Future Streamflow of Brahmaputra River Basin under Synthetic Climate Change Scenarios

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Abstract: The Brahmaputra River Basin (BRB) is one of the major fresh water sources in South Asia. The current research attempts to assess impacts of climate change on streamflow of BRB using a physically based semidistributed hydrological model, namely, soil and water assessment tool (SWAT). SWAT was calibrated and validated for the climate normal period (1981–2010) at the Bahadurabad station in Bangladesh, and good agreement between observed and simulated streamflow was found. The model was then applied to simulate 24 synthetic climate change scenarios (combination of perturbed precipitation and temperature) to investigate the basin's sensitivity, in terms of streamflow, under the potential impact of climate change. It was found that the basin's projected streamflow responded almost linearly with projected temperature and precipitation. Mean annual streamflow changes of the BRB due to 1°C change in temperature (keeping the 1981–2010 baseline precipitation unchanged) was about 1.35%, whereas about 1.37% changes in mean annual streamflow were projected for 1% change in precipitation (keeping the baseline temperature unchanged). The results obtained using perturbed scenarios were used to develop a multivariable linear regression model representing future streamflow of BRB under the projected changes in temperature and precipitation. **DOI: 10.1061/(ASCE)HE.1943-5584.0001435.** *© 2016 American Society of Civil Engineers.*

Author keywords: Synthetic climate change; Brahmaputra River Basin; SWAT.

Introduction

Brahmaputra River Basin (BRB), one of the largest basins in the Ganges-Brahmaputra-Meghna (GBM) river system, carries enormous amounts of water and sediment to the Bay of Bengal through China, India, Bhutan, and Bangladesh. Being a lower riparian country of the GBM basin, the socioeconomic conditions (e.g., poverty, regional development, food production, etc.) of Bangladesh depend on the GBM river flows. Moreover, this basin is one of the most vulnerable areas in the world under the potential impact of climate change (Gain et al. 2011). Climate change will potentially alter the annual flow pattern and seasonal variation of streamflow, which will have a significant impact on economic development of Bangladesh (Climate Change Cell 2006). Because of global warming, type, frequency, and intensity of cyclones and heavy precipitation are expected to increase, which may increase the risks of flooding (UNFCCC 2007). In contrast, increased temperature may cause reduction of dry season flow (Oki and Kanae 2006) which may impact agricultural production, navigation, and sedimentation issues in rivers. Thus, it is very important to investigate the response of this basin to potential climate change in order to plan for proper adaptation measures.

In the past, several climate change studies on water availability in BRB have been conducted (e.g., Mirza and Dixit 1997; Seidel et al. 2000; Mirza 2002; Mirza et al. 2003; Gain et al. 2011; Ghosh and Dutta 2012). Mirza and Dixit (1997) used an empirical model to test the sensitivity of runoff of the GBM basin. According to their study, the projected increase in mean annual runoff for the BRB at Gauhati station, for a 2°C increase in temperature and 10% increase in precipitation changes, was about 13%. With a higher increase in temperature (5°C) and precipitation (20%), the increase in the average annual runoff was projected as 22%. Seidel et al. (2000) applied the snowmelt runoff model (SRM) to determine the changes in the monsoon flood for a 1.5°C increase in temperature and a 10% increase in summer precipitation. Under this synthetic climate change scenario, the monsoon flood peaks are projected to increase by about 30% for the BRB (compared to the 1995 level). Mirza (2002) and Mirza et al. (2003) studied sensitivity of the mean annual discharges and the monsoon flooding of GBM basin because of several synthetic changes in temperature (e.g., 2, 4, and 6°C) and standardized precipitation changes. They used meteorological output from various general circulation models (GCMs) such as CSIRO9, HadCM2, GFDL, LLNL, and HadCM2 in an empirical model to evaluate these sensitivities. Gain et al. (2011) investigated effects of climate change on both low and high flows of the lower Brahmaputra River by applying climate scenarios of twelve GCMs forced by the A1B and A2 special report on emissions scenarios (SRES) scenarios of the Intergovernmental Panel on Climate Change (IPCC). Ghosh and Dutta (2012) used downscaled climate data of the A2 SRES scenario from the regional climate modeling system providing regional climates for impacts studies (PRECIS) to estimate magnitude and frequency of mean annual peak discharge of BRB using a distributed hydrological model rice irrigation system evaluation (RISE). According to this study, the BRB will potentially experience a 12% increase in median premonsoonal peak discharge at the Tezpur gauging site (Bangladesh). Masood et al. (2015) assessed impact of climate change on the GBM basin for three 25-year periods, viz. present-day (1979–2003), near-future (2015–2039), and far-future (2075–2099). They used a macroscale global water resources model (H08) to simulate the hydrology of the GBM basin. According to their study, the BRB will potentially

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experience a 14% increase in mean annual discharge by the end of 21st century because of a 14% increase in precipitation and 3°C increase in temperature.

The aforementioned review of literature on greater GBM basin, or BRB, shows that a wide number of climate change impact studies have been conducted using empirical/conceptual/lumped hydrological models that are generally not physically based, and may not consider spatial variations of basin characteristics (e.g., land use, topography, soil type). However, in order to consider the long-term prediction of basin streamflow changes because of the potential impact of climate change, consideration of spatial heterogeneity is crucial. This can be achieved by using a physically-based hydrological model. Moreover, physically-based hydrologic models are based on known scientific principles of energy and water fluxes, whereas conceptual models are based on conceptual storages and model parameters that require rigorous calibration (Islam and Gan 2015). Conceptual hydrologic models generally require substantially less data, but model parameters require extensive model calibration. Moreover, some calibrated model parameters may not be valid when the hydrologic regime of the river basin changes because of anthropogenic impacts. In contrast, it requires a significant amount of atmospheric, soil, and topographical data to drive a semidistributed or fully distributed, physically-based hydrologic model.

In the current research, an attempt has been made to apply the physically-based semidistributed hydrologic model soil and water assessment tool (SWAT) of Arnold and Allen (1996) to simulate the hydrologic processes of the BRB. Moreover, the model's sensitivity to simulating changes in mean annual and seasonal streamflow due to the potential changes in precipitation and temperature has also been investigated using 24 synthetic climate change scenarios (combination of perturbed temperature and precipitation). Additionally, results obtained from these synthetic climate change scenarios have been used to develop a multivariate regression model in order to predict the future streamflow of BRB for any potential changes in temperature and precipitation. In a future extension of this study, the calibrated model will be used to simulate hydrologic responses of BRB under the representative concentration pathways (RCP) scenarios projected by multiple GCMs of the IPCC to provide recommendation on potential adaptation measures.

Brahmaputra River Basin

The BRB, as shown in Fig. 1, is a part of the greater GBM basin. It is one of the major river basins in the world, draining an area of about 530, 000 km^2 through China (50.5% of the entire basin area), India (33.6%), Bangladesh (8.1%), and Bhutan (7.8%) (Immerzeel 2008). The BRB receives flow from 22 major tributaries in Tibet, 33 in India, and three in Bangladesh (Sarkar et al. 2012). The main channel is generally wide and has a gentle bed slope in the lower reaches (about 0.079 m/km), whereas in the upstream Himalayan region the channel is generally narrow and the gradient is about 16.8 m/km (Sarkar et al. 2012). Mean annual discharge of the BRB at the Bahadurabad station of Bangladesh (as shown in Fig. 1, at the downstream end of the BRB) is about 20,000 m^3/s (Immerzeel 2008). The BRB can be classified into three different physiographic zones, the Tibetal Plateau (elevation is greater than 3,500 m), the Himalayan Belt (elevation ranges between 100 and 3,500 m), and the floodplain (elevation is less than 100 m), covering 44.4, 28.6, and 27% of the basin area, respectively (Immerzeel 2008). The climate of the BRB is mainly driven by monsoon season (June to September) which accounts for 60–70% of annual rainfall (Immerzeel 2008). Total annual rainfall at the downstream end of the BRB is 2,354 mm (Gain et al. 2011).

