Streamflow Response to Climate Change in the Brahmani River Basin, India

Adlul Islam · Alok K. Sikka · B. Saha · Anamika Singh

Abstract Climate change can significantly affect the water resources availability by resulting changes in hydrological cycle. Hydrologic models are usually used to predict the impacts of landuse and climate changes and to evaluate the management strategies. In this study, impacts of climate change on streamflow of the Brahmani River basin were assessed using Precipitation Runoff Modeling System (PRMS) run under the platform of Modular Modeling System (MMS). The plausible hypothetical scenarios of rainfall and temperature changes were used to assess the sensitivity of streamflow to changed climatic condition. The PRMS model was calibrated and validated for the study area. Model performance was evaluated by using joint plots of daily and monthly observed and simulated runoff hydrographs and different statistical indicators. Daily observed and simulated hydrographs showed a reasonable agreement for calibration as well as validation periods. The modeling efficiency (E) varied in the range of 0.69 to 0.93 and 0.85 to 0.95 for the calibration and validation periods, respectively. Simulation studies with temperature rise of 2 and 4°C indicated 6 and 11% decrease in annual streamflow, respectively. However, there is about 62% increase in annual streamflow under the combined effect of 4°C temperature rise and 30% rainfall increase (T4P30). The results of the scenario analysis showed that the basin is more sensitive to changes in rainfall as compared to changes in temperature.

Keywords Hydrological modeling · PRMS · Model calibration · Climate change

1 Introduction

Global climate change caused by increasing atmospheric concentration of carbon dioxide and other trace gasses, as well as anthropogenic activities are expected to alter regional hydrological condition and result in a variety of impacts on water resources. Such hydrologic changes will affect nearly every aspect of human well being, from agricultural water

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productivity and energy production to flood control, municipal and industrial water supply, and fish and wildlife management (Ragab and Prudhomme 2002; Xu and Singh 2004; Minville et al. 2008). Several studies (Whitfield and Cannon 2000; Muzik 2001; Risbey and Entekhabi 1996) have shown that small perturbations in the magnitude and/or frequency of precipitation can result in significant impacts on the mean annual discharge. Quantifying streamflow response to potential impacts of climate change and variability is the first step to developing long-term water resource management plans. An understanding of the hydro-logical response of a river basin under changed climatic conditions would help to resolve potential water resources problems associated with floods, droughts and availability of water for agriculture, industry, hydropower, domestic and industrial use, and to develop the adaptation and preparedness strategies to meet these challenges, in case of their occurrences.

India is a large developing country with nearly two-thirds of the population depending directly on agriculture, which is highly climate sensitive. Any temporal and spatial variations in rainfall have reflective effect on water availability in both irrigated and rainfed areas, affecting the agriculture based economy of the region. There are preliminary reports that the recent trend of decline in yields of rice and wheat in Indo-Gangetic plains could have been partly due to weather changes (Aggarwal et al. 2004). Hydrologic modeling of different river basins of India using SWAT (Soil and Water Assessment Tool; Arnold et al. 1999) in combination with the outputs of the Hadley Centre Regional Climate Model (HadRM2) for the control (1981–2000) and future greenhouse gas (GHG) (2041–2060) climate data indicated an increase in the severity of drought and intensity of floods in different parts of the country (Gosain et al. 2006). The study also revealed that the increase in rainfall due to climate change does not result in an increase in the surface runoff as may be generally predicted. Mirza (1997) reported changes in mean annual runoff in the range of 27 to 116% in the nine sub-basins of the River Ganga at doubled CO_2 condition and that the runoff was more sensitive to climate change in the drier subbasins than in the wetter subbasins. Sharma et al. (2000) reported a decrease in runoff by 2 to 8% in the Kosi basin depending upon the areas considered and models used under the scenario of temperature rise by 4°C and no changes in precipitation. Mehrotra (1999) observed that basins belonging to relatively dry climatic region are more sensitive to climate change scenarios. The Sher (dry sub-humid) and the Kolar (moist sub-humid) are comparatively more sensitive to climate change, whereas Damanganga (humid) is least sensitive. The greater sensitivity of the Sher and the Kolar basin was attributed to the aridity of the basin, higher evapotranspiration rate, and regional metamorphic characteristics of the basin that governs the moisture retention in the basin. Arora et al. (2008) reported 10, 28 and 43% increase in snowmelt runoff and 7, 19 and 28% increase in total streamflow runoff in Chenab River basin for T+1°C, T+2°C and T +3°C scenarios, respectively. Singh et al. (2006) reported increase in summer stream-flow in glacierized Himalayan basin with a temperature rise of 2°C, whereas ±3.5% change in streamflow with ±10% change in rainfall. Further, Singh and Bengtsson (2005) found that annual snow-melt was reduced by about 18% for a T+2°C scenario for the snow-fed basin, whereas it increased by about 33% for the glacier-fed basin in the Himalayan region. Under warmer climate, reduction in snowmelt from the snowfed was due to availability of lesser amount of snow in the basin. They also found that the snowfed basins are more sensitive in terms of reduction in water availability due to compound effect of increase in evaporation (attributed to warmer climate and increase in snow free area with time due to disappearance of snow) and decrease in melt. As future climate changes will impact regional water availability,

region specific assessments of climate change impact are of utmost importance for regional water resources planning and management.

