100
70		100811	50	40	85	80	100	100
100		104161	45	40	85	80	100	100

Thresholds of hydrologic flow regime of a river and investigation of climate change impact – the case of the Lower Brahmaputra river Basin

Animesh K. Gain*, Heiko Apel, Fabrice G. Renaud, Carlo Giupponi

*Corresponding author. Tel.: +39 041 234 9109; Fax: +39 041 2349176

E-mail address: animesh.gain@gmail.com (A.K. Gain)

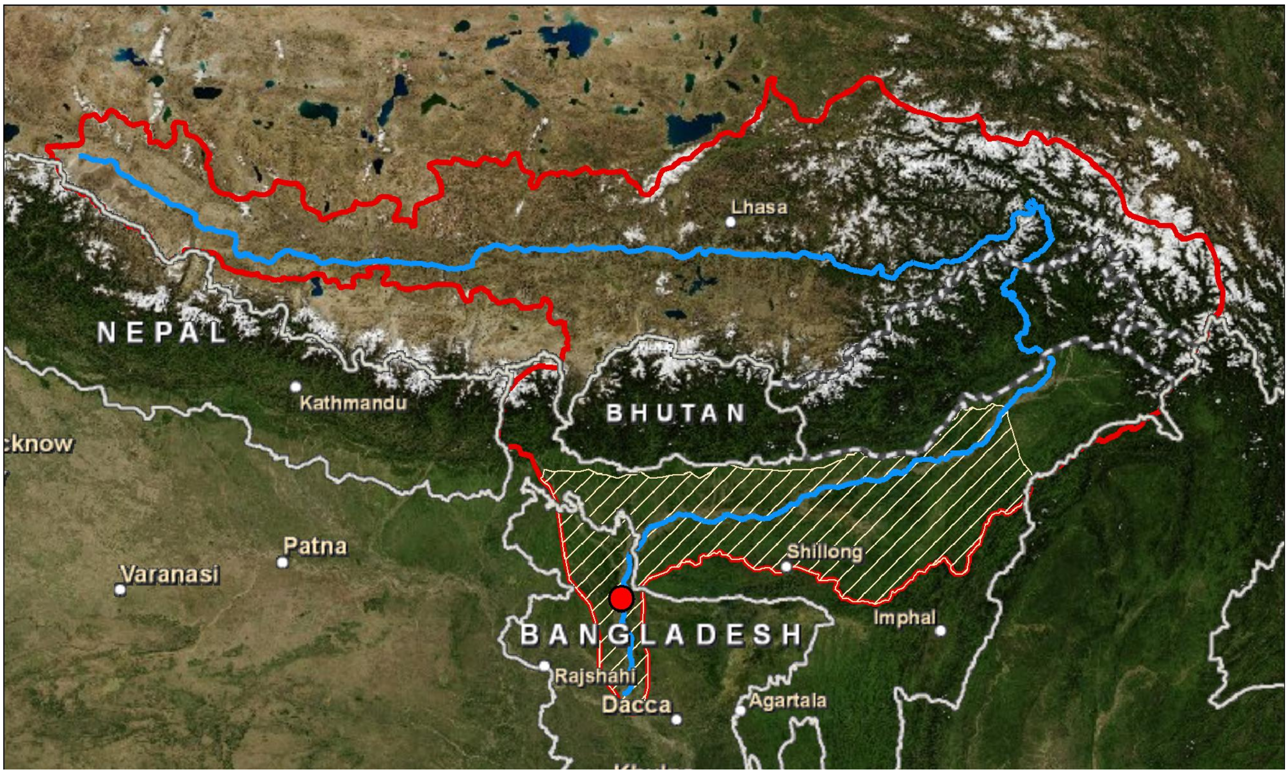

Fig. S 1 Overview of the Brahmaputra river basin (red polygon), the Brahmaputra river (blue line), and the outlines of the lower Brahmaputra river basin (shaded white)