The BRB is regulated by several hydroelectric dams in India and China. Most of these dams are constructed on the tributaries flowing through the Nagaland, Assam, Meghalaya, Sikkim, and Arunachal states of India. Recently, China has constructed a run-of-the-river hydroelectric dam (Zangmu Dam), which is one of the four dams planned to be constructed on the main stem of the Brahmaputra River. Moreover, there are other dams in China constructed in the tributaries of the Brahmaputra River (e.g., Pangduo and Zhikong hydropower stations in the Lhasa River, Yamdrok hydropower station in Yamdrok Lake, etc.). Other than hydroelectric power generation, river water is also diverted for irrigation purposes. More than twenty barrages are constructed on

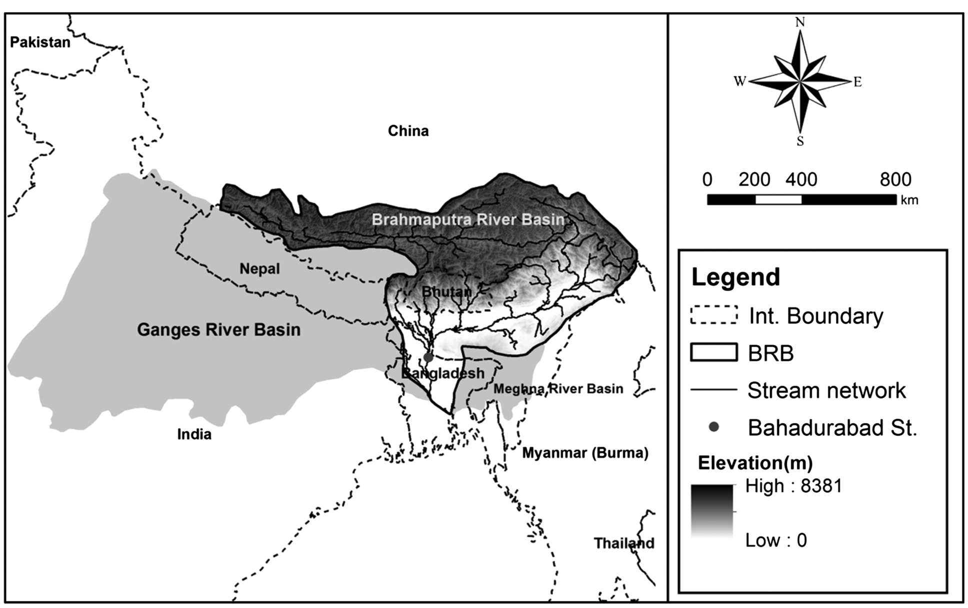

Fig. 1. Map of BRB within the spatial extent of greater GBM basin (map data from World Resource Institute 2011)

several tributaries of Brahmaputra River in India and Bangladesh (e.g., Teesta Barrage in Bangladesh and in India).

Even though Brahmaputra is a perennial river and more than 70% of the mean annual runoff is contributed from the baseflow (combination of shallow groundwater inflow and subsurface flow; please see the "Annual Water Balance for the Climate Normal Period (1981–2010)" section for details), the variation in mean dry season and wet season discharge is quite high. Based on the observed streamflow of the BRB for the 1981–2010 period, the mean annual discharge at Bahadurabad station is about 21,250 m^3/s, whereas the mean dry season (November–March) and wet season (April–October) discharges are about 7,565 m^3/s and 30,840 m^3/s, respectively. Only 15% of the total annual streamflow is available throughout the dry season (5 months) and the remaining 85% is available in wet season (7 months).

Model and Data

SWAT Model

The physically-based hydrological model SWAT of Arnold and Allen (1996), selected for this study, operates on a daily time step and uses physiographical data (e.g., elevation, soil use, land use), meteorological data, and streamflow data. The hydrological processes included in the model are evapotranspiration (ET), surface runoff, infiltration, percolation, shallow and deep aquifer 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 subbasins based on drainage areas of tributaries. Then, these subbasins are further divided into a number of hydrological response units (HRUs) based on the land cover, slope 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 land uses and soils. All the computations are performed at HRU level (Mengistu and Sorteberg 2012). The hydrologic cycle as simulated by SWAT is based on the water balance equation

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

where SW_t = final soil water content on day t; SW_0 = initial soil water content; R_{day} = amount of precipitation; Q_{surf} = amount of surface runoff; E_a = amount of evapotranspiration; W_{seep} = amount of water entering vadose zone from soil profile; and Q_{gw} = amount of return flow on day i. Note that all units except time are presented as mm of water.

Data

Table 1 shows different input data applied in SWAT modeling of the Brahmaputra River Basin. SWAT requires several spatially distributed physiographical data, such as topographical data or digital elevation model (DEM), soil properties map, and land-use map (Fig. 2). A DEM of 90-m grid resolution was downloaded from the Shuttle Rudder Topography Mission (SRTM) website (http://srtm.csi.cgiar.org/). This was further used to delineate the watershed and the drainage pattern for the surface area analysis (e.g., terrain slope, channel length, channel slope). Soil map of the selected area was collected from the Harmonized World Soil Database (HWSD). The HWSD has 1-km 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, and saturated hydraulic conductivity. A land-use map of the basin area was collected from the United States Geological Survey (USGS); it has a spatial resolution of 1 km and consists of different classes of land-use type. Land-use classes have been parameterized based on existing SWAT land-use classes. The BRB consists of several land-use areas, including snow and ice (5.86%), forest (29.08%), grassland (49.77%), cropland (14.52%), urban area (0.03%), and barren land (0.74%) (Whitehead et al. 2015).

SWAT requires different types of meteorological data to simulate the hydrological processes. These data include daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. For this study, meteorological data have been collected from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy (POWER) database; NASA-POWER data consists of reanalysis data of Modern-Era Retrospective Analysis for Research and Applications (MERRA). MERRA is a NASA reanalysis data source for the satellite era that uses the new version of the Goddard Earth Observing System Data Assimilation System Version-5 (GEOS-5). This provides a state-of-the-art global analysis, which emphasizes improved estimates of the hydrological cycle (Schubert et al. 2008). Daily meteorological data (precipitation, minimum temperature, and maximum temperature) for the climate normal period (1981–2010) has been collected for the SWAT model. These precipitation and temperature data were then applied to the SWAT to simulate the streamflow of the BRB at Bahadurabad station in Bangladesh, and finally compared with the measured discharge data collected from the Bangladesh Water Development Board (BWDB).

Table 1. Different Input Data Applied in SWAT Modeling of Brahmaputra River Basin

Type	Description	Source/reference	Spatial resolution	Period	Remarks
Physical data	Digital elevation map (DEM)	SRTM[a]	90 × 90 m		DEM was resampled to get relatively coarser resolution (270 × 270 m) for faster computation
	Soil data	HWSD[b]	—	—	—
	Land-use data	USGS	—	—	—
Meteorological data	Precipitation, temperature	NASA POWER[c]	$1^\circ \times 1^\circ$	1981–2010	—
Hydrological data	Discharge	Bangladesh water development board (BWDB)	Gauged	1981–2010	Discharge data at Bahadurabad station was collected. Some data were missing mostly during dry period flow

[a]Shuttle rudder topographic mission.
[b]Harmonized world soil database (FAO/IIASA/ISRIC/ISSCAS/JRC 2012).
[c]NASA prediction of worldwide energy resource (NASA 2016).