The most commonly used approach for studying the effects of climate change on hydrology and water resources involves employing hydrological models at the basin or watershed scale driven by climatic data obtained either directly from the General Circulation Model (GCM) outputs or from hypothetical or GCM-based scenarios of climate change. Hydrologic models provide a framework to conceptualize and investigate the complex effect of both climate and landuse changes (Leavesley 1994; Xu 2000), and have been applied in many studies in order to assess the effect of land use and climate changes on runoff. Physically based distributed models that represent the spatial variability of landuse and climatic characteristics are the most useful for studying hydrologic effects of landuse changes and climatic variability for large basins (Borah and Bera 2003). The scientific literature of the past two decades contains a large number of research papers dealing with the application of different hydrologic models to the assessment of the potential effects of climate change on a variety of water resource issues. For example, Hattermann et al. (2011) applied semi-distributed model SWIM (Soil and Water Integrated Model; Krysanova et al. 1998) for assessing climate change impact on water resources in the German State of Saxony-Anhalt; Bekele and Knapp (2010) applied SWAT model in the Fox River watershed to assess the impact of potential climate change on water supply availability; Veijalainen et al. (2010) used Watershed Simulation and Forecasting System (WSFS; Vehviläinen et al. 2005) to simulate the hydrological effects of climate change on water resources and lake regulation in the Vuoksi watershed in Finland; Minville et al. (2009) applied physically-based distributed model Hydrotel (Fortin et al. 2001) in the Peribonka River water resource system (Quebec, Canada) to evaluate the impacts on hydropower, power plant efficiency, unproductive spills and reservoir reliability due to changes in the hydrological regimes under projected climate change scenarios; and Qi et al. (2009) used Precipitation Runoff Modeling System (PRMS; Leavesley et al. 1983) for assessing potential impacts of climate and land use changes on the monthly streamflow of the Trent River basin on the lower coastal plain of eastern North Carolina. Passcheir (1996) compared five "event" (single runoff event) models and 10 continuous hydrological models for rainfall-runoff modeling of the Rhine and Meuse basin for land use impact modeling, climate change impact modeling, real-time flood forecasting and physically based flood frequency analysis. Four continuous models, namely, PRMS, SACRAMENTO (Burnash 1995), HBV (Hydrologiska Byrans Vattenbalansavdelning; Bergstrom and Forsman 1973) and SWMM (Storm Water Management Model; Huber 1995) and one event model HEC-1 (U.S. Army Corps of Engineers Hydrologic Engineering Centre hydrological model; Feldman 1995) were evaluated as the best ones. The HEC-1 and HBV model models were evaluated as the most appropriate for flood frequency analysis, the HBV and SLURP (Semi-distributed Land Use Runoff Process; Kite 1995) models for climate change impacts on peak discharges, and the PRMS and SACRAMENTO model for assessment of climate change impact on discharge regimes. In this paper an attempt has been made to: (1) test the U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS) for modeling streamflow of the Brahmani River basin, and (2) to perform a hydrologic sensitivity assessment and quantify the magnitudes of hydrologic response to possible climate changes in the basin. The paper first presents the main characteristics of the basin, followed by hydrological models, data used, delineation of basin into hydrological response units (HRUs), and sensitivity of streamflow to different hypothetical climate change scenarios.

2 Study Area and Data Description

2.1 Study Area

The Brahmani River basin is located in the eastern part of India, and lies between latitudes 20°30'10" and 23°36'42"N and longitudes 83°52'55" and 87°00'38"E. The basin is situated between Mahanadi basin (on the right) and Baitarani basin (on the left). Chhotanagpur Plateau in the east and south bound the basin, in the north a ridge separates it from Mahanadi basin, and the Bay of Bengal and the Baitarani basin in the east of the basin. It has a total catchment area of 39,313.50 km^2 and is spread over Orissa (57.3% of the basin area), Jharkhand (39.2% of the basin area) and Chhattisgarh (3.5% of the basin area) states of Indian Union. The basin is composed of four distinct sub-basins, namely Tilga, Jaraikela, Gomlai and Jenapur (Fig. 1). The Brahmani River rises near Nagri village in Ranchi district of Jharkhand at an elevation of about 600 m and travels a total length of 799 km before it outfalls into the Bay of Bengal. The basin has a sub-humid tropical climate with an average annual rainfall of 1305 mm, most of which is concentrated in the southwest monsoon season of June to October. The Brahmani River basin is a water surplus basin and key source of water supplies for different towns and industries, and for irrigation in the state of Orissa, India. However, rapid economic development and population growth in this region have caused concerns over the adequacy of the quantity and quality of water withdrawn from the Brahmani River in the future. Rainfed agriculture is predominant except in lower deltaic parts where irrigation plays a major role. The flood is a common feature in the delta region. Considering the land and water resources problems, and availability of hydrometeorological, soil, landuse and other data Brahmani basin was selected as the study area for the present study.

2.2 Data

Daily streamflow and rainfall data (1979–2003) of four stream gauging stations, namely, Tilga, Jaraikela, Gomlai and Jenapur were collected from Central Water Commission
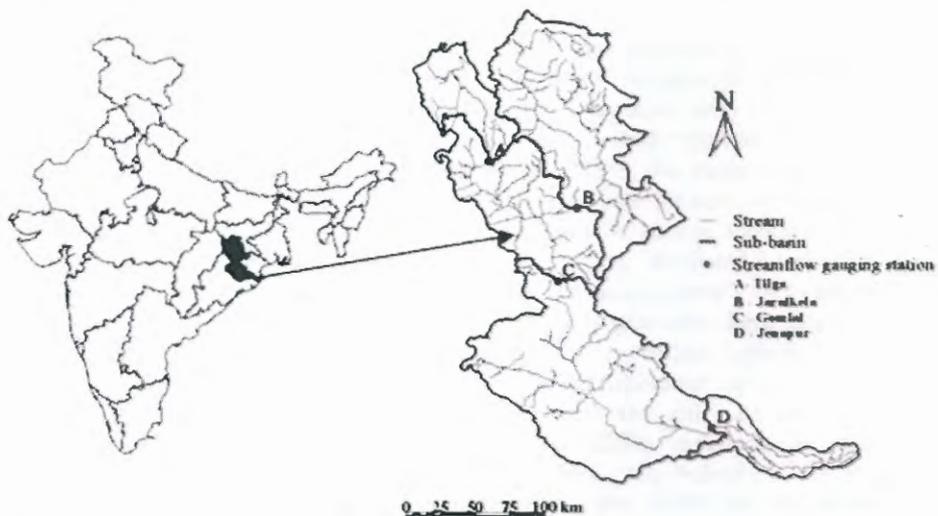

Fig. 1 Location map of the Brahmani River basin

(CWC). Daily rainfall and temperature data for 11 stations spread over the basin were collected from India Meteorological Department (IMD), Pune. Catchment map with location of streamflow gauging stations is collected from Central Water Commission, and soil and land use maps were collected from National Bureau of Soil Survey and Land Use Planning (NBSS and LUP). Toposheets of 1:250,000 scale with Universal Transverse Mercator (UTM) projection and 200 ft (60 m) contour intervals were downloaded from USGS website. These maps were processed under geographic information system (GIS) and image processing environment with the help of PCI Geomatica (PCI Geomatics) and TNTmips (MicroImages, Inc.) software for delineation of basin into sub-basin and HRUs.

