Simulation of climate change impact in a river basin in Eastern India

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Abstract: This study simulates the impact of climate change in Subarnarekha river basin in eastern India using climate projections of regional climate model (PRECIS) of the Hadley Centre, UK, for A1B scenario. Hydrological model, HEC-HMS (of Hydrologic Engineering Center, USA), calibrated for the basin was used to simulate the daily hydrological condition for baseline period and future period of 2015–2030. A comparative analysis of precipitation, potential evapotranspiration, streamflow under changed climate scenario and those parameters (under baseline scenario) revealed decrease of rainfall and corresponding decrease of stream flow in the June–September (JJAS) period for almost half of the future years. Increase of potential evapotranspiration for the months of February to June, increase of annual 24-h maximum rainfall and associated increase in the annual flood maxima with time of occurrence of peak rainfall and peak flow shifting from monsoon period to the month of May were also noted.

Keywords: climate change impact; Subarnarekha River; HEC-HMS; PRECIS model.

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1 Introduction

Climate change is one of the most important global environmental challenges, with implications for food production, water supply, health, energy etc. (Christensen and Lettenmaier, 2007). The associated impact would be particularly severe in the tropical areas which mainly consist of developing countries (including India) (Sathaye et al., 2006). The Subarnarekha River flows through an industrial belt and mineral-rich zone of eastern India. The basin of this river has been experiencing rapid urbanisation, deforestation, mineral exploitation, industrialisation and agricultural expansion during the last decades and thus impact of climate change on water availability would be of particular concern in this inter-state river basin. In this background, a study on the assessment of impact of climate change on water resources of the Subarnarekha River basin lying in eastern part of India has been carried out using a physically-based hydrologic model HEC-HMS for future climate change scenario corresponding to IPCC-SRES A1B emission scenario (moderate GHG emission scenario – for first phase of the study) comprising daily precipitation and temperature data as provided by IITM Pune, India (Kumar et al., 2011). A high-resolution regional climate model, PRECIS, developed by the Hadley Centre was run at the IITM Pune, at 50 km × 50 km horizontal resolution over the south Asian domain in order to develop high resolution climate change scenario for a continuous period of 1961–2098 for impact assessment studies.

Many studies on impact of climate change on water resources have been conducted worldwide in the past two decades. Gosain et al. (2006) investigated the impact of climate change on rainfall, evapotranspiration and discharge over 12 river basins in India (including detailed analyses of Krishna and Mahanadi River basins) using hydrologic model SWAT and projection of the climate model HadRM2 of the Hadley Centre, UK. Ozkul (2009) carried out a study on sensitivity of runoff to changes in precipitation and temperature for Gediz and Buyuk Menderes River basins in Turkey using publicly available model for the assessment of greenhouse gas induced climate change (MAGICC; version 4.1) coupled with a regional climate change scenario generator (SCENGEN), developed by NCAR-CRU based upon over a dozen AOGCMs.

Bae et al. (2011) attempted to analyse the effects of hydrological models and potential evapotranspiration (PET) computation methods on climate change impact assessment of water resources by using Inter-Governmental Panel on Climate Change (IPCC) fourth assessment report (AR4) general circulation model (GCM) simulations for Chungju Dam basin, Korea. Grillakis et al. (2011) assessed the climate change impact on the future hydrology of Spencer Creek Watershed located in Southern Ontario, Canada under the A2 scenario of the special report on emissions scenarios (SRES) using North American Regional Climate Change Assessment Program (NARCCAP) climate simulations between 2040 and 2069 and HEC-HMS Model. Hughes et al. (2011) assessed the hydrological response to scenarios of climate change (constructed from an ensemble of seven climate models assessed in the IPCC AR4) in the Okavango River catchment in Southern Africa. Meenu et al. (2012) assessed hydrologic impacts of climate change in Tungabhadra River basin in India with HEC-HMS model for A2 and B2 scenarios for 2011–40, 2041–70 and 2071–99 using climate projections of the Hadley Centre (UK) coupled model version 3. Acharya et al. (2013) used the HEC-HMS model successfully for analysing impacts of climate change on extreme precipitation events for the Flamingo Tropicana watershed in USA. Bias corrected and spatially disaggregated multi-model multi-scenario (A1B, A2, and B1) data from the World Climate Research Programme's (WCRP's) database was used for future climatic conditions. Das and Simonovic (2013) investigated the climate change related uncertainty in the flood flows for the Upper Thames River basin (Ontario, Canada) using a wide range of climate model scenarios and a continuous daily hydrologic model, HEC-HMS, calibrated for the basin and reported that frequency and magnitude of flood flows in the Upper Thames River basin would most certainly change in the future due to climate change. Kankam-Yeboah et al. (2013) used the soil and water assessment tool (SWAT) and downscaled climate projections from the ensemble of two global climate models (ECHAM4 and CSIRO) forced by the A1FI greenhouse-gas scenario to estimate the impact of climate change on stream flow in the White Volta and Pra River basins, Ghana. Kure et al. (2013) analysed the regional climate change impact for the snowfed and glacierfed basins of the Pyanj and Vaksh Rivers in the Republic of Tajikistan using HEC-HMS model and the downscaled atmospheric data from three GCMs (CCSM3, CSIRO and ECHAM5) and three scenarios (A1B, A2 and B1). Chatterjee et al. (2014) evaluated the impact of climate change on water resources of the Damodar River basin in Eastern India using hydrologic model HEC-HMS for future period 2014–2025 for A1B scenario (output of regional climate model PRECIS (developed by the Hadley Centre, UK) as applied for south Asian domain by IITM Pune). Kling et al. (2014) detailed the hydrological impact modelling of water resources development and climate change scenarios on discharge conditions in the Zambezi basin in Southern Africa using future precipitation and temperature (daily data of global climate models) obtained from EU WATCH project (Water and global change, published in 2011, http://www.eu-watch.org for the IPCC A2 emission scenario).