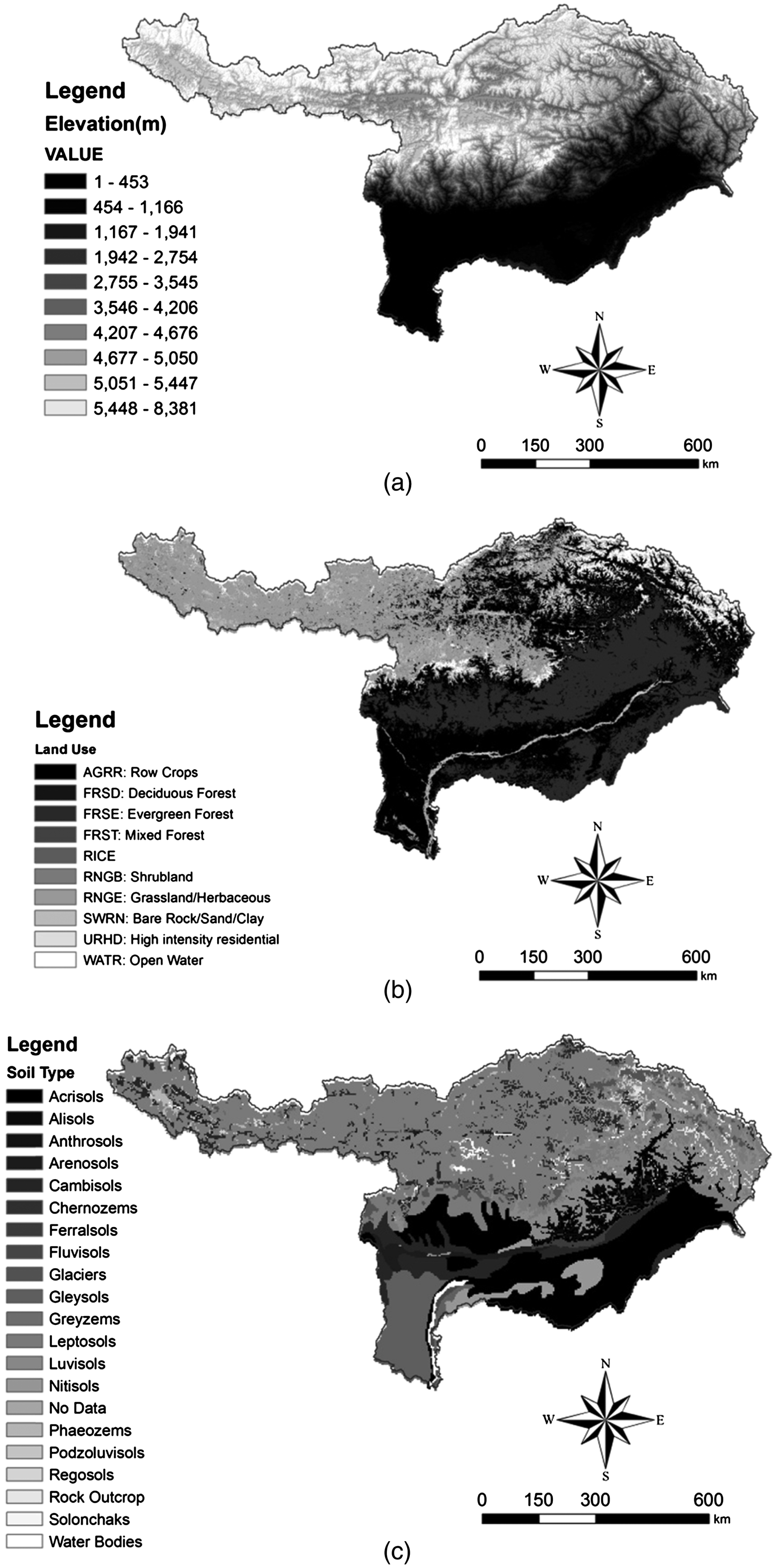

Fig. 2. Physiographical data of BRB: (a) digital elevation model; (b) land-use map; (c) soil map

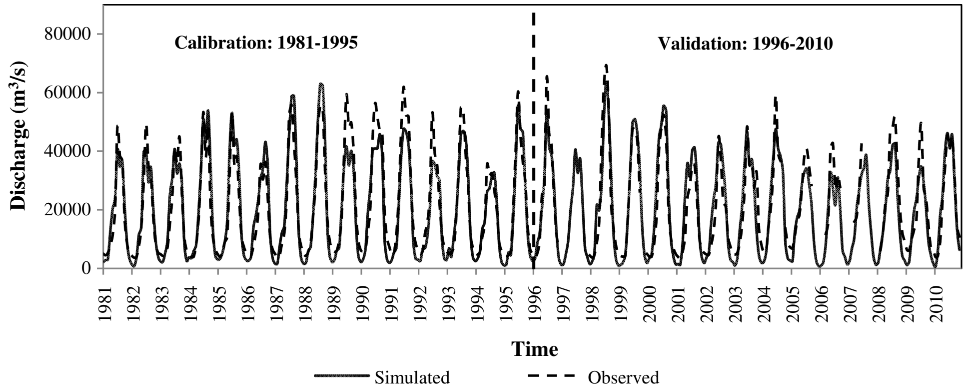

Fig. 3. Comparison of observed and SWAT simulated monthly streamflow at Bahadurabad stations for calibration (1981–1995) and validation (1996–2010) period

Methodology

Model Setup

The first step in the model setup involves a delineation of the basin and subbasin boundaries. This was accomplished using the automatic watershed delineation tool of *ArcSWAT* (version 2012.10.2.16) using the 90 m DEM of SRTM. Because it takes a large computation effort to use 90 m resolution DEM for a large basin like the BRB, the SRTM 90 m DEM has been resampled to obtain relatively coarser resolution of 270 × 270 m. After delineation, the BRB was divided into 149 subbasins. Soil and land-use maps were loaded into SWAT to extract land-use 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 the basin into HRUs allows a detailed simulation of the spatial variability of the hydrological processes. Daily precipitation, maximum temperature, and minimum temperature data were then applied for the 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 model was simulated from 1978 to 2010 with a daily time step where initial 3 years (1978–1980) were used as a model warm-up period.

Calibration and Validation

The model was calibrated from 1981 to 1995 and validated from 1996 to 2010 with monthly observed streamflow data of the BRB at the Bahadurabad station in Bangladesh. In the calibration and validation stages, model performances were evaluated statistically and graphically. Fig. 3 shows the graphical representation of monthly observed and simulated flow for both calibration and validation period. It was found that the simulated streamflow is in good agreement with the observed discharge for both monsoon and dry seasons.

Statistically, the performance of the model in both calibration and validation stages 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 and 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 the calibration and validation period, respectively. The coefficient of determination (R^2) is 0.90 for the calibration period and 0.87 for the validation period. The PBIAS and RSR values are found to be 3.49 and 0.28 in the calibration stage, and 3.28 and 0.34 in the validation stage, respectively. These statistics demonstrate that SWAT generally performed well in both calibration and validation stages based on historical measured data for BRB, which establishes the basis for conducting climate change studies based on the simulations of the SWAT, assuming the basin's physical conditions remain basically unchanged.

Synthetic Climate Change Scenarios

Sensitivity analysis of the model under potential future climate change was performed by perturbing the baseline climate (e.g., precipitation and temperature of climate normal period of 1981–2010) by an arbitrary value and then run the model with changed precipitation and temperature.

