Indicator of Necessary Storage for Flood and Drought Management: Towards Global Maps

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Abstract. Storage is the only means to smooth out discharge variability to meet the targets for flood and drought management. At the same time, it serves as an indicator of discharge variability expressed in a human term which directly conveys the difficulty and the ease of managing discharge variation for water resource management. Such an indicator has a distinct advantage over other statistical indicators such as standard deviation (SD) or coefficient of variation (CV). This paper proposes the use of necessary storage as an indicator of discharge variability in human sense and examines its use, both necessary storage [km^3] and normalized necessary storage [months] divided by the local long term mean discharge, especially their geographical distribution, to analyse the basin characteristics of hydrological heterogeneity.

As a method of calculating necessary storage, the flood duration curve (FDC) and drought duration curve (DDC) method was employed that have considerable advantage over other methods to easily calculate the indicator over many grid points in a large basin. As a case study area, the Ganges-Brahmaputra-Meghna (GBM) basin was selected and the spatial distribution of the FDC–DDC based necessary storage was calculated based on the discharge dataset obtained by hydrological simulation of the WATCH Forcing Data (WFD) using the hydrological model BTOPMC developed at University of Yamanashi and ICHARM.

The geographical distribution of necessary storage over the GBM basin was analysed and its relation with geophysical and geographical conditions was examined. Similarly, the relations between necessary storage and catchment area (A) and statistical variability indices SD and CV were examined in 12 sub-basins having different catchment characteristics selected within the GBM basin. Scatter of necessary storage from the basin average was found to reflect the heterogeneity of local conditions although specific relations are yet to be identified. A creation of global maps of necessary storage would be a challenge for assessment of current state of water resources as well as to extend the study of hydrological variability measured in storage domain with hydrological heterogeneity.

1 Introduction

Storage is the only means to smooth out discharge variability to meet the targets for flood and drought management. Necessary storage depends on discharge variation, flood control target and water use target. By fixing flood control and water use targets, the necessary storage depends only on discharge variability and serves as an indicator of discharge variability expressed in a human term which directly conveys the difficulty and the ease of managing discharge variation for water resource management. Such a characteristic is a distinct advantage over other statistical indicators of variability such as standard deviation (SD) or coefficient of variation (CV). Besides, by plotting the indicator in a geographical map, the hydrological variability in time and space can be analysed in relation to geographical distribution of hydrological heterogeneity over a basin which includes hydro-meteorological, topographical, vegetation and land use conditions and others. This is an attempt to look into if the hydrological variability can be analysed by necessary storage, through its absolute volume [km^3] or its normalized form [months] divided by a local long term mean discharge, to get new insights on the controlling factors of the relation between hydrological variability and hydrological (including geophysical and geographical) heterogeneity.

1.1 Objectives

There are three objectives in this paper. One is to propose necessary storages to smooth out discharge variation during flood and drought as a new indicator of discharge variability in time. Another is to analyse the geographical distribution of such the indicator to relate hydrological variability with various hydrological heterogeneity of a basin. The other is to introduce an efficient methodology to calculate necessary storage at all grid points of a basin to make their geographical analyses possible, that is, the flood duration curve and drought duration curve (FDC-DDC) method. Those objectives are elaborated below.

1.1.1 Necessary storage as an indicator of hydrological variability in time

Necessary storage to smooth out the variation of the flow in time to make hazards under control and resources useful depends on the variation of flow, flood channel capacity and the target level of water use. While flood channel capacity and the target water use are socio-economic parameters that vary by societal needs for water and environment, the flow variation depends on natural hydrological phenomena of the basin over time and space. Therefore, if the socio-economic targets are fixed to certain levels, the necessary storage can be used as an indicator of natural flow variability. While the flow variability is most often described by standard deviation (SD) or coefficient of variation (CV) of discharge time series, its physical meaning is not necessarily clear in human terms. On the other hand, the necessary storage has concrete meaning that can be directly related with physical size of reservoir necessary for flood and drought management. It is the necessary physical volume of storage space for flood control or volume of water to be stored for drought management in order to keep outflow downstream a certain level. In this paper, the authors propose the use of necessary storage as an indicator of hydrological variability in time and try to relate it with the hydrological heterogeneity of a basin over time and space.

Hydrological heterogeneity has been studied by many researchers such as Wood et al. (1988) on scale aspects, Creager et al. (1945) on extreme aspects and Bloschl et al. (2013) on predictability aspect. This paper extends such analyses to water resources manageability aspect in terms of necessary storage to smooth out hydrological variation as an integrated indicator.

Bloschl et al. (2013) proposed 6 runoff signatures that determine runoff variability, namely, annual runoff, seasonal runoff, flow duration curve, low flow, floods and hydrographs. They are indeed important indicators of river runoff phenomena especially for analytical diagnosis on flow prediction. On the other hand, for flood control and water supply managers would be more interested in integrated information that indicate water resources manageability. For that purpose necessary storage to smooth out hydrological variation into given levels of constant flow must serve as an informative indicator. Necessary storage is an integrated result of hydrological variation that reflects short term and long term means; daily, seasonal and long term patterns of variation; extremes, duration or persistence characteristics and frequencies or periodicities; available flood channel capacity, necessary water withdrawal etc. It is truly an integrated indicator.

1.1.2 Geographical mapping of necessary storage

In order to analyse necessary storage as an indicator of discharge variability in relation to hydrological heterogeneity in a basin, it is essential to plot the indicator in geographical distribution maps. For this purpose, the necessary storage is calculated not only along main streams in a river basin like for reservoir design but also at all grid cells where stream network is formed. It is an areal information rather than a point information. It is useful for water resources managers to regionally grasp the relative easiness of managing discharge variability for floods and droughts in natural conditions.

In this paper, however, as necessary storage are calculated without accounting for the real situation of channel capacity or water withdrawal at any location but treating them as given parameters, the indicator cannot be interpreted as the real necessary storage for reservoir design and water management. It only serves as an integrated indicator of discharge variability in the unit of necessary storage to maintain certain constant flow levels for flood control and water use downstream. As the certain flow levels the mean annual flow or some percentages of it are used to help users to easily imagine the assumptions.

The geographical maps of necessary storages for flood and drought will be compared with geographical maps of elevation, temperature, precipitation, land use and land cover, discharges, their standard deviation and coefficient of variation etc. By this, the relation between hydrological variability and geographical heterogeneity can be better understood.

1.1.3 Flood Duration Curve and Drought Duration Curve (FDC-DDC) to calculate necessary storages

In order to produce a spatial distribution map of necessary storages of a large basin, eventually a global map, it is necessary to employ an efficient methodology of calculating necessary storages. There are various ways of calculating necessary storage depending on various conditions and focus objectives. The most widely known is the mass curve method developed by Rippl (1883) which have been used over a century as a standard 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 the 1950's (Maass et al., 1962). The former initiated the epoch 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 this paper, instead of those methods the flood duration curve and drought duration curve (FDC-DDC) method was used as it is relatively "easy" to calculate the necessary storage under any given constant level of target release and better suited to calculate at many grid points over space for areal mapping of reservoir storage. Such a relative ease comes from the short term focus in an annual smoothing rather than inter-annual smoothing, which is in a sharp contrast to the long term asymptotic focus of Range analyses. The main theory of the Range analysis is briefly introduced in 2.3.2. The drought duration curve (DDC) was first proposed by Kikkawa and Takeuchi in the 1970s (Kikkawa and Takeuchi, 1975; Takeuchi and Kikkawa, 1980). The DDC was shown useful for reservoir operation (Takeuchi, 1986) and the FDC-DDC was, by adding flood duration curve (FDC), for hydrological statistics and classification (Takeuchi, 1988).

1.2 The case study area

This paper takes a case study approach to demonstrate the use of the proposed necessary storage as an indicator of discharge variability. For that purpose, the Ganges-Brahmaputra-Meghna (GBM) basin was selected as it has heterogeneous geographical conditions and large enough to eventually extend the analyses into the globe. Figure 1 depicts the Ganges-Brahmaputra-Meghna (GBM) basin (Pfly, 2011). 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. Figure 2 shows the land cover distribution which well reflects the elevation and precipitation depicted in Fig. 3a and 3b, respectively. The land cover data has been collected from the Global Land Cover by National Mapping Organizations (GLCNMO) which is prepared by using MODIS data with remote sensing technology (Tateishi *et al.*, 2014). It classifies the status of land cover of the whole globe in to 20 categories based on Land Cover Classification System (LCCS) developed by FAO. The elevation data of Fig. 3a is acquired from HydroSHEDS which is derived from remote sensing data of the Shuttle Radar Topography Mission (SRTM) at 3 arc-second (90 m) resolution during an 11-day mission in February of 2000 (Lehner *et al.* 2006). The mean precipitation map of Fig. 3b is created from the daily rainfall and snowfall data from WATCH Forcing Data (WFD) set to be explained in 3.1.1.

These data would be useful to relate the geographical distribution of necessary storage indicators to hydrological heterogeneity of the basin. All geographical maps except Fig.1 indicate the borders of the Ganges, the Brahmaputra and the Meghna in thick black lines, the selected inner sub-basins in thin black lines and national boundaries in white lines.

As Fig. 3b indicates, the Ganges basin is characterized by large spatial variation of precipitation that causes water scarcity especially in in the western Ganges and water excess in the southeast. 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 in the eastern India and large amount of snow in the upstream that provide huge volume of discharge to the river. On the other hand, the Meghna is a comparatively smaller, rain-fed, and relatively flashier river. The basin contains the world's top two highest precipitation (about 12,000 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 municipal, agricultural and industrial water requirement. In addition, the basin is also recognized as a home ground of waterborne natural hazards, 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.

1.3 Structure of the paper

In Chapter 2, the methodology is presented; namely, the flood and drought duration curves FDC-DDC in 2.1 and the method of calculating necessary storage using FDC-DDC are described in 2.2. The comparison of this method with the standard mass curve method and the analysis of spatial distribution of necessary storage in contrast to analysis of asymptotic temporal nature in the several decades ago are also discussed in 2.3. In Chapter 3, application of the methodology to the case study area, the GBM basin, is described. The necessary precipitation and temperature data set of Watch Forcing Data (WFD) and the BTOPMC hydrological model to translate them to discharge data are described. Chapter 4 presents application results and discusses their implication. In Chapter 4.1 discussed are on geographical distribution of necessary storage, in 4.2, on the relation between necessary storage and catchment characteristics such as area A and SD and CV of discharge and in 4.3 their zoom up relations in the selected 12 sub-basins. Chapter 5 presents 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 storage which follows the procedure originally introduced in Kikkawa and Takeuchi (1975) and in Takeuchi (1986) but in a more elaborated way. Finally, in 2.3 other discussions related this paper will be introduced that include the relation between the FDC-DDC method and the traditional mass curve method (Takeuchi and Kikkawa, 1980) and the discussion of Hurst formula (Hurst, 1951).

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

Both FDC and DDC are basically an intensity-duration-frequency (IDF) curves of discharge time series but not on real discharge data but their moving averages. 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,

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

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

$$\mathrm{Prob}\big(X(m) \geq f_\alpha(m)\big) \leq \alpha \quad (3)$$

$$\mathrm{Prob}\big(X'(m) \leq f'_\beta(m)\big) \leq \beta \quad (4)$$

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 (GEV) 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). The GEV distribution Type-1, Gumbel distribution, was used in this study as it was recommended for the major rivers in Bangladesh by Mirza (2002) and for relatively smaller data samples by Hirabayashi et al. (2013).

Figure 4a depicts the FDC and DDC of the Brahmaputra River at Bahadurabad station (Fig. 1). 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. In this paper, however, as will be explained in 2.3.2, the portion for m up to 365 days or one year, i.e., Fig. 4b is used throughout the discussion to get a practical indicator.

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 storage

In this section, the detail procedure of calculating necessary storage to smooth out discharge variations over time using FDC-DDC will be illustrated. In short, the necessary storage is 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 storage 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)

Figure 5 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/she 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. 5 (which may not be realistic but useful for simplicity to get a practical indicator).
3. Suppose he/she chooses return period 20 years or failure rate 0.05. Then he/she 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=ADEB.
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:

$$V_{f,\alpha} = \max_{m} m * f_{\alpha}(m) \tag{5}$$

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 increases with time, eventually to infinity as Hurst (1951) showed which is briefly discussed in 2.3.2.

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. 5 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/she 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/she chooses a drought duration curve $f'_{0.05}(m')$.
4. Suppose he/she 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'D'EB'.
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:

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

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 storage 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. 6. 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 storage V_f for flood control and V_d for drought management can be calculated as in Fig. 6. As mentioned above, however, this study uses the long term mean for an indicator for simplicity.