2 Study area

The Subarnarekha River is one of the longest east flowing inter-state rivers. It originates near Nagri Village (23°18'N, 85°11'E) in Ranchi Plateau in Chhotanagpur highland of Jharkhand at an elevation of 740 m and flows in a south easterly direction for about 450 km before debouching into Bay of Bengal. The river basin (a meso watershed) extends over 19,296 km^2, covering 0.6% of geographical area of the country. The average annual rainfall in the basin is 1,400 mm; quantum of rain is relatively more in lower part. The annual yield of water within the basin constitutes about 0.4% of the country's total surface water resources. The annual utilisable water resource in the basin has been estimated to be 9.66 km^3 (CWC, 1988). The climate in the sub-basin is tropical with hot summer and cold winter. The basin lies between north latitudes of 21°33' to 23°32' and east longitudes of 85°09' to 87°27' in the eastern part of India. The basin is bounded on the north-west by the Chhotanagpur Plateau, in the south-west by Brahmani basin, in the south by Burhabalang basin and in the south-east by the Bay of Bengal (Figure 1).

The basin of the river extending from Jamshedpur up to its outfall, measuring 7,070 km^2 and lying between the latitudes 22°53'N and 21°58'N and longitudes 86°02'E and 87°16'E forms the study area for the present work (Figure 1).

Figure 1 Location map of the study area (see online version for colours)

2.1 Data

Gridded (0.5° × 0.5°) daily rainfall data and gridded (1° × 1°) daily mean temperature data encompassing the study area were collected from National Data Centre, India Meteorological Department, Pune. Other daily meteorological data such as maximum and minimum air temperature, relative humidity, wind speed and solar radiation for Jamshedpur station for the study period have been collected from India Meteorological Department, GoI, Kolkata and those for Jhargram and Midnapore stations from Irrigation Division, Midnapore, Irrigation and Waterways, GoWB. The daily discharge data was obtained from Central Water Commission, GoI, Bhubaneswar. Satellite imagery Data (IRS P6 with LISS III sensor) was collected from National Remote Sensing Center, GoI, Hyderabad. Soil Resource Map was collected from National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), GoI, Salt Lake, Kolkata. Daily rainfall, temperature, relative humidity and wind speed data under A1B scenario of Regional Climate Model PRECIS (Providing Regional Climates for Impacts Studies) of the Hadley Centre, (the resolution being 0.44° × 0.44° latitude/longitude, giving a grid spacing of

50 km) was collected for 1985–1990 and 2015–2030 for the study area from Indian Institute of Tropical Meteorology (IITM), Government of India (GoI), Pune. The Thiessen polygon method has been used to determine the daily mean rainfall and mean temperature over each sub-basin and Penman's method has been used to calculate the PET for the basin for the above noted years.

3 Methodology

3.1 HEC-HMS model

The HEC-HMS (HEC, 2000) Model is designed to simulate the precipitation-runoff process of dendritic watershed systems and with soil moisture accounting (SMA) algorithm, it accounts for a watershed's soil moisture balance over a long-term basis (HEC, 2000), takes explicit account of all runoff components including direct runoff (surface flow) and indirect runoff (interflow and groundwater flow) (Ponce, 1989).

The HEC-HMS model is very adaptable software as it includes a variety of model choices for each segment of the hydrologic cycle and is also freely available and less data-intensive model (Meenu et al., 2012). The physically-based model HEC-HMS had been pointed out as being a standard model in the private sector in the USA for the design of drainage systems, quantifying the effect of land use change in flooding, etc. (Singh and Woolhiser, 2002). The model has been widely applied in many geographical locations for solving a variety of hydrological problems (Grillakis et al., 2011; Fleming and Neary, 2004) and it has also been used by the local water authority (the Upper Thames River Conservation Authority – UTRCA, Canada) in everyday practice (Das and Simonovic, 2013). Thus, HEC-HMS model has been used for this study. The model requires inputs of precipitation, soil, land use and other hydro meteorological data.

The model with SMA algorithm, involves parameters viz., canopy interception storage, surface depression storage, maximum infiltration rate, soil storage, tension zone storage and soil zone percolation rate, groundwater 1 and 2 storage depths, storage coefficients and percolation rates. For the present study, runoff depth was computed using SMA method. Clark's unit hydrograph technique (with the peak and time to peak computed by Snyder's unit hydrograph method) was adopted for basin transformation as the method takes explicit account of both translation and attenuation processes in the transformation of excess precipitation to runoff. Linear reservoir method was used to model base flow. Muskingum method of channel routing was used to generate discharge hydrograph at downstream point in channel.

The parameters needed for the SMA method (canopy interception storage, surface depression storage, land imperviousness, maximum infiltration rate, soil storage, tension zone storage and soil zone percolation rate) were estimated using land use, land cover and soil information.

Groundwater 1 and 2 (hereafter referred as GW1 and GW2) storage depths and storage coefficients were estimated by stream flow recession analysis of historical stream flow observations. The groundwater 1 and 2 percolation rates were determined through model calibration. The standard lag parameter for the Snyder's unit hydrograph technique was estimated from extracted information on basin and drainage network. The UH peaking coefficient parameter was found via calibration. The storage coefficient as required by Clark's method was estimated via calibration. The storage coefficients for the GW1 and GW2 in the linear reservoir method (for base flow computation) were taken to be those used for calibrated SMA model. The storage-time constant K and coefficient X for Muskingum method of channel routing were estimated from observed inflow and outflow hydrographs.

