Indicators of Necessary Storages for Flood and Drought Management: Towards Global Maps

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Abstract. Storage is the only means to smooth out the discharge variation necessary to control hazards and utilize water resources. Necessary storage depends on the levels of discharge variation, required flood control and water use. The main methodologies to calculate necessary storage include mass curve method and simulation. The use of flood duration curve (FDC) and drought duration curve (DDC) that this paper presents is an alternative way that has considerable advantages over the others. The diagram of FDC-DDC serves as the classification indicator of basin hydrology and the FDC-DDC based estimates of necessary storages can be used for reservoir operation. The FDC-DDC based necessary storages pay an attention to the finite term hydrological variation rather than the asymptotic infinite memory of variation that Range analysis focuses. On the other hand the FDC-DDC focus on spatial distribution of necessary storages and try to find spatial rules of hydrological heterogeneity in necessary storages. For a case study, the Ganges-Brahmaputra-Meghna basin was selected and its spatial distribution of the FDC–DDC based necessary storages was calculated based on the discharge dataset obtained by hydrological simulation of the MRI-AGCM3.2S projections using the hydrological model BTOPMC developed at University of Yamanashi and ICHARM. The spatial distribution of necessary storages indicate the relative difficulty of managing the temporal variation of river discharges for human use at respective locality. The climate change impacts on the necessary storages were analysed and found the increase in difficulty of managing high flows and the general ease of managing low flows. But local differences were rather large that indicates the need of careful study to respond unique spatial structure of local discharge variation. The relation to catchment area was also analysed and found such regional heterogeneity diminishes into a basin average slowly in several 10,000 km². A representative elementary area of necessary storages for discharge smoothing is a new concept that deserves for further study. A creation of global maps would be a useful challenge for assessment of current state of water resources, climate change impact on water resources and for study of hydrological heterogeneity and its scale effect of hydrological variability in storage domain.

1 Introduction

Storage is the only means to smooth out the variation of the flow and make hazards under control and resources useful. How much smoothing is necessary depends on variation of the flow, flood channel capacity and target levels of water uses. There

are various ways of calculating necessary storages under given levels of out-flows. The most widely known is the mass curve method developed by Rippl (1883) which have been used as the basic methodology of calculating necessary storage with a given constant target water use (Klemes, 1979). For more complicated target water use patterns, simulation method was introduced and extensively studied by Harvard Water Program in 1950's (Maass et al., 1962). The former initiated the epoch

5 making research movements on storage analyses on Range (Hurst, 1951; Feller, 1951; Moran, 1959) and the latter streamflow synthesis (Thomas and Fiering, 1962; Young, 1967; Mandelbrot and Wallis, 1969; Valencia and Schaake, 1972). In the 1970s, a new method was invented based on Drought Duration Curves (DDC) by Kikkawa and Takeuchi (Kikkawa and Takeuchi, 1975; Takeuchi and Kikkawa, 1980). The DDC was shown useful for reservoir operation (Takeuchi, 1986) and the FDC-DDC, by adding flood duration curves (FDC), for hydrological statistics and classification (Takeuchi, 1988).

10 In this paper, the FDC-DDC based storage calculation method is extended to spatially indicate the necessary storage to smooth out the discharge at each grid point in a basin. It indicates the difficulty or easiness of controlling discharge for water resource management both flood control and water use at a local site. It is applied as an example to the Ganges-Brahmaputra-Meghna (GBM) basin and analysed the spatial distribution of impacts of climate change on the necessary storages and the spatial heterogeneity of necessary storages in relation to catchment areas. On the FDC-DDC measured climate change impact, Masood

15 and Takeuchi (2015) showed a preliminary analysis on the GBM basin at selected points, which will be extended in this paper spatially to a basin.

There are many number of climate change impact assessments such as on precipitation, snow and ice, discharge, floods, droughts, soil moisture, vegetation etc. But none for necessary storages to smooth out the variation of discharge for given flow targets. Compared with any other hydrological variables, the necessary storages more directly indicate the tractability of

20 discharges for managing water resources and serve as an indicator of local to global distribution of manageability of hydrology and climate change impacts on hydrological phenomena.

In addition, this paper looks into the spatial distribution of necessary storages to smooth out discharge variations over time in relation to the catchment area. This is a study of scale effect of necessary storages over a catchment. Since discharge is an integrated phenomena over a heterogeneous surface and underground hydrology including surface flow concentration, its scale

25 effect is different from that of elementary hydrological processes in a small catchment.

In Chapter 2, methodology is presented, namely, the flood and drought duration curves FDC-DDC are introduced and the necessary storage calculation method based on FDC-DDC is described. The comparison of this method with the standard mass curve method is also discussed. In Chapter 3, application of the methodology for a case study in the GBM basin is described. The case study area and the input data based on MRI-AGCM and the hydrological model BTOP are described. Chapter 4

30 presents application results and discusses their implication. In Chapter 4.1 discussed are on spatial distribution of necessary storages and the climate change impacts on them and in Chapter 4.2, the necessary storage-area relation or scale effect of hydrological heterogeneity in necessary storages. Chapter 5 shows conclusions.

2 Methodology

This chapter first introduces in 2.1 the methodology of calculating FDC-DDC which basically follows the similar notation used in Takeuchi (1988) but slightly modified to a simpler form neglecting a seasonal parameter τ. Then it introduces in 2.2 the methodology of calculating necessary storages which follow the procedure originally introduced in Kikkawa and Takeuchi (1975) and in Takeuchi (1986) but much more systematic way. Finally in 2.3, FDC-DDC method for calculating necessary storages will be compared with the traditional mass curve method.

2.1 Flood duration curve (FDC) and drought duration curve (DDC)

Let x_t denote any hydrological variable at time t and a random variable $X(m)$ denote the annual maximum of moving averages of any x_t over m days starting any day t_1 of a certain year. Its quantile value for exceedance probability α denoted by $f_a(m)$ is defined as a flood duration curve. Similarly a random variable $X^{'}(m)$ denotes the annual minimum of moving averages of m days starting from any day belonging to the year. Its quantile value for non-exceedance probability β denoted by $f^{'}_{\beta}(m)$ is defined as a drought duration curve. Namely,

$$X(m) = \max_{t_1 \epsilon \, a \, certain \, year} \frac{1}{m}\sum_{t=t_1}^{t_1+m-1} x_t \tag{1}$$

$$X^{'}(m) = \min_{t_1 \epsilon \, a \, certain \, year} \frac{1}{m}\sum_{t=t_1}^{t_1+m-1} x_t \tag{2}$$

$$\text{Prob}\big(X(m) \geq f_{\alpha}(m)\big) \leq \alpha \tag{3}$$

$$\text{Prob}\left(X^{'}(m) \leq f^{'}_{\beta}(m)\right) \leq \beta \tag{4}$$

In this study, the hydrological variable x_t is discharge and the quantiles of flood duration curve (FDC) $f_a(m)$ and drought duration curve (DDC) $f^{'}_{\beta}(m)$ in Eq 3 and 4 were estimated fitting generalized extreme value distribution where parameters were estimated by the maximum likelihood method for α and β being 0.2, 0.1, 0.05 and 0.02 corresponding to 5, 10, 20 and 50-years return periods (T).

Fig. 1 depicts the FDC and DDC of the Brahmaputra River at Bahadurabad station (Fig. 2). It shows for m up to 1095 days or three years. The duration curves oscillate with duration time length reflecting the annual periodicity of hydrograph. For higher return periods, duration curves lay outer from the long term mean discharge line, implying higher flood discharges and lower drought discharges.

The duration curves are theoretically nothing but the intensity-duration-frequency (IDF) curves but practically they are considerably different. Ordinarily IDF curves are nearly exclusively used for design of a storm drainage system and accordingly concern precipitation in its high intensity side for rather short term such as several hours to a few days. On the other hand, the FDC-DDC applies precipitation, discharge or any other time series not only in high intensity side but also low intensity side. Also the concerned time length or duration extends to over months to multi years.