3 Methodology

3.1 Hydrologic Model

The U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS), which is embedded in the Modular Modeling System (MMS), was selected for this study. MMS is an integrated system of computer software designed to provide a framework for the development and application of models to simulate a variety of water, energy, and biogeochemical processes (Leavesley et al. 1996, 2002). MMS uses a module library containing algorithms for simulating variety of hydrologic and ecosystem processes. The central model in MMS is the Precipitation-Runoff Modeling System (Leavesley et al. 1983, 2002). PRMS is a modular design, distributed parameter, physically based watershed model designed to analyze the effects of precipitation, climate, and landuse on streamflow and other general basin hydrology (Leavesley et al. 1983). The model simulates basin response to normal and extreme rainfall and snowmelt, and can be used to evaluate changes in water-balance relationships, flow regimes, flood peaks and volumes, soil water relationships, and groundwater recharge. Parameter optimization and sensitivity analysis capabilities are also provided to fit selected model parameters and to evaluate their individual and joint effects on model outputs (Leavesley et al. 1983, 2002).

Distributed parameter capabilities of the model are provided by partitioning the basin into smaller modeling subunits where the runoff response is considered to be homogeneous. These units are called hydrologic response units (HRUs) and are typically based on physiographic characteristics such as soil type and infiltration rate, slope, aspect, land cover/land use, and altitude. In PRMS, the basin is conceptualized as a series of reservoirs (Fig. 2). These reservoirs include interception storage in the vegetation canopy, storage in the soil zone, subsurface storage between surface of watershed and the water table, and groundwater storage. Simulated streamflow from PRMS is a summation of three flow components: 1) surface flow; 2) subsurface flow; and 3) groundwater flow. Surface or overland flow is generated from saturated soils and runoff from impervious surfaces. Subsurface flow is shallow subsurface flow that originates from soil water in excess of available water-holding capacity of the soil. Groundwater flow, or baseflow, is sourced from both the soil zone and subsurface reservoir. The sum of the water balances of all HRUs, weighted by unit area, produces the daily watershed response. PRMS uses daily values of precipitation, and minimum and maximum temperature as input. The model can be operated in daily and storm mode. In this study, the daily mode was used for modeling daily and monthly streamflow.
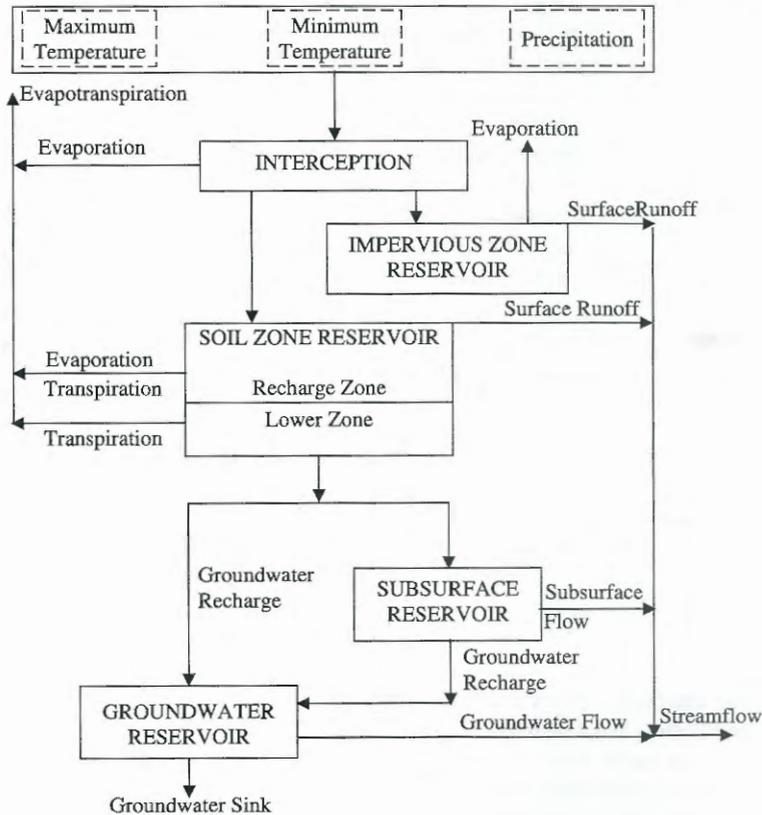
Fig. 2 Conceptual diagram of Precipitation-Runoff Modeling System (Leavesley et al. 1983)

In PRMS model, interception is computed as a function of vegetation cover density and the storage available on the predominant vegetation type of an HRU. Daily surface runoff from rainfall is computed using a contributing area concept. The percent of an HRU contributing to surface runoff is computed as a nonlinear function of antecedent soil moisture and rainfall amount using the following equation:

$$ca\_percent = smidx\_coef \times 10^{(smidx\_\exp \times smidx)} \qquad (1)$$

$$smidx = soil\_moist \times 0.5 \times net\_rain \qquad (2)$$

$$srp = ca\_percent \times net\_rain \qquad (3)$$

where smidx_coef and smidx_exp are coefficients and exponents in the nonlinear contributing area algorithm, respectively, soil_moist is the soil moisture content for each HRU, net_rain is rain minus interception for the HRU, and srp is the surface runoff from the pervious area. In case of impervious areas, rainfall or snowfall first satisfies the retention storage and then remainder becomes available for surface runoff.