Information in the control specifications (part of HEC-HMS model setup) includes a starting date and time, ending date and time, and computation time step. The computation time interval used in the work is daily.

Soil storage was found to be the most sensitive parameter for the simulated stream flow for the sub-basins followed by tension zone storage for sub-basin S-G and sub-basin S-B. Additionally, land imperviousness and soil percolation rate also caused the most variation in simulated stream flow for sub-basin S-J. Thus the model was calibrated for sub-basins for respective identified parameters.

The Nash-Sutcliffe model efficiency criterion, percentage error in volume and the percentage error in peak which were used for performance evaluation, have been found to range from (0.72 to 0.84), (4.39 to 12.2%) and (1.9 to 19%) respectively, indicating a good performance of the model for simulation of stream flow (Roy et al., 2013).

The study basin has been divided into four sub-basins (hereafter referred as, S-G, S-J, S-B and S-Bh) in order to account for spatial variability of precipitation and runoff response characteristics.

3.2 Climate change scenario

This work uses future climate change scenario (corresponding to IPCC-SRES A1B emission scenario (moderate GHG emission) and comprising daily precipitation and temperature data) provided by IITM Pune, India (Kumar et al., 2011). This emission scenario has been used to reflect the impact of moderate potential climate change on Subarnarekha basin for the first phase of the climate change impact study for the basin. A high-resolution regional climate model, PRECIS, developed by the Hadley Centre was run at the IITM Pune, at 50 km × 50 km horizontal resolution over the south Asian domain in order to develop high resolution climate change scenario for a continuous period of 1961–2098 for impact assessment studies.

The statistics of the observed and the PRECIS simulated values along with the bias (the difference between the PRECIS value and the corresponding observed value of the statistics) for daily rainfall and maximum and minimum air temperature for the sub-basins for baseline period are shown in Tables 1 and 2 respectively. Estimates of percent of wet days for the sub-basins are also shown in Table 1. It may be noted that percent of wet days may be used as performance criteria for model evaluation as stated by Meenu et al. (2012).

It is evident from Table 1 that PRECIS model yields lower estimates of mean (in the range of 0.04 to 0.29), variance (in the range of 10.14 to 11.93) for daily rainfall and higher estimates of percent of wet days (in the range of –5 to –8) compared to the observed values. Again, it is evident from Table 2 that PRECIS model yields lower estimates of mean (0.67 to 2.12) and higher estimates of variance (in the range of –4.1 to –14.52) for both maximum and minimum air temperature compared to the observed values. Thus, bias of PRECIS output for rainfall, maximum and minimum air temperature is low. The coefficient of determination (R^2) values were found to be quite high (86% to 87%) for minimum air temperature, moderate (65 to 73%) for maximum air temperature. However, the coefficient of determination (R^2) value was found to be rather low (about 25%) for daily rainfall for the sub-basins.

Table 1 Statistics of observed and PRECIS simulated rainfall for baseline period

Sub basin	*Mean (mm/day)*			*Variance (mm^2)*			*R^2*	*% of wet days*		
	Obs.	*PRECIS*	*Bias*	*Obs.*	*PRECIS*	*Bias*		*Obs.*	*PRECIS*	*Bias*
S-G	3.95	3.66	0.29	39.59	29.40	10.18	0.27	30.00	35.00	–5
S-J	4.10	4.06	0.04	38.25	26.74	11.51	0.32	28.00	36.00	–8
S-B	4.50	4.34	0.15	36.01	25.87	10.14	0.26	31.00	36.00	–5
S-Bh	5.00	4.79	0.21	40.61	28.67	11.93	0.19	31.00	37.00	–6

Table 2 Statistics of observed and PRECIS simulated maximum and minimum temperature for baseline period

Sub basin	*Mean*			*Variance*			*R^2*
	Obs.	*PRECIS*	*Bias*	*Obs.*	*PRECIS*	*Bias*	
				Max. temperature (°C)			
S-G	31.71	30.22	1.49	14.1	23.92	–9.82	0.65
S-J	31.81	30.72	1.09	12.52	23.63	–11.11	0.67
S-B	31.65	30.69	0.96	10.5	21.69	–11.19	0.68
S-Bh	31.97	29.85	2.12	7.97	12.07	–4.1	0.73
				Min. temperature (°C)			
S-G	20.38	19.04	1.34	23.74	36.95	–13.21	0.87
S-J	20.91	19.99	0.92	22.44	36.96	–14.52	0.86
S-B	22.57	21.9	0.67	18.56	28.33	–9.77	0.87
S-Bh	21.41	20.45	0.96	21.26	28	–6.74	0.86

Figures 2 and 3 show plots of observed and PRECIS simulated average monthly rainfall and average daily maximum and minimum temperature during baseline period for sub-basin S-B and sub-basin S-Bh respectively. It is evident from Figure 3 that there is good agreement between the observed and PRECIS simulated maximum and minimum temperatures throughout the year during the baseline period.

The hydrological model was used to generate the streamflow for the sub-basins of the study area for baseline (1985–1990) and future period (2015–2030 – for first phase of study) by using the temperature, precipitation, relative humidity and wind speed data provided by PRECIS. A comparative analysis of precipitation, temperature, PET, streamflow under changed climate scenario and those (under baseline scenario) was carried out to analyse impact of climate change on water resources in the basins.