In fact the original development of this duration curve was DDC rather than FDC for reservoir management during drought and the idea was totally independent of IDF (Kikkawa and Takeuchi, 1975). Its central interest was the surely available minimum discharge that can be expected in the future m days as the worst case scenario. Takeuchi (1986) applied the DDC for chance-constrained reservoir operation as DDC $f'_\beta(m)$ indicates the average inflow that can be expected in any m days in the future with the failure rate less than β. Further later, the idea was extended to flood side and developed FDC-DDC as a means of classifying the persistence characteristics of regional hydrology, precipitation as well as discharges that serve as an indicator or a palm print of basin hydrology (Takeuchi, 1988).

2.2 Necessary storages

In this section, the detail procedure of calculating necessary storages to smooth out discharge variations over time using FDC-DDC will be illustrated. In short, the necessary storages are obtained as the largest inner rectangular area that just fits to the area surrounded by a duration curve, the target discharge level (such as the long term mean) and the vertical axis at the origin. The necessary storages indicate the empty space necessary for flood control at the beginning of flood season and the stored volume of water necessary for water supply at the beginning of drought season with the failure rate indicated by the duration curves.

2.2.1 Necessary storage to smooth out high flows (floods)

Fig. 3 depicts a schematic FDC-DDC of discharge at the dam site concerned.

1. Suppose at a time before flood season, a flood manager considers how much flood control space he needs to smooth out all the high flows expected in the season.
2. Suppose the flood channel capacity or the target river discharge level is the long term mean of the river discharge EM in Fig. 3 (which may not be realistic but easy to proceed the discussion).
3. Suppose he chooses return period 20 years or failure rate 0.05. Then he chooses a flood duration curve $f_{0.05}(m)$.
4. Suppose he focuses on point A on the FDC $f_{0.05}(m)$ where m=50 days.
5. The horizontal line DA passing through point A, namely, $f_{0.05}(50)$ is the annual maximum average discharge per day over any 50 days starting from any date in any year that will exceed only with probability 0.05. In other words, this level is the average flood discharge that the flood manager expects and likes to smooth out.
6. How much volume is the total flood discharge in those 50 days? It is simply $f_{0.05}(50) * 50$ which is the area of the rectangular ADOC.
7. Now, how much flood discharge can the river safely flow down, or what is the flood channel capacity? That is, he assumes the long term average discharge indicated by the line EB (on EM). The flood volume safely flow down is the area indicated by the rectangular BEOC.

8. Therefore the necessary storage capacity the flood manger needs to prepare for flood space before the season is ADOC-BEOC=AOEB.

9. Now the flood manger has to consider the necessary storage space by moving point A all the way from the start to the end, in this case point A_0 to A_{end} and identify the largest volume necessary for flood control. This can be expresses as:

$$V_{fc,\alpha} = \max_m m * f_\alpha(m) \qquad (5)$$

In this study, the interest duration is limited to a year neglecting the need of multi-year smoothing. In reality, an over year storage is very important and in many practical cases critical especially in arid/semi-arid zone but as an indicator for an eventual global map, we first concentrate on intra annual smoothing for simplicity. The necessary storage for inter-annual smoothing eventually faces the Hurst phenomena as briefly discussed in 5.1.

By this simplification, the necessary storage can be expressed in a narrative way as the area of the largest rectangular that just fits to a right triangle surrounded by a flood duration curve, channel capacity line and the vertical axis of the origin.

2.2.2 Necessary storage to smooth out low flows (droughts)

Similar discussion for the necessary storage for drought management will follow below. Again Fig 3 will be used for explanation.

1. Suppose a drought manager considers how much water is necessary to be stored before a dry season starts.

2. Suppose he is obliged to keep supplying water equal to the long term mean of the river discharge that is indicated by the line EM.

3. Suppose he chooses return period 20 years or failure rate 0.05. Then he chooses a drought duration curve $f'_{0.05}(m)$.

4. Suppose he focuses on point A' on the DDC $f'_{0.05}(m')$ where $m' =150$ days.

5. The horizontal line D'A' passing through point A', namely, $f'_{0.05}(150)$ is the annual minimum average discharge per day over any 150 days in a year that will go below only with probability 0.05. In other words, this level is the average low flow over the next 150 days that the drought manager expects and likes to go around by augmentation from reservoir storage.

6. How much volume is the total discharge he can expect in those 150 days? It is simply $f'_{0.05}(150) * 150$ which is the area of the rectangular A'D'OC'.

7. Now, how much water is necessary to be released to meet the water supply target during next 150 days? The drought manger is obliged to supply the long term average discharge indicated by the line EB'. The necessary volume to be released to meet the target is indicated by the area of the rectangular B'EOC'.

8. Therefore the necessary reservoir storage the drought manger needs to prepare for drought management before the dry season starts is A'D'OC'-B'EOC'=A'OEB'.

9. Now the drought manger has to consider the necessary storage to be reserved for augmentation by moving point A' all the way from the start to the end, in this case point A'$_0$ to A'$_{end}$ and identify the largest volume necessary for drought management. This can be expresses as:

$$V_{dm,\beta} = \max_m m * f'_\beta(m) \tag{6}$$

Again in this study, the range of averaging time length m was limited to 365 days or a year. This assumption is more critical for drought management than for flood management as the multiyear drought is frequently experienced and a serious concern in many arid and semi-arid nations. But as an indicator, the time length of a year is selected. However, the methodologies themselves Eq (5) and (6) are valid for any m and can work for calculating necessary storages of multiyear drought regardless of its length.

2.2.3   With arbitrary target releases

Instead of assuming the target releases always equal to the long term mean, the targets can be set to the real flood channel capacity and the safe yield level of water supply as seen in Fig. 4. In such cases the line of the long term mean EM in the item 2 and 7 of the procedures above should be replaced by the channel capacity for flood control and the target water supply for drought management. The resultant necessary storages V_{fc} for flood control and V_{dm} for drought management can be calculated as in Fig. 4. As mentioned above, however, this study uses the long term mean for an indicator for simplicity.

2.2.4   Expression in km^3 and months

Necessary storages expressed in km^3 increase with catchment area as Fig. 7-left and if necessary storage at each grid point is plotted in a map, the dominant areal distribution becomes similar to the distribution of catchment area. In order to better express the hydrological characteristics of geographical distribution of necessary storages, a normalized indicator may be useful by dividing the necessary storage volume [km^3] by the local long term mean discharge Q_{mean} [m^3/s] and expressed in [months]. The geographical distribution of months was plotted in a map as seen in Fig. 7-right.

2.3   Relation with the standard mass curve method

The methodology presented in 2.2 is considerably different from the standard mass curve method originally proposed by Rippl (1883) and widely used in engineering fields (Klemes, 1979). The major difference is its assignment of return period. The original mass curve method does not translate the original hydrograph into the frequency domain or an intensity-duration-frequency (IDF) curve which has the same return period along a particular IDF curve for any duration. In reality there is no hydrograph that has always a same return period at any time for any duration but a mixture of many different high and low flow episodes with different return periods. As the mass curve method utilizes the real hydrological time series, the assignment of return period or rate of failure is not necessarily in a strict manner. The total negative run sum or negative run length are

often used to identify the return period which largely depends on the length of time that an analysis focuses on. The FDC-DDC method is free from such selection of length of time and the practical differences are in fact minor as shown by Takeuchi and Kikkawa (1980).

3.   Application

5   In order to demonstrate an example of the spatial distribution of FDC-DDC necessary storages, this study presents a case study in the the Ganges-Brahmaputra-Meghna (GBM) basin. The discharge dataset was created by using a distributed hydrological model BTOP with the precipitation and radiation dataset MRI-AGCM3.2S projected by Meteorological Research Institute of Japan. As the objective of the case study is methodological demonstration, no other projections are analyzed.

3.1   The case study area

10   Fig. 2 depicts the case study area Ganges-Brahmaputra-Meghna (GBM) basin. According to FAO AQUASTAT (2011), the total basin area is about 1.7 million km^2 shared by India (64%), China (18%), Nepal (9%), Bangladesh (7%) and Bhutan (3%). It is the world third largest freshwater outlet to the oceans. The Ganges basin is characterized by large spatial variation of precipitation that causes water scarcity in some areas and abandoned water in other areas. The Ganges is a snowmelt-fed river, which is regulated by 75 artificial dams (Lehner et al., 2011). The Brahmaputra basin is characterized by high precipitation,
15   large volume of snow in the upstream that provide huge volume of discharge in the river. On the other hand, the Meghna River is a comparatively smaller, rain-fed, and relatively flashier river. The basin contains world's top two highest precipitation (about 12000 mm $year^{-1}$) areas; Mawsynram and Cherrapunji (Masood and Takeuchi, 2015b).