First, precipitation perturbations (ΔP) were generated as a percentage change in precipitation (precipitation is multiplied with a given factor), whereas temperature perturbations (ΔT) were generated adding the prescribed changes to the baseline simulation temperature

$$\Delta T = 0°, +2°, +4°, \text{and} + 6°\text{C}$$

$$\Delta P = 0, \pm 10\%, +20\%, \text{and} + 40\%$$

The precipitation and temperature perturbations were selected such that they capture the GCM-projected temperature and precipitation changes in the 21st century for the BRB. Fig. 4 shows projected changes in precipitation and temperature in the BRB based on the RCP scenarios (RCP 2.6, RCP 4.5, RCP 6, and

Table 2. Model Performance Presented as Goodness-of-Fit Statistics for Calibration (1981–1995) and Validation Period (1996–2010) of Brahmaputra River Basin (Table 3 for details)

Period	Observed mean (m^3/s)	Simulated mean (m^3/s)	NSE	R^2	PBIAS	RSR
Calibration	21,205	20,468	0.90	0.90	3.49	0.28
Validation	21,902	19,944	0.86	0.87	3.28	0.34

Note: NSE = Nash–Sutcliffe efficiency; PBIAS = mean relative bias; RSR = root mean square error-standard deviation ratio; and R^2 = coefficient of determination.

Table 3. Definitions of Goodness-of-Fit Statistics and Their General Reported Ratings (Data from 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 0.54 to 0.65 >0.50	Very good Adequate Satisfactory
$PBIAS = \left\{\frac{\sum_i^n[xobs(i) - ymod(i)]}{\sum_i^n xobs(i)}\right\}$	< ±20% ±20 to ±40% > ±40%	Good Satisfactory Unsatisfactory
$RSR = \left\{\frac{\sqrt{\sum_i^n[xobs(i) - ymod(i)]^2}}{\sqrt{\sum_i^n[xobs(i) - \overline{xobs}]^2}}\right\}$	$0.0 \leq RSR \leq 0.5$ $0.5 \leq RSR \leq 0.6$ $0.6 \leq RSR \leq 0.7$ $RSR \geq 0.70$	Very good Good Satisfactory Unsatisfactory
$R^2 = \left(\frac{\{\sum_i^n[xobs(i) - \overline{xobs}][ymod(i) - \overline{ymod}]\}^2}{\{\sum_i^n[xobs(i) - \overline{xobs}]^2 \sum_i^n[ymod(i) - \overline{ymod}]^2\}}\right)$	≥ 0.6	Satisfactory

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

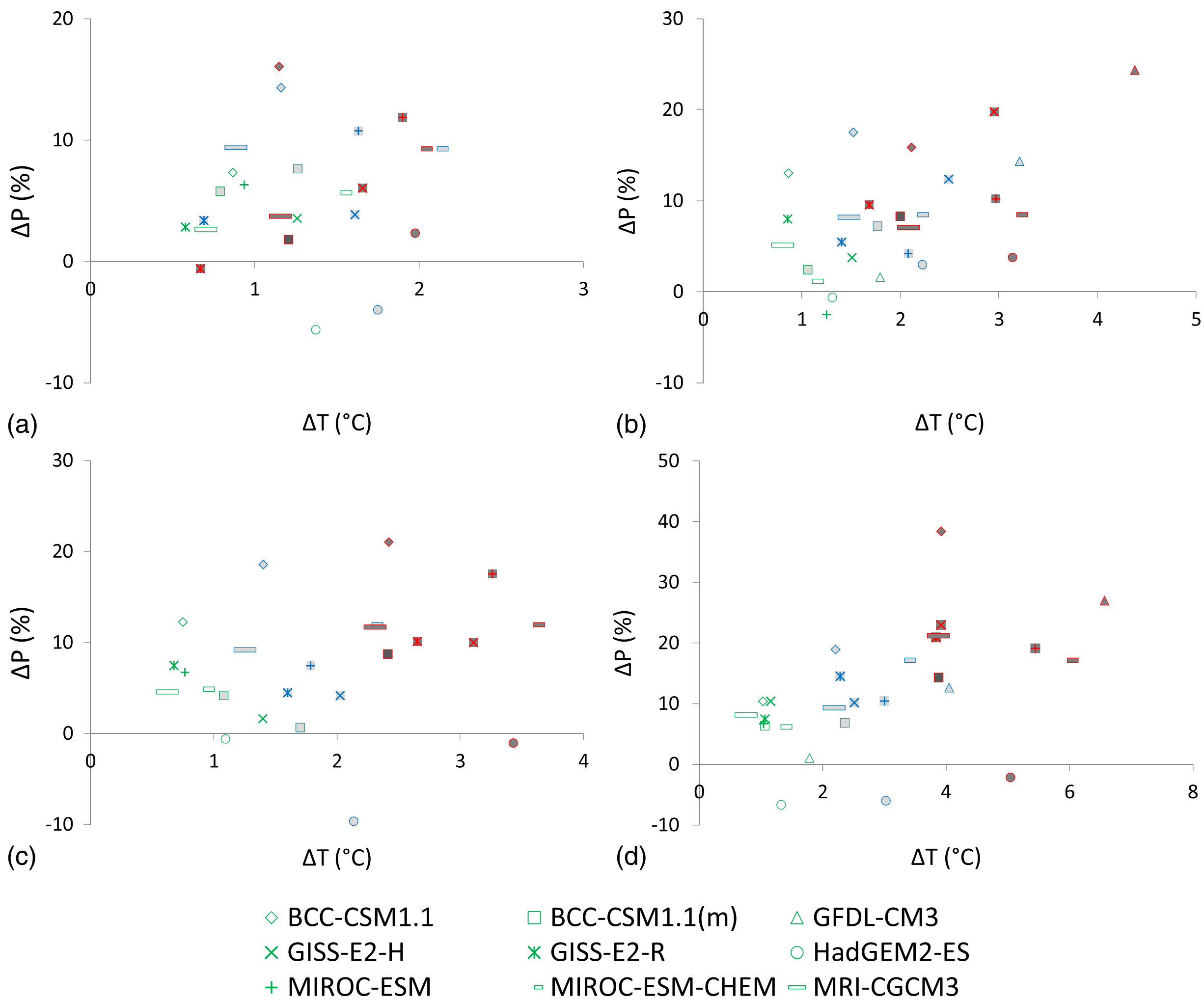

Fig. 4. Projected changes in precipitation and temperature in Brahmaputra River Basin based on the RCP scenarios of multiple GCMs (unshaded, light shaded, and dark shaded legends represents projections from 2020s, 2050s, and 2080s, respectively): (a) RCP 2.6; (b) RCP 4.5; (c) RCP 6; (d) RCP 8.5

RCP 8.5) of multiple GCMs (BCC-CSM1.1, BCC-CSM1.1 (m), GFDL-CM3, GISS-E2-H, GISS-E2-R, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3). According to the these scenarios (IPCC 2014), projected changes in precipitation in BRB range from −10% (at the early 21st century) to about 40% (by the end of 21st century), whereas the temperature can increase from about 1°C (at the early 21st century) to about 6°C (by the end of 21st century) (IPCC 2014). Thus, the designed synthetic climate change scenarios are representative of the projected RCP climate change scenarios in the BRB.

Table 4. SWAT-Simulated Changes in Mean Annual Discharge (%) Due to Changes in Temperature and Precipitation of Brahmaputra River Basin

Temperature changes	$\Delta P = -10\%$	$\Delta P = 0\%$	$\Delta P = 10\%$	$\Delta P = 20\%$	$\Delta P = 30\%$	$\Delta P = 40\%$
$\Delta T = 0°C$	−13.61	0.00	13.67	27.37	41.10	54.80
$\Delta T = 2°C$	−16.01	−2.40	11.26	24.95	38.65	52.34
$\Delta T = 4°C$	−18.77	−5.19	8.44	22.11	35.80	49.49
$\Delta T = 6°C$	−21.46	−7.96	5.61	19.23	32.89	46.56

Historical time series of climatic normal data (1981–2010) were adjusted for temperature and precipitation perturbations to generate climate data for the synthetic climate change scenarios

$$T_2 = T_1 + \Delta T \tag{2}$$

$$P_2 = P_1 + \Delta P \tag{3}$$

where T_1 and T_2 = climate normal (1981–2010) and future temperature; and P_1 and P_2 = climate normal (1981–2010) and future precipitation, respectively.