2.2.4 Expressions in km³ and months

Necessary storages V_f and V_d at each grid point may be expressed in [km^3] and in general expressed as V_{km3}. However, the dominant areal distribution of necessary storage V_{km3} would be similar to the distribution of catchment area because with catchment area, discharge increases in general and magnitude of flow variation, too, which would result in the increase of necessary storage to smooth out the variation. In order to better analyse the necessary storage in relation to hydrological heterogeneity in a basin, therefore, a normalized indicator may better be used by dividing the necessary storage volume V_{km3} by the local long term mean discharge Q_{mean} [m^3/s] expressed in [km^3/months] and expressed in [months] and expressed as V_{months}. Namely,

$$V_{months} = V_{km3}/Q_{mean} \quad (7)$$

The value V_{months} indicates an average residence or renewal time of water in the reservoir whose capacity is equal to the necessary storage and assumed full all the time. This is free from the mean annual flow and reflects other factors of hydrological variability.

2.3 Related discussions on necessary storage

2.3.1 Relation between the FDC-DDC method and 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).

2.3.2 Necessary storage in temporal domain and in spatial domain

Here the research on Range will be briefly reviewed as it is the analysis of necessary storage in an asymptotic long term behaviour while this paper focuses on the contrary on a short term spatial characteristics. Hurst (1951) considered the necessary storage as "adjusted range" R_n to keep the long term mean flow $Q_m = \bar{x}_n$ for n consecutive time periods as follows:

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

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

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

and found from his Nile study that:

$$R_n^* = R_n / s_n \propto n^H \quad (8)$$

where R_n^* is named as "rescaled adjusted range" and H, the Hurst coefficient, was $\cong 0.72$.

This indicates that the relation of necessary storage R_n increases limitless with time length n to be considered and is proportional to s_n as:

$$R_n \propto s_n n^H \quad (9)$$

or in different form by dividing both sides by the long term mean $\bar{x}_n$ as:

$$R_n / \bar{x}_n \propto C_v n^H \quad (10)$$

where $C_v = s_n / \bar{x}_n$ coefficient of variation of discharge.

$R_n / \bar{x}_n$ is necessary storage normalized by the long term mean flow which may be called normalized necessary storage or a mean residence time or a mean renewal time of water of the reservoir having the necessary storage and have the unit "time". Eq. 9 and 10 provide the theoretical background for V_{km3} and V_{months} of Eq. 7, namely, V_{km3} is proportional to s_n and V_{months} is to C_v.

In this study, the length of available discharge data is 22 years (1980-2001) as explained in 3.1 and there is no way of considering infinite length behaviour. But in theory, regardless of the choice of expression, the formula Eq. 8 says that the necessary storage R_n or its normalized form $R_n / \bar{x}_n$ increases with the time periods n to be considered. It is a serious fact in terms of water resources management if a long term mean $\bar{x}_n$ is indeed the target of water supply or flood channel capacity and it should be kept for a very long time such as over years. But in reality, it is not a usual case. Because, the flood control and water supply targets do not usually require all the fluctuations removed and keep the flow constant to the long term mean. People living along rivers are settled in the way to safely accommodate several years return periods of natural floods and droughts. Namely, they can accommodate, without having storage reservoirs, the floods far above the long term mean discharge and can live with the water use far below the long term mean flow. It at the same time means that the necessary smoothing of the discharge variation is much shorter than over years but quite often, especially in humid regions and particularly in small basins with limited reservoir capacity, the target water smoothing is a short term in practice.

This paper therefore looks into spatial distribution of necessary storage with limited temporal scale, namely, a year or $m \leq 365$ days. But admitting some contradiction in approach, the target water control level is still assumed as the long term mean discharge to make the discussion simple. Note again that the objective of this paper is not reservoir design for construction but development of an indicator to express the manageability of hydrological variability in relation to hydrological heterogeneity. Based on such assumptions, the necessary storage is calculated at each grid cell of the basin and instead of focusing on their temporal behaviour but their spatial behaviour will be examined. The geographical distribution of necessary storage will be discussed in 4.1 and the scale effects of normalized necessary storage will be discussed in 4.2.

3. Application

In order to demonstrate an example of the spatial distribution of FDC-DDC necessary storage, this study presents a case study in the the Ganges-Brahmaputra-Meghna (GBM) basin. As the objective of the case study is methodological demonstration, no other cases are analyzed.

3.1 Data used

The necessary discharge data at all internal grid points of the GBM basin for the case study were obtained by model simulation with the reanalysis precipitation and radiation data and the observed discharge data for calibration as described below.

3.1.1 Precipitation and temperature data used

The precipitation and temperature data used over the GBM basin for the input to the distributed hydrological model were the Water and Global Change (WATCH) Forcing Data set (WFD) (Weedon et al., 2011) for the period of January 1, 1980 to December 31, 2001. The WFD is the dataset based on the three-hourly ERA-40 reanalysis product of the European Centre for Medium Range Weather Forecasting (ECMWF) developed in the European Union WATCH project (www.eu-watch.org). ERA-40 was derived from successive short-term integrations of a general circulation model (GCM) that assimilated various satellite data along with atmospheric soundings and land-sea surface observations. The one-degree resolution ERA-40 reanalysis data were interpolated into the half-degree resolution on the Climate Research Unit of the University of East Anglia (CRU) land mask. Average temperature and average diurnal temperature range from CRU TS2.1 gridded observations were used to remove monthly bias and lack of climatic trends which was existed in 2-m temperatures product of ERA-40. After bilinear interpolation elevation correction on temperature data was done via environmental lapse rate. Monthly bias of precipitation data was corrected by using CRU number of ‘‘wet days’’, version four of the Global Precipitation Climatology Centre (GPCCv4) precipitation totals and ERA-40 rainfall-snowfall proportion. FLUXNET data (https://fluxnet.ornl.gov/) were used to validate the data. For details on WFD data generation see Weedon et al., 2010, 2011.

3.1.2 Discharge data used

Using the forcing data above, the discharge data at all grid points of the GBM basin were created by model simulation using a distributed hydrological model BTOPMC. The model and the model set up and verification are described below in 3.2 and 3.3. For calibration of the model, 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 Processing and Flood Forecasting Circle, Bangladesh Water Development Board (BWDB) by using the rating equations developed by the Institute of Water Modelling (IWM, 2006) and Masood et al. (2015c).

3.2 Hydrological model to obtain discharge data

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 catchment but only a portion of it. Based on this concept, the original topographical index is modified by replacing an upstream catchment area a by an effective catchment area $af(a)$ 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 the continuity of water volume at each segment of river reach (Masutani and Magome, 2009). The BTOPMC has been applied in many river basins throughout the world including poorly gauged basins utilizing globally available data and 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).

3.3 Model set up and verification

The BTOPMC model was setup for simulations of the WFD dataset at the 10-arc-min grid (approximately 20-km grid resolution) using DEM data derived from HydroSHEDS. The model set up procedure followed the work by Masood and Takeuchi (2015a) although there, a used hydrological model was, instead of BTOPMC, H08 (Hanasaki, 2008).

The calibration period was from 1980 to 1990 (11 years) and verification was from 1991 to 2001 (11 years). 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 co-efficient (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 conducted. The identified parameters are listed in Table 1.

Figure 7 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 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 overall model performance is satisfactory.

The simulated daily discharge data set at all grid cells of the GBM basin were obtained. Figure 8a shows the distribution of the annual mean discharge Q_{mean} [m^3/s], Fig. 8b, the distribution of standard deviation s (SD) of daily discharge [m^3/s] and Fig. 8c, the distribution of coefficient of variation C_v (CV) of the daily discharge. The necessary storage was also calculated by the DDC-FDC method described in 2.2 which will be discussed and analysed in the next section.

4. Results and discussion

In this chapter the results obtained by the case study described in Chapter 3 will be presented and analysed. Namely, in 4.1, the geographical distribution of necessary storage over the basin and in 4.2, the effects of catchment characteristics, i.e., catchment area A and statistical parameters of discharge SD and CV on the necessary storage and in 4.3 their zoom-up relations in the selected 12 basins in the GBM basin are presented. In addition, in 4.4 potential future study agenda are briefly discussed.

4.1. The geographical distribution of necessary storage over the basin

Figure 9, 10 and 11 show the spatial distribution of necessary storage to smooth out the discharge variation over the Ganges-Brahmaputra-Meghna basin. Figure 9 and 10 assume the target release equal to the long term mean Q_{mean} both for flood and drought management while Fig. 11 assumes $3Q_{mean}$ for flood and $0.5Q_{mean}$ for drought management. Fig 9 and Fig. 11a and 11b are in physical volume [km^3] and Fig. 10 and Fig. 11c and 11d, in residence time expression [months], the necessary storage divided by the long term mean Q_{mean}. All those figures directly imply the difficulty or easiness of water resources management in a discharge variability aspect. Although the hydrological aspect is only a part of the real difficulty of water resources management, its manageability is definitely an important factor. As Eq. 9 indicates, the distribution of necessary storage must be proportional in physical nature similar to the distribution of standard deviation (SD) of discharges in Fig. 8b, but its physical meaning in [km^3] is much more directly indicative to the size of dams, retardation ponds, tanks and the like than SD. Similarly, Eq. 10 indicates the normalized necessary storage is proportional to coefficient of variation (CV), but the mean residence time or renewal time in [months] is much more understandable than CV in human sense.

Comparing Fig. 9 and 10 or necessary storage in km^3 and in months under the target release Q_T=Q_{mean}, the most obvious characteristics identifiable are:

1) The distributions of necessary storage for flood and drought management, namely, the upper and lower maps of Fig. 9 and those of Fig. 10 are similar but Fig. 9 and 10 are very different. It means that necessary storage for flood and that for drought are rather similar but the expressions in km^3 and in months make totally different maps. Note that Fig. 9a and 9b seem to more resemble than Fig. 10a and 10b which is simply because Fig. 9 is expressed in logarithm to make small storage visible but Fig. 10 in real number.

2) The main difference between Fig. 9 and 10 is in the main stream. In terms of km^3 in Fig. 9, along the main stream, the necessary storage increases with increasing catchment area towards downstream and in the upstream basins, the necessary storage is small and vary by location.

3) Both for flood and drought, necessary storage is small in the Himalayan high mountain areas where discharge would be stable with snow and glacier. But in terms of months in Fig. 10, along the main stream, months or the mean residence time decreases with catchment area. Also in the Northern India approaching to Himalayan area, the area with very high months is concentrated in Fig. 10 but not in km^3 in Fig. 9.

Such characteristics well correspond with SD and CV of Fig. 8b and 8c which are the proof of Eq. 9 and 10.

1) Indeed, the geographical distribution of necessary storage in km^3 in Fig. 9 and that of SD in Fig. 8b show a remarkable agreement and similarly, months in Fig. 10 and CV in Fig. 8c.

2) In Fig. 10a of the normalized necessary storage in months, a wide range of scattering in color 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 storage for flood but not necessarily drought.

Figure 11 is the same as Fig. 9 and 10 but with different target discharges, $3Q_{mean}$ for flood and $0.5Q_{mean}$ for drought management. Figure 11a and 11b in km^3 and 11c and 11d in months.

1) The most remarkable feature of Fig. 11 is that there are many blank areas in the maps, meaning that no storage is necessary as the natural discharge variation itself is within ($0.5Q_{mean}$, $3Q_{mean}$) range as long as 5 year return period discharges are concerned.

2) The blank areas well coincide with the low necessary storage areas in Fig. 9 and 10. Both for flood and drought, the blue areas correspond with the white areas. They are mostly headwater areas especially high Himalayan mountain areas with snow or the area with little precipitation shown Fig. 3b.

4.2 Necessary storage, catchment area and SD and CV of discharges

Spatial distribution of necessary storage depends on local geophysical and geographical conditions that determine local hydrology. The controlling factors include other than meteorological forcing factors, geology, topography, soil, vegetation and other land cover factors. This section and the next, 4.2 and 4.3, look into the relation between necessary storage and such hydrological heterogeneity conditions.

Figure 12 shows the relation between necessary storage V_{km3} [km^3] and catchment area A [km^2] and Fig. 13, normalized necessary storage V_{months} [months] and catchment area A. Figure 14 shows the relation between normalized necessary storage in [months] and standard deviation SD [m^3/s]. Figure 15 shows the relation between normalized necessary storage V_{months} and coefficient of variation CV of daily discharge. Figure 14 and 15 are the examination of indicated formula of Eq. 9 and 10 based on Eq. 8, the finding of Hurst (1951). Each dot corresponds to each 10-arc-min grid cell in the basin and there are all together 5263 dots (Ganges 3220, Brahmaputra 1812 and Meghna 231) in all Fig. 12-15.