The GBM river basin contains about a tenth of the world's population. As the population is still steadily increasing the usage of water is increasing rapidly to meet the anthropological, agricultural and industrial water requirement. In addition, the basin
20   is also recognized as a home ground of waterborne natural disasters, floods and droughts which threat this large number of population each year. Therefore, the management of water resources is a crucial part to ensure the sustainability of the region.

3.2   Data used

3.2.1   Climate projection data

Climate projection data for present (1979–2003) and far-future (2075–2099) used are the super-high-resolution (20 km)
25   atmospheric forcing data of Meteorological Research Institute Atmospheric General Circulation Model with SRES-A1B scenario (MRI- AGCM3.2S) (Mizuta et al., 2012) which is the finest available GCM data so far for the globe.

3.2.2 Discharge data

The discharge data were created by model simulation using a distributed hydrological model BTOPMC with the input of MRI-AGCM3.2S. The model and the model set up procedure are described below.

3.2.2.1 Hydrological model to obtain discharge data

5   A physically based distributed hydrological model BTOPMC was used for simulating runoff. The BTOPMC (Block-wise use of TOP model with Muskingum-Cunge method) was developed at the University of Yamanashi and ICHARM, PWRI, Japan (Takeuchi *et al.*, 1999, 2008; Ao *et al.*, 1999, 2006; Hapuarachchi *et al.*, 2008). It is an extension of TOPMODEL (Beven and Kirkby, 1979) to apply for large basins. The extension is made by introducing the effective contributing area concept, that is, the discharge generation from a grid cell in a large basin is not necessarily contributed by its whole upstream

10   catchment but only a portion of it. Based on this concept, the original topographical index is modified by replacing an upstream catchment area by an effective catchment area and the transmissibility coefficient T_0 by dischargeability D_0 (Takeuchi, 2008). For flow routing basically the Muskingum-Cunge (MC) method (Cunge, 1969) is adopted to take the diffusive factors into account. But a modification was made to conserve water at each segment of river reach (Masutani and Magome, 2009).

15   The BTOPMC has been applied in many river basins throughout the world especially in poorly gauged basins utilizing globally available data such as USGS HydroSHEDS (Lehner et al., 2008) and Hydro1K of USGS EROS Centre for DEM, FAO soil maps, IGBP land cover data, climate forcing data CRU TS3.1 of University of East Anglia for potential evapotranspiration, APHRODITE precipitation data (Yatagai et al., 2012) etc. The Normalized Difference Vegetation Index (NDVI) data were used to compute potential evapotranspiration (PET) using Shuttleworth-Wallace (S-W) model (Zhou et

20   al., 2006). Through these applications, it was found that BTOPMC can simulate river discharges quite well especially in warm humid regions (Takeuchi et al., 2013, Magome et al., 2015; Gusyev et al., 2016).

3.2.2.2 Model set up and verification

The BTOPMC model was setup for simulations of MRI-AGCM3.2S projections at the 10-arcmin grid (approximately 20-km grid resolution) using DEM data derived from HydroSHEDS. The model set up procedure followed the work by Masood and

25   Takeuchi (2015a) although there, a used hydrological model was, instead of BTOPMC, H08 (Hanasaki, 2008).

Most of BTOPMC parameters are related to and identifiable by physical features of land cover and soil as specified by Takeuchi *et al.* (2008). For three particular parameters: decay factor (m), drying function (α) and Manning's roughness coefficient (n_0) were determined by calibration examining all the combinations of three parameters in 8 (eight) different values selected from their feasible physical ranges described in Takeuchi et al. (2008). A total of 8^3 (=512) simulations were

30   conducted.

The precipitation and temperature data used for model set up were WATCH Forcing Data set (WFD) (Weedon et al., 2011). The discharge data at Hardinge Bridge, Bahadurabad and Bhairab Bazar, three outlets of Ganges, Brahmaputra and Meghna were constructed from the observed daily water level data, provided by the Hydrology Division, Bangladesh Water Development Board (BWDB) by using the rating equations developed by the Institute of Water Modelling (IWM, 2006) and

5   Masood et al. (2015c). The calibration period was from 1980 to 1990 (11 years) and verification was from 1991 to 2001 (11 years). The identified parameters are listed in Table 1.

Fig. 5 plots the daily hydrograph comparisons at the outlets of three river basins with the corresponding daily observations for both calibration and validation periods. Model performance is evaluated by comparing observed and simulated daily streamflow by the Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), the optimal objective function for assessing

10   the overall fit of a hydrograph (Sevat and Dezetter, 1991). The obtained NSEs are ranging from 0.80 to 0.91 for three basins (Table 1). Statistical indices suggest that the model performance is overall satisfactory.

To follow are the DDC-FDC analyses of the simulated discharge data obtained by the calibrated BTOPMC model described in 3.2.2 using MRI-AGCM3.2S projections of the present (1979-2003) and the future (2075-2099).

4.   Results and discussion

15   In this chapter the results obtained by the case study described in Chapter 3 will be presented and analysed. In 4.1 the spatial distribution of necessary storages in km^3 over the basin and in 4.2, the effects of catchment area on the necessary storage normalized by the long term mean expressed in months are presented.

4.1.   The spatial distribution of necessary storages over a basin

The spatial distribution of necessary storages to smooth out the discharge variation are calculated over the Ganges-

20   Brahmaputra-Meghna basin. This indicator expresses the necessary storages in terms of physical volume [km^3] which directly implies the difficulty or easiness of water resources management in a quantitative aspect. Although the quantitative aspect is only a part of the real difficulty of water resources management, the manageability of hydrological variation is definitely an important factor. The indicator may be in physical nature similar to the distribution of coefficient of variation (CV) of discharges but its physical meaning is much more directly indicative to the size of dams, retardation ponds, tanks and the like.

25   Fig. 6 shows the mean annual precipitation [mm], the mean discharge [m^3/s], standard deviation and CV of discharge as the basic information for discussion. This section shows its spatial distribution at present [1979-2003] in 4.1.1 and the impact on the indicator of climate change in the future [2075-2099] in 4.1.2.

4.1.1   Under present climate

Fig. 7 shows the spatial distribution of necessary storages considering the target release $Q_T=Q_{mean}$. The most obvious are the

30   upper and the lower are similar but left and right are very different, meaning necessary storages for flood and drought are

rather similar but the expression in km^3 and months (normalized by long term mean discharge) expression make totally different maps. In terms of km^3 in Fig. 7-left, along the main stream, the necessary storage increases with increasing catchment area and in the upstream basins, the necessary storages vary. Both for flood and drought, the blue areas where necessary storages are small in the Himalayan high mountain areas where discharge would be stable with snow and glacier, which well

5 accords with small CV in Fig. 5. The major difference between necessary storages and CV is in river courses where necessary storages are large but CV is small. Also in the Northern India approaching to Himalayan area, very high CV is scattered but not in necessary storages. In Fig. 7-right of the normalized necessary storages in months, such scattering is visible for flood, very similar to CV. But for drought, it is not visible meaning more difficulty for flood control than drought in Northern India. At the same time it implies that CV resembles with necessary storages for flood but not drought.

10 Fig. 8 is the same as Fig. 7 but with different target discharges. In Fig. 7 the target discharges are the long term mean discharge for both flood and drought. Instead of long term mean (Q_{mean}), in Fig. 8, the flood channel capacity is set as 3 times of the long term mean ($3Q_{mean}$) and the water supply demand as 0.5 times of the long term mean (0.5 Q_{mean}). The most visible difference from Fig. 7 is that there are many blank areas in the maps, meaning no storages are necessary. Those blank areas well coincide with the low necessary storage areas in Fig. 7. This is because the necessary levels of smoothing for $3Q_{mean}$ and $0.5Q_{mean}$ are

15 too low, there is no need of storages to smooth out variations. In those blank areas, the natural discharge variation itself is within (0.5Q_{mean}, 3Q_{mean}.) range as long as 5 year return period discharges are concerned. This context may well be illustrated in Fig. 9 where necessary storages are still not zero as they are in downstream at the outlets of the GBM basins. Other characteristics are very similar to Fig. 7.