The soil-zone reservoir is treated as a two-layered system (Fig. 2). Losses from the recharge zone occur as evaporation and transpiration; losses from the lower zone occur only through transpiration. Three different procedures are available for estimation of potential evapotranspiration, namely, from pan-evaporation data, Hamon method and Jensen-Haise method. When the soil zone reservoir reaches maximum storage capacity, additional infiltration is routed to the subsurface and groundwater reservoirs. The apportioning of soil water in excess of the maximum storage capacity to the subsurface and groundwater reservoirs is done using a user-defined daily groundwater recharge rate. The subsurface flow is considered to be relatively rapid movement of water from unsaturated zone to stream channel. The subsurface flow is computed using reservoir routing system, and reservoir can be defined as linear or nonlinear. The groundwater reservoir simulates the slower component of flow from the groundwater zone. It is conceptualized as a linear reservoir and is assumed to be the source of all baseflow. The vertical movement of water from a subsurface reservoir to a groundwater reservoir is computed as a function of the current volume of storage in subsurface reservoir and a linear routing coefficient. The movement of water through the groundwater reservoir to points outside the surface drainage boundary is treated using a groundwater sink, which is computed as a function of storage in the groundwater reservoir and groundwater routing coefficient. The equations used for computation of different water balance components are described in Leavesley et al. (1983).

3.2 HRU Generation

Contours at 60 m intervals were digitized after geo-referencing the toposheets for generation of the Digital Elevation Models (DEM). DEM layer was developed with 30 m of spatial resolution, using triangulated irregular network interpolation with linear interpolation algorithm. The elevation layer was sliced into the three classes representing hilly, plateau, and plain region. Seed points/pour points were placed on the DEM layer according to geographical location of the streamflow gauging stations to delineate sub-basin, and the basin was divided into four sub-basins namely Tilga, Jaraikela, Gomlai, and Jenapur. Finally, thematic map of soil with six textural classes and land use map with four classes were generated. Sliced elevation layer, soil layer and landuse layer were overlaid for delineation of basin into HRUs. Different HRU parameters such as area, elevation, slope, landuse and soil type of each HRU were then extracted through the HRUs vector layer and individual thematic layer.

For distributed hydrological modeling the Brahmani River basin was delineated into 66 spatially distributed HRUs. Physiographic undulation is quite prominent in the entire basin and elevation varied between 28 to 1159 m. Hilly, plateau and plain region comprises of 3.1, 41.5 and 55.40% of the total catchment area, respectively. The slope varied between 0.28 and 20.52% with a mean slope of 6.13%. Cultivated land (69.86%) is the major land use class followed by forest (27.73%) and settlement (0.23%). The water bodies occupy 2.18% of the catchment area. Sandy loam is the major soil type occupying 43.6% of the catchment area followed by loamy sand (22%), clay loam (15.6%), silt loam (13.9%) , loamy (4.8%), clay (0.1%) soil. The area, elevation, slope, land use and soil type extracted for each HRU were used as input to the hydrological model.

3.3 Calibration and Validation of Model

Determination of input parameter values is a critical step for application of hydrological model. Daily rainfall and temperature data were used as input to the PRMS model and model was calibrated and validated for the period 1980–84 and 1984–86, respectively, by matching

the simulated and observed streamflow of Jenapur gauging station. The availability of concurrent streamflow and climate data primarily dictated the selection of the time periods used for model calibration and validation. The model was first run in a daily runoff-prediction mode with parameter values estimated for the basin. After selection of initial parameter values, sensitivity analysis was used to identify the sensitive parameters that affect the prediction of daily streamflow during the calibration period. Results of the sensitivity analysis indicated that the basin response is more sensitive to the monthly temperature adjustment factor for calculation of PET (jh_coef), soil moisture related parameter SOIL_-MOIST_MAX and subsurface flow related parameter SSRCOEF_ LIN and surface runoff related parameter CAREA_MAX, SMIDX_EXP and SMIDX_COEF. These parameters were selected for the calibration process and realistic model parameter and coefficient values for the study area were estimated so that the PRMS model closely simulates the hydrological processes of the basin. A trial and error adjustment of the selected parameters was performed until a reasonable match between observed and simulated streamflow hydrographs was obtained. Simulation results were examined both graphically and statistically to assess the model performance. Statistically model performance at daily and monthly temporal scales was evaluated using the standard Nash-Sutcliffe coefficient (E) (Nash and Sutcliffe 1970), index of agreement (d_1) (Legates and McCabe 1999) for the calibration and validation periods. In addition, the commonly used statistical indicators such as root mean squared error (RMSE) and coefficient of determination (r^2) were also used. Following equations were used for calculating the values of RMSE, r^2, E, and d_1.

$$RMSE = \sqrt{\frac{\sum\limits_{i=1}^{n} (Q_{oi} - Q_{si})^2}{n}} \qquad (4)$$

$$R^2 = \left\{ \frac{\sum\limits_{i=1}^{n} (Q_{oi} - \overline{Q}_o)(Q_{si} - \overline{Q}_s)}{\left[\sum\limits_{i=1}^{n} (Q_{oi} - \overline{Q}_o)^2\right]^{0.5} \left[\sum\limits_{i=1}^{n} (Q_{si} - \overline{Q}_s)^2\right]^{0.5}} \right\}^2 \qquad (5)$$

$$E = 1 - \frac{\sum\limits_{i=1}^{n} (Q_{oi} - Q_{si})^2}{\sum\limits_{i=1}^{n} (Q_{oi} - \overline{Q}_o)^2} \qquad (6)$$

$$d_1 = 1 - \frac{\sum\limits_{i=1}^{n} (Q_{oi} - Q_{si})}{\sum\limits_{i=1}^{n} (|Q_{si} - \overline{Q}_o| + |Q_{oi} - \overline{Q}_o|)} \qquad (7)$$

where, Q_o = observed flow, Q_s = simulated flow, $\overline{Q}_o$ = mean observed flow, $\overline{Q}_s$ = mean simulated flow, and n = total number of observation.