Figure 2 Plots of observed and PRECIS simulated average monthly rainfall during baseline period for sub-basin S-B (see online version for colours)

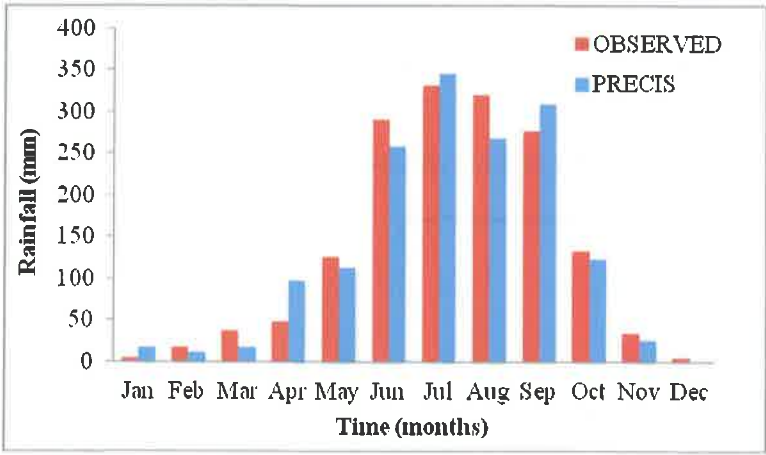
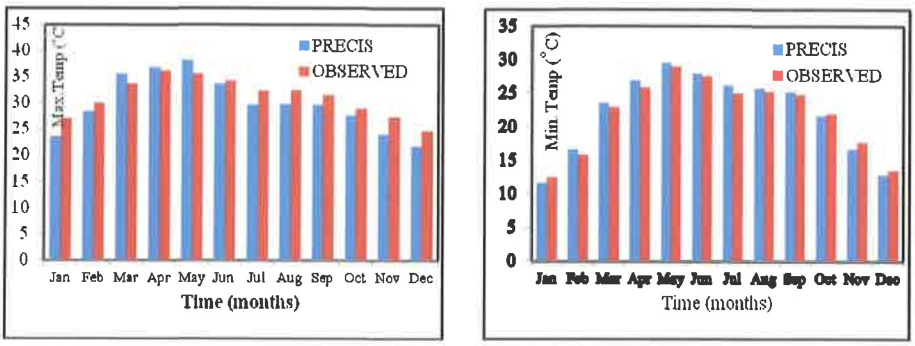


Figure 3 Plots of observed and PRECIS simulated average daily maximum and minimum temperature during baseline period for sub-basin S-Bh (see online version for colours)



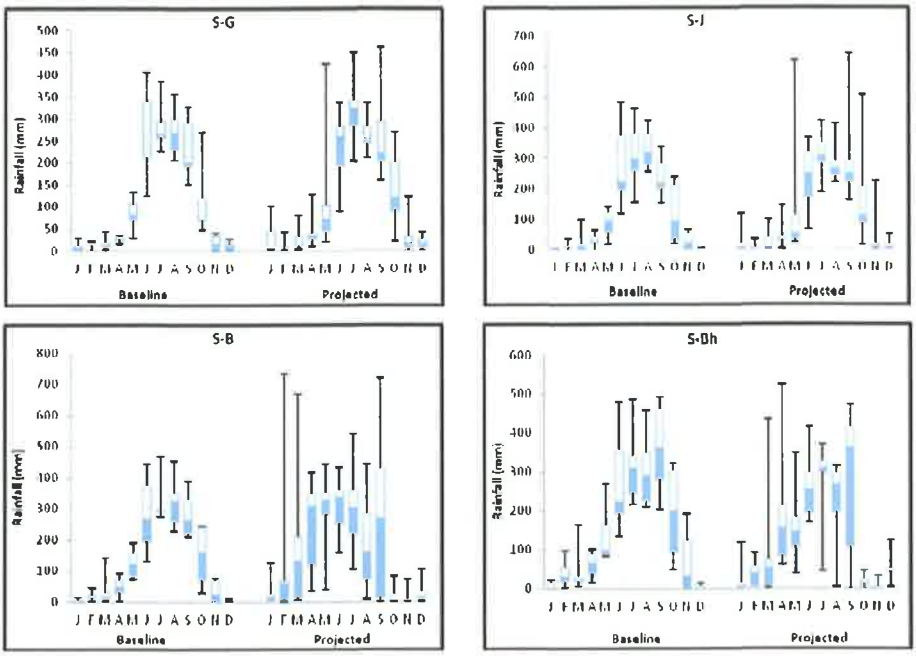
4 Results and discussion

Figures 4–12 show box plots of monthly and annual rainfall, PET, streamflow and also annual 24-h maximum rainfall and annual maximum flow and diurnal temperature range for baseline and future periods for the sub-basins. The line in the middle of the boxes denotes the median values and the upper and lower boundaries show the 25th (quartile 1) and 75th percentiles (quartile 3) respectively. The ticks outside of the boxes denote the maximum and minimum values of the data.

4.1 Monthly rainfall

Decrease of projected rainfall by 4% to 65% (median) for month of August for all sub-basins (Figure 4), 4% (median) increase for the month of July for S-B sub-basin, 2.4% and 0.05% increase in median values of rainfall for the month of September for S-B and S-Bh sub-basins respectively and increase in rainfall for the month of June for the sub-basins from corresponding baseline values were noted. Increased rainfall (median) in April and December was projected for future years for all sub-basins and same was also projected in October for sub-basins S-G and S-J and during January and February for S-B and S-Bh sub-basins. A marked increase (46% to 807%) in the rainfall (median) of March, April and May and also in December (increment of 330 to 2,530%) was noticed in sub-basins S-B and S-Bh.