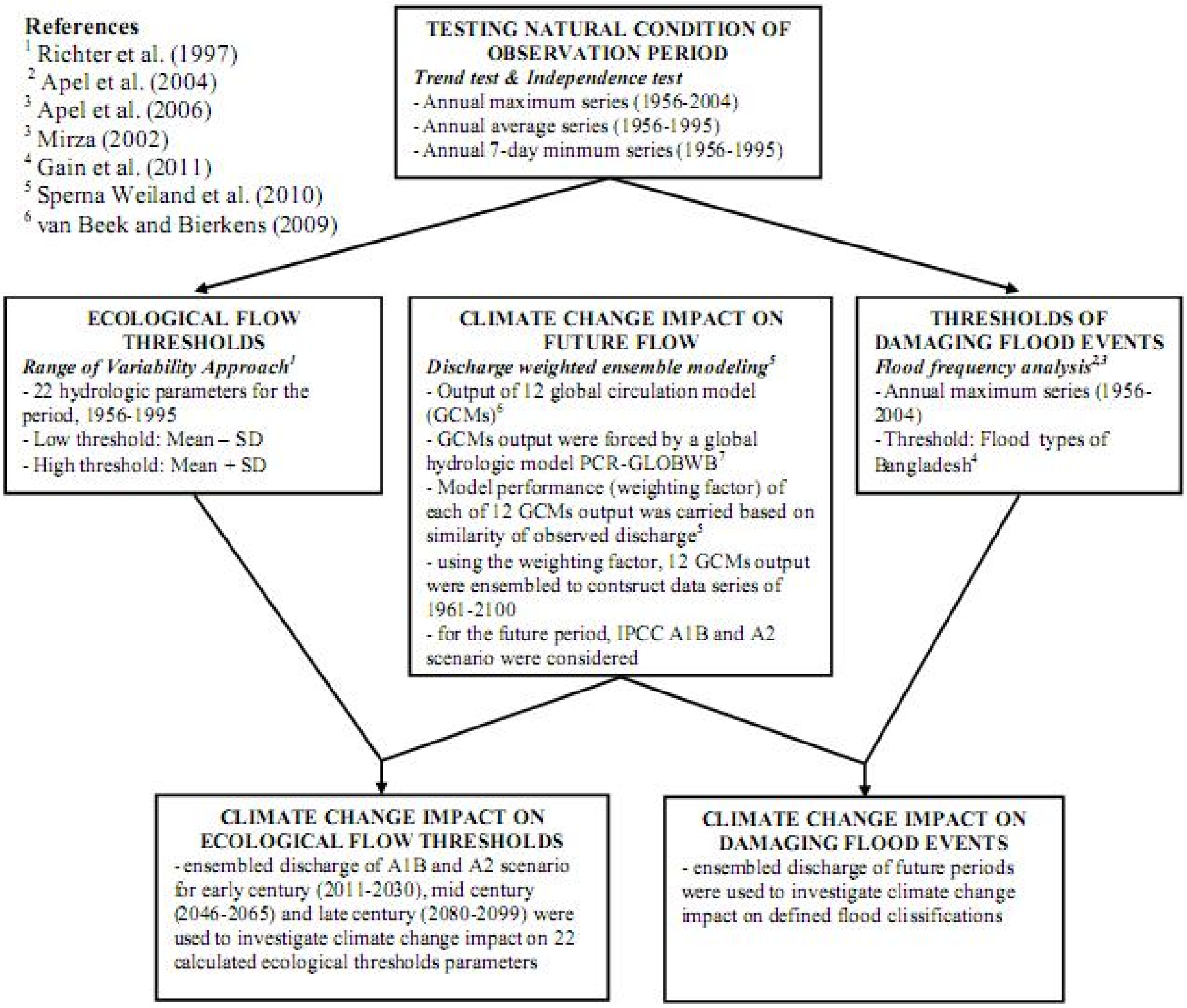

Fig. S 2 Flow chart for the assessment of thresholds and climate change impact