Figure 12 V_{km3}-A relation reflects the magnitude of overall hydrological variability along the main stream. The necessary storage increases in high rate with catchment area in the Meghna both for flood and drought that must reflect large specific discharge with large variability. The Brahmaputra has a distinct slope change from low to high at around 250,000 km^2 point which corresponds to the outlet from the Tibet. As Fig. 3b indicates, in the upstream precipitation is low with snow and glacier dominant and downstream high precipitation making specific discharge and variability similar to the Meghna. It is also interesting to see the rather low stable slope of the Ganges in the entire river length that must reflect the low specific discharge and low variability along the main stream. The slope is as low as the Tibetan part of the Brahmaputra.

Figure 13 V_{month}-A relation has a distinct feature that in the areas with smaller catchments less than a few 10,000 km^2, the normalized necessary storage varies widely but as the catchment area becomes large it converges to some particular value unique to each basin forming a rather stable horizontal line. This is a scale effect of normalized necessary storage and briefly discussed 4.4.2. The level of such line is higher for the Ganges and lower for the Brahmaputra both for flood and drought. The Meghna case seems between the two but too short to observe convergence.

As the converged lines only represent the normalized necessary storage along the main stream, to analyse the effect of hydrological heterogeneity, sub-basins should be examined as Fig. 16 to be discussed in 4.3.

From Fig. 14 V_{km3}-SD and Fig. 15 V_{month}-CV, the following are observable:

1) Figure 14 shows a remarkable proportionality between V_{km3} and SD as indicated by Eq. 9 of Hurst (1951). The relation seems by visual judgment roughly the following:
   V_f (km^3) ≈ (1/70) SD (m^3/s)
   V_d (km^3) ≈ (1/80) SD (m^3/s)
2) Such relations would, however, apply only along the large main streams of the GBM basin because the most points visible in Fig. 14 are along large main streams having large discharge with large SD. The majority of the points in the figure are concentrated near the origin with small SD and small V to which those formula would not hold.
3) The slope of the V-SD relation seems highest in the Meghna, then the Brahmaputra and the least, the Ganges. This relation is same both for flood and drought. Such difference should depend on the hydrological heterogeneity of the basins.
4) Comparing Fig. 14 and Fig. 15, the relation V_{km3}-SD is quite different from the relation V_{month}-CV despite that the latter is only divided by the long term mean Q_{mean} in both sides. This is because variation of CV is independent from the size of the basin and the magnitude of discharge, while SD is roughly proportional to the magnitude of discharge and accordingly the size of the basin. As a result, the points representing smaller head basins are more visible in Fig.15 and their hydrological heterogeneity is more prominently reflected there as seen by widely scattered points. Note that in small basins, hydrological heterogeneity more directly influences discharge variability at the outlet than in large basins.
5) Nevertheless, Fig. 15 indicates the average linear relations of V_{month}-CV in different basins seem "in very crude sense" by visual judgement as follows:
   $V_{month-f}$ ≈ 5 CV for the Meghna, 3.3 CV for the Ganges and 3.3 CV for the Brahmaputra
   $V_{month-d}$ ≈ 3.5 CV for the Meghna, 2 CV for the Ganges and 2.5 CV for the Brahmaputra
6) The normalized necessary storage for drought management is smaller than flood management which would be because the limit of a year ($m \leq 365$) for smoothing of discharge variation is too short for drought management while it is reasonable for flood management.
7) The linear relation between V_{km3}-SD and V_{month}-CV above is again the proof of Eq. 9 and 10 based on the genius finding of Eq. 8 of Hurst (1951). The scatter around the average lines is very large reflecting the hydrological heterogeneity of sub-basins.

4.3 Effect of heterogeneity of basin hydrology on necessary storage

This section further looks into the relation between necessary storage and basin characteristics in different sub-basins. As found in the analyses 4.1 and 4.2, the variations of necessary storage from their average relation with catchment area, SD and CV depend on characteristics of basin hydrological conditions such as elevation, topography, geology, precipitation, temperature, and land cover conditions including vegetation, soils and land use of which some are shown in Fig. 2 and 3. This section looks into details of Fig. 13 V_{month}-A and 15 V_{month}-CV by Fig. 16 and 17, respectively in selected 12 sub-basins indicated in the map in the center. They are selected to cover different areas of hydrological heterogeneity.

Note that the zoom up of Fig. 14 V-SD relation was found largely similar to Fig. 12 V-A relation because of strong linearity of catchment area A with SD. That is why this section chose the zoom up of Fig. 15 as the large departure from the average relation of V_{month}-CV would more clearly indicate the difference in relation to the hydrological heterogeneity of sub-basins.

Figure 16 shows the relation between normalized necessary storage V_{month} and catchment area A in sub-basins. It indicates:

1) Blue dots for flood are above red dots for drought which is same as Fig 12. The reasons are also same as stated in 4.2 6).
2) The general shape is that dots scattered widely at catchment near 0 and converges to near horizontal line or lines as catchment area increases, where the length corresponds to the total catchment area. It looks again that the critical scale that shows near convergence or low scattering seems a few 10,000 km^2 in most sub-basins. The hydrological mechanism to determine such critical scale may be a good subject of further study as discussed in 4.4.2.
3) Dots arrays are often discontinuous and jump to form larger catchments. Such a jump occurs where a branch river confluences to the main river and both discharge and catchment area suddenly increase.
4) The six basins along the western edges to the northern Himalayan Nepal of the Ganges basin: Chambal, Yamuna, Ganga, followed by Ghaghara, Gandak, Kosi, the range of distribution of V_{month} near 0 km^2 (or head basins) are especially wide.
5) Three basins originating in the Himalayan mountain ranges to join the Indian part of the Brahmaputra: Teesta, Subansiri and Lohit and three basins originating the southern edges of the Ganges and the Meghna: Betwa, Son and Barak have rather similar concentrated distributions which may be because not only the size of the catchment is smaller than the other six sub-basins above but also the basin conditions are more uniform than the other six.
6) The six sub-basins originated from the Himalayan Mountains, the Yamuna to the Teesta, show no stable convergence of necessary storage but show upward slopes heading to higher V_{month}. In the southern slopes of the Himalayan Mountains, as Fig. 3b shows, the catchment has high precipitation and as rivers flow down more discharges join and the necessary storage increase along the river course towards downstream. It implies $\frac{dV_{km3}}{dx} > \frac{dQ_{mean}}{dx}$ where x denotes the distance along the main stream towards downstream. Its hydrological meaning is yet to be analysed.
7) On the contrary, in the southern part of the Ganges, from Chambal to the Son extending to the very high precipitation areas of the Meghna to eastern Brahmaputra, from the Barak to the Lohit, the normalized necessary storage seems already converged which indicates that the increase of V_{km3}-Q_{mean} relation is already in the same proportion. Namely, $\frac{dV_{km3}}{dx} \cong \frac{dQ_{mean}}{dx}$ with implication yet to be analysed.

Figure 17 shows that the relation between the normalized necessary storage V_{month} and the coefficient of variation of daily discharge CV in sub-basins. It indicates:

1) Again, the normalized necessary storage is larger for flood management than for the drought management as stated 1) above on Fig. 16.
2) Similar to Fig. 16, the six sub-basins in the west most and the northern Ganges, from the Chambal to the Kosi, have wide ranges of CV, 0-6 or 0-8. They are relatively large sub-basins having heterogeneous conditions.
3) On the other hand, the other six located in the Brahmaputra and the southern edges of the Ganges and the Meghna show rather concentrated cluster of dots. This should mean the same as the case of Fig. 16, more uniform conditions than the first six of the western to the northern Ganges.
4) The scatter is especially large in the Yamuna and the Ganga which, as Fig 3a indicates, originate from the high Himalayan Mountains and flow down to the highland plateau and eventually to the lowland plain. In the plateau and the plain of these basins, it is rather dry region and, as Fig. 2 shows, used for extended cropland. Such land use heterogeneity contributes for the large scatter of normalized necessary storage.
5) The scatter from the average relation in each sub-basin reflects basin characteristics and to find the governing principle would be a challenging subject of hydrological science for further study.

4.4 Some other thoughts on future investigation

Although a number of unknown areas are mentioned for further analyses in discussions above, some more important areas are briefly described below.

4.4.1 Potential use of spatially distributed necessary storage information for water resources management

In this paper, necessary storage is proposed as an indicator of hydrological variability in time. Its advantage over other statistical indicators is obvious as it is in human terms and has a direct implication of ease and difficulty of water resources management. But what about its spatially distributed information? Does this have any use to water resource managers? It is a difficult question and the next step of this analysis. But some potential areas of investigation may be indicated. One would be an implication of spatial differences of necessary storage in months in independent sub-basins that may have a potential benefit of water transfer. It may be beneficial to transfer water stored in an area with smaller mean refilling time (months) to another area with longer refilling time (months). Another would be the relation to land use for agriculture, that is, the area with smaller necessary storage may indicate relative advantage for water demanding vegetation. Gao et al. (2014) looked into the terrestrial ecosystem's root zone moisture capacity at the catchment scale and found it equivalent to the necessary storage for 10-40 year drought. If the necessary storage is small, it would need smaller root zone capacity and larger if not, that may indicate some suited agricultural or forestry land use. The other potential area to investigate would be the impact to downstream when a reservoir was built or to be operated, that would necessitate a study on longitudinal change of necessary storage along river lines that may indicate the advantageous site of dam construction or operation in hydrological sense. Reservoir construction site or reservoir operation which has less impact to downstream would be desirable from the environmental point of view.

4.4.2 Scale effect of normalized necessary storage in months

Another potential area of further study is scale effect of normalized necessary storage in months, the V_{month}-A relation. Figure 13 is its large basin behaviour and Fig. 16 is its zoom up in the selected 12 sub-basins. All figures indicate that in a few 10,000 km^2 catchment area, the normalized necessary storage becomes stable unless different large branch rivers join with different characteristics months. This may have a conceptual analogy similar to the discussion of representative elementary area (REA) concept (Wood et al., 1988) based on the finding that the variability of hydrological processes becomes low once the area becomes larger than around 1 km^2. Hydrological variability in storage domain and its governing mechanism would deserve for further attention.

5. Conclusions

This paper introduced an indicator of necessary storage to smooth out the discharge variation for flood and drought management given target water release levels. It serves as an indicator of discharge variability in time expressed in concrete human terms. The indicators presented here are the case to maintain the long term mean discharge Q_{mean} in 5 year return period. But such target level can be chosen arbitrarily such as $3Q_{mean}$ for flood and $0.5Q_{mean}$ for drought (Fig. 11) and in different return periods or rate of failure. The indicators are calculated by intensity-duration-frequency curves of daily discharge called flood duration curves (FDC) and drought duration curves (DDC) and plotted to geographical maps for the Ganges-Brahmaputra-Meghna (GBM) basins. Although the application results are limited to those in the GBM basin, the 12 selected sub-basins were analysed to relate the necessary storage indicator with their geophysical and geo-graphical characteristics. This is a first trial of the use of the proposed indicator and yet a first step of analysing its geographical distribution, the authors believe that the validity of the indicator and its potential use are demonstrated and the following may be concluded:

1) The necessary storage serves as an indicator of discharge variability in time and a means of analysing geographical distribution of hydrological heterogeneity.
2) The necessary storage indicator has a distinct advantage to measure hydrological variability over other conventional statistical indicators such as SD and CV, as it has human terms "reservoir storage in km^3 or mean refilling time in months" which directly indicates the ease and difficulty of flood and drought management.

3) The necessary storage is an indicator that has potential to show something extra to statistical variability indicators such as SD and CV. The analyses of the scatter from the normal relations of V-A, V-SD and V-CV would lead hydrological sciences to new insights on geographical distribution of hydrological heterogeneity.

4) To calculate the necessary storage by intensity-duration-frequency curves FDC and DDC is a practical and convenient way that is beneficial to extend the study to the globe.

5) The indicator in km^3 generally becomes larger with catchment area so that the major river routes emerge out as blood vessels with larger values than the surrounding. The indicator in months, normalized by the local long term mean, however, converges to smaller values than the surrounding with smaller catchment as the river discharge is stabilized as catchment becomes larger.