4.1.2 Climate change impacts

20 Climate change impact on necessary storages can be assessed by the difference of FDC and DDC, which is the direct indicator of the difficulty or ease of water resources management under the climate change. Note again, since the objective of this study is to show the methodology and the way of interpretation, the example climate projections are limited to MRI-AGCM3.2S only and no ensemble studies.

Fig. 9 shows the differences in FDCs and DDCs at the outlets of the GBM. Black is present (1979-2003) and red is future

25 (2075-2099). Distinct increase of severity in floods and little but positive change in drought are visible. In this impact assessment, the target release is set equal to that of the present without considering future changes. Fig. 10 shows the necessary storages in km^3 and months to maintain the present long term mean Q_{mean}. The maps are similar to Fig. 7 of the present climate with some differences of increase (more red) for flood and decrease (more blue) for drought. Such difference is much better visible in Fig. 11 that shows the difference between future and present. Dark blue to green indicates increase and pink to light

30 blue does decrease. In river courses in Fig. 11-left where real dam reservoirs are present, more storage for floods and less for drought. There are local variation here and there but such variation seems small. But in terms of km^3, even 1 or 2 means huge amount in real change in necessary reservoir storages. Also in the North-western India, local changes in months in Fig. 11-

right are up to 10 months meaning 10 months more storages become necessary to smooth out flood increases. Thus in climate change assessment such local detail would be very important.

The impacts at the outlets of the GBM basins are summarized in Table 2. It is clearly visible that the difficulty of flood control increases and that of drought management decreases. Although the constant provision of long term mean is not practical, but

5 the magnitudes of such difference is remarkable. It is important to note that if the current target is conservative or low, the relative increase of severity for flood is large and the relative ease for drought is also large.

4.2   Scale effect of necessary storages to catchment area

This section looks into the relation between necessary storages and catchment area or the scale effect of necessary storages. As catchment area increases, necessary storages also increase as illustrated in Fig. 9a. In terms of months normalized by the

10 long term mean discharge, however, it becomes totally different as Fig. 9b. Before looking into the spatial characteristics, this section reviews temporal characteristics first which were extensively studied around a half century ago.

4.2.1   Necessary storage in temporal domain

Hurst (1951) considered the necessary storage R_n to keep the long term mean flow $Q_m = \bar{x}_n$ for n consecutive time periods as follows:

15 $S_t = S_{t-1} + (x_t - \bar{x}_n)$

$R_n = \max_{t=1,\dots,n} S_t - \min_{t=1,\dots,n} S_t$

where $S_0 = 0$, $\bar{x}_n = \frac{1}{n}\sum_{t=1}^{n} x_t$, $s_n = \sqrt{\frac{1}{n-1}\sum_{t=1}^{n}(x_t - \bar{x}_n)^2}$

From his study on the Nile, he found that:

$R_n^* = R_n/s_n \propto n^H$

20 where H, the Hurst coefficient, $\cong 0.72$.

This formula says that with time, the necessary storage increases to infinity. It is a serious fact in terms of water resources management if the long term mean is indeed the target of water supply or the flood channel capacity. But in reality, nobody got panic with this finding of the infinite increase of necessary storages over long time. This is because the constant long term mean discharge assumption both for flood control and water supply is not practical. People living along rivers are always

25 settled in the way to safely accommodate at least several years return periods of floods and droughts. Therefore, the scientific focus did not go to the water resources implication but rather the mathematical implication of the relation. Fellow (1952) showed that if the original hydrological process x_t depends only on x_{t-1} which is called a Markovian process, then the power H should be 0.5. This opened a serious debate among hydrologists dividing into Markovian and non-Markovian believers. While Markovian hydrologists believe that the process is Markovian but with nonstationary processes combined, the Hurst

30 coefficient becomes greater than 0.5 (Klemes, 1979). On the other hand the non-Markovian scholars say that the hydrological

processes are fractal with self-similarity and designed a synthetic data generation method with and arbitrary fractal dimension $f = H + 0.5$ (Mandelbrot and Wallis, 1969).

This debate took place widely involving many hydrologists (Klemes, 1975). From the applied hydrology point of view such discussion stimulated a research on discharge data synthesis to be used for assessment of the probabilistic performance of

5 water resource systems. But simulation of a system using hydrology with or without the Hurst phenomena makes little practical difference if not none to the results as the system is not designed or operated to keep the long term mean as a constant target yield and no multi centuries effects were of a major concern.

This paper instead looks into spatial distribution of necessary storages with limited temporal scale, namely, $m \leq 365$ days. The geographical distribution was discussed in 4.1 above and in the next section, the scale effects of normalized necessary

10 storages will be discussed.

4.2.2 Necessary storages with catchment area

Spatial distribution of necessary storages depend on local geophysical conditions that determines local hydrology. The controlling factors include other than meteorological forcing factors, geology, topography, soil, vegetation and other land cover factors. Such spatial heterogeneity reflects the spatial distribution of necessarily storages. Fig.12 shows the relation between

15 necessary storages normalized by average monthly flow to express the necessary storages equivalent to the number of months of flow necessary to smooth out the variation [months] and the catchment area [km^2]. It has a distinct feature that in the areas with smaller catchments such as less than 10,000 km^2, the normalized necessary storages varies widely but in the areas bigger than that, the normalized necessary storages converge to some particular values which are unique to each large basin. It seems to have some similarity to the concept of representative elementary area (REA) introduced by Eric Wood and his colleagues

20 (Wood et al., 1988) as an epoch making view on scale effects on spatial heterogeneity of hydrological processes. The study on spatial heterogeneity of hydrology in storage domain would be a new challenge for hydrological sciences which requires extension of similar study in the world.

5. Conclusions

This paper introduced an indicator of necessary storages that represents the necessary storage to be prepared filled before a

25 dry season starts or necessary storage space to be prepared open before a flood season starts in order to smooth out the discharge variation. The indicators presented here are mainly for the case to maintain the long term mean discharge in 5 year return period. But such target level can be chosen arbitrarily such as three times long term mean discharge or half of the long term mean discharge and in different return periods or rate of failures. The indicators are calculated by intensity-duration-frequency curves of daily discharges called flood duration curves (FDC) and drought duration curves (DDC) and plotted to

30 geographical maps for the Ganges-Brahmaputra-Meghna basins. Although the application results are limited to the use of MRI-AGCM3.2S projections, the following may be concluded:

1) The way of calculating necessary storages to smooth out variations from an intensity-duration-frequency curve is a practical and convenient way that can be applied to any time series phenomena.

2) An indicator of necessary storages using FDC-DDC of discharge provides concrete physical information on hydrological conditions that can be interpreted as difficulty or ease of water resources management at each local area of a basin.

5 3) The indicators in km^3 generally become larger with catchment area resulting major river routes emerging as blood vessels. The indicators in months, normalized by the local long term mean, the major river routes similarly emerges but with smaller values than the surrounding as the river discharge is stabilized with larger catchments.

4) In the headwater areas where river routes do not distinctly emerge as catchment is small and concentration effect is not dominant, indicators both in km^3 and months reflect the spatial distribution of heterogeneity of hydro-climatological
10 conditions.

5) In head water areas of the GBM basins, it was found that necessary storages both for flood and drought management in terms of km^3 are small in snow and glacier affected high mountain areas and large in lower plains. In terms of months, elevation effects are more distinct and, in addition, the northern India approaching to highlands of Himalaya mountains has particularly high in months. The reason is not identified but reflects the high variability as indicated by the coefficient
15 of variation in Fig. 5.

6) In case of the flood channel capacity is $3Q_{mean}$ and the water supply target during drought is $0.5Q_{mean}$, the necessary storages for 5 year return period in high-mountain areas indicate zero, meaning that no storage is necessary as the discharge variation is small lying between $0.5Q_{mean}$ and $3Q_{mean}$.

7) The climate change impact on floods increases the necessary storages especially in the northern India approaching to the
20 Himalaya. On the other hand the impact decreases the necessary storage for drought management in most of the GBM basin especially in the Himalayan high mountain areas.

8) The heterogeneity of basin characteristics influences the necessary storages a great deal and the normalized necessary storages expressed in the equivalent months of flow widely varies. But as the catchment area increases, such variation converges to the average basin characteristics. Such scale effects would be an important area to be studied along with
25 drawing a global map of necessary storages.