Figure 4 Box plot for monthly rainfall in projected and baseline years (see online version for colours)



Decrease of projected rainfall for the months of July and August and increase of projected rainfall for months of December, April and May was also reported for sub-basins of Damodar River (Eastern India) for A1B scenario for 2015–2030 (climate projections of regional climate model PRECIS of the Hadley Centre, UK as prepared by IITM Pune for India) by Chatterjee et al. (2014). Meenu et al. (2012) reported increase in precipitation for the months of April, June, September and November for one of the sub-basins of Tungabhadra dam in India under the A2 scenario for 2011–40 [using climate projections of the Hadley Centre (UK) coupled model version 3].

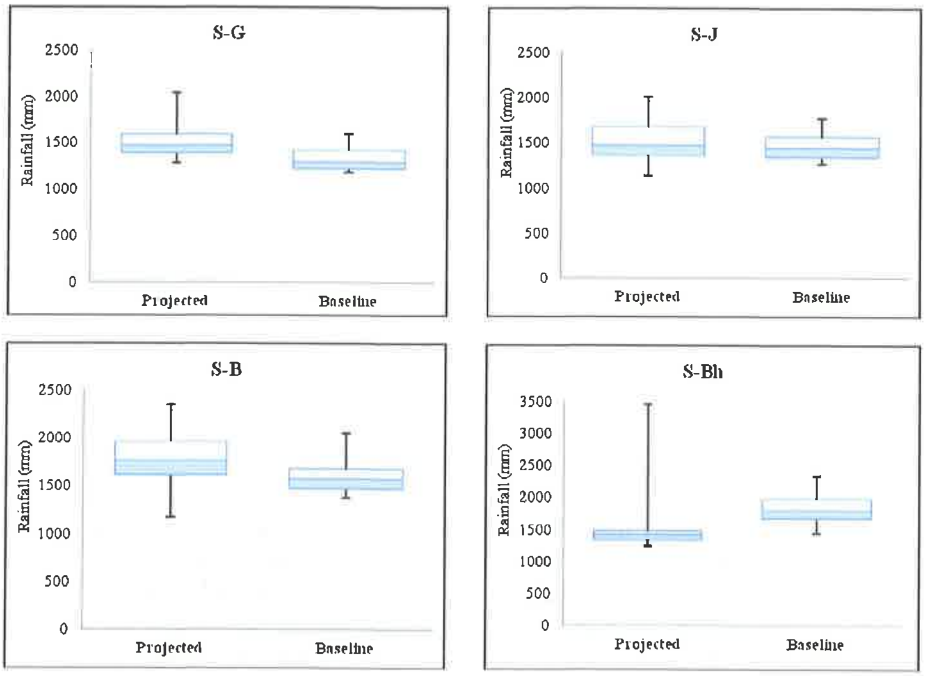
Analysis of quartile 1, quartile 3 and median rainfall values indicates an increasing trend for rainfall for the month of April and December for all sub-basins. Change in seasonal distribution of rainfall (decrease of rainfall in the JJAS period by 35% to 45%) for almost half of the future years was noted.

A decrease in precipitation in the JJAS period was also observed in 2022 and 2023 (by 20% to 72%) for all the sub-basins and (by 48% to 66%) in 2024 and 2025 for the sub-basins on the main stretch of the Damodar River system (Chatterjee et al., 2014).

4.2 Annual rainfall

Figure 5 shows an increase of 12–22% in annual rainfall (median) in the future for the sub-basins S-G, S-B and S-Bh and an increase of 2% only for S-J sub-basin. The annual increases in precipitation for sub-basins are mainly caused by increases in precipitation in April, October and December.

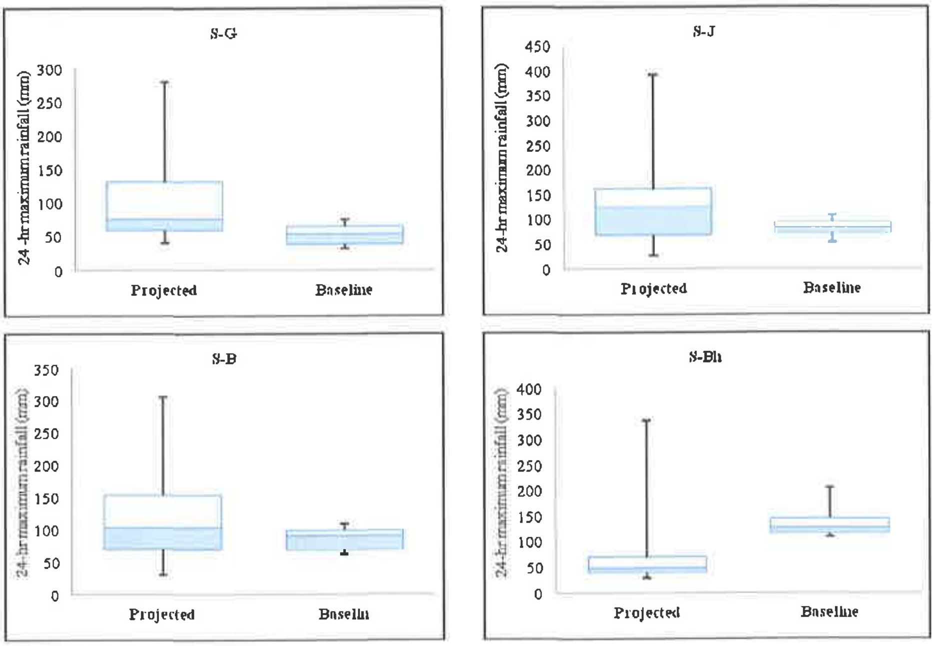
Figure 5 Box plot for annual rainfall in projected and baseline years (see online version for colours)



4.3 Annual 24-h maximum rainfall

Increase in the annual 24-h maximum rainfall with the time of occurrence shifting from monsoon to month of October in future years of 2015, 2019, and 2020 and in the month of May for 2023 and 2030 for all sub-basins was noted. Marked increase (range being 20% to 35%) in the annual 24-h maximum rainfall was simulated for the year 2030 for all the sub-basins. Increase of 1 to 49% of median values, 38% to 100% of quartile 3 values of annual 24-h maximum rainfall (Figure 6) in comparison to baseline period for all sub-basins have been noted indicating an increasing trend for annual 24-h maximum rainfall.