6) 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 much on the spatial distribution of hydrological heterogeneity.

7) The necessary storage both for flood and drought management in terms of km^3 is 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 the Himalayan Mountains has particularly high values in months reflecting the magnitude of discharge variability.

8) In contrast to head water areas, in the main streams, the variation converges to the average basin characteristics. Such scale effects would be an important area to be studied in the future along with drawing global maps of necessary storage. It seems to have some similarity to the concept of representative elementary area (REA) introduced by Eric Wood and his colleagues (Wood et al., 1988) on scale effects on spatial heterogeneity of hydrological processes.

9) A creation of global maps of necessary storage would be a useful challenge for assessing the current state of water resources and climate change impact on water resources as well as for the scientific analyses of hydrological heterogeneity in storage domain.

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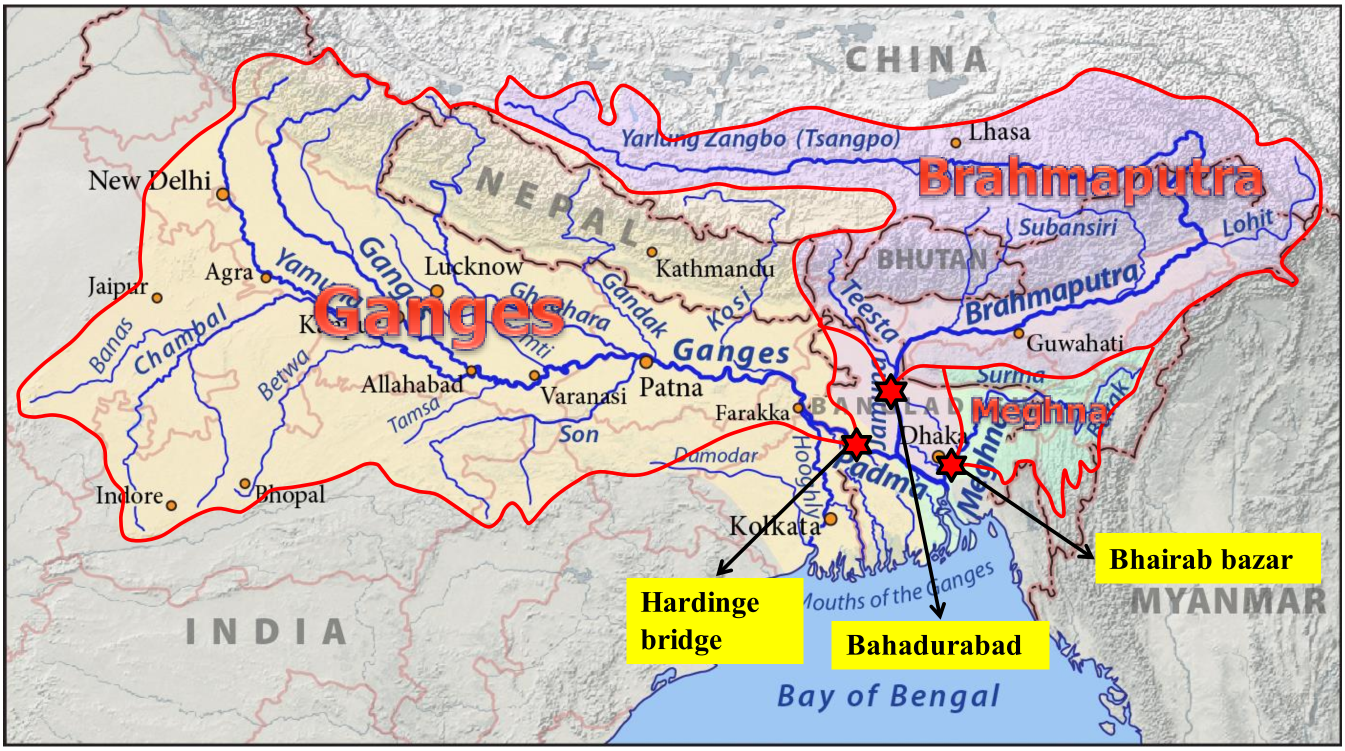
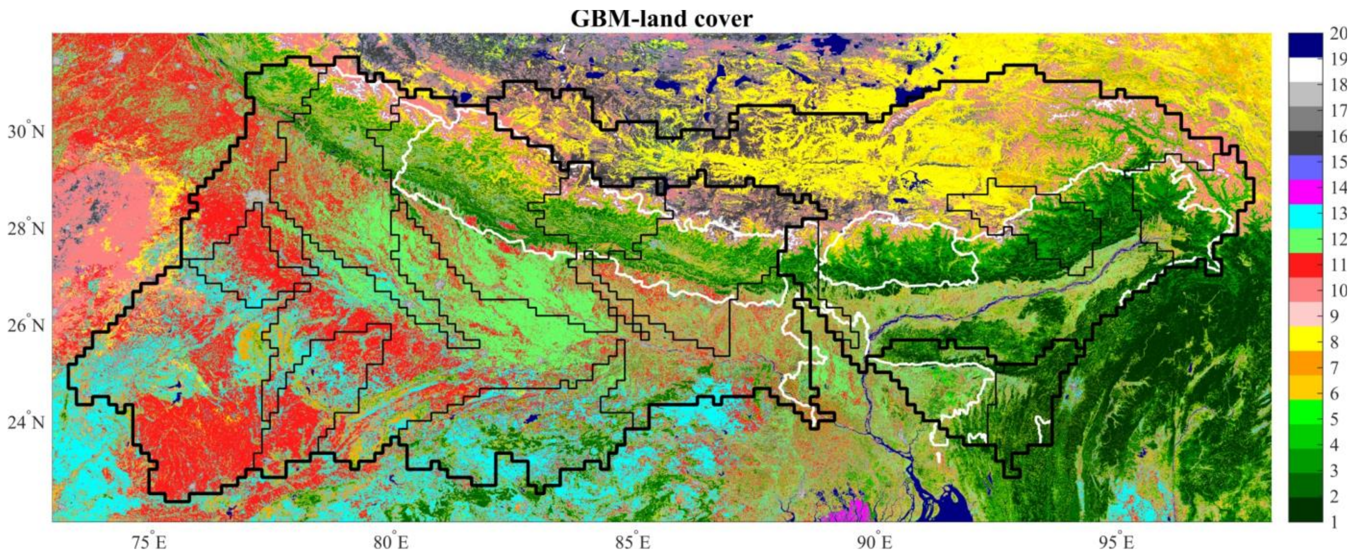


Figure 1: The Ganges-Brahmaputra-Meghna (GBM) basin (modified from Pfly, 2011).



Code	Class Name	Code	Class Name
1	Broadleaf Evergreen Forest	11	Cropland
2	Broadleaf Deciduous Forest	12	Paddy field
3	Needleleaf Evergreen Forest	13	Cropland / Other Vegetation Mosaic
4	Needleleaf Deciduous Forest	14	Mangrove
5	Mixed Forest	15	Wetland
6	Tree Open	16	Bare area,consolidated(gravel,rock)
7	Shrub	17	Bare area,unconsolidated (sand)
8	Herbaceous	18	Urban
9	Herbaceous with Sparse Tree/Shrub	19	Snow / Ice
10	Sparse vegetation	20	Water bodies

Figure 2: Land cover of the GBM basin from GLCNMO (Tateishi et al, 2014).

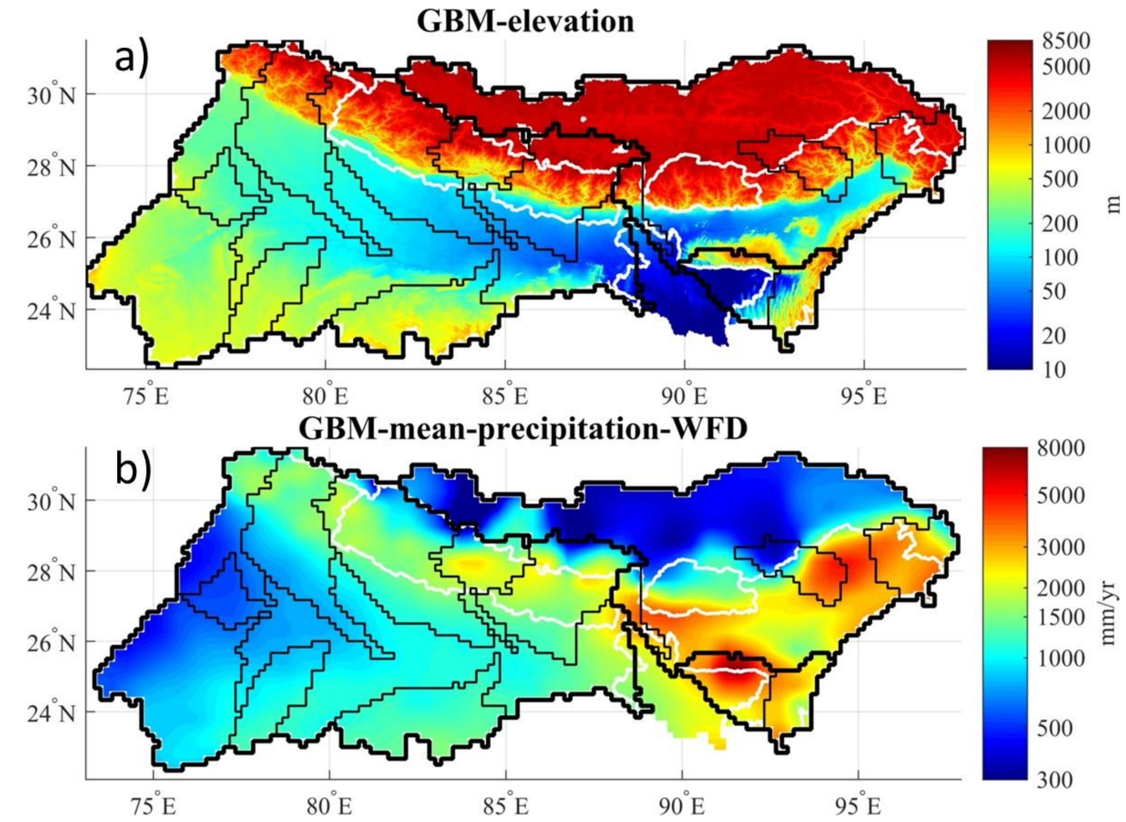


Figure 3: The a) elevation and b) precipitation distributions of the GBM basin.

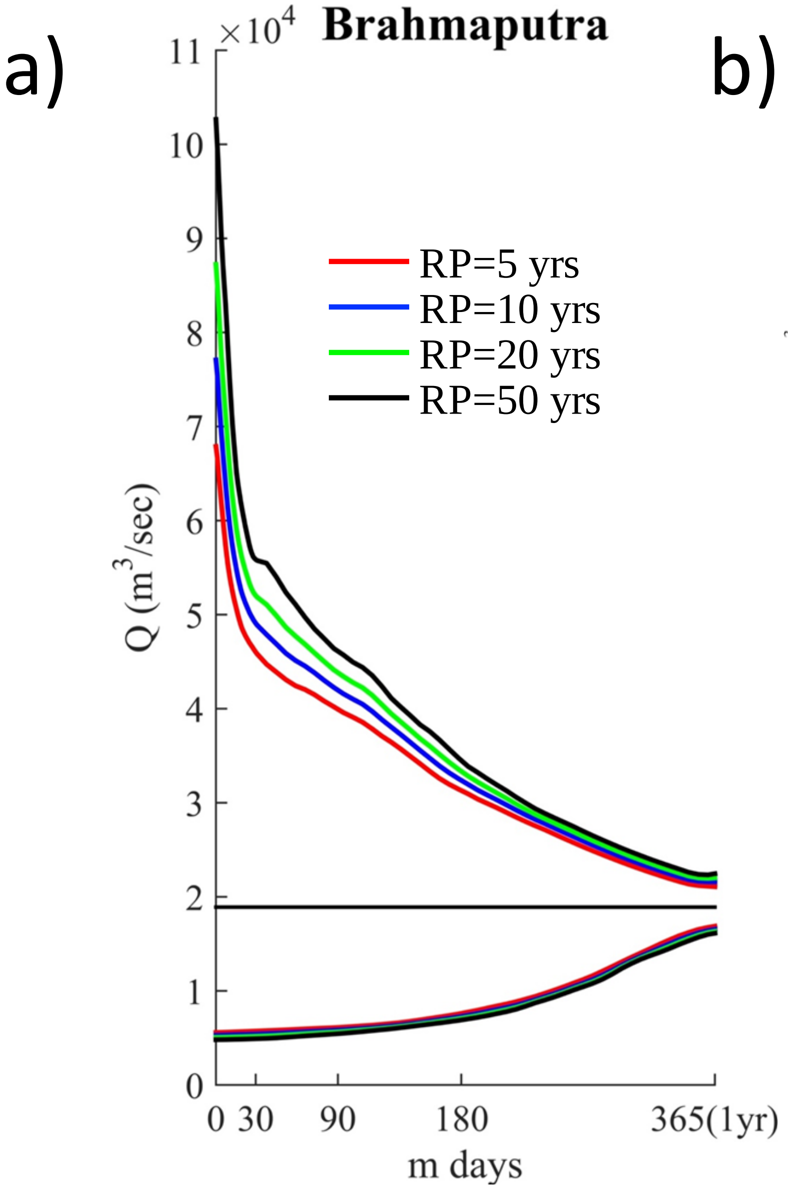


Figure 4: FDC-DDCs of the Brahmaputra River at Bahadurabad station a) for one year and b) for three years. The discharge data are the BTOPMC simulated using the WFD data.