3.4 Climate Change Scenarios

The general circulation models (GCMs) are the primary source of data for use in the climate change impact assessment studies. Although there have been great advances with GCMs predictions over the past decade, large uncertainties are there regarding future changes in climate for particular regions or basins. In fact, different GCMs provide different estimates of changes in precipitation and temperature. Hydrological perturbation studies using the simple and direct approach of hypothetical scenarios of changes in temperature and precipitation are useful to explore the potential bounds of hydrological response for any basin (Nash and Gleick 1991). They are usually adopted for exploring system sensitivity prior to the application of more credible, model-based scenarios (Mearns et al. 2001). Xu (2000) considered 15 hypothetical climate change scenarios with different combination of temperature (1, 2, 3, and 4°C) and precipitation (0, ±10 and ±20) changes for modeling climate change impact on water resources in Central Sweden. Bekele and Knapp (2010) generated eight different climate change scenarios data for the Fox River watershed using delta change approach. They considered precipitation changes of +127, 0 (no change) and −127 mm, and temperature changes of 0, 1.7 and 3.3°C based on the review of GCM outputs. In the present study, we considered a range of climate change cases with rainfall changes varying from ±10 to 30% with an increment of 10% and temperature changes varying from 0 to 4°C with an increment of 2°C. The changes in temperature and rainfall considered here are based on the outputs of different GCMs (Table 1) for the study basin. Most of the GCMs predicted about 4°C increase in mean temperature during 2080 (2070–2099) except NIES (National Institute for Environmental Studies) GCM, which predicated 4.9°C increase in mean temperature under A2 emission scenarios. Hence, maximum increase of 4°C in the mean temperature is considered in this study. There are lots of variations in the mean monthly rainfall predicted by different GCMs and average annual changes in rainfall varied in the range of −3.30 to 29.6%. With different combination of temperature and rainfall changes, 14 different hypothetical scenarios were considered. Observed time series of rainfall and temperature data (1980–1990) were modified by adding changes in temperature to historic temperature series, and by multiplying by changes in rainfall to rainfall series (Xu 2000). These scenarios do not necessarily present a realistic set of changes that are physically plausible. Hydrological response was then simulated for the period 1980–1990 under the present climatic conditions (i.e., no change in rainfall and temperature) as well as 14 hypothetical climate change scenarios representing future climate.

4 Results and Discussion

4.1 Calibration and Validation of Hydrological Model

The PRMS model was calibrated for the period 1980–84 and validated for the period 1984–86 by matching the simulated and observed streamflow data. Daily observed and simulated streamflow hydrographs showed a reasonable agreement for both calibration and validation period (Fig. 3). It is clear from the figure that though the model could produce the similar trend between observed and simulated streamflow hydrographs, but it could not capture some of the peak flow events. In general, model underestimated the daily streamflow for large peaks occurring primarily during July–August. This underestimation of streamflow may be attributed to imprecise / uneven representation of spatial distribution of rainfall and underestimation of areal rainfall in such a large basin as local amount of rainfall may vary greatly across the basin. The different statistical indicators computed using mean monthly streamflow for the calibration

Table 1 Projected changes in the mean temperature and rainfall in the basin

Model	A2			B2		
	2020	2050	2080	2020	2050	2080
Changes in mean temperature (°C)						
CCCMA- CGCM2[a]	1.50	2.50	3.30	0.90	1.00	1.60
CSIRO-MK2	0.80	1.80	3.20	1.00	1.80	2.50
ECHAM4	0.50	1.70	3.30	0.80	1.40	2.30
GFDL –R30	0.70	1.90	3.40	0.80	1.60	1.90
HadCM3	0.80	2.30	3.90	0.90	1.70	2.80
NIES	1.00	2.40	4.90	1.10	2.30	3.70
Changes in precipitation (%)						
CCCMA- CGCM2	−1.30	−0.75	12.40	−2.25	8.20	3.50
CSIRO-MK2	−3.30	4.00	16.70	5.40	3.60	9.80
ECHAM4	5.80	18.10	29.60	11.30	16.90	23.00
GFDL –R30	2.60	10.40	9.80	5.20	6.70	10.70
HadCM3	6.20	6.50	13.10	5.40	9.30	10.30
NIES	2.00	9.00	16.45	5.10	6.25	12.60

[a] *CCCMA-CGCM2* Canadian Center for Climate Modeling and Analysis, Canada; *CSIRO-MK2* Commonwealth Scientific and Industrial Research Organisation, Australia; *ECHAM4* Max Planck Institute für Meteorologie, Germany; *GFDL-R30* Geophysical Fluid Dynamics Laboratory, USA; *HadCM3* Hadley Centre for Climate Prediction and Research, UK; *NIES* National Institute for Environmental Studies, Japan

and validation periods indicated that the model was able to maintain a very good representation of the overall water balance as well as streamflow patterns and volumes at monthly time step (Table 2). The RMSE value varied from 68.40 to 98.20 m³/s during calibration periods and 55.00 to 132.90 m³/s during the validation periods. The higher value of RMSE during 82–83 and 84–85, could be attributed to relatively higher overestimation in streamflow in the month of October and June, respectively. The mean monthly observed and simulated streamflow showed a better agreement with the Nash-Sutcliffe coefficient and index of agreement varying in the range of 0.69 to 0.93 and 0.78 to 0.90, respectively, for the calibration period. This shows that the model was able to represent the dynamics of the hydrograph reasonably well at the monthly scale. For the validation period Nash-Sutcliffe coefficient and index of agreement varied from 0.85 to 0.95 and 0.85 to 0.88, respectively. The value of R^2 varied from 0.78 to 0.99 and 0.94 to 0.96 during calibration and validation periods, respectively. These values clearly indicated that the PRMS model captured the hydrologic characteristics of the basin reasonably well and reproduced simulated streamflow within an acceptable level of accuracy.