9) A creation of global maps of necessary storages would be a useful challenge for assessment of the current state of water resources and climate change impact on water resources and for the scientific analyses of hydrological heterogeneity in the world including scale effects in storage domain.

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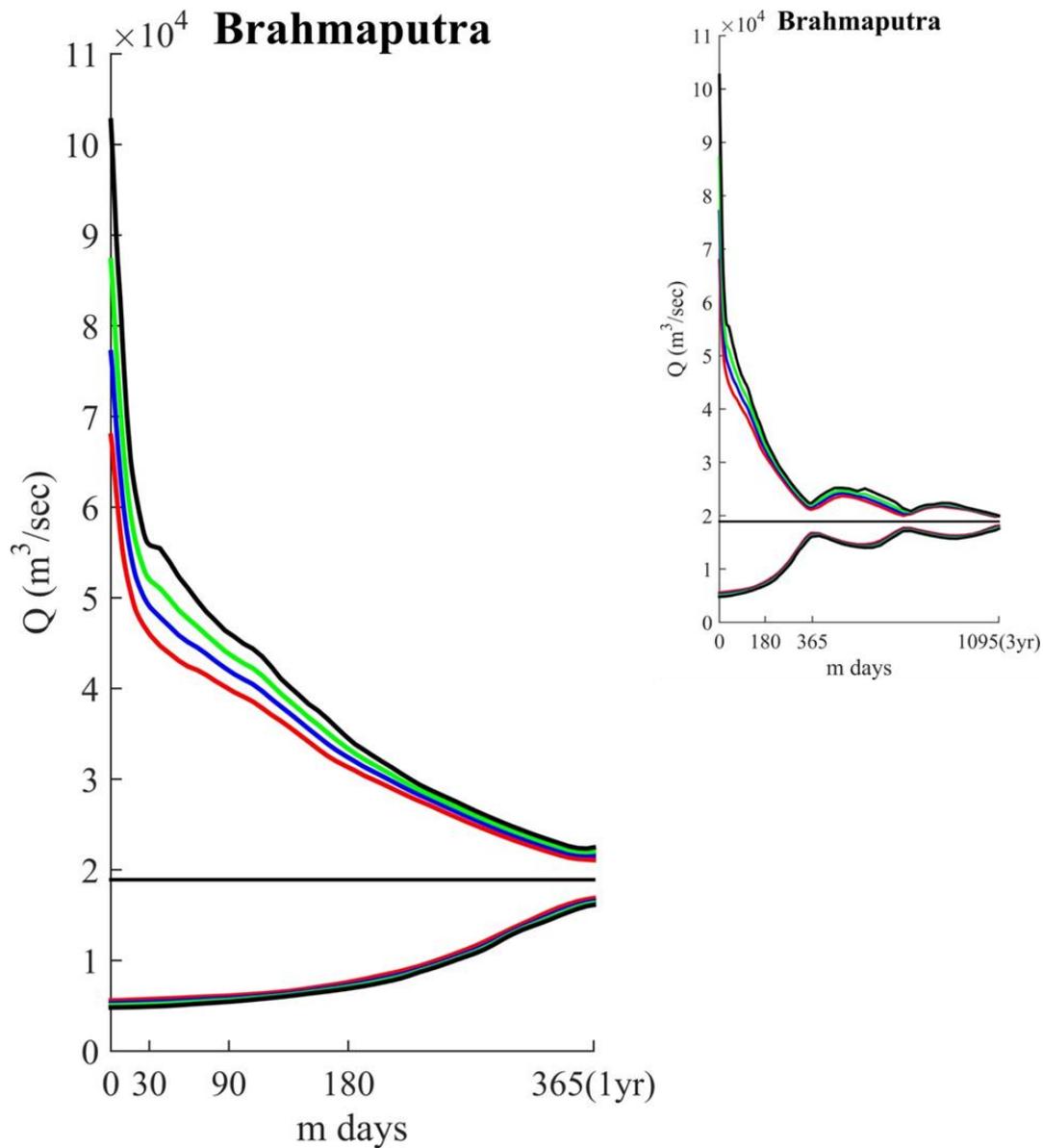
Figure 1: FDC-DDCs of Brahmaputra river at Bahadurabad station. The discharge data are BTOPMC simulated MRI-AGCM3.2S under present climate.