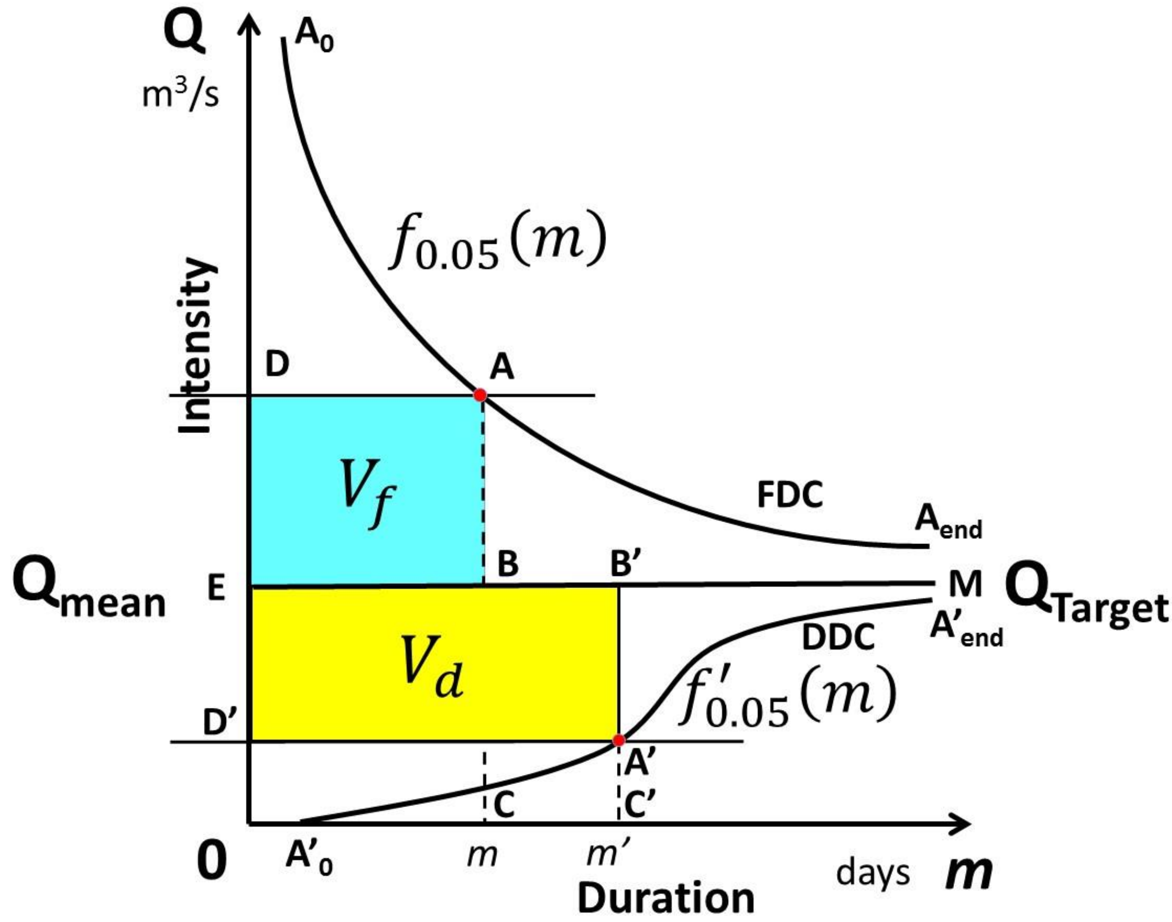


Figure 5: Schematic illustration of how to calculate necessary storages V_f and V_d to smooth out the hydrological variation to the long term mean Q_{mean} for flood control and drought management.

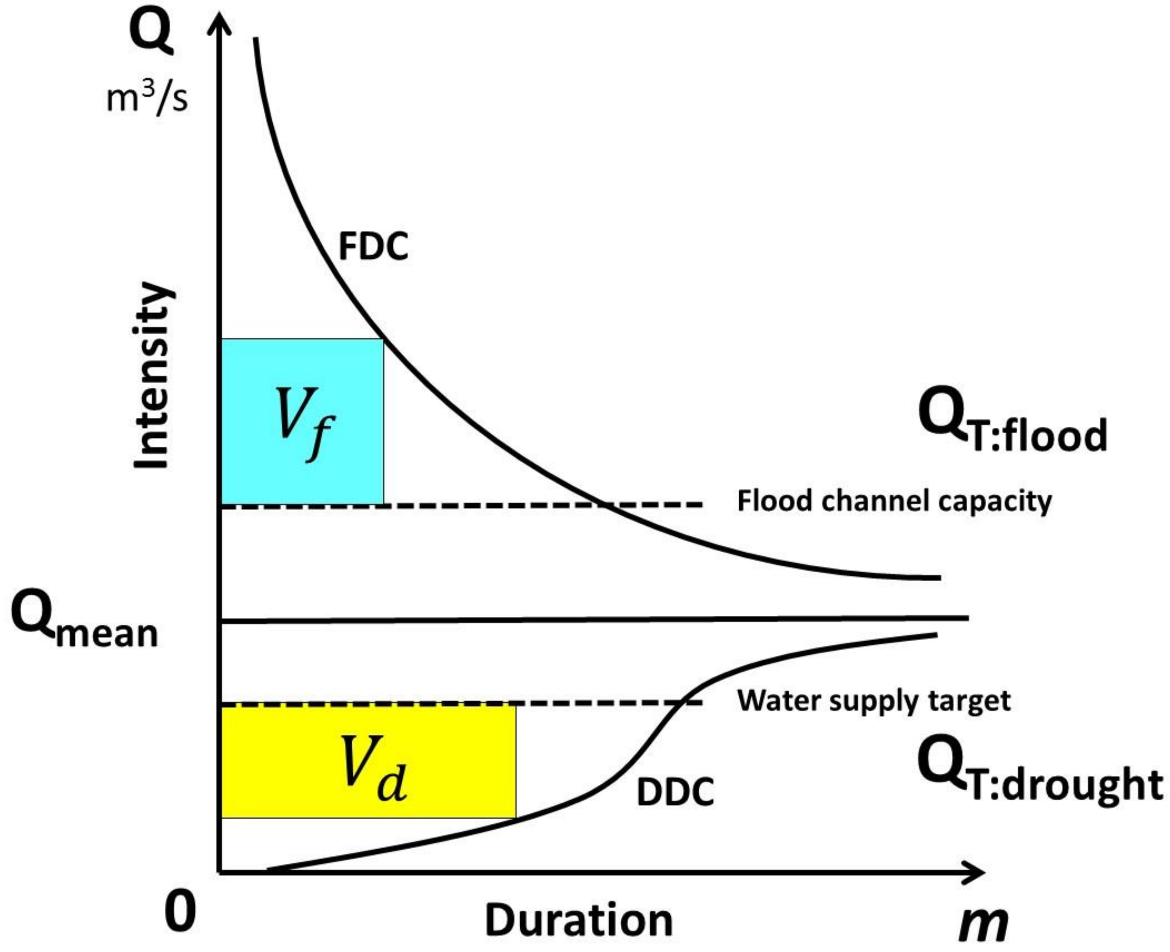


Figure 6: **Schematic illustration of how to calculate necessary storages V_f and V_d to smooth out the hydrological variation to $3Q_{mean}$ for flood control and $0.5Q_{mean}$ for drought management.**

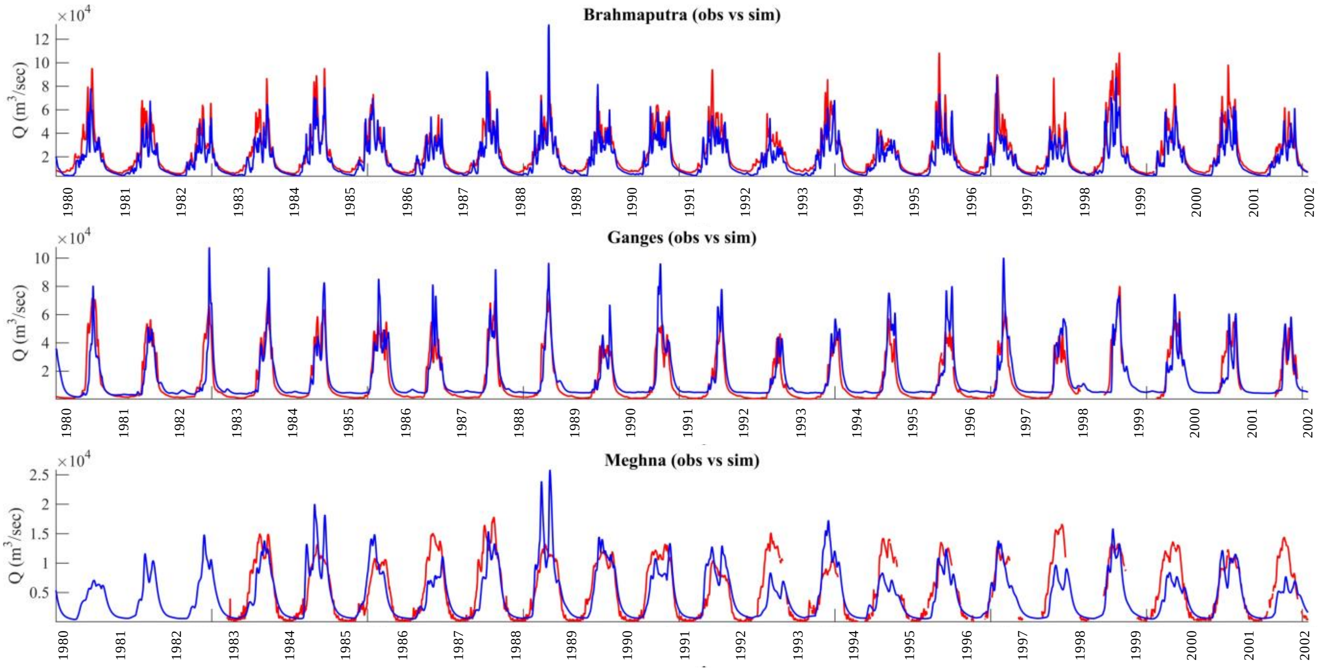


Figure 7: Comparisons of the observed (red) and the BTOPMC simulated (blue) discharges at (top) Bahadurabad, the Brahmaputra, (middle) Hardinge Bridge, the Ganges and (bottom) Bhairab Bazar, the Meghna. Calibration period is 1980-1990. Precipitation data used are WATCH Forcing Data (WFD). See Table 1 for Nash-Sutcliffe efficiency.