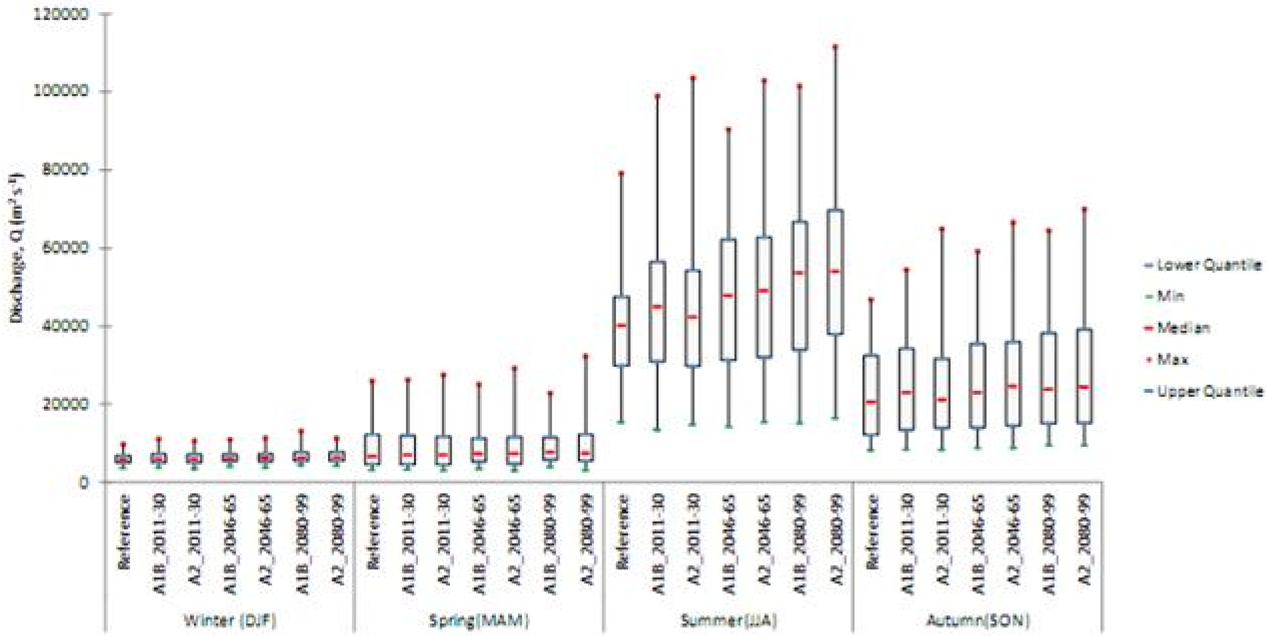

Fig. S 3 Multi-model weighted variation of discharge for different seasons and for different time slices