Figure 2: Ganges-Brahmaputra-Meghna (GBM) basin
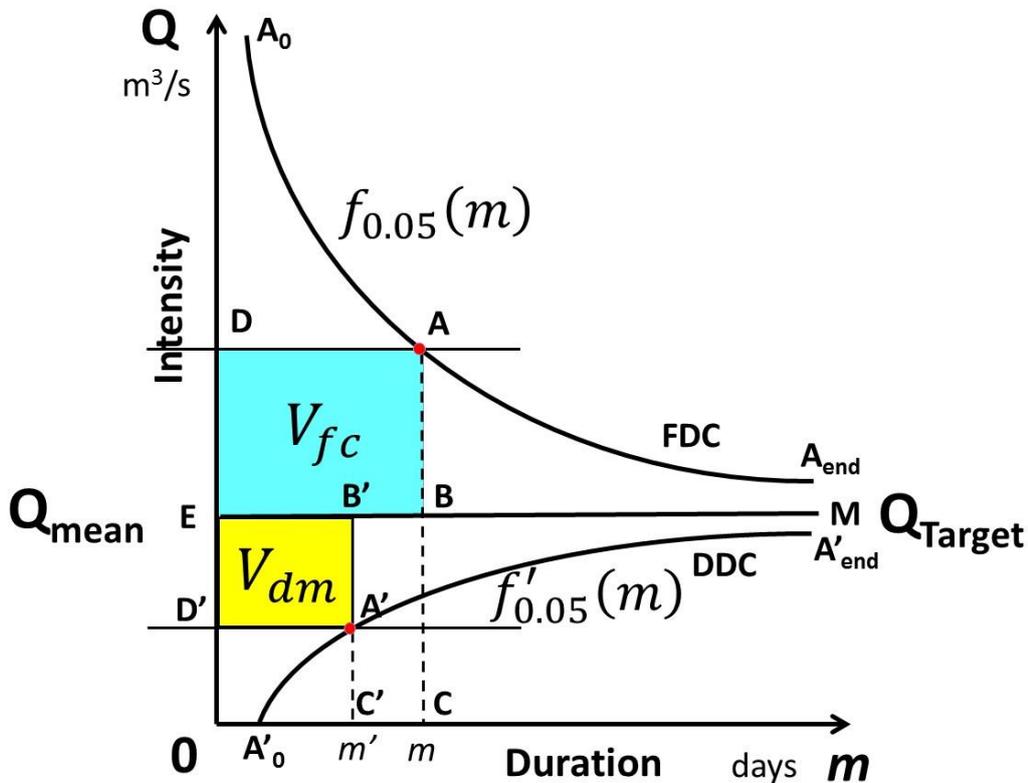
Figure 3: Schematic illustration how to calculate necessary storages to smooth out the hydrological variation for the long term mean for flood control and drought management.
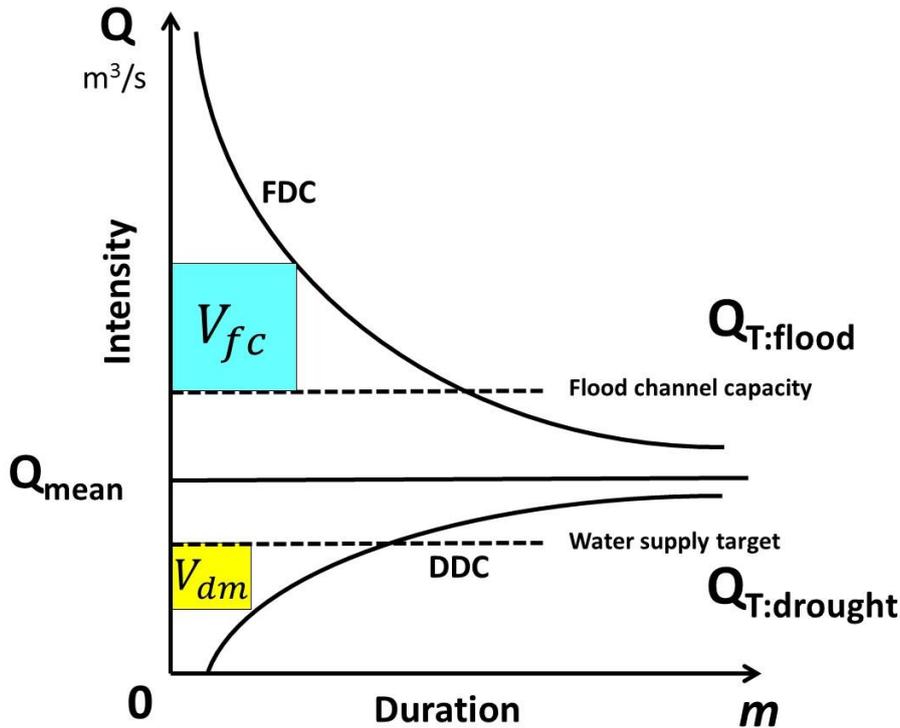
Figure 4: Schematic illustration of calculating necessary storages with flood channel capacity and water supply target different from the long term mean
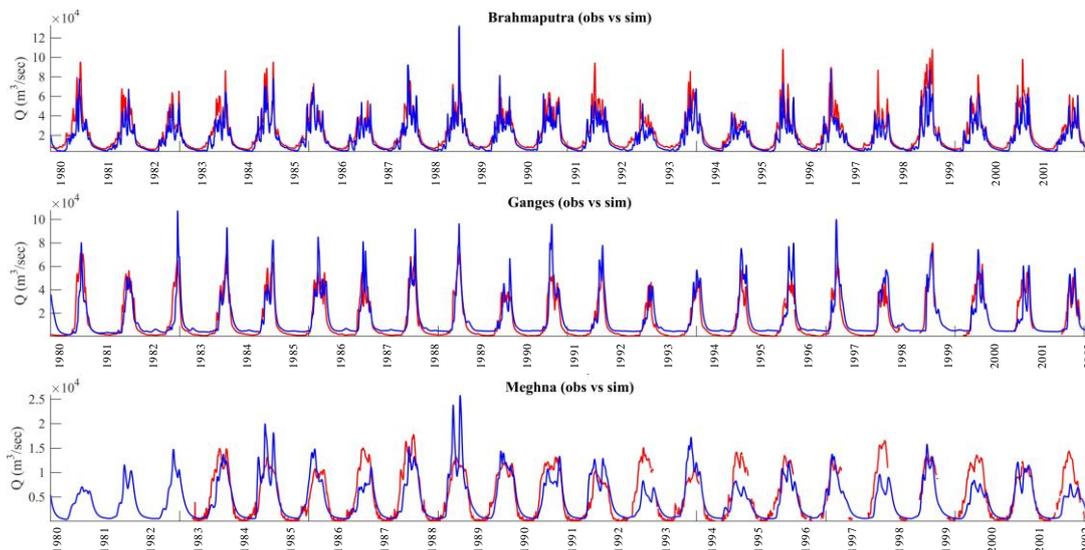
Figure 5: Comparisons of the observed (red) and the BTOPMC simulated (blue) discharges at (top) Bahadurabad, the Brahmaputra, (middle) Hardinge Bridge, the Ganges and (bottom) Bhairab Bazar, the Meghna. Calibration period is 1980-1990. Precipitation data used are WATCH Forcing Data (WFD). See Table 1 for Nash-Sutcliffe efficiency.
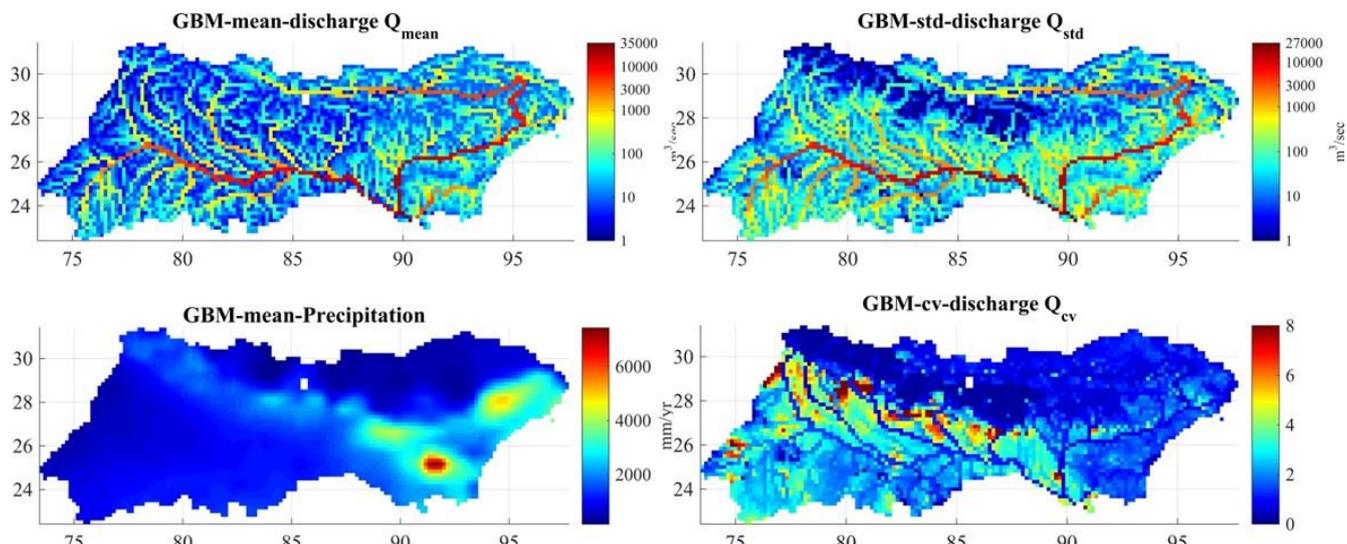
Figure 6: Map of the mean precipitation, the mean, standard deviation and CV of the simulated discharge for MRI-AGCM3.2S present (1980-2003)
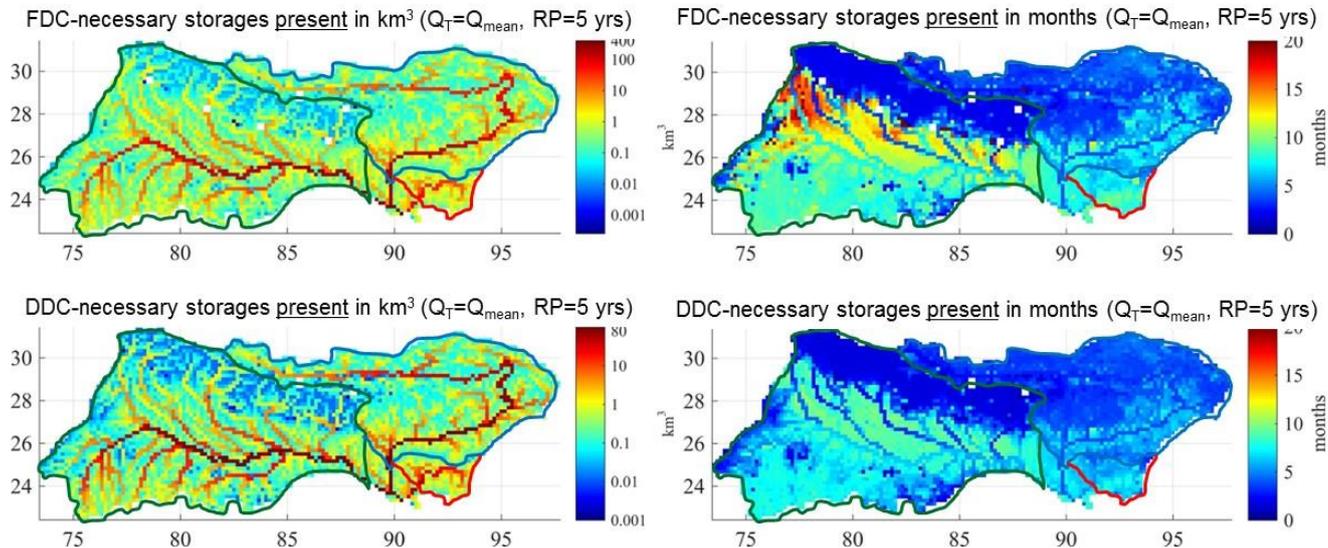
Figure 7: Necessary storage (km3) and (months) at present with maintaining discharge $Q_T=Q_{mean}$ in return period 5 years.
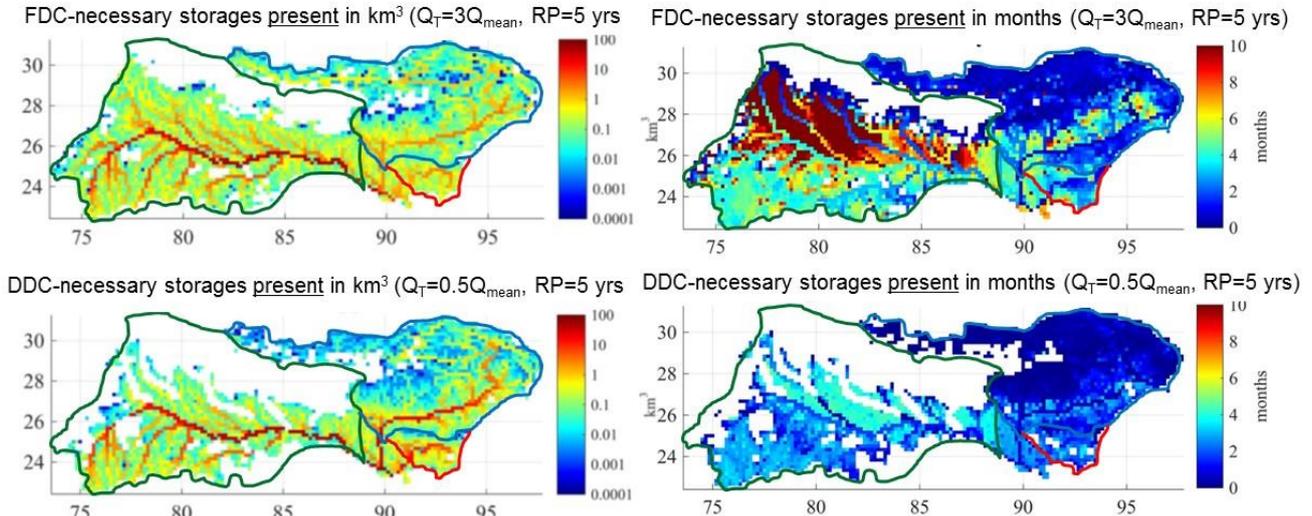