Finally, SWAT was run for 24 combinations of perturbed temperature and precipitation (Table 4) in order to simulate changes in the hydrological processes due to potential climate changes.

Many climate change studies on water resources impact assessment are based on this synthetic approach of climate change modeling (e.g., Nemec and Schaake 1982; Gleick 1986, 1987; McCabe and Ayers 1989; Schaake and Liu 1989; Nash and Gleick 1990; Vehviläinen and Lohvansuu 1991; Panagoulia 1991; Arnell 1992; Ng and Marsalek 1992; Whetton et al. 1993; Avila et al. 1996; Singh and Kumar 1997; Xu and Halldin 1997; Xu 2000; Guo et al. 2002; Davies 2004; Jiang et al. 2007). Major advantages of this method are: it is the simplest approach to account for climate change studies, some of the uncertainties associated with GCM projection may be avoided, it facilitates the sensitivity analysis by estimating the amount of change in a hydrologic variable resulting from incremental changes in climate variable, it can assist in identifying critical thresholds or discontinuities of response to a changing climate, and it can be replicated in different studies and regions. In contrast, this approach has some disadvantages too: this type of climate change scenario is not based on the consequences of increased greenhouse gas concentrations and may not be realistic because the range in variability of the generated climate data remains unchanged (Githui et al. 2009; Xu 1999, 2000; IPCC 2001; Praskievicz and Chang 2009). Moreover, this approach does not consider any seasonal variability in changes in precipitation and temperature.

Although climate scenarios based on GCM simulations have been used increasingly, that approach has limitations too: GCMs remain coarse in spatial resolution and are unable to resolve various subgrid scale features required for impact studies (Fowler et al. 2007); GCM-simulated climate variables used for hydrologic impact studies (e.g., precipitation, temperature) are more reliable in seasonal or monthly scales, whereas hydrological models typically use daily time step (Schulze 1997; Xu 1999); GCM simulations are more accurate for calculating the free troposphere variables than the surface variables, whereas the ground surface variables directly affect the surface processes (Xu 1999); and GCMs can predict climate related variables (e.g., wind speed, temperature, humidity, air pressure, etc.) more accurately than the variables important for hydrologic impact assessment (e.g., precipitation, runoff, soil moisture, evapotranspiration) (Xu 1999). Significant downscaling techniques are required to incorporate GCM simulation results in hydrologic impact studies in order to avoid those limitations. The sensitivity of the SWAT hydrological model in the BRB under a wide number of temperature and precipitation changes needed to be analyzed before applying any complex downscaling techniques.

It is beyond the scope of this study to consider the impact of changes in the physical condition of the BRB to its future streamflow projecting climate change impact based on these synthetic climate scenarios. There is no basis to assume possible changes to the physical condition of BRB in the 21st century even though such changes are possible.

Multivariable Regression Analysis

Multiple linear regression attempts to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to observed data. In this study, the SWAT simulated streamflow obtained for perturbed precipitation and temperature changes have been used to develop a multivariate regression between changes in the climatic input (ΔT and ΔP) and the mean annual and the mean seasonal discharges of the BRB

$$Q = a_1 + a_2 \times (\Delta T) + a_3 \times (\Delta P) \tag{4}$$

where Q = mean annual or seasonal discharge of the BRB; ΔT and ΔP = changes in temperature (°C) and precipitation (%) respectively; and a_1, a_2, and a_3 = regression coefficients.

Results and Discussions

Annual Water Balance for the Climate Normal Period (1981–2010)

Water balance in SWAT considers precipitation as the inflow to the delineated subbasins, evapotranspiration and deep percolation as the water loss, and surface runoff and lateral inflow as the outflow to the basin outlet. According to the conservation of mass, the difference between total incoming water and total losses will be balanced by the water storage in a river basin. Results obtained for the 30-year climate normal (1981–2010) simulation were used for evaluation of the water balance of the BRB. Streamflow (combination of surface runoff, subsurface runoff, and shallow groundwater flow into the river) was found to be 66% of the total basin precipitation, whereas 24% of the precipitation turned into evapotranspiration and 2% moved to deep percolation. Baseflow (combination of subsurface runoff and lateral inflow from shallow aquifer) and surface runoff contributed 72 and 28% of the total flow, respectively.

Future Streamflow of BRB Subjected to Changes in Precipitation

For the BRB, changes in average annual streamflow because of projected changes in precipitation (±10, +20, +30, and +40%) while keeping the temperature unchanged at 0, 2, 4, and 6°C are shown in Fig. 5(a). A linear regression analysis of the streamflow responses for the various scenarios indicated that a 10%

