POTENTIAL IMPACT OF CLIMATE CHANGE ON WATER AVAILABILITY OF BRAHMAPUTRA RIVER BASIN

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Abstract: Brahmaputra river basin (BRB) is one of the largest basins among Ganges-Brahmaputra-Meghna (GBM) river system carrying enormous volume of water through Bangladesh. The response of this basin due to variable climate changes is one of the key issues to be investigated due to its socio-economic and environmental vulnerability. A semi-distributed hydrological model of the BRB has been developed using the Soil Water Assessment Tool (SWAT). It has been calibrated and validated for the streamflow measured at the Bahadurabad station for the climate normal period (1981 to 2010). The calibrated model has been used to assess the impact of climate change on water availability of BRB by applying different climate change scenarios of selected General Circulation Models (GCM). The selection of GCM was based on the Representative Concentration Pathways (RCPs) scenarios of eight Intergovernmental Panel on Climate Change (IPCC) GCMs for the 21st century. The high resolution spatial distribution of temperature and precipitation of these GCMs were obtained using the pattern scaling technique and were further applied to the SWAT hydrological model. Model results subsequently provided the projected increasing trend of mean annual and seasonal streamflow of BRB under the impact of climate change in 21st century.

1 Introduction:

The Ganges-Brahmaputra-Meghna (GBM) river basin is one of the most vulnerable areas in the world under the potential impact of climate change (e.g., the combined effects of glacier melt, extreme monsoon rainfall and sea level rise) (Gain, 2011). About 92.5% of the watershed area of GBM basin lies outside of Bangladesh and about 80% of the annual precipitation occurs in the monsoon (June-September) period (Mirza, 2002). Brahmaputra River Basin (BRB) is one of the major basins in the world draining an area of about 5,30,000 km^2 through China (50.5%), India (33.6%), Bangladesh (8.1%) and Bhutan (7.8%) (Figure 1). After originating from Kailash range in Tibet (China), it flows 2,900 km and meets Ganges in Bangladesh. The combined flow (Padma) is then join Upper Meghna and formed Lower Meghna to ultimately drain into the Bay of Bengal. The average annual discharge is about 20,000 m^3/s (Immerzeel, 2008).

Few studies have previously been conducted to assess the impact of climate change on the basin hydrology and water availability of GBM basin (e.g. Mirza and Dixit, 1997; Seidal et al., 2000; Mirza, 2002; Mirza, 2003; Immerzeel, 2008; Gain et al., 2011; Ghosh and Dutta, 2012). However, only a few studies have been conducted to assess the water availability of Brahmaputra river basin. In most of the cases empirical or regression model were developed relating the climate parameters to the streamflow.

There are different approaches to generate climate change scenarios for hydrological impact studies. They can be broadly classified as synthetic approach, analogue approach and climate model based approach. In synthetic approach, the future climatic variables (e.g., temperature, precipitation) are changed incrementally by arbitrary amounts. In analogue approach, climate change scenarios are constructed by identifying recorded climate regimes which may resemble the future climate in a given region (IPCC, 2001). In this approach the fundamental assumption is that climate will respond in the same way to a unit change in forcing despite its source or the boundary conditions in place at the time.

Finally the climate model based approach, which are the most advanced tools currently available for simulating the response of the global climate system to changing atmospheric composition.

With the aforementioned background information, the objective of this study is to apply a physically based hydrological model for Brahmaputra river basin to investigate the potential impact of climate change in a relatively accurate and realistic manner. In this study a hydrological model of Brahmaputra river basin has been developed using physically based semi-distributed hydrological model, namely Soil Water Assessment Tool (SWAT). The model has been calibrated and validated for climate normal period (1981-2010). Then high resolution climate data for selected GCM were generated using pattern scaling method. These data were further used to drive the hydrological model and obtain projected flow of selected scenarios.