Figure 8: Necessary storages (left) in km3 and (right) in months to maintain $Q_T=3*Q_{mean}$ during flood and $Q_T=0.5*Q_{mean}$ during drought with 5 years return period under present climate.
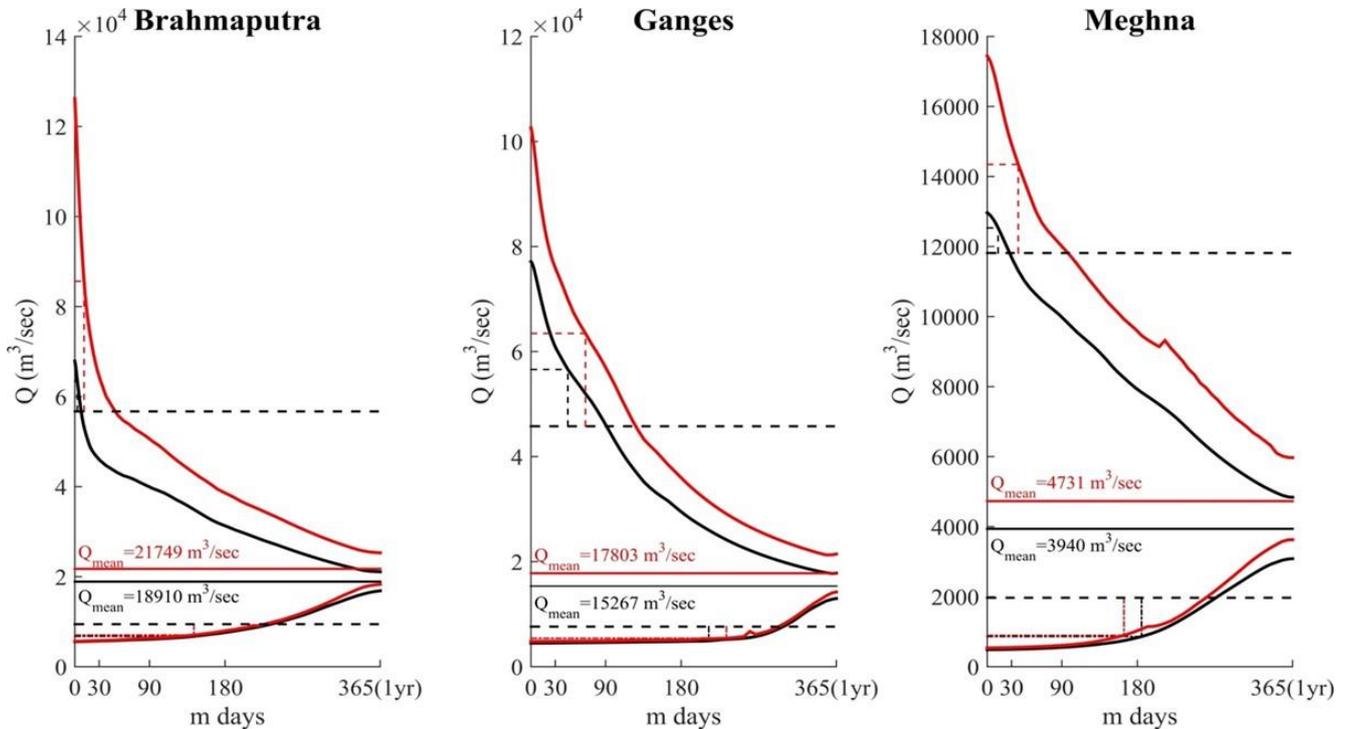
Figure 9: Climate change impact on FDC and DDC, black line for present, 1979-2003 and red line for future, 2075-2099. Necessary storage to maintain $Q=3*Q_{mean}$ (of the present climate) during flood and $Q=0.5*Q_{mean}$ during drought with 5 years return period at (left) Bahadurabad, the Brahmaputra, (middle) Hardinge Bridge, the Ganges and (right)
10 **Bhairab Bazar, the Meghna.**
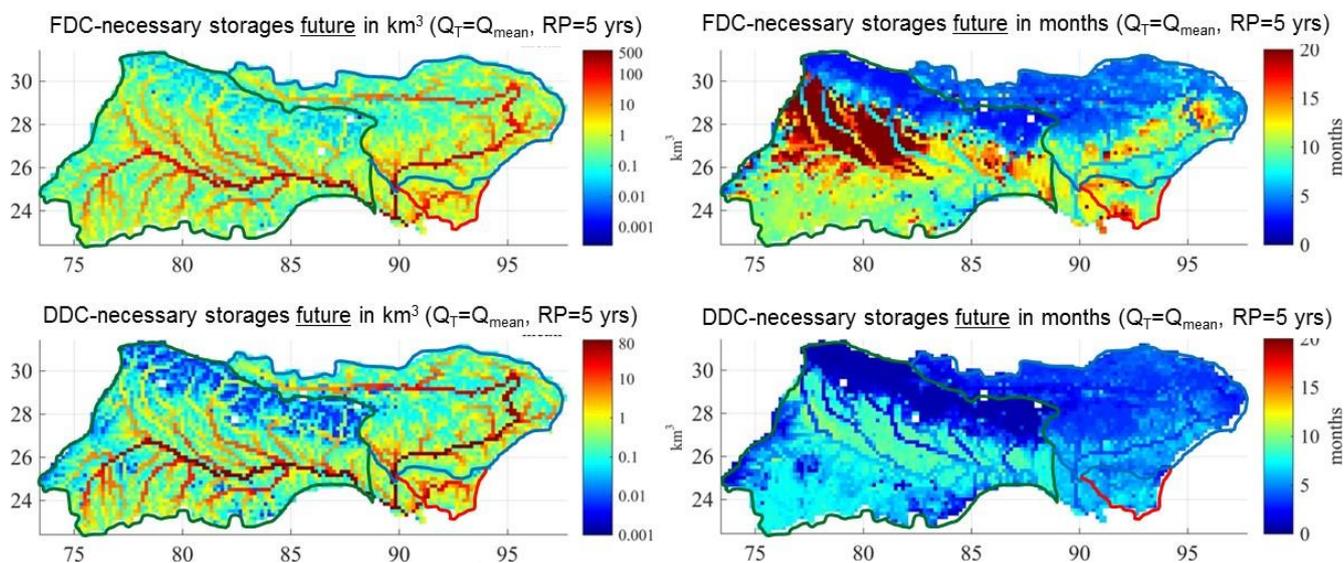
Figure 10: Necessary storage (left) in km³ and (right) in months with maintaining discharge $Q_T=Q_{mean}$ with 5 years return period under future climate
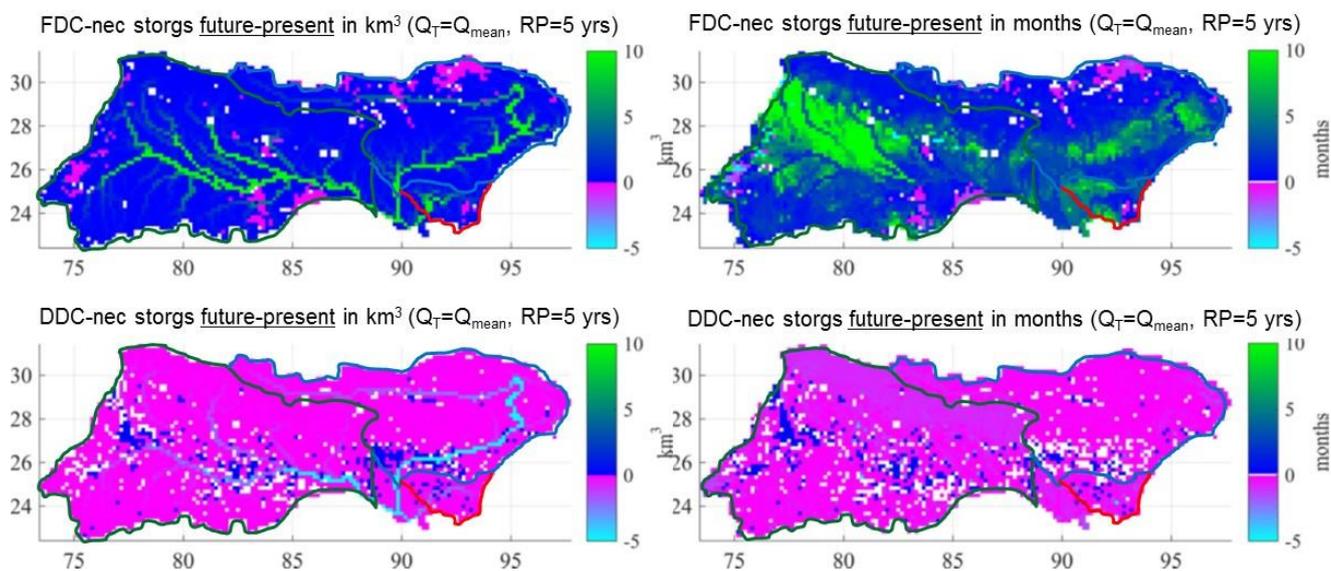
Figure 11: Changes of necessary storage (future-present) (left) in km³ and (right) in months with maintaining discharge $Q_T=Q_{mean}$ with 5 years return period
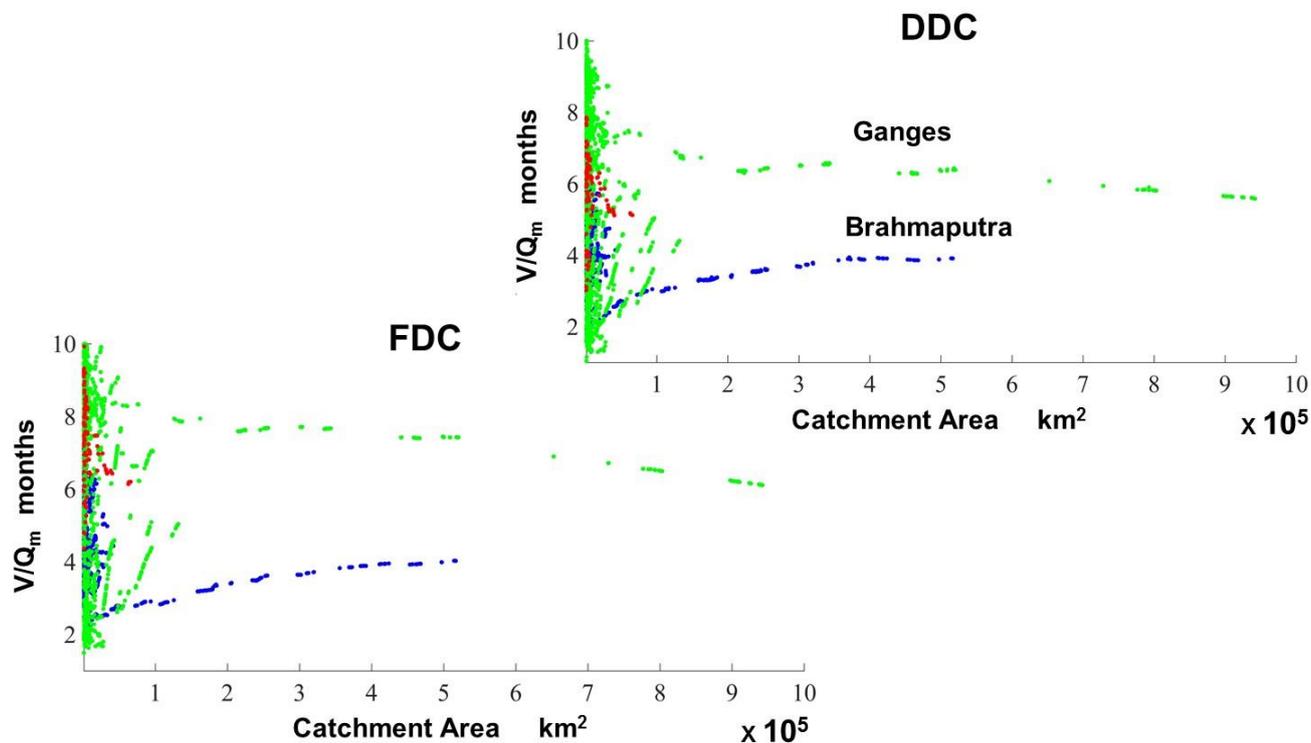
Figure 12: Necessary storages in month in relation with catchment area at all grid points of the basin with maintaining discharge $Q_T=Q_{mean}$ during flood (below) and during drought (above) with 5 years return period at present climate