4.2 Hydrological Response of Streamflow to Climate Change

Results of the simulated scenarios revealed that the streamflow is sensitive to both temperature and rainfall changes, but changes in rainfall have a greater effect on streamflow. A 4°C rise in temperature resulted in 11.40% decrease in annual streamflow, whereas 10% decrease in rainfall resulted in 22.90% decrease in annual streamflow (Fig. 4). As shown in Fig. 4, a 10% decrease in rainfall resulted in 25.00, 12.40, and 21.10% decrease in streamflow during monsoon, pre-monsoon, and post-monsoon season respectively, whereas 4°C increase in temperature resulted in 12.00, 2.70, and 11.20% decrease in streamflow during the same
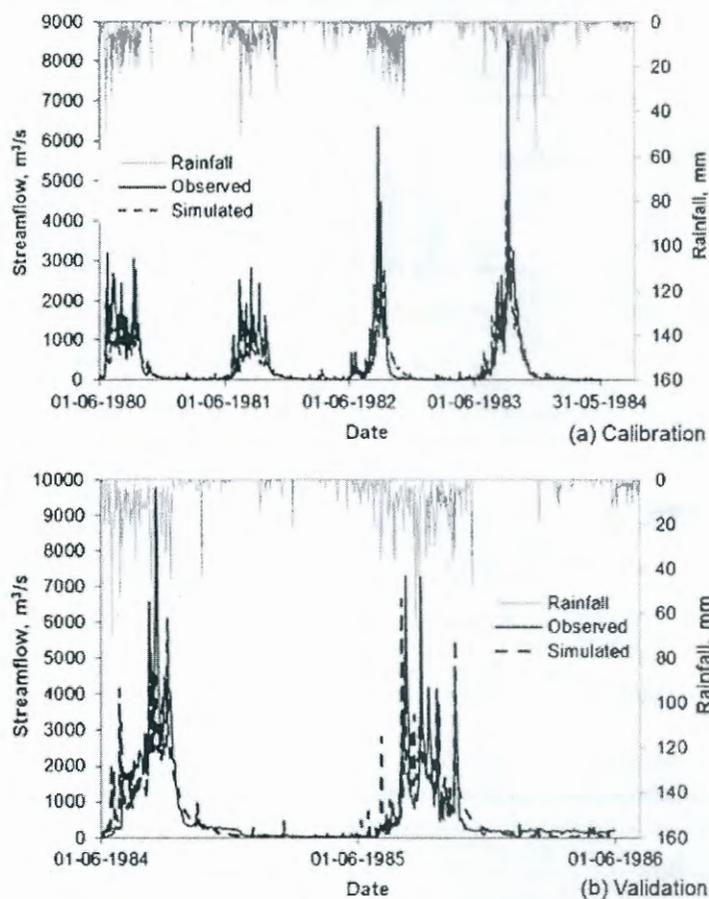
Fig. 3 Observed and simulated hydrographs at Jenapur outlet for calibration and validation periods

seasons. The combined effect of rainfall and temperature changes is shown in Fig. 5. The magnitude of changes in mean annual streamflow varied in the range of −32.90 to 62.20% (Fig. 5). A temperature rise of 4°C and a 10% decrease in rainfall (T4P-10) resulted in 32.90, 35.00, 14.70, 31.70, and 20.80% decrease in annual, monsoon, pre-monsoon, post-monsoon and winter season streamflow, respectively. However, 4°C rise of temperature coupled with 30% increase in rainfall (T4P30) resulted in 62.20, 72.50, 38.50, 51.90 and 29.60% increase in annual, monsoon, pre-monsoon, post-monsoon and winter season streamflow, respectively. Analysis of monthly streamflow data revealed that there are significant changes in mean monthly streamflow, particularly during monsoon months (Table 3). Maximum absolute

Table 2 Model performance statistics for the calibration and validation periods

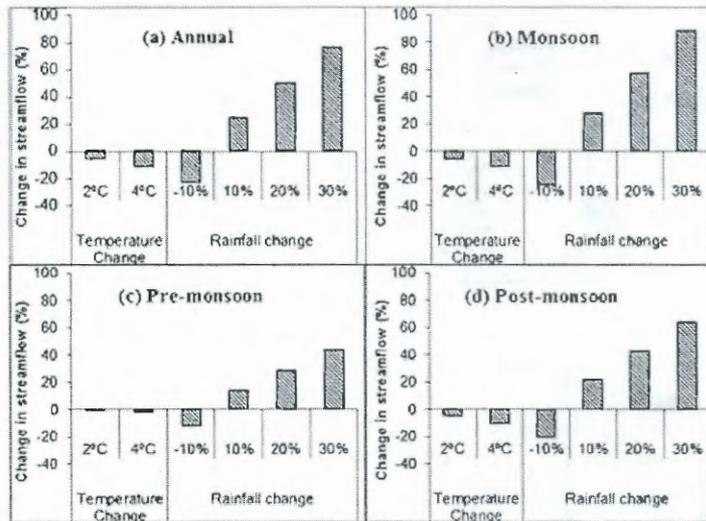|	Calibration				Validation	
	80–81	81–82	82–83	83–84	84–85	85–86
RMSE	77.20	75.70	98.20	68.40	132.90	55.00
R^2	0.96	0.98	0.78	0.99	0.94	0.96
E	0.81	0.69	0.74	0.93	0.85	0.95
d_l	0.83	0.78	0.80	0.90	0.85	0.88

Fig. 4 Response of streamflow to potential rainfall and temperature changes

changes in streamflow occurred during the month of July when streamflow was almost doubled with 30% increase in rainfall, and minimum absolute changes (32.90%) occurred in the month of January under same (i.e., 30% increase) scenarios of rainfall change. With 30% increase in rainfall and 4°C increase in temperature, the magnitude of changes in mean monthly streamflow ranged from 83.40% (July) to 26.90% (January). A maximum decrease of 37% (July) was estimated with 4°C increase in temperature together with 10% decrease in rainfall. The effects of 10% decrease in rainfall changes in annual and seasonal streamflow is about two times greater than that of 4°C increase in temperature. This indicates that changes in temperature had a relatively lesser effect on the magnitude of annual and seasonal streamflow as compared to rainfall changes in the Brahmani basin. This could be attributed to sub-humid climatic condition in the basin with lower part of the basin being located in the coastal region.