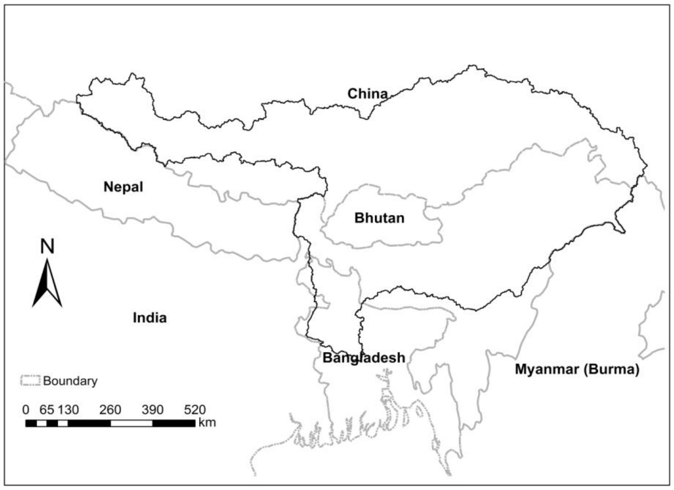


Figure 1: Brahmaputra river basin

2 Data and Methodology

2.1 Model Description

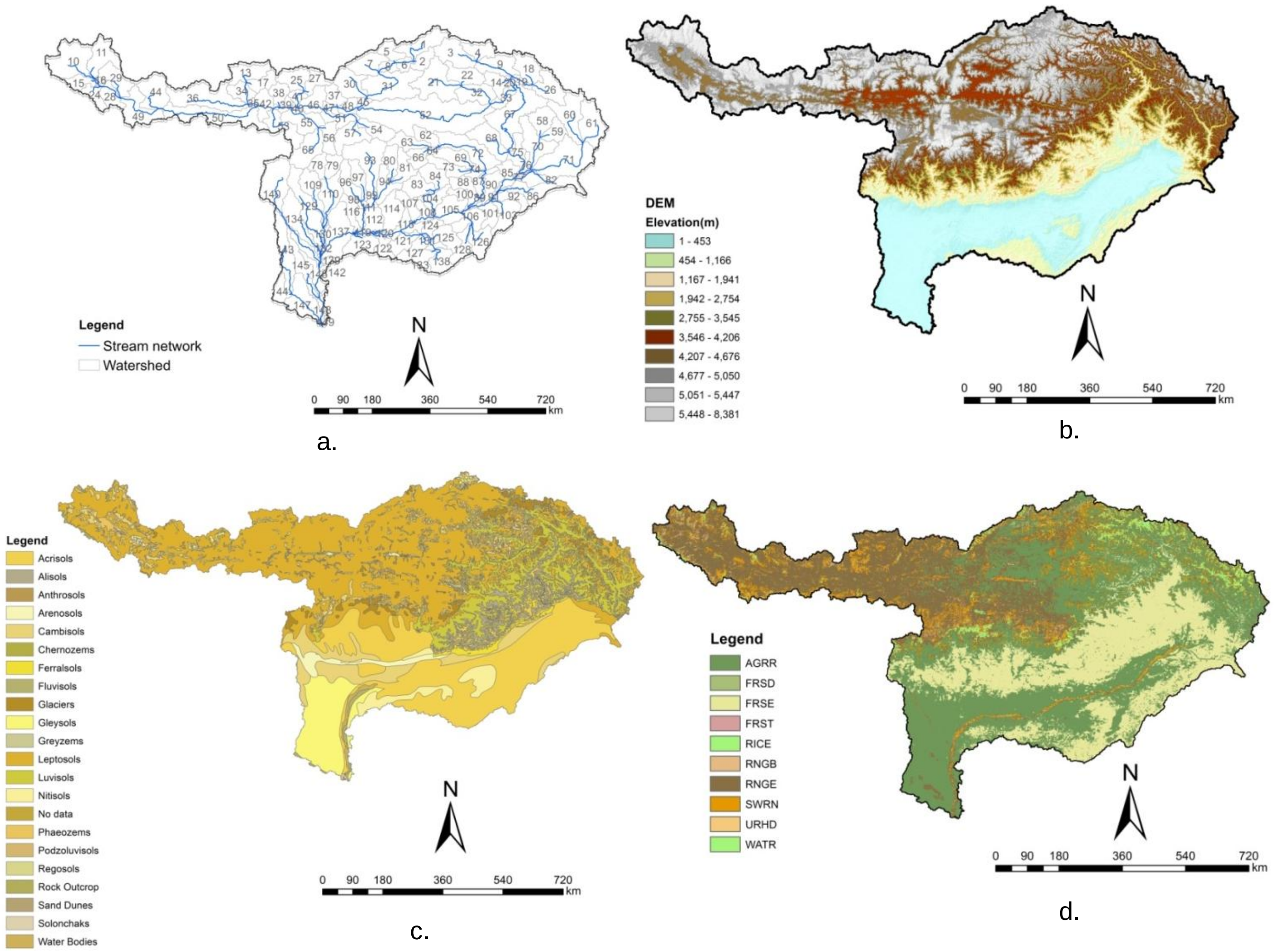
The physically based hydrological model SWAT of Arnold and Allen (1996) selected for this study operates on daily time step and uses physiographical data such as elevation, soil use, land use, meteorological data and river discharge. The hydrological processes included in the model are evapotranspiration (ET), surface runoff, infiltration, percolation, shallow and deep aquifers flow, and channel routing. The effects of spatial variations in topography, land use, soil and other characteristics of watershed hydrology are incorporated by dividing a basin into several sub-basins based on drainage areas of tributaries and then the sub-basins are further divided into a number of Hydrological Response Units (HRUs) based on land cover and soils. Each HRU is assumed to be spatially uniform in terms of land use, soil, topography and climate. The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. All the computations are performed at HRU level (Mengistu, 2012). The hydrologic cycle as simulated by SWAT is based on the water balance equation (Equation 1)