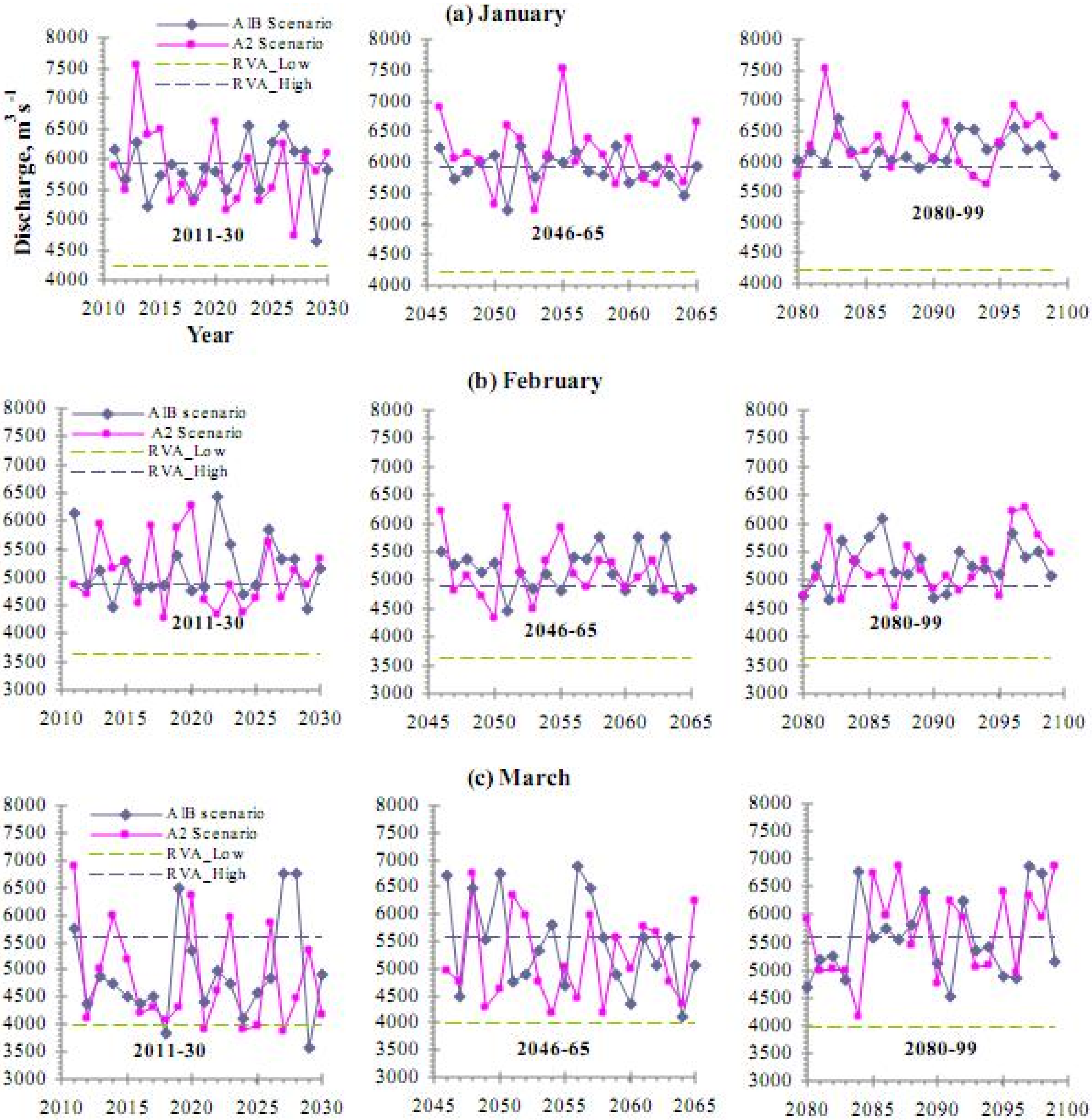

Fig. S 4 RVA thresholds and estimated future monthly means flow by A1B and A2 scenarios during low flow period: January (a); February (b); March (c)