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Table 1: BTOPMC sensitive parameters and their optimal parameter values with simulation performance.

Name of parameter	Drying function parameter (α)	Decay factor (m)	Block average Manning's roughness coefficient (n_0)	
Unit	-	meter	s/m$^{-1/3}$	
Value range (Takeuchi *et al.*, 2008)	-10 ~ 10	0.01 ~ 0.1	0.01 ~ 0.8	
Basin	**Best Parameter values obtained from parameter-sampling simulation**			**NSE (Nash-Sutcliffe efficiency)**
Brahmaputra	-10	0.06	0.009	0.80
Ganges	10	0.3	0.005	0.81
Meghna	2	0.3	0.1	0.91

Table 2: Impact of climate change on necessary storages at the outlets of the GBM basins, at Bahadurabad, the Brahmaputra, at Hardinge Bridge, the Ganges and at Bhairab Bazar, the Meghna.

				FDC				DDC			
				Target discharge				Target discharge			
		Mean discharge (Q_{mean})		$Q_T=Q_{mean}$		$Q_T=3Q_{mean}$		$Q_T=Q_{mean}$		$Q_T=0.5Q_{mean}$	
Basin	**Period**	km^3/month	% change	months	% change	months	% change	months	% change	months	% change
Brahmaputra	present	49.7		4.0		0.05		3.9		0.7	
	future	57.1	15	6.2	55	0.6	1200	3.7	-5	0.6	-14
Ganges	present	40.1		6.0		1.0		5.5		1.2	
	future	46.8	15	8.4	40	2.5	150	5.3	-4	1.1	-8
Meghna	present	10.4		6.1		0.1		5.1		1.7	
	future	12.4	20	9.6	58	0.8	700	4.8	-6	1.5	-11