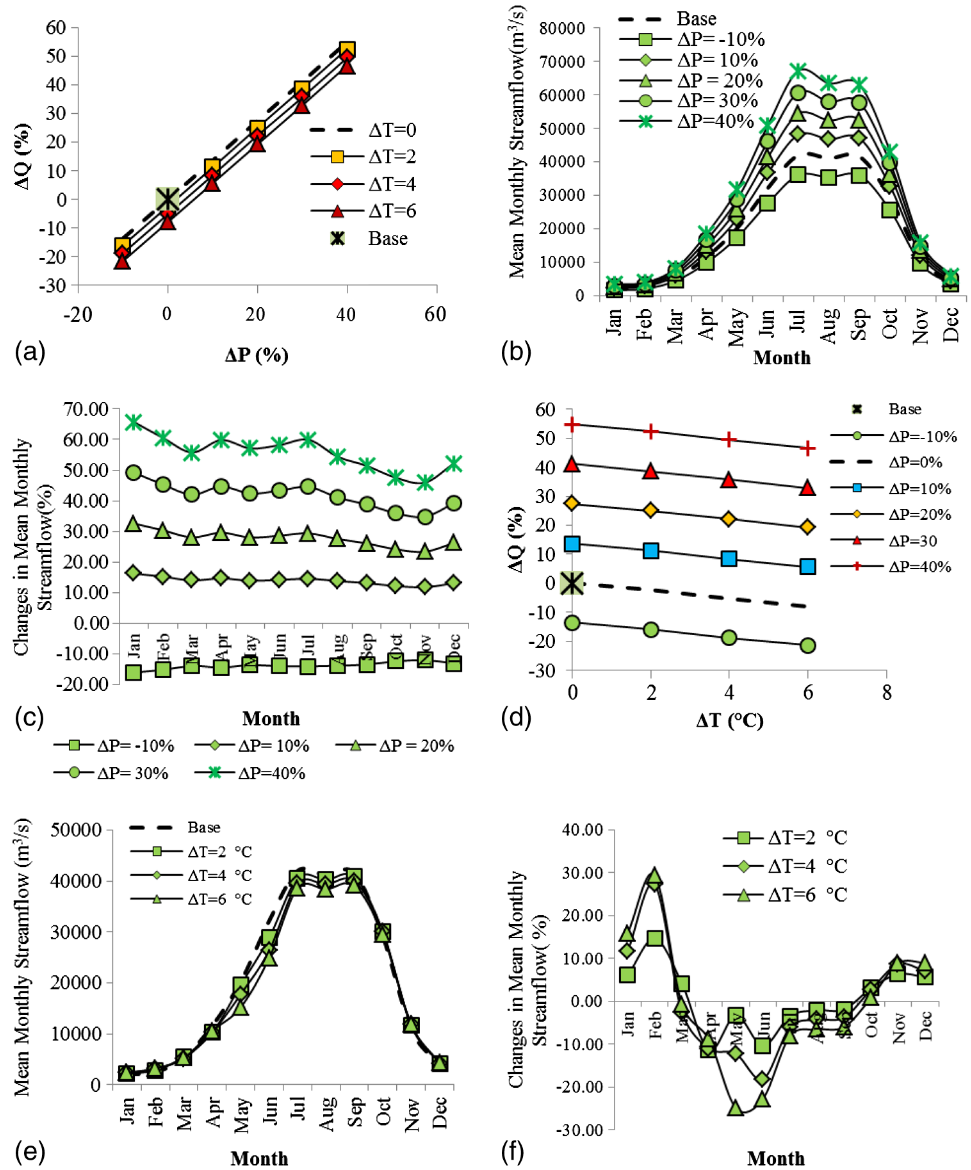

Fig. 5. (a) Changes in annual mean streamflow ($\Delta Q\%$) of the Brahmaputra River Basin at the Bahadurabad station versus changes in precipitation ($\Delta P\%$) at different temperature changes (ΔT); (b) mean monthly streamflow at various $\Delta P\%$ (keeping temperature unchanged); (c) changes in mean monthly streamflow at various $\Delta P\%$ (keeping temperature unchanged); (d) $\Delta Q\%$ versus ΔT at different $\Delta P\%$; (e) mean monthly streamflow at various ΔT (keeping precipitation unchanged); (f) changes in mean monthly streamflow at various ΔT (keeping precipitation unchanged)

change in precipitation would produce about 13.7% change in streamflow for the BRB. Fig. 5(a) shows that the BRB is almost equally sensitive to both reduction and increase in precipitation (while keeping the temperature unchanged), and the basin's streamflow is almost linearly related to the precipitation changes. Mean monthly discharge for variable precipitation (while keeping the temperature unchanged) is shown in Fig. 5(b). Annual peak discharge appears in July for almost every scenario. Changes in the mean monthly discharge (while keeping the temperature unchanged) from the climate normal (1981–2010) are shown in Fig. 5(c). Streamflow changes from the climate normal are almost uniform in every season. Although this increase/decrease in streamflow is more prominent in the dry season (e.g., November–March), much of this seasonal uniformity is probably because of the seasonally uniform changes in precipitation and temperature. Seasonal variations in changes in streamflow due to projected changes in precipitation are presented in Fig. 6(a). In general, future dry season (November–March) streamflow (with respect to projected increase in precipitation) are projected to increase more than the projected wet season (April–October) streamflow.

Future Streamflow of BRB Subjected to Changes in Temperature

Fig. 5(d) shows changes in the mean annual streamflow due to the projected changes in temperature (+2, +4, and +6°C) while keeping the precipitation unchanged. A linear regression analysis of the streamflow responses for the various temperature scenarios indicated that a 1°C increase in temperature would produce a 1.35% reduction in annual streamflow for the BRB (while keeping precipitation unchanged). Mean monthly discharge for different temperature increase scenarios (while keeping precipitation unchanged) are presented in Fig. 5(e). Compared to the climate normal scenario (1981–2010), mean monthly flow decreases if temperature of the

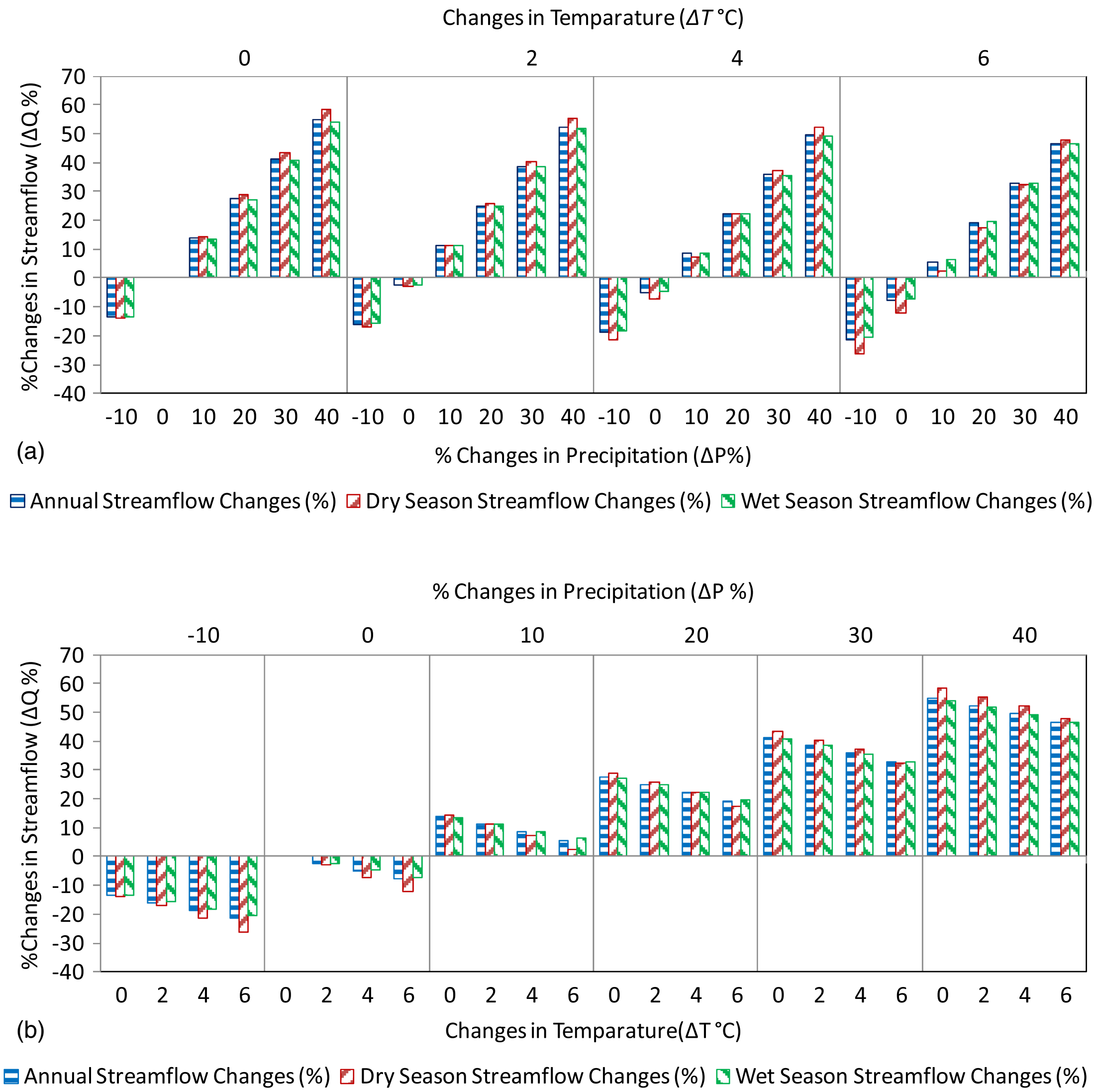

Fig. 6. Comparison of changes in annual streamflow and seasonal streamflow under various changes in temperature and precipitation

BRB increases. Increased temperature enhances evaporation, which increases water loss from the system. Changes (%) in the monthly mean discharge are also shown in Fig. 5(f). During the high flow season (April–September), monthly streamflow of the BRB decreases if temperature increases. In contrast, monthly discharge in October–March (mostly dry period) projected to increase (for increased temperature) with respect to the climate normal because of enhanced snowmelt caused by increased temperature. Seasonal variations of the changes in streamflow because of projected changes in precipitation are presented in Fig. 6(a). In general, future mean dry season streamflow is projected to be higher than the projected mean wet season streamflow. Seasonal variations in streamflow changes due to the projected changes in temperature are presented in Fig. 6(b). Future dry season (November–March) streamflow (with respect to projected increase in temperature) is projected to be higher than the projected wet season (April–October) streamflow.