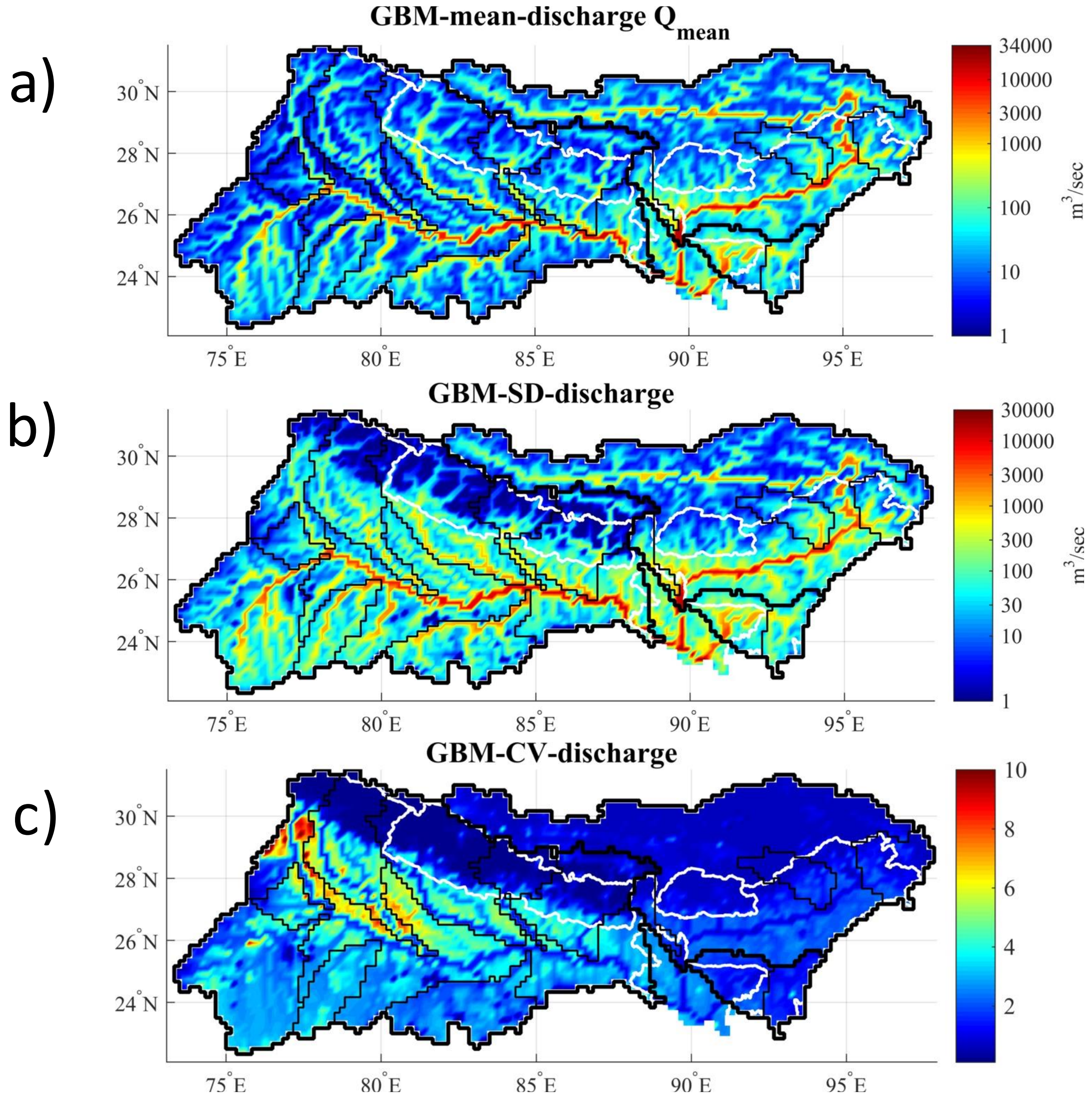


Figure 8: Maps of a) the mean, b) SD and c) CV of the simulated discharge for 1980-2001.

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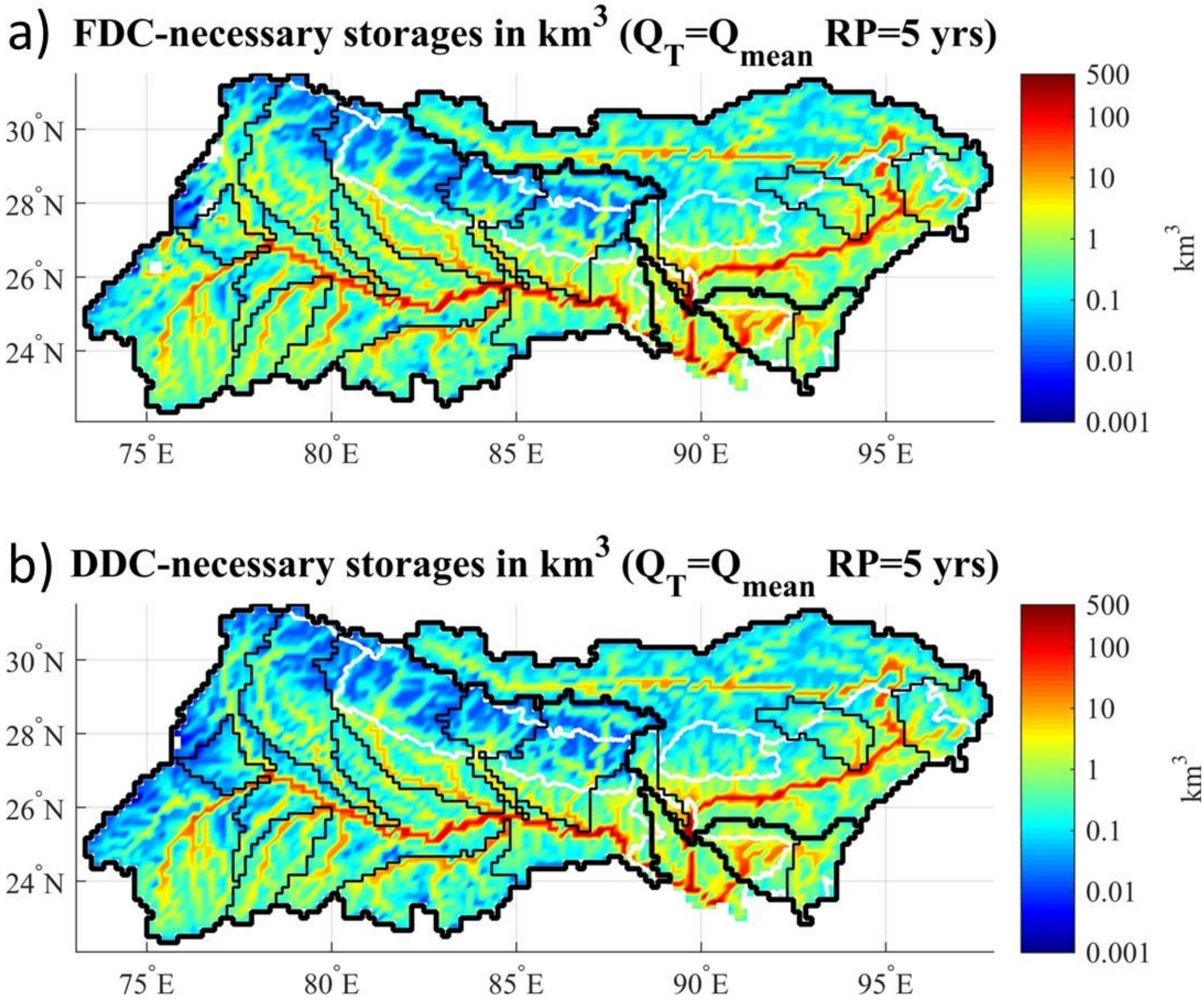

Figure 9: Necessary storages (km^3) for a) flood and b) drought management with target discharge Q_T=Q_{mean} of return period 5 years. The simulated discharge was for 1980-2001.

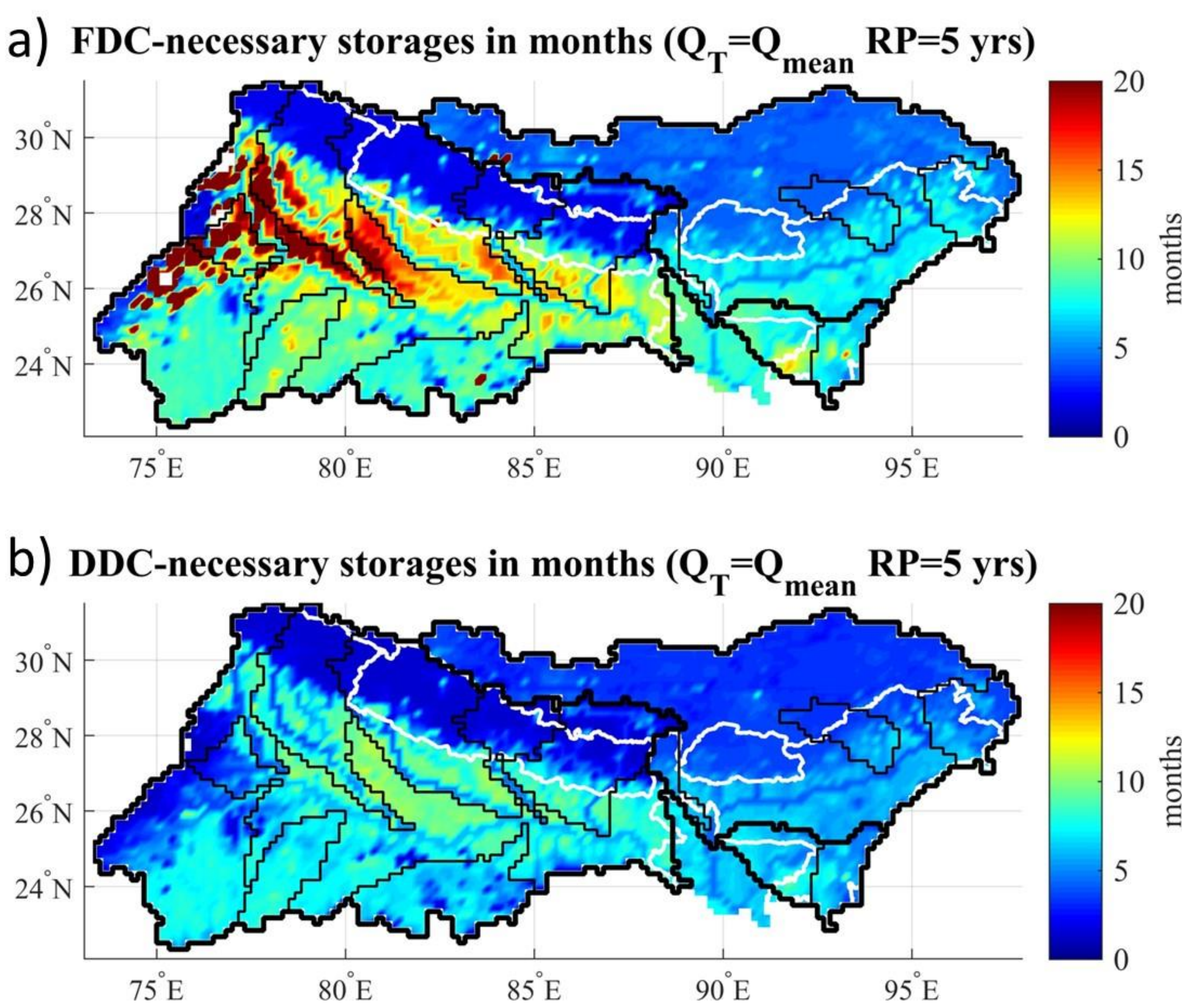

Figure 10: Necessary storage in months for a) flood and b) drought management with maintaining discharge Q_T=Q_{mean} of return period 5 years. The simulated discharge was for 1980-2001.

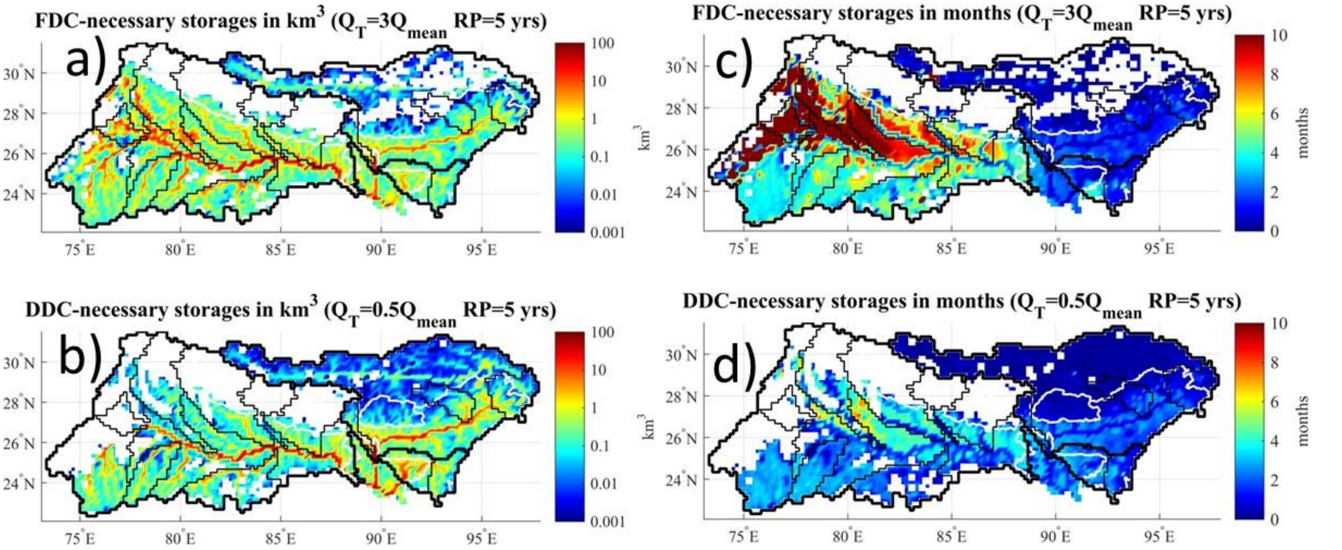

Figure 11: Necessary storages (a, b) in km^3 and (c, d) in months (a, c) for flood and (b, d) for drought management to maintain Q_T=3Q_{mean} during flood and Q_T=0.5Q_{mean} during drought of return period 5 years. The simulated discharge was for 1980-2001.