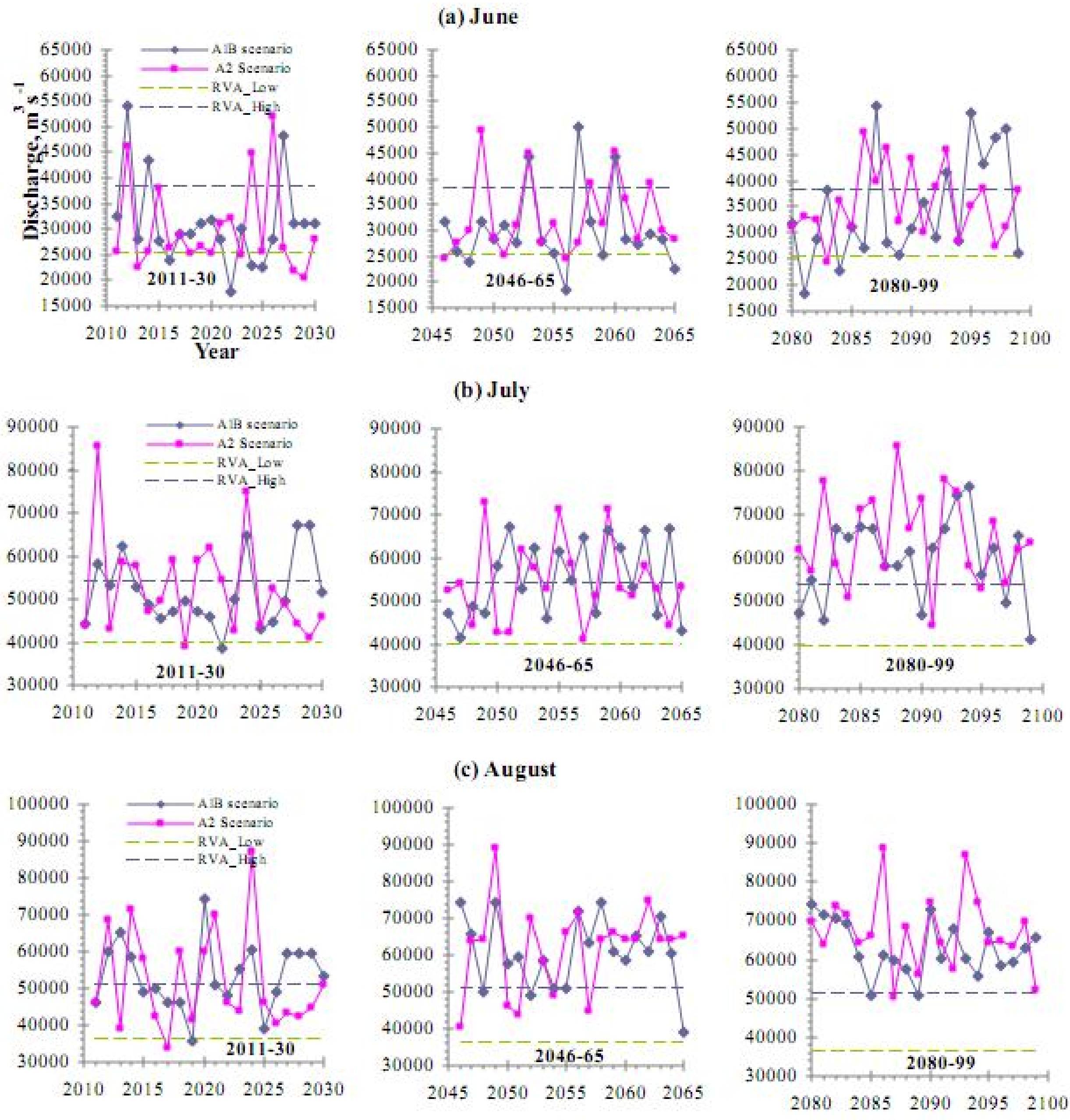

Fig. S 5 RVA thresholds and estimated future monthly means flow by A1B and A2 scenarios during ascending high flow period: June (a); July (b); August (c)

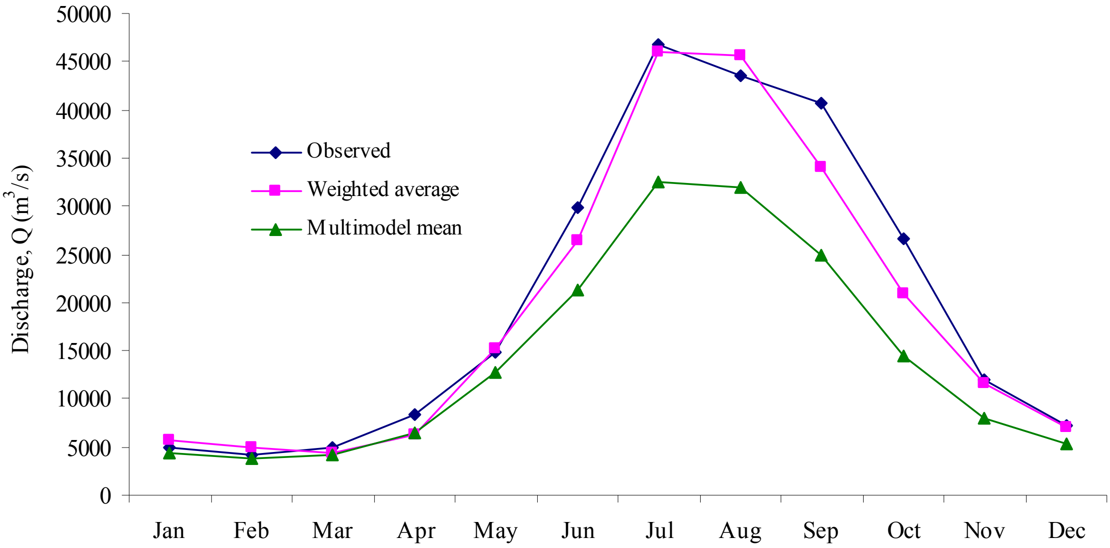

Fig. S 6 Comparison of weighted average and multi-model mean (of 12 GCMs) with monthly mean observed discharge for the reference period 1973-1995.