Future Streamflow of BRB Subjected to Combined Changes in Temperature and Precipitation

In general, an increase or decrease in precipitation causes a respective increase or decrease in mean annual streamflow in the BRB if temperatures remain unchanged. In contrast, increased temperature (keeping precipitation unchanged) enhances evaporative loss from the terrestrial surfaces and the shallow aquifer, resulting in a decrease in mean annual streamflow. If we allow both temperature and precipitation changes at the same time, there could be different scenarios as discussed in the following subsections. The monthly mean discharge and different components of the water balance (e.g., precipitation, evaporative loss, streamflow, groundwater recharge) under these scenarios are also presented in Figs. 7(a and b), respectively.

1. Warm and dry condition (e.g., $\Delta T = +6°\text{C}$, $\Delta P = -10\%$): enhanced evaporation (increased by 21% compared to the 1981–2010 period) because of increased temperature and decreased precipitation will decrease mean annual discharge, and the basin will experience dry conditions. Mean annual streamflow could be decreased by about 22% compared to the climate normal (1981–2010).
2. Warm and wet condition ($\Delta T = +6°\text{C}$, $\Delta P = +40\%$): enhanced basin runoff due to increased precipitation will offset the enhanced evaporation (increased by 28% compared to the climate normal period) due to increased temperature. Mean annual streamflow could be increased by about 47%. This is a representative condition at the end of 21st century.

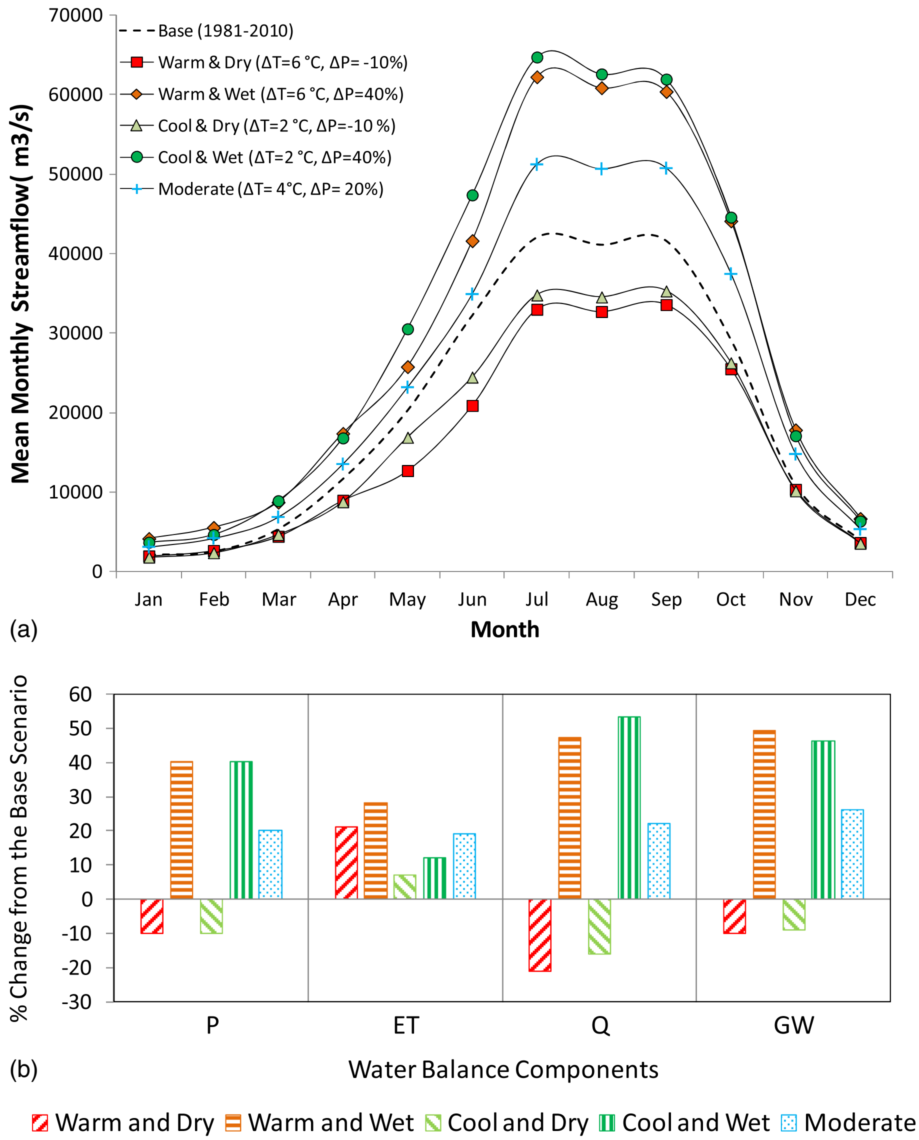

Fig. 7. Water balance of BRB at Bahadurabad station due to combined impact of temperature (ΔT) and precipitation changes ($\Delta P\%$): (a) mean monthly discharge; (b) annual water balance

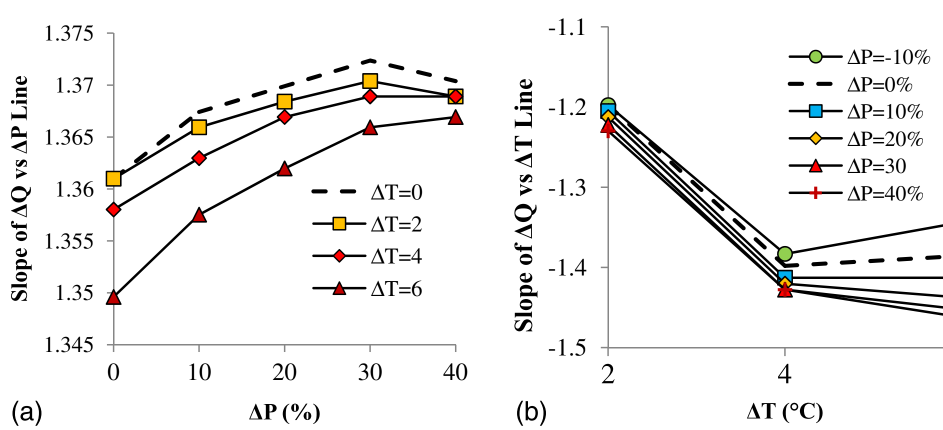

Fig. 8. (a) Changes in ΔQ versus $\Delta P\%$ slope at Bahadurabad station due to changing $\Delta P\%$; (b) changes in ΔQ versus ΔT slope at Bahadurabad station due to changing ΔT (°C)

3. Cool and dry ($\Delta T = +2$°C, $\Delta P = -10\%$): surface runoff will be less because of lower precipitation, enhanced evaporation (increased by 7% compared to the climate normal period) will be caused by the moderate increase in temperature, and the basin will experience dry conditions. Mean annual streamflow could be decreased by about 16% compare to the climate normal period (1981–2010). This is a representative condition at the early stage of 21st century.