$$\boldsymbol{SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})} \qquad \textbf{(1)}$$

where SWt is the final soil water content, SW_0 is the initial soil water content on day i , t is the time in days, R_{day} is the amount of precipitation on day i , Q_{surf} is the amount of surface runoff on day i , E_a is the amount of evapotranspiration on day i , W_{seep} is the amount of water entering the vadose zone from the soil profile on day i and Q_{gw} is the amount of return flow on day i (All units except the time are presented as mm of water).

2.2 DEM, Landuse and Soil data

Digital Elevation Model (DEM) of 90 m grid resolution was downloaded from Shuttle Rudder Topography Mission (SRTM) website. This was further used to delineate the watershed and the drainage pattern for the surface area analysis. Soil map of the selected area was collected from Harmonized World Soil Database (HWSD). It has 1km grid resolution and provides soil properties of two layers (0-30 cm) and (30-100 cm) depth. It includes soil properties like particle-size distribution, bulk density, organic carbon content, available water capacity, saturated hydraulic conductivity etc.



a.

b.

c.

d.

Figure 2: (a) Sub basin and delineated stream network (b) DEM (c) Soil map and (d) Land use map of Brahmaputra River Basin

Land use map of the basin area was collected from United States Geological Survey (USGS). The map has a spatial resolution of 1km and it consists of different classes of land use type. Land use classes have been parameterized based on existing SWAT land use classes. Figure 2 shows the delineated stream network, DEM, soil and land use maps for the BRB.

2.3 Weather and Discharge Data

The SWAT model requires different types of meteorological data to simulate the hydrological processes. These include daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed. For this study, meteorological data for the BRB have been collected from the National Aeronautics and Space Administration Prediction of Worldwide Energy (NASA POWER). The data includes daily meteorological data (precipitation, minimum and maximum temperature) for the climate normal period (1981 to 2010). However, NASA POWER precipitation data were corrected for bias after comparing with the measured precipitation data at six stations in BRB. These bias corrected precipitation data were applied to SWAT to simulate the streamflow of BRB at Bahadurabad and compared with the measured discharge data collected from the Bangladesh Water Development Board (BWDB).