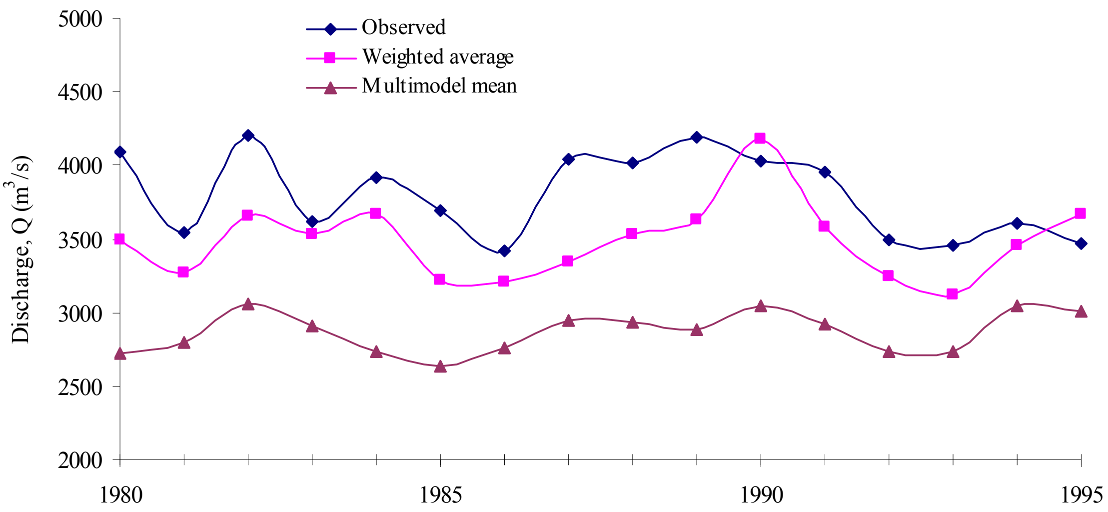

Fig. S 7 Comparison of weighted average and multi-model mean (of 12 GCMs) 7-day low flow with observed discharge for the reference period 1980-1995.

Table S 1

Results of selected RVA parameter analysis (Unit: $m^3 s^{-1}$)

	Mean value of each parameter	Standard Deviation	RVA Threshold	
			Low	High
January	5056	851	4205	5907
February	4243	632	3611	4875
March	4774	807	3967	5581
April	8091	1860	6231	9951
May	15871	3994	11877	19865
June	31716	6437	25279	38153
July	46835	7113	39722	53948
August	43657	7386	36271	51043
September	37920	7371	30549	45291
October	24405	7190	17215	31595
November	11232	2754	8478	13986
December	6922	1364	5558	8286
1-day minimum	3869	553	3316	4422
3- day minimum	3890	533	3357	4423
7- day minimum	3943	519	3424	4462
30- day minimum	4161	638	3523	4799
90- day minimum	4632	715	3917	5347
1- day maximum	66225	11250	54975	77475
3- day maximum	65265	10830	54435	76095
7- day maximum	62836	9979	52858	72815
30- day maximum	53081	7584	45496	60665
90- day maximum	44334	5730	38604	50063

Table S 2

Flood classification of Bangladesh in terms of probability of occurrence, area inundated and physical damage (Source: Mirza 2002)

Types of floods	Parameters			
	Probability of occurrence (equivalent return period, in years)	Range of flooded area (km^2)	Percent of inundation	Parameters affected
Normal flood	>0.5 (<2)	31,000	21	- Contributes to increasing soil fertility - Cropping pattern is adjusted with inundation - Hampers normal human activities - Minimum economic loss
Moderate flood	0.3 (3.33)	31,000-38,000	21-26	- Contributes to increasing soil fertility - Damage limited to crops - Hampers human activity moderately - Moderate economic loss - People cope by themselves
Severe flood	0.10 (10)	38,000-50,000	26-34	- Damage to crops, infrastructures and certain urban centres - Hampers human activities severely - Economic loss is higher - Requires evacuation & relief operation
Catastrophic flood	0.05 (20)	50,000-57,000	34-38.5	- Hampers human activities drastically - Extensive damage to crops, cultured fisheries, lives and property in both urban and rural centres, all types of infrastructure, etc. - Requires extensive relief operation - Very high economic loss - Requires international support
Exceptional flood	<0.05 (>20)	>57,000	>38.5	- Hampers human activities exceptionally - Extensive damage to crops, cultured fisheries, lives and property in both urban and rural centres, all types of infrastructure, etc. - Requires extensive relief operation - Disrupts communication - Closing of educational institutions - Exceptional economic loss - Usually requires international support

Table S 3

Computed discharge for different return periods

Return Period [years]	Different flood classification	Computed discharge (m^3s^{-1})					
		Gumbel	LN3	GL	PE3	GEV	Composite *
2	Normal flood	65606	66308	66433	66299	66278	66378
3.33	Moderate flood	72021	72775	72260	72845	72786	72434
10	Severe flood	83829	83607	82774	83699	83740	83123
20	Catastrophic flood	90792	89497	89298	89500	89628	89416
50	Exceptional flood	99805	96732	98383	96509	96673	97710
70		103088	99284	101905	98948	99087	100811
100		106559	101942	105768	101469	101557	104161

*Composite distribution was calculated using maximum likelihood weights of the distributions. The weights are: Gumbel = 0.0129, LN3 = 0.1314, GL = 0.6381, PE3 = 0.0759, GEV = 0.1417;