Figure 6 Box plot for annual 24 hr maximum rainfall in projected and baseline years (see online version for colours)



4.4 Diurnal temperature range

Variations in mean monthly diurnal temperature range in the sub-basins for the baseline and future periods are shown in Figure 7. The diurnal range was found to increase in month of June and decrease in winter months of December, January and February and also for summer months of March, April and May for all sub-basins for the future periods. Decrease of diurnal range in the winter months for two sub-basins of Tungabhadra Dam whereas considerable increase in diurnal range throughout the year of for another sub-basin of the aforesaid dam under the A2 and B2 scenarios for future periods of 2011–40, 2041–2070 and 2071–2099 was reported by Meenu et al. (2012).

Figure 7 Average diurnal temperatures variation for baseline and projected years (see online version for colours)

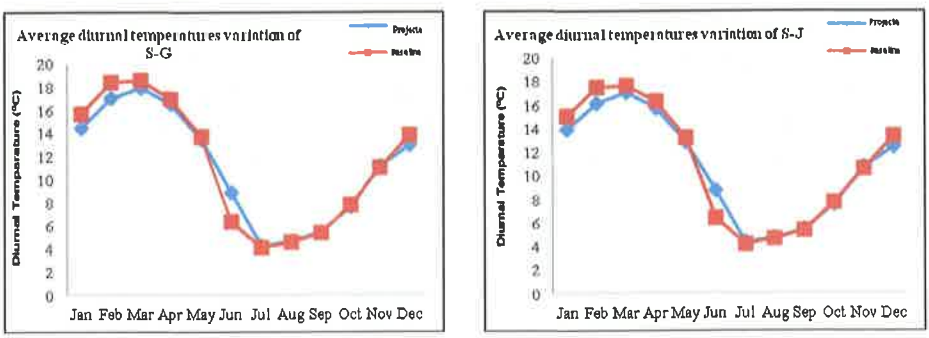
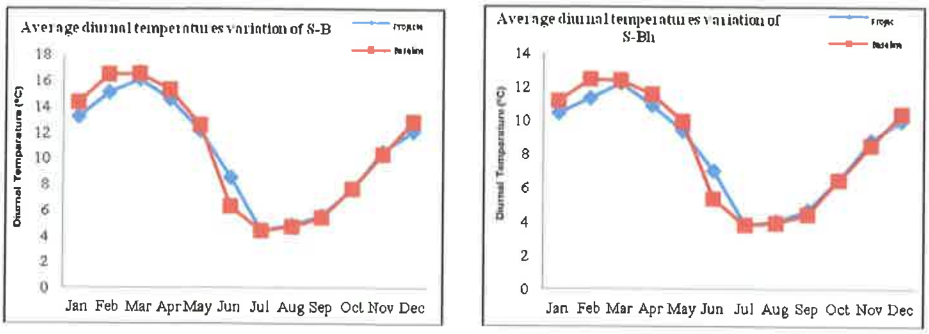


Figure 7 Average diurnal temperatures variation for baseline and projected years (continued) (see online version for colours)



4.5 *Monthly PET*

The monthly distribution of projected PET values (median or average) was found to follow the pattern of monthly distribution of baseline PET values. The projected PET values (median) for all sub-basins were found to be (Figure 8) higher (by 5 to 17%) than corresponding baseline values (median) for the months of February to June and lower (by 1 to 17%) than corresponding baseline values for the remaining months (except July, wherein change is insignificant); the decrease being larger (by 12 to 17%) for the months of November and December. Future projection of PET values for all the sub-basins of the Damodar River system was reported (Chatterjee et al., 2014) to be the same as that noted above for sub-basins of Subarnarekha River for the months of February to June and November and December.

The projected monthly PET values (maximum value) for all sub-basins were also found to exceed the corresponding baseline values for all the months (excepting for December for all basins and for September for S-G and S-J); the quantum of increase was larger (11 to 22%) for May, June and November for all sub-basins and also for months of March and April for S-B and S-Bh. Analysis of quartile 1, quartile 3 and median PET values indicate an increasing trend for projected PET for the months of February to June and a decreasing trend for projected PET for the months of September to December for all sub-basins in comparison to baseline values.

Figure 8 Box plot for monthly PET in projected and baseline years (see online version for colours)

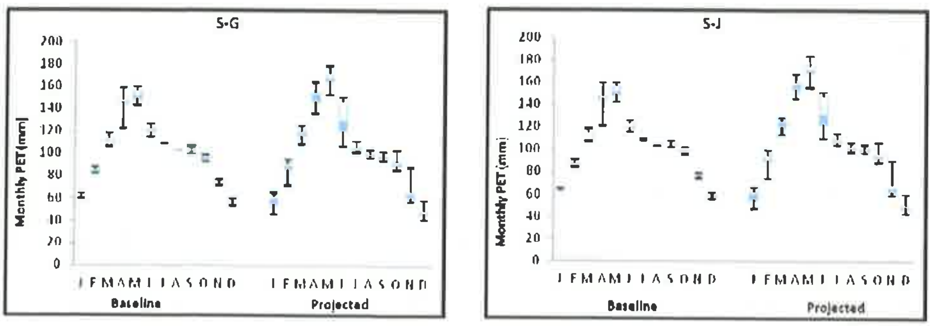
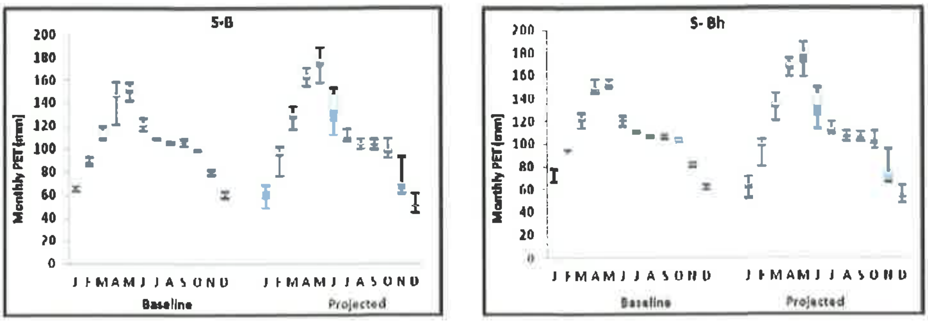