2.4 Model Setup

The first step in the model setup involves a delineation of the basin and sub-basin boundaries. This was accomplished using the automatic watershed delineation tool of ArcSWAT 2012.10.2.16 using the 90 m DEM of SRTM. All the watershed delineation steps such as filling sink, defining flow direction and accumulation were done automatically through the user interface. After delineation, the basin was divided into 149 sub-basins as shown in Figure 2a. Soil and landuse maps were loaded into SWAT to extract the landuse and soil information of the BRB. The land use, soil layer and slope class were overlaid to define the HRUs of the BRB. A total of 1020 HRUs (Average area 687 km^2) were produced and included in the simulation. The discretization of basin into HRUs allows a detailed simulation of the hydrological processes. Daily precipitation, maximum and minimum temperature data were then applied for climate normal period (1981-2010). The Soil Conservation Service (SCS) curve number procedure (USDA-SCS, 1972) was applied to estimate surface runoff volumes. The potential evapotranspiration (PET) estimates and channel routing were performed using Hargreaves and Variable storage methods, respectively. The skewed normal distribution method has been used for rainfall distribution. Note that, the model was applied for 1978 to 2010 with a daily time step in order to facilitate the 3 years warm-up period.

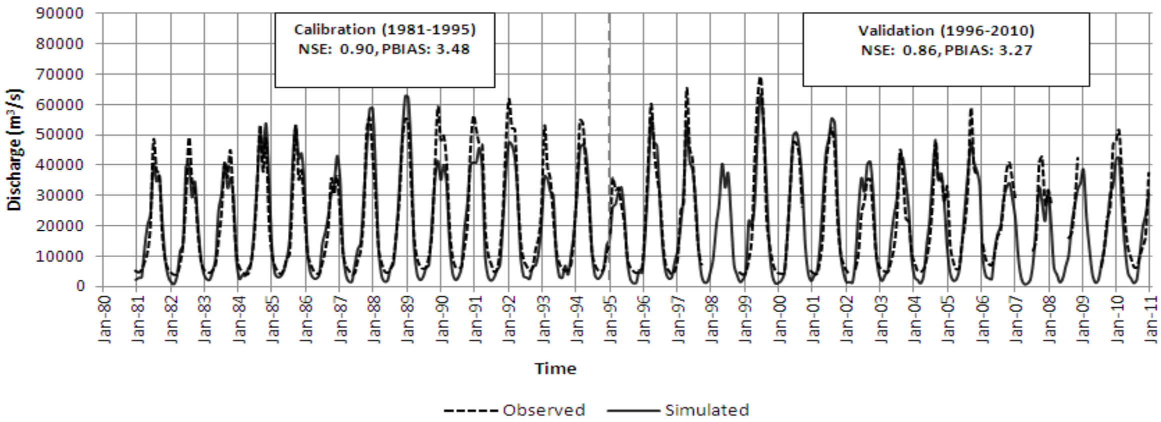


Figure 3: Monthly observed and simulated flows for the calibration and validation period 1981 to 2010

3 Calibration and Validation

There are numerous parameters in hydrological models which can be classified as physical parameters (i.e., parameters that can be physically measurable from the properties of watershed) and process parameters (i.e., parameters represents properties which are not directly measurable) (Sorooshian and Gupta, 1995). A sensitivity analysis of parameters was carried out by regressing Latin Hypercube generated parameters against objective function values (SWAT-cup, 2012). It was found that, out of 27 selected parameters, the Ground water revap co-efficient, threshold water depth in the shallow aquifer for flow, soil evaporation compensation factor, available water capacity, threshold water depth in the shallow aquifer for revap, manning’s n for main channel, curve number, saturated hydraulic conductivity, maximum canopy storage, groundwater delay time and baseflow alpha factor were identified as being parameters to which the flow has sensitivity. However the curve number (CN2) was found to be the main sensitivity parameter for all outlets. The model was calibrated from 1981 to 1995 and validated form 1996 to 2010 with monthly observed stream flow data at Bahadurabad station.

In calibration and validation stage, model performance is evaluated based on statistically and graphically. Figure 3 shows the graphical representation of monthly observed and simulated flow for both calibration and validation period. It was found that the simulated flow is in great compliance with the observed discharge for both monsoon and dry season.