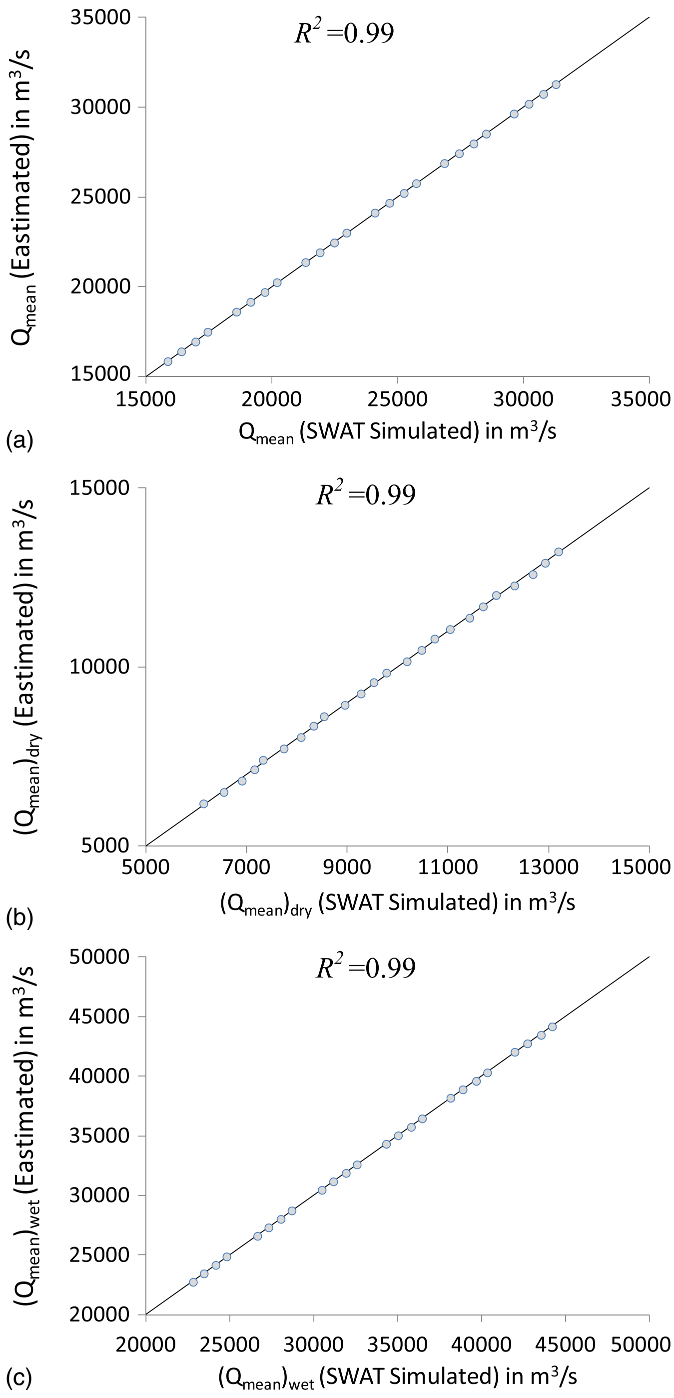

Fig. 9. Mean streamflows of Brahmaputra River Basin estimated from multivariate regression equation [Eqs. (5a)–(5c), respectively)] are plotted against SWAT-simulated mean annual streamflow: (a) mean annual streamflow; (b) mean dry season streamflow; (c) mean wet season streamflow

4. Cool and wet condition ($\Delta T = +2$°C, $\Delta P = +40\%$): enhanced basin runoff because of increased precipitation will significantly offset the enhanced evaporation (increased by 12% compared to the climate normal) because of the moderate increase in temperature. Mean annual streamflow could be significantly increased by about 52%.
5. Moderate condition ($\Delta T = +4$°C, $\Delta P = +20\%$): Even though the evaporative loss may increase by 28% compared to the climate normal period, a moderate increase in temperature and precipitation could cause about 22% increase in mean annual discharge of the BRB. This is a representative scenario of the mid-21st century.

Figs. 8(a and b) shows the change in slope of ΔQ (changes in streamflow) versus ΔP (changes in precipitation) at different ΔT (temperature changes), and $\Delta Q - \Delta T$ slope at different ΔP, respectively. The $\Delta Q - \Delta P$ slope slightly increases with ΔT, and then become gradual. Average $\Delta Q - \Delta P$ slope is about 1.37. The $\Delta Q - \Delta T$ slope shows a decreasing trend with increasing ΔT up to 4°C, and then it becomes almost horizontal.

Multivariable Regression

The SWAT simulated mean annual discharge (Q_{Mean}), mean dry season discharge $(Q_{\mathrm{Mean}})_{\mathrm{dry}}$, and mean wet season discharge $(Q_{\mathrm{Mean}})_{\mathrm{wet}}$ for different combinations of temperature and precipitation changes are fitted against these climatic changes (ΔT, ΔP) to determine the coefficients a_1, a_2, and a_3 of Eq. (4). The fitted regressions are given by

$$Q_{\mathrm{mean}}(\mathrm{m^3/s}) = 20,245 - 273.3 \times \Delta T + 275.9 \times \Delta P\% \quad (5a)$$

$$(Q_{\mathrm{mean}})_{\mathrm{dry}}(\mathrm{m^3/s}) = 8,353 - 158.8 \times \Delta T + 121.9 \times \Delta P\% \quad (5b)$$

$$(Q_{\mathrm{mean}})_{\mathrm{wet}}(\mathrm{m^3/s}) = 28,740 - 355.2 \times \Delta T + 386 \times \Delta P\% \quad (5c)$$

To assess the performance of these fitted regression equations, mean annual discharge and seasonal discharges (at different temperature and precipitation changes) calculated using Eqs. (5a)–(5c) were plotted against the SWAT simulated discharges (Fig. 9). Also, statistical performance has been checked through root-mean square (R^2), and the equation is in good compliance with the simulated flow with a R^2 of almost one. Although we have used a very simple approach to develop these regression equations, it could be very useful for the water managers or planners in the BRB to estimate future mean annual and seasonal streamflow at Bahadurabad station for various projected changes in temperature and precipitation before applying more complex models.

Summary and Conclusions

In this study, a physically based semidistributed hydrological model (SWAT) has been used to simulate the hydrological processes of the BRB at the Baharadurabad station in Bangladesh for a climate normal period of 1981–2010. Mean annual water balance for the BRB implies that about three-fourths of the precipitation transforms into streamflow (combination of surface runoff, subsurface runoff, and shallow groundwater flow into the river), about one-fourth leaves as evapotranspiration, and the rest (a very small component) enters into the deep aquifer through percolation.

The calibrated and validated model was then used to simulate streamflow of the BRB for various combinations of temperature and precipitation changes expected in the 21st century. The mean annual streamflow of the BRB decreased by about 1.35% (from climate normal) due to 1°C change in temperature, while keeping the precipitation unchanged. In contrast, a 1% change in precipitation could increase the streamflow by 1.37% if there are no changes in the temperature. Impacts of combinations of temperature and precipitation changes on future streamflow of the BRB were also assessed. A cool and dry climate (temperature increased by 2°C, precipitation decrease by 10%), expected at the early stage of 21st century, could cause the mean annual streamflow to be decreased by about 16%. In contrast, a warm and wet future climate (temperature increased by 6°C, precipitation increase by about 40%), expected at the end of 21st century, could increase the mean annual streamflow of the BRB by about 47% from the 1981–2010 climate normal level. A moderate climate (temperature increased by 4°C, precipitation increase by about 20%), expected in the mid-21st century, will potentially increase the mean annual streamflow by about 22%. Based on these simulation results, the mean annual and seasonal streamflow of BRB, under the impact of potential climate change, can be presented as a linear function of projected temperature and precipitation changes.

The current study provides a basis of applying the calibrated SWAT model for simulating future streamflow of the BRB in a changing climate. In a future extension of this work, the calibrated model will be used to simulate hydrologic responses of the BRB under the RCP scenarios projected by multiple GCMs of the IPCC, which will provide more insight into possible changes to the management of the water resources of the BRB and adaptation strategies to enhance its resiliency against possible future climatic changes.

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