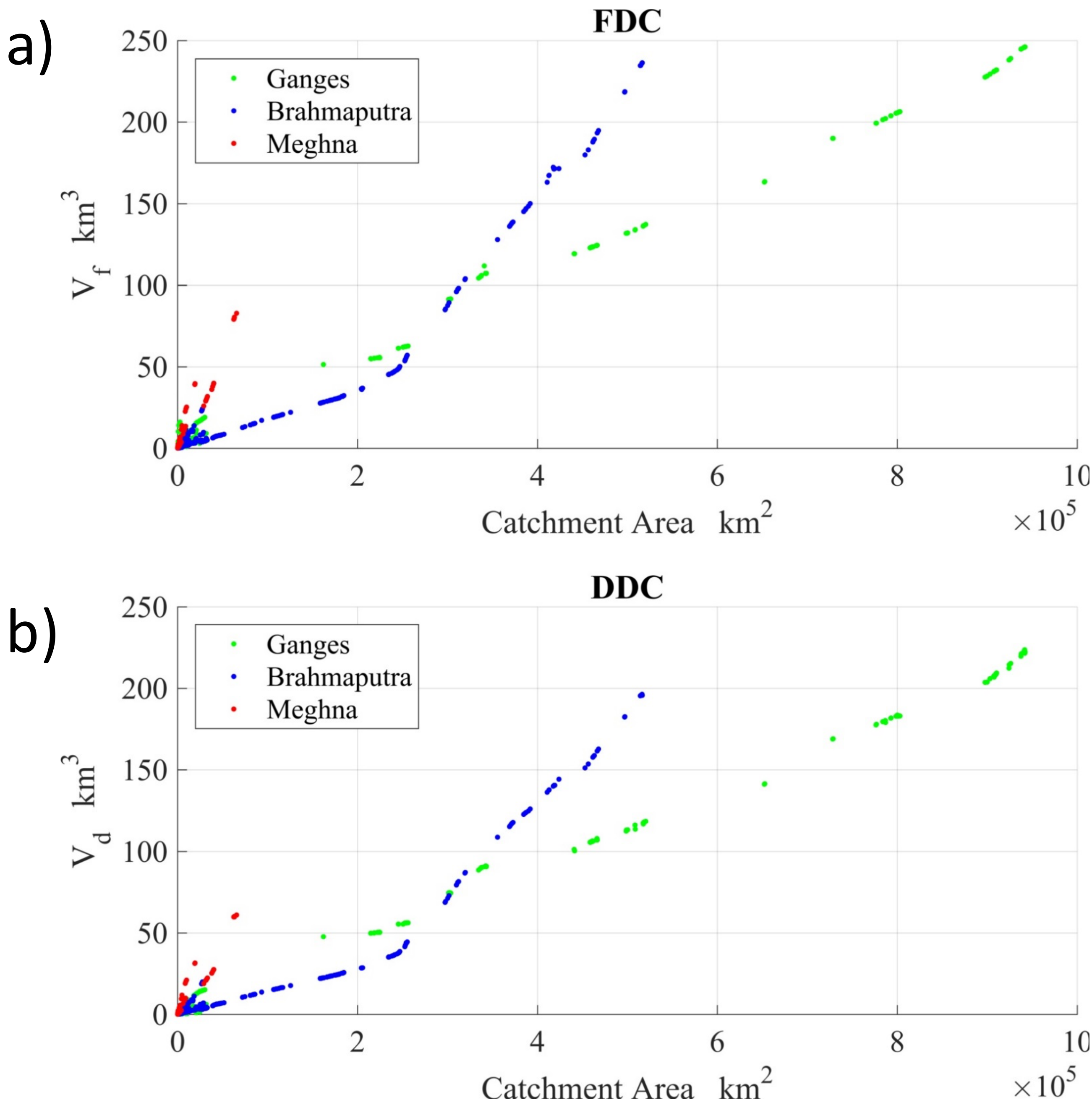

Figure 12: Relation between necessary storage (km^3) and catchment area (km^2) for a) flood and b) drought management in three basins of the GBM basin.

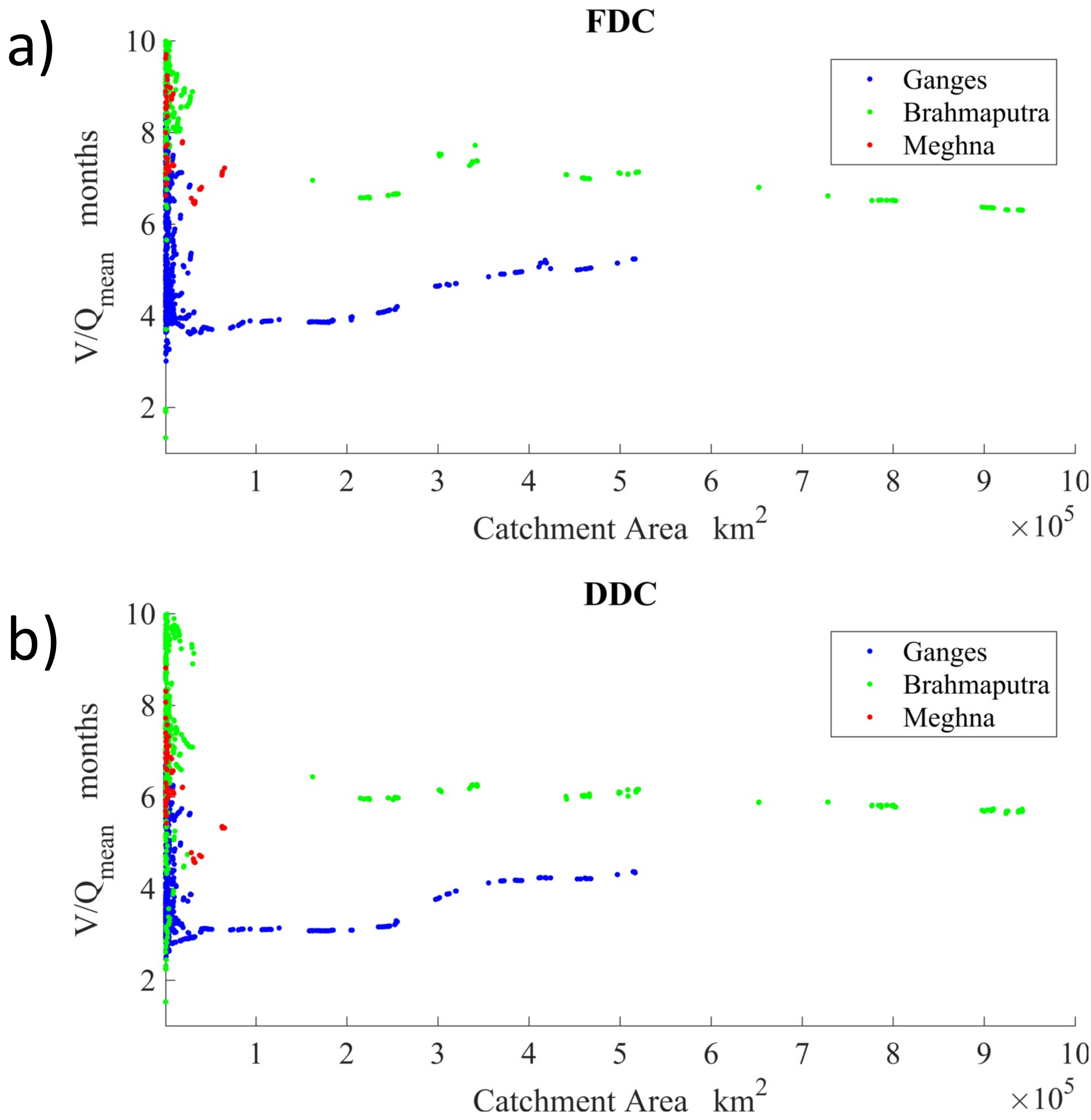

Figure 13: Relation between necessary storage in months and catchment area (km^2) at all grid points of the basin with maintaining discharge Q_T=Q_{mean} for a) flood and b) drought management with 5 years return period

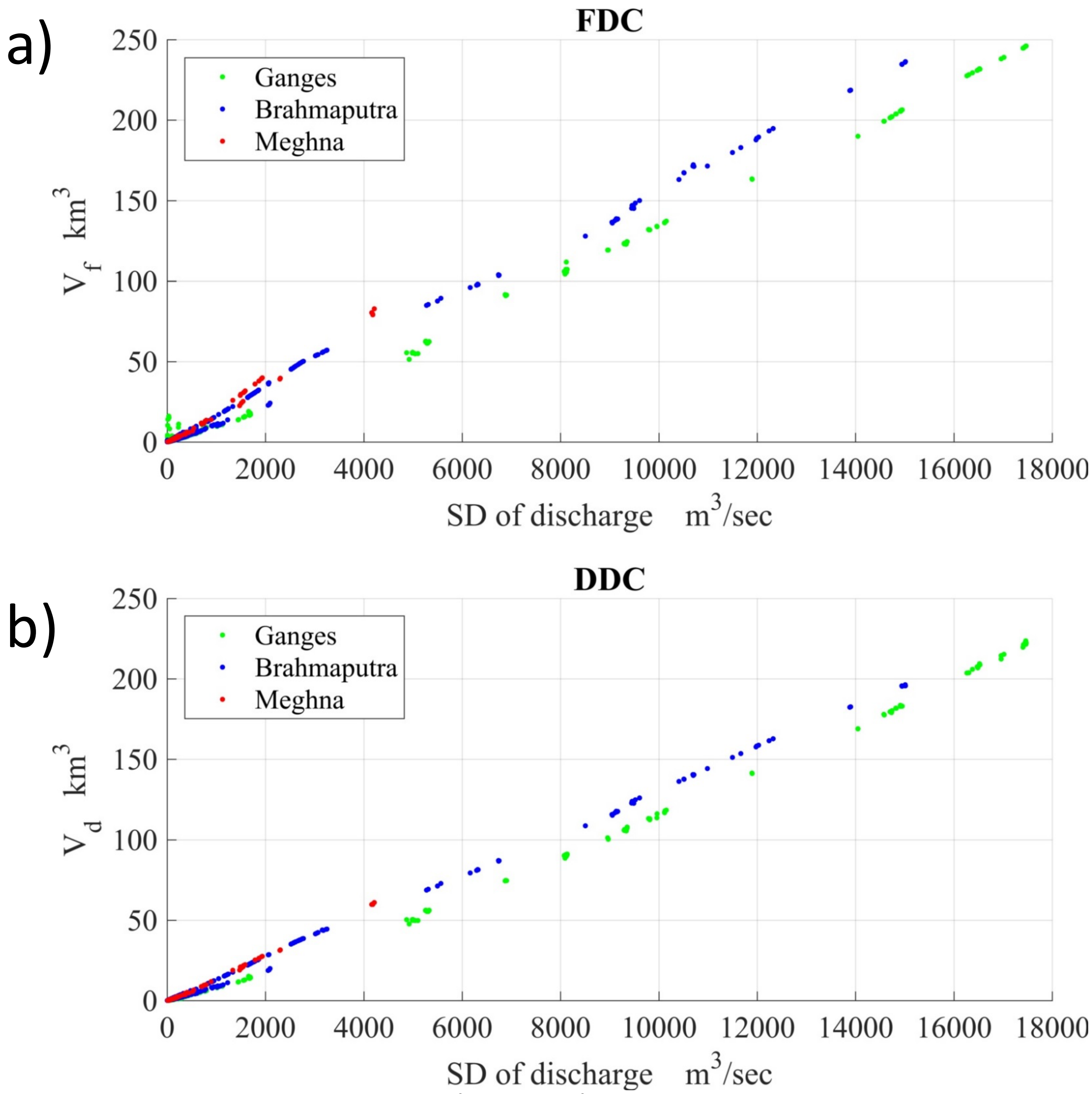

Figure 14: Relation between necessary storage (km^3) and SD (m^3/s) of discharge at all grid points in the GBM basin for a) flood and b) drought management.