Statistically the performance of the model has been evaluated using the Nash–Sutcliffe Efficiency value (NSE), the coefficient of determination (proportion of the variance in the observations explained by the model, R^2), percent bias (PBIAS) and the ratio of the root mean square error between the simulated and observed values to the standard deviation of the observations (RSR). The statistical model performance is given in table 1. General reported rating of NSE, R^2, PBIAS and RSR are given in table 2. The NSE values are 0.90 and 0.86 for calibration and validation period respectively. The co-efficient of determination (R^2) values are 0.90 for calibration and 0.87 for validation period. The PBIAS and RSR values are found to be 3.48 and 0.32 in calibration stage and 3.27 and 0.56 in validation stage, respectively. These statistics demonstrate SWAT generally performed well in both calibration and validation stages based on historical measured data for BRB (Moriasi et al. 2007), which establishes the basis for conducting climate change studies based on the simulations of SWAT, assuming the basins physical conditions remain basically unchanged.

Table 1: Model performance statistics for calibration (1981-1995) and validation period (1996-2010) of the Brahmaputra river basin

Period	**Observed Mean (m^3/s)**	**Simulated Mean (m^3/s)**	**Model performance**			
			NSE	**R^2**	**PBIAS**	**RSR**
Calibration	21205.3404	20468.2983	0.90	0.90	3.48	0.32
Validation	22060.59	19735.3	0.86	0.87	3.27	0.56

Table 2: General Reported ratings for Nash-Sutcliffe efficiency (NSE), Mean relative bias (PBIAS), Root mean square error-standard deviation ratio (RSR) and Coefficient of determination (R^2) for calibration and validation process (Rossi et al, 2008).

Formula	**Value**	**Rating**
$NSE = 1 - \left[\frac{\sum_i^n (xobs(i) - ymod(i))2}{\sum_i^n (xobs(i) - \overline{xobs})2}\right]$	>0.65	Very Good
	0.54 to 0.65	Adequate
	>0.50	Satisfactory
$PBIAS = \left[\frac{\sum_i^n (xobs(i) - ymod(i))}{\sum_i^n xobs(i)}\right]$	< ± 20%	Good
	± 20% to ± 40%	Satisfactory
	> ± 40%	Unsatisfactory
$RSR = \left[\frac{\sqrt{\sum_i^n (xobs(i) - ymod(i))^2}}{\sqrt{\sum_i^n (xobs(i) - \overline{xobs})^2}}\right]$	0.0 ≤ RSR ≤ 0.5	Very Good
	0.5 ≤ RSR ≤ 0.6	Good
	0.6 ≤ RSR ≤ 0.7	Satisfactory
	RSR ≥ 0.70	Unsatisfactory
$R^2 = \left[\frac{\left[\sum_i^n (xobs(i) - \overline{xobs})(ymod(i) - \overline{ymod})\right]^2}{\left[\sum_i^n (xobs(i) - \overline{xobs})^2 \sum_i^n (ymod(i) - \overline{ymod})^2\right]}\right]$		Satisfactory

Note: xobs=observed flow, ymod= model/simulated flow

3.1 Selection of Climate Change Scenarios

Temperature and precipitation change for eight GCMs over Brahmaputra river basin are analyzed for RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The results are separated for three periods; viz. 2010-2039 (2020s), 2040-2069 (2050s) and 2070-2099 (2080s). Monthly precipitation/temperature data for each model was averaged and compared with the base period data (1980-2010). All the GCM results for 2080s were compared to obtain the driest and wettest scenarios. Based on the analysis HADGEM2-ES (RCP 8.5) and BCC-CSM1.1 (RCP 8.5) have been found as the driest and the wettest scenario consecutively.

3.2 Pattern Scaling

Pattern scaling in particular is used to generate climate change scenarios under changes in anthropogenic forcing that have not been simulated by full GCMs, but can inexpensively be simulated by simpler (and computationally faster to run) climate models. In this study, Pattern scaling has been used to obtain future climate change scenarios. An open source tool namely MarkSim has been used for projecting climate change and downscaling the parameters of selected scenarios. MarkSim is a third-order Markov rainfall generator that has been developed over 20 years or so (Jones and Thornton, 1993, 1997). Climate parameters derived from MarkSim have further been used as an input in SWAT model to generate future projected streamflow of BRB for the 21st century.