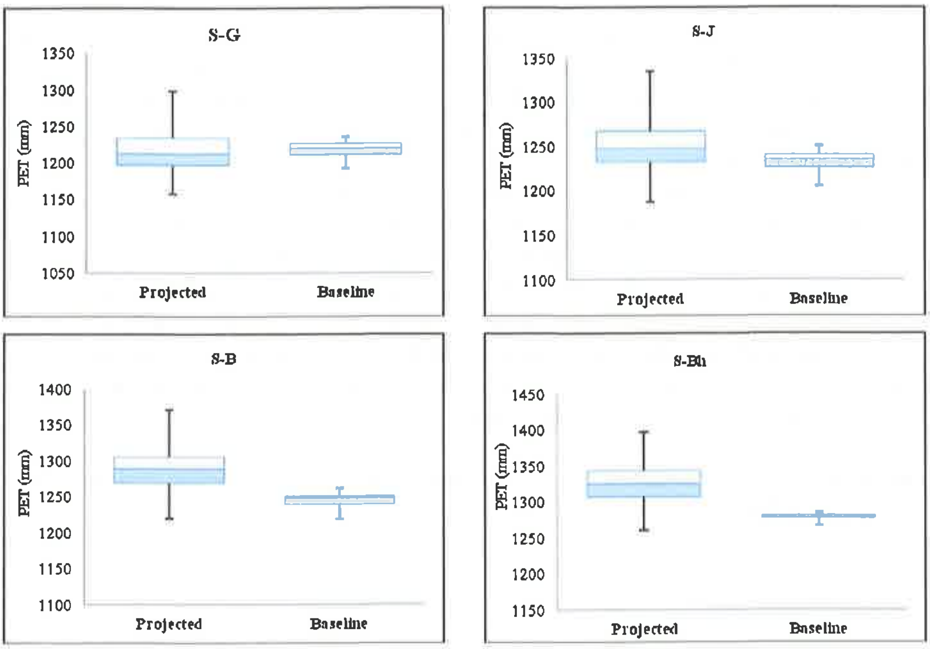
Figure 8 Box plot for monthly PET in projected and baseline years (continued) (see online version for colours)



4.6 Annual PET

Figure 9 shows an increase of 1 to 3% in annual PET (median) in the future for all the sub-basins and very small decrease of 0.7% in annual PET (median) for sub-basin S-G only. These increases are mainly caused by increased PET during February to June.

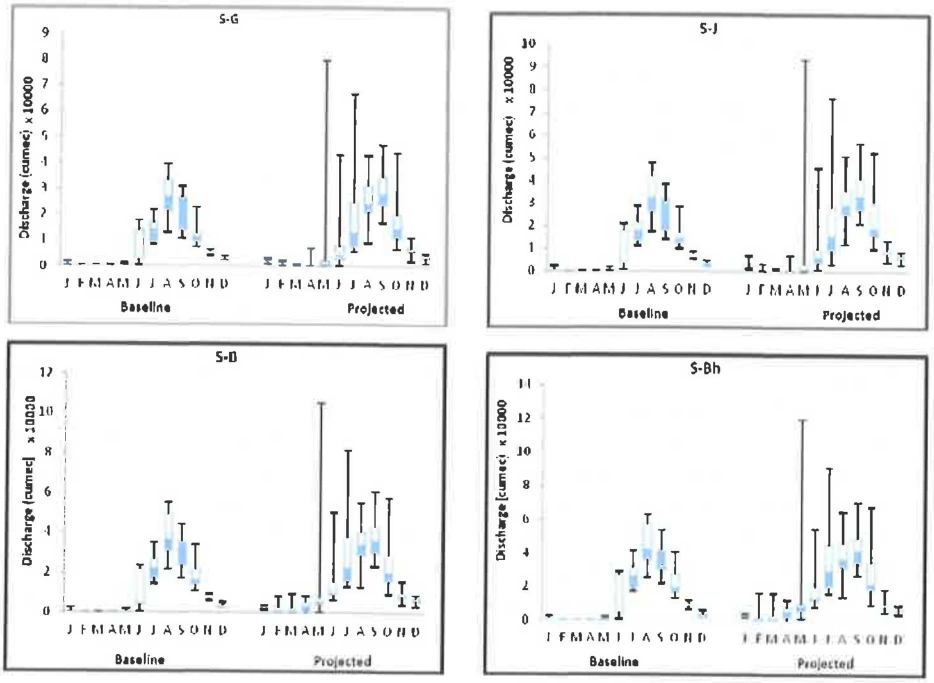
Figure 9 Box plot for annual PET in projected and baseline years (see online version for colours)



4.7 Monthly streamflow

The projected flow (median) was found to increase (by 1 to 7%) in the month of September, (by 8.3 to 36%) in the month of October and in the month of June (65 to 182%) for all sub-basins and to decrease by (9 to 11.2%) in months of August and by (6.9 to 13.5%) in July (excepting for S-B and S-Bh) for all the sub-basins (Figure 10).