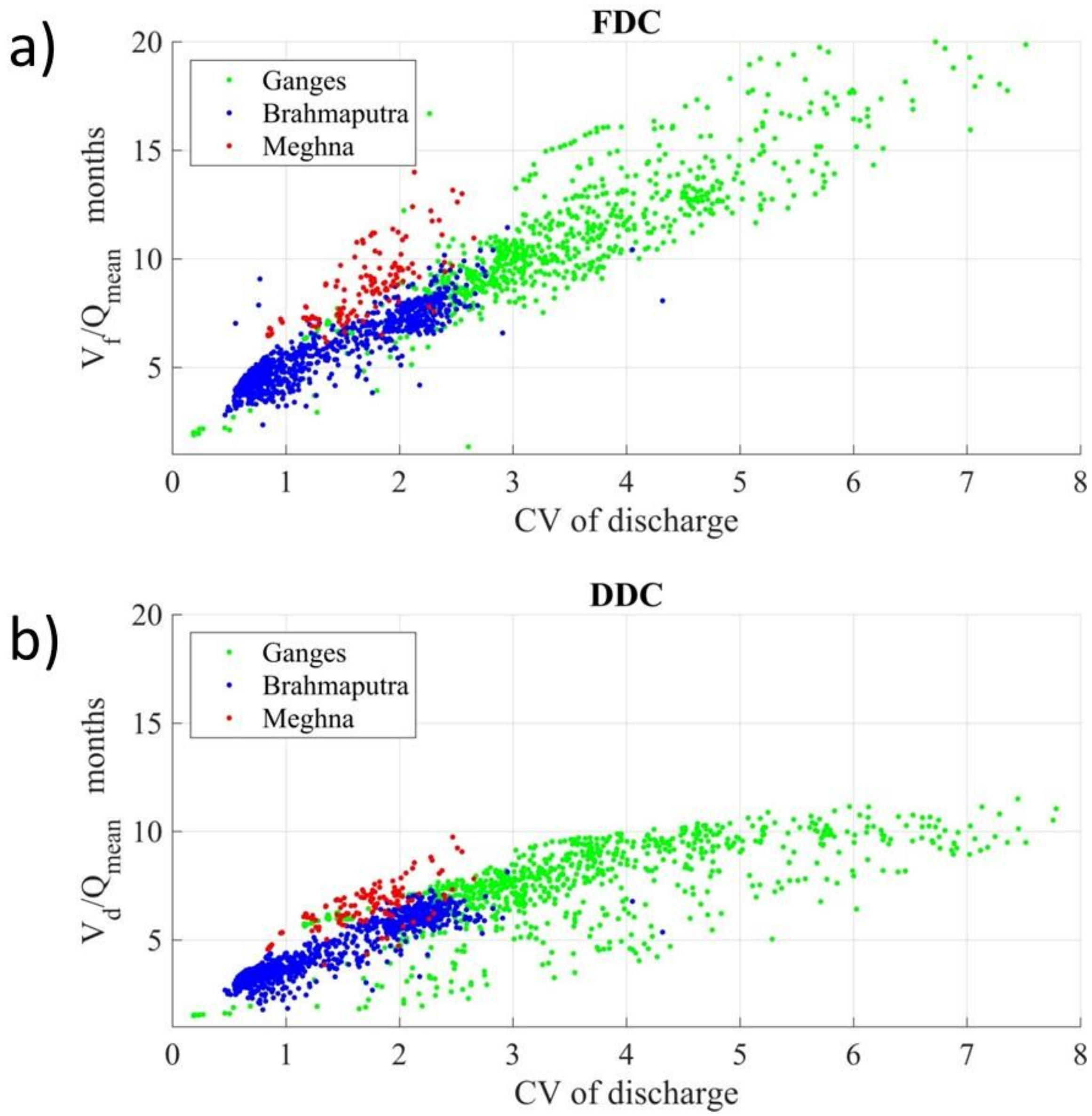

Figure 15: Relation between necessary storage in months and CV of daily discharge of 5-year return period for a) flood and b) drought management at all grid points of the GBM basin.

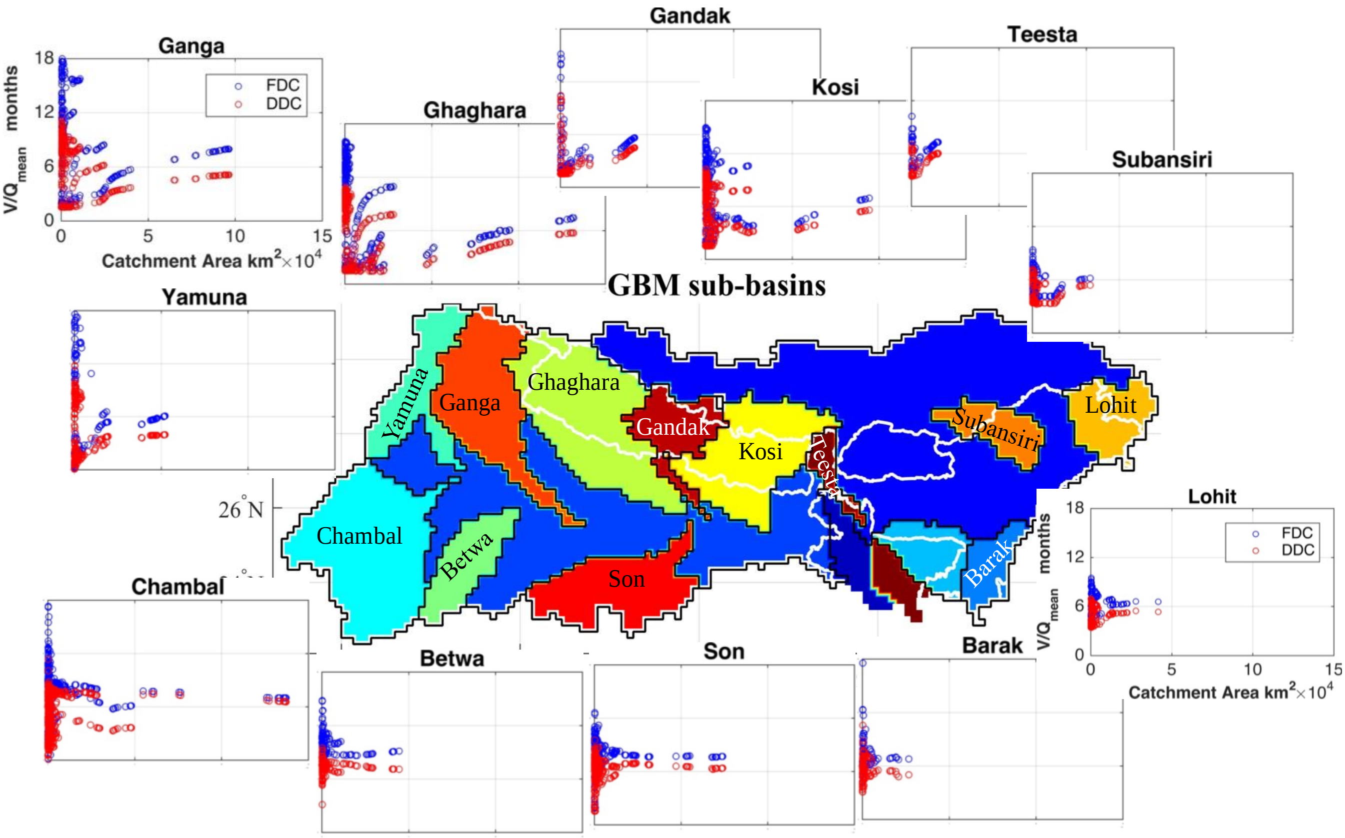

Figure 16: Relation between necessary storage in months for flood (blue) and drought (red) management and catchment area (km^2) at all grid points of 12 GBM sub-basins as indicated in the center with maintaining discharge Q_T=Q_{mean} during discharge with 5 years return period. The simulated discharge was for 1980-2001.

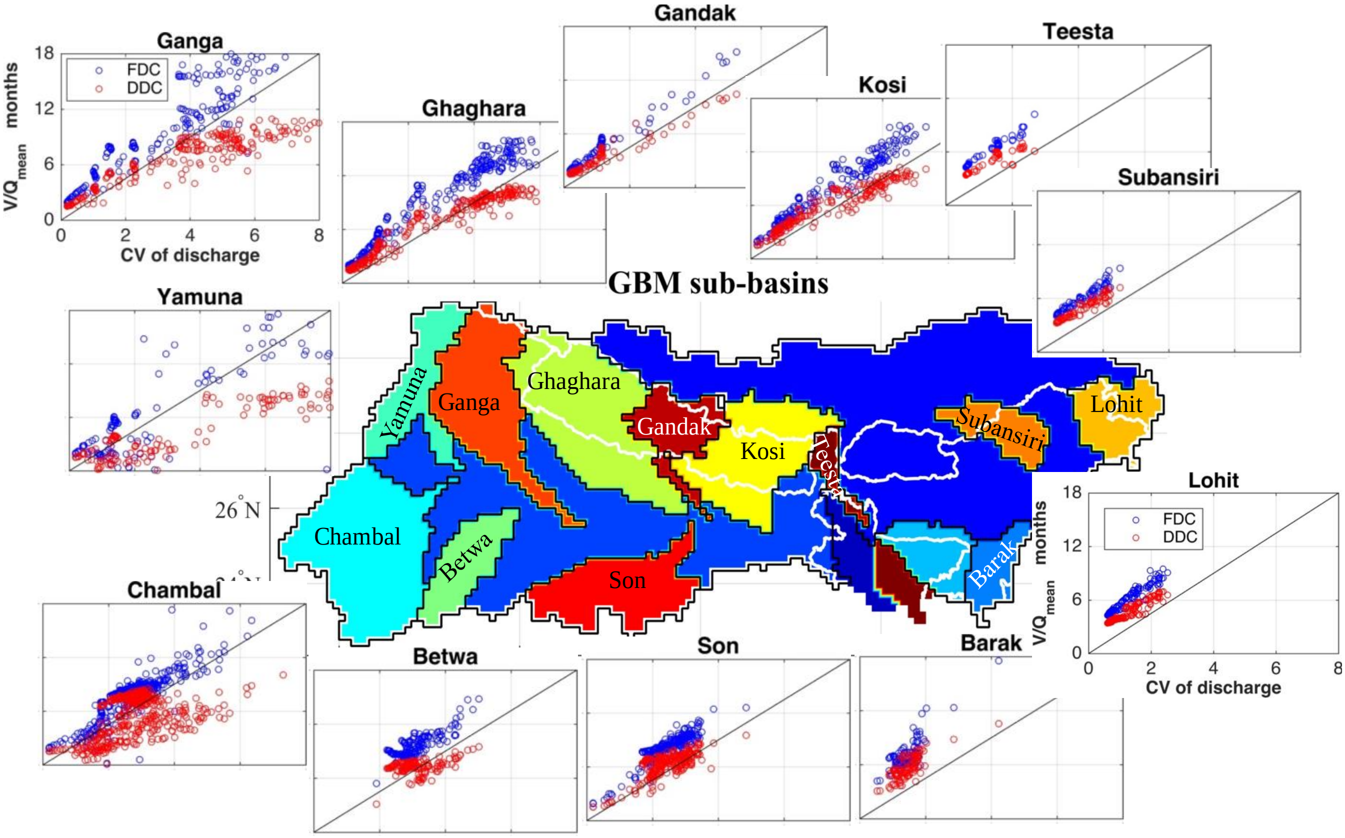

Figure 17: Relation between necessary storage in months and CV of daily discharge for flood (blue) and drought (red) management at all grid points of 12 GBM sub-basins as indicated in the center with maintaining discharge Q_T=Q_{mean} during with 5 years return period. The simulated discharge was for 1980-2001.

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	-10 ~ 10	0.01 ~ 0.1	0.01 ~ 0.8	(Takeuchi *et al*., 2008)
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