Model simulation results are subject to various sources of uncertainty. Some uncertainties are inherent in the model structure and some are due to errors in the calibration and parameter estimation. The accuracy of the model calibration is dependent on the accuracy of the input data. Precipitation data is one of the most critical input variables in any hydrological modeling studies and errors associated with the distribution of rainfall over the basin affect the model results. Lack of reliable meteorological and hydrological data of sufficient length are one of the
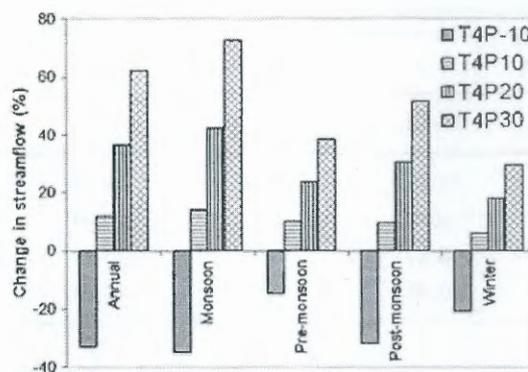

Fig. 5 Response of streamflow to combined effect of rainfall and temperature changes

Table 3 Changes in streamflow under different climate change scenarios

Month	Change in streamflow (%)													
	T0P-10[a]	T0P10	T0P20	T0P30	T2P0	T2P-10	T2P10	T2P20	T2P30	T4P0	T4P-10	T4P10	T4P20	T4P30
Jun	−23.20	26.80	56.20	89.80	−4.00	−26.50	22.10	50.70	83.10	−7.70	−29.40	17.90	45.80	77.20
Jul	−27.00	31.20	66.20	103.80	−7.10	−32.40	22.80	56.30	93.30	−13.30	−37.10	15.40	47.60	83.40
Aug	−24.30	25.90	52.50	80.00	−6.30	−30.00	19.10	45.40	72.60	−12.20	−34.90	12.70	38.90	65.80
Sep	−21.80	22.10	44.50	67.00	−5.80	−27.40	16.10	25.30	45.70	−11.30	−32.40	10.40	32.50	54.80
Oct	−20.80	20.90	41.90	62.90	−6.00	−26.60	14.70	35.50	56.40	−11.50	−31.80	9.00	29.50	50.40
Nov	−17.30	16.30	31.80	46.80	−5.00	−22.30	11.30	26.80	41.70	−9.70	−26.90	6.70	22.20	36.90
Dec	−14.80	13.50	26.00	38.00	−4.30	−19.30	9.40	21.90	33.90	−8.30	−23.40	5.60	18.20	30.10
Jan	−13.00	11.80	22.60	32.90	−3.40	−16.60	8.60	19.50	29.70	−6.60	−20.00	5.70	16.60	26.90
Feb	−12.20	11.80	23.70	36.10	−2.00	−14.40	9.70	21.40	33.40	−4.00	−16.40	7.80	19.40	31.20
Mar	−13.30	13.00	26.90	41.40	−2.30	−15.50	10.60	23.90	38.10	−4.80	−17.50	8.40	21.50	35.40
Apr	−11.90	12.50	25.70	39.40	−1.20	−12.90	11.30	24.20	37.70	−2.20	−13.80	10.10	22.80	36.10
May	−12.40	14.10	29.80	47.30	−1.20	−13.20	12.30	27.60	44.30	−2.10	−14.10	10.90	25.70	41.70

[a] T0P-10 = 0°C increase in temperature and 10% decrease in rainfall; T4P30 = 4°C increase in temperature and 30% increase in rainfall

challenges in model calibration. Land use and land cover changes are also crucial factors affecting the hydrologic system of the catchment. The study assumes that model calibration will hold in future scenarios too. The land use changes have been assumed to be static and only the effect of changes temperature and rainfall has been studied. The hypothetical scenarios considered in this study compute the changes in climate by uniformly changing the current values of daily temperature and rainfall for all the months of the year and do not account for changes in variance. Consideration of more scenarios using outputs of different GCMs will help to reduce these uncertainties. The use of number of GCMs output along with land use changes will help more reliable estimation of changes in streamflow due to climatic and land use changes in the basin.

5 Conclusions

Assessment of climate change impact on water resources is very important for its planning and management, and developing suitable adaptation strategies. In this study precipitation runoff modeling system (PRMS) was used to assess the impacts of climate changes on the streamflow of the Brahmani River basin. The model was found to perform reasonably well in simulating daily and monthly streamflow hydrographs for both calibration and validation periods. Different statistical performance indicators showed that the PRMS model was able to simulate the monthly streamflow reasonably well. The modeling efficiency (E) varied in the range of 0.74 to 0.93 and 0.85 to 0.95 during calibration and validation period, respectively. Hypothetical climate change scenarios, considered based on the review of different GCMs outputs, were used to simulate the response of streamflow to climate change and compared with the present climate condition (base line). Hypothetical scenarios considered include individual as well combined scenarios of rainfall and temperatures changes. Simulation results indicated about 6 and 11% decrease in annual streamflow with temperature rise of 2 and 4°C, respectively. A 10% increase in rainfall resulted in 24% increase in annual streamflow. Under the combined effect of rainfall and temperature changes, annual streamflow increased by about 62% with 4°C rise of temperature and 30% increase in rainfall (T4P30). Results of the scenario analysis indicated that the streamflow in the Brahmani River basin is more sensitive to changes in rainfall as compared to changes in temperature. The results presented in this paper are not the predictions, but are plausible changes in the streamflow. The hypothetical scenarios considered in the basin do not account for the changes in the variance, and do not necessarily represent the future climate. Future study should focus on effect of land use change and consideration of number of GCMs output to arrive at more reliable estimation of the streamflow in the basin.