4 Results and Discussions

4.1 Annual Water Balance

The annual water balance for the BRB during the climate normal period (1981-2010) indicate that on the average out of 1342 mm of rainfall, 328 mm (24%) are back to atmosphere through evapotranspiration, 246.65 mm (18.38%) converted into surface runoff, 119.31 (8.9%) mm contributed to stream flow through lateral flow and 621.27 mm (46.29%) percolated to shallow aquifer. From the shallow aquifer, 555.52 mm converted to stream flow through return flow and 21.74 mm recharge the deep aquifer. About 69% of the total rainfall contributes to stream flow. Baseflow contributes 73% of the total flow. Averaged monthly basin values for various components of the developed model (Rain, SurfQ= Surface runoff, LatQ= Lateral flow, GWQ=Ground water contribution to the stream, Water yield, ET=Evapotranspiration, PET=Potential Evapotranspiration) is shown in Figure 4.

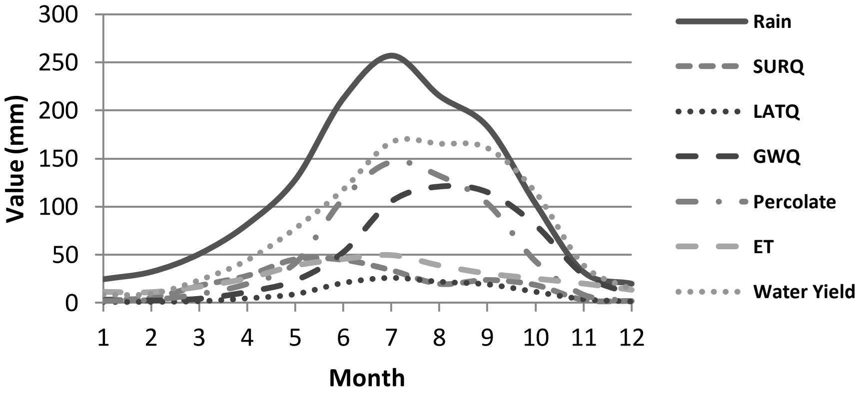


Figure 4: Average monthly water balance of BRB

4.2 Climate Change Analysis

SWAT simulated mean annual streamflow for two projected climate change scenarios (e.g., driest and wettest) for 2020s, 2050s, and 2080s have been compared with the observed streamflow for the the climate normal period (1981-2010). It is found that the mean annual streamfow of BRB is projected to be increased in both cases over 21st century. In general the projected increase in streamflow is less for driest scenario than the wettest scenario as in driest scenario, the enhanced evaporation due to increased temperature tries to balance the increase in streamflow due to increased precipitation. A monthly hydrograph for both driest and wettest scenarios along with climate normal scenarios are presented Figure 5 for three climate change periods (2020s, 2050s, and 2080s). Table 3 and Figure 6 shows the percentage changes in BRB mean annual streamflow, mean dry season (December-May) streamflow and mean wet season (June-November) streamflow with respect to the climate normal period for the driest and wettest scenarios.

4.2.1 Changes in streamflow in 2020s

In 2020s, mean annual streamflow is projected to increase by about 11% for the wettest scenario, whereas a decrease (about 3%) in flow is projected for the driest scenario. Mean dry season (December-May) flow is projected to increase for both of the scenarios in 2020s (e.g., wettest scenario projected about 80% increase, while the driest scenario projected about 12.5% increase). Mean wet season (Jun-November) streamflow was projected to increase for the wettest scenario (by about 9%), whereas a decrease in streamflow was projected for the driest scenario (by about 4.5%).

4.2.2 Changes in streamflow in 2050s

In 2050s, mean annual streamflow is projected to increase in both the scenarios. A moderate increase (about 3%) in average annual streamflow is projected for the driest scenario and a significant increase (about 26%) in mean annual streamflow is projected for the wettest scenario. While looking at the seasonality of projected streamflow, it was found that mean dry season streamflow are projected to increase by about 77% and 49% for the wettest and driest scenarios consecutively. Mean wet season streamflow is projected to increase for the wettest scenario (about 23% increase) while projected to decrease for the driest (about 1%) scenario.

4.2.3 Changes in streamflow in 2080s

By the end of the 21st century (e.g., 2080s), mean annual streamflow is projected to increase significantly for both scenarios. The maximum projected increase in streamflow (about 48%) was found for the wettest scenario (BCC-CSM1.1, RCP 8.5). The driest scenario (HADGEM2-ES, RCP 8.5) also projected significant increase in streamflow (about 19%). Mean dry season and wet season streamflow also increases for both scenarios in 2080s. The driest and the wettest scenarios projected an increase of 173.80% and 189.48% increase in dry season streamflow, respectively. The enhanced glacier melt induced by increased temperature is primarily responsible for this increase in streamflow which is also attributed by the increased snow fall in the headwaters. Mean wet season flow is projected to increase by about 35% and 6% for the wettest scenario and the driest scenario, respectively.

Table 3. Annual average, Dry period and wet period average streamflow change(%) at Bahadurabad station due for driest and wettest scenarios

Scenarios	**Q_{annual} (%)**			**Q_{dry} (%)**			**Q_{wet} (%)**		
	2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
Driest	-3.29	2.78	18.96	12.42	48.82	173.80	-4.62	-1.12	5.86
Wettest	11.04	26.89	47.44	31.37	77.16	189.48	9.32	22.63	35.42

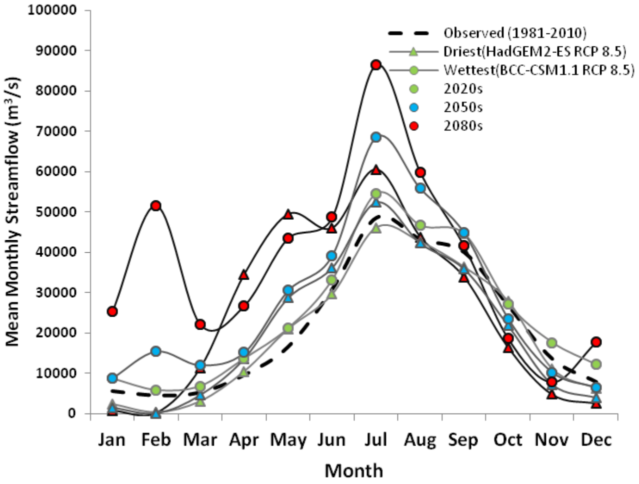
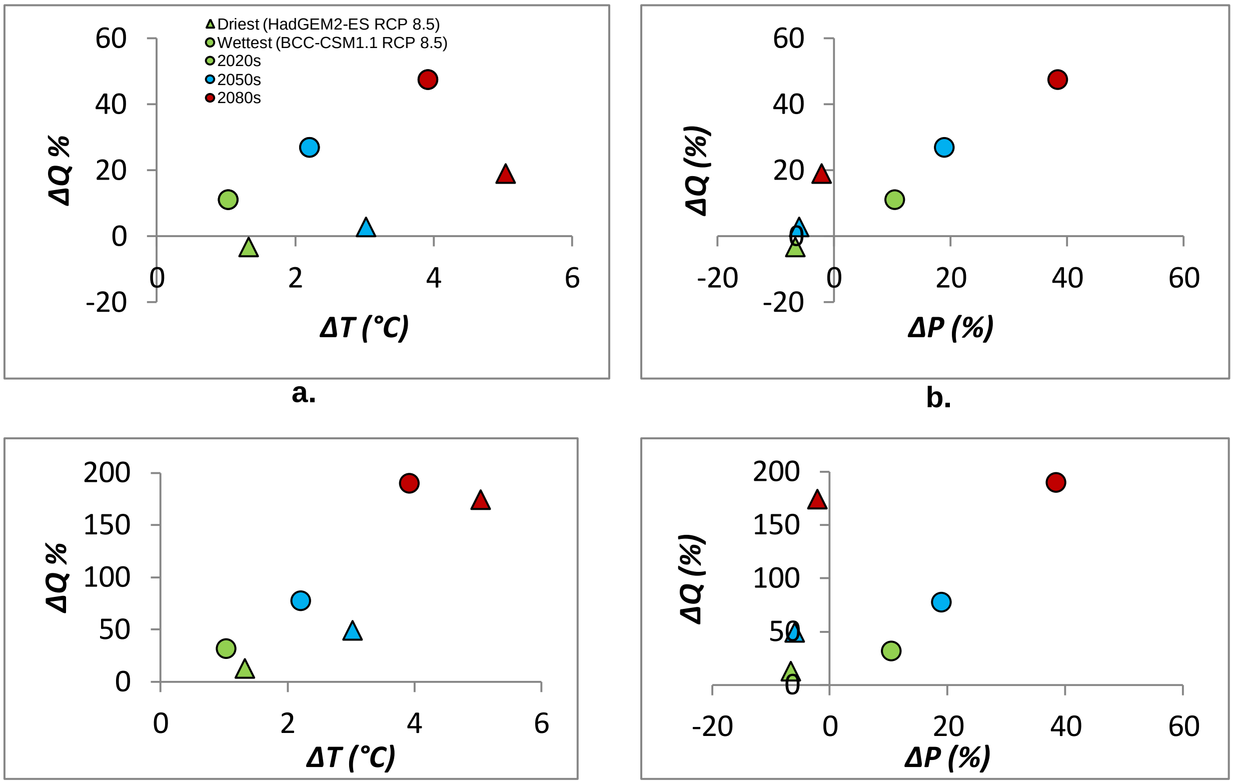