References

Aggarwal PK, Joshi PK, Ingram JSI, Gupta RK (2004) Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. Environ Sci Pol 7:487–498
Arnold JG, Williams JR, Srinivasan R, King KW (1999) SWAT: soil and water assessment tool. Temple, USDA, Agricultural Research Service

Arora M, Singh P, Goel NK, Singh RD (2008) Climate variability influences on hydrological responses of a large Himalayan Basin. Water Resour Manag 22:1461–1475

Bekele EG, Knapp HV (2010) Watershed modeling to assessing impacts of potential climate change on water supply availability. Water Resour Manag 24:3299–3320

Bergstrom S, Forsman A (1973) Development of a conceptual deterministic rainfall-runoff model. Nordic Hydrol 4:147–170

Borah DK, Bera M (2003) Watershed-scale hydrologic and non-point source pollution models: review of mathematical basis. Trans ASAE 46(6):1553–1566

Burnash RJC (1995) The NWS river forecast system—catchment modeling. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, pp 311–366

Feldman AD (1995) HEC-1 flood hydrograph package. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, pp 119–150

Fortin J-P, Turcotte R, Massicotte S, Moussa R, Fitzback J, Villeneuve J-P (2001) Distributed watershed model compatible with remote sensing and GIS data. 1: description of the model. J Hydrol Eng 6(2):91–99

Gosain AK, Rao S, Basuray D (2006) Climate change impact assessment on hydrology of Indian river basins. Curr Sci 90(3):346–353

Hattermann FF, Weiland M, Huang S, Krysanova V, Kundzewicz ZW (2011) Model-supported impact assessment for the water sector in Central Germany under climate change—a case study. Water Resour Manag 25:3113–3134

Huber WC (1995) EPA storm water management model—SWMM. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, pp 783–808

Kite GW (1995) The SLURP model. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, pp 521–562

Krysanova V, Muller-Wohlfeil D-I, Becker A (1998) Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. Ecol Model 106(2–3):261–289

Legates DR, McCabe GJ (1999) Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resour Res 35(1):233–241

Leavesley GH (1994) Modeling the effects of climate change on water resources—a review. Clim Change 28:159–177

Leavesley GH, Lichty RW, Troutman BM, Saindon LG (1983) Precipitation-runoff modeling system: user's manual. U. S. Geological Survey Investigation Report 83-4238, pp. 207.

Leavesley GH, Restrepo PJ, Markstrom SL, Dixon M, Stannard LG (1996) The Modular Modeling System (MMS): user's manual. U. S. Geological Survey Open-file Report 96-151, pp. 142.

Leavesley GH, Markstrom SL, Restrepo PJ, Viger RJ (2002) A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modeling. Hydrolog Process 16(2):173–187

Mearns LO, Hulme M, Carter TR, Leemans R, Lal M, Whetton P (2001) Climate scenario development. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 881

Mehrotra R (1999) Sensitivity of runoff, soil moisture and reservoir design to climate changes in central Indian River basins. Clim Change 42:725–757

Minville M, Brissette F, Leconte R (2008) Uncertainty of the impact of climate change on the hydrology of a nordic watershed. J Hydrol 358:70–83

Minville M, Brissette F, Krau S, Leconte R (2009) Adaptation to climate change in the management of a Canadian water resources system exploited for hydropower. Water Resour Manag 23:2965–2986

Mirza MQ (1997) The runoff sensitivity of the Ganges river basin to climate change and its implications. J Environ Hydrol 5:1–13

Muzik I (2001) Sensitivity of hydrologic systems to climate change. Can Water Resour J 26(2):233–253

Nash I, Gleick P (1991) Sensitivity of streamflow in Colorado basin to climate changes. J Hydrol 125:119–146

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models. I. A discussion of principles. J Hydrol 10:282–290

Passcheir RH (1996) Evaluation of hydrologic model packages. Technical Report Q2044, WL/Delft Hydraulics, Delft, pp. 103.

Qi S, Sun G, Wang Y, McNulty SG, Myers JAM (2009) Streamflow response to climate and landuse changes in a coastal watershed in North Carolina. Trans ASABE 52(3):739–749

Ragab R, Prudhomme C (2002) Climate change and water resources management in arid and semi-arid regions: prospective and challenges for 21st century. Biosystems Eng 81(1):3–34

Risbey JS, Entekhabi D (1996) Observed Sacremento basin streamflow response to precipitation and temperature changes and its relevance to climate impact studies. J Hydrol 184:209–223

Sharma KP, Vorosmarty CJ, Moore B III (2000) Sensitivity of the Himalayan hydrology to land-use and climatic changes. Clim Change 47:117–139

Singh P, Bengtsson L (2005) Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region. J Hydrol 300:140–154

Singh P, Arora M, Goel NK (2006) Effect of climate change on runoff of a glacierized Himalayan basin. Hydrolog Process 20(9):1979–1992

Vehviläinen B, Huttunen M, Huttunen I (2005) Hydrological forecasting and real time monitoring in Finland: the watershed simulation and forecasting system (WSFS). In: Innovation, advances and implementation of flood forecasting technology, conference papers, 17–19 October 2005, Tromsø, Norway.

Veijalainen N, Dubrovin T, Marttunen M, Vehviläinen B (2010) Climate change impacts on water resources and lake regulation in the Vuoksi watershed in Finland. Water Resour Manag 24:3437–3459

Whitfield PH, Cannon AJ (2000) Recent variation in climate and hydrology in Canada. Can Water Resour J 25 (1):19–65

Xu CY (2000) Modeling the effects of climate change on water resources in Central Sweden. Water Resour Manag 14:177–189

Xu CY, Singh VP (2004) Review on regional water resources assessment models under stationary and changing climate. Water Resour Manag 18:591–612