Figure 5: Monthly averaged hydrograph of BRB for climate normal (1981-2010) and for the driest and wettest climate change scenarios for the 2020s, 2050s and 2080s.



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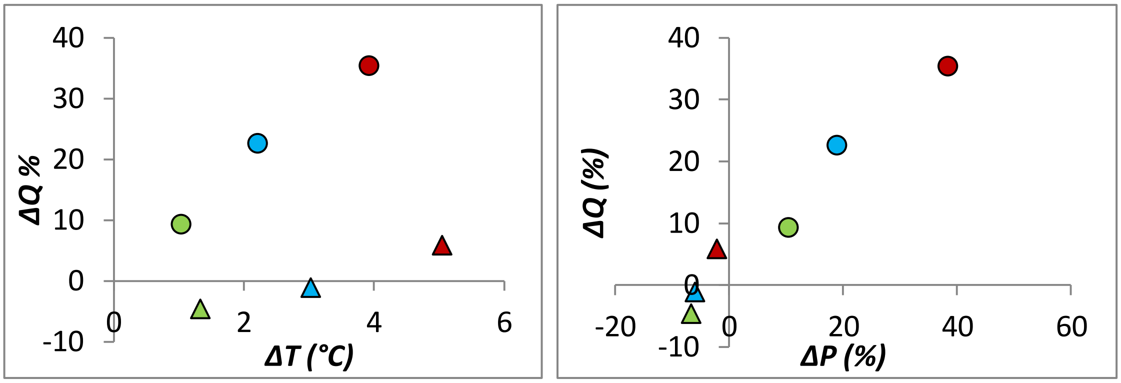

e. **f.**

Figure 6: Projected changes (from the climate normal period of 1981-2010) in mean annual (a and b), and mean dry seasonal (c and d), and mean wet seasonal (e and f) streamflow of Brahmaputra River Basin for the 21st century with respect to the potential changes in precipitation and temperature as simulated by two GCMs and RCPs scenarios (RCP 8.5 of HadGEM2-ES and (RCP 8.5 of BCC-CSM1.1).

5 Conclusion

A physically based hydrological model has been developed for Brahmaputra River Basin (BRB). The model has been calibrated and validated against measured streamflow for the climate normal period. Finally the future streamflow of the BRB has been simulated by running the model using two extreme climate change scenarios (driest scenario and wettest scenario). It was found that, by the end of the 21st century, mean annual streamflow is projected to increase significantly for both scenarios. The enhanced glacier melt induced by increased temperature is primarily responsible for this increase in streamflow in dry season while the increases rainfall primarily attributed the increased streamflow in wet season.

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