Figure 10 Box plot for monthly flow in projected and baseline years (see online version for colours)



Increased flow (median) in November (6.3 to 36%) and in December (35.2 to 109%) was also projected for future years for all sub-basins. Higher increase in flow (median) by (79 to 950%) was noted for sub-basins S-G, S-J, S-B, S-Bh for the months of January to May. Marked increase (1495 to 3367%) was noted for flow (median) for sub-basins S-B and S-Bh for the month of March and April. Streamflow was noted to increase for months June for all sub-basins of the Damodar River system (except for the Tenughat sub-basin) and was noted to decrease for the months of July and August for all sub-basins of the Damodar River system (Chatterjee et al., 2014). The same study reported a marked increase (by 706.4% to 2207.5%) in the projected monthly flow during March, April and May for some sub-basins of the Damodar River system. It may be noted that Meenu et al. (2012) also reported increase of projected flow for months of May, June, July and September and decrease of flow in the month of October to April and August for at the outlet of the Tungabhadra basin in India in future periods of 2011–2040 (A2 and B2 scenarios) obtained from the Hadley Centre coupled model version 3.

Analysis of quartile 1, quartile 3 and median discharge values indicate an increasing trend for projected discharges for the months of January to May and September to December for all the sub-basins and also an decreasing trend for projected discharges for the months of August for all sub-basins and for the months of June and July for S-G, S-J sub-basins in comparison to baseline values. Change in seasonal distribution of stream flow (decrease of stream flow in the JJAS period) for almost half of the future years was noted. Decrease in stream flow in the JJAS period was observed in 2015, 2019, 2023 and 2030 (by 29% to 39%) for all the sub-basins (not shown). Decrease of streamflow by 14% to 37% in the JJAS period (June, July, August and September) in the future years was noted also for the sub-basins of Konar, Tenughat and Panchet (on the main stretch of the Damodar River system). Decrease in streamflow in the JJAS period was observed in 2022 and 2023 (by 41% to 78%) for all the sub-basins and (by 45% to 75%) in 2024 and 2025 for the sub-basins on the main stretch of the Damodar River system (Chatterjee et al., 2014). Dhar (2010) reported seasonal change of stream flow pattern for Ajay River catchment (West Bengal, India) for future period of 2040–2050 (using output of regional climate model PRECIS (derived from Hadley Centre, UK climate model HadRM2) as prepared by IITM Pune).

4.8 Annual streamflow

Figure 11 show an increase of 21.5 to 22.5% in annual flow (median) in the future for all the sub-basins with respect to the baseline flows. It is clear from the box plots of future annual streamflow that there is an increasing tendency of annual streamflow in the future for all the sub-basins. Increase in annual flow in the future for some sub-basins of the Damodar River was reported by Chatterjee et al. (2014) and the same was reported at the outlet of the Tungabhadra basin by Meenu et al. (2012). However, Gosain et al. (2006) reported reduction in annual average precipitation by about 20%, decrease in water yield by 30% to 50% for sub-basins of the Krishna River in India and increase in annual average precipitation and water yield for all sub-basins of Mahanadi in India for 2041–2060 period using hydrologic model SWAT and climate projection of climate model HadRM2 of the Hadley Centre, UK.

Figure 11 Box plot for annual flow in projected and baseline years (see online version for colours)

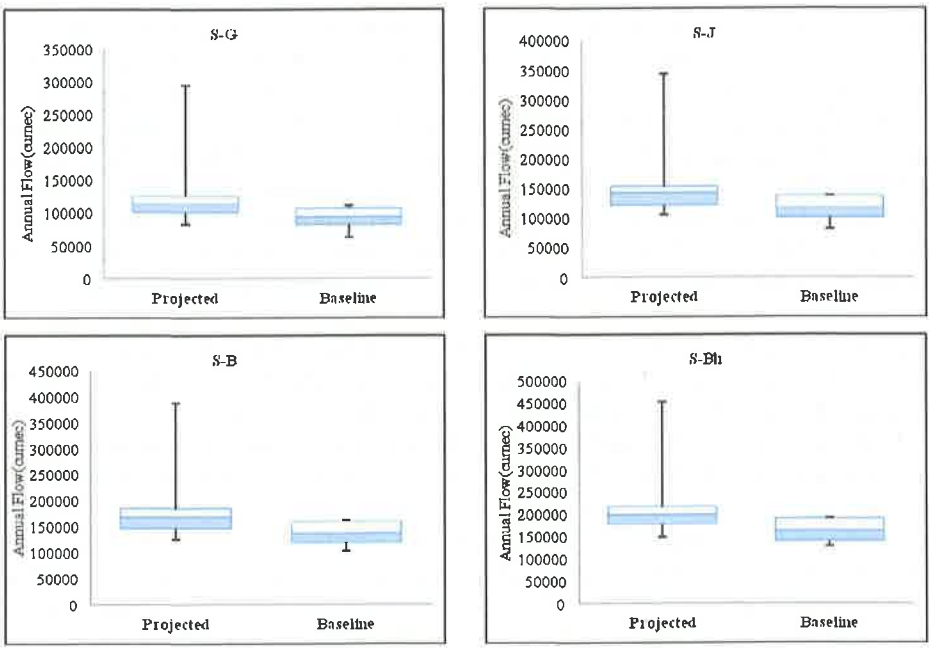


Figure 12 Box plot for annual maximum flow in projected and baseline years (see online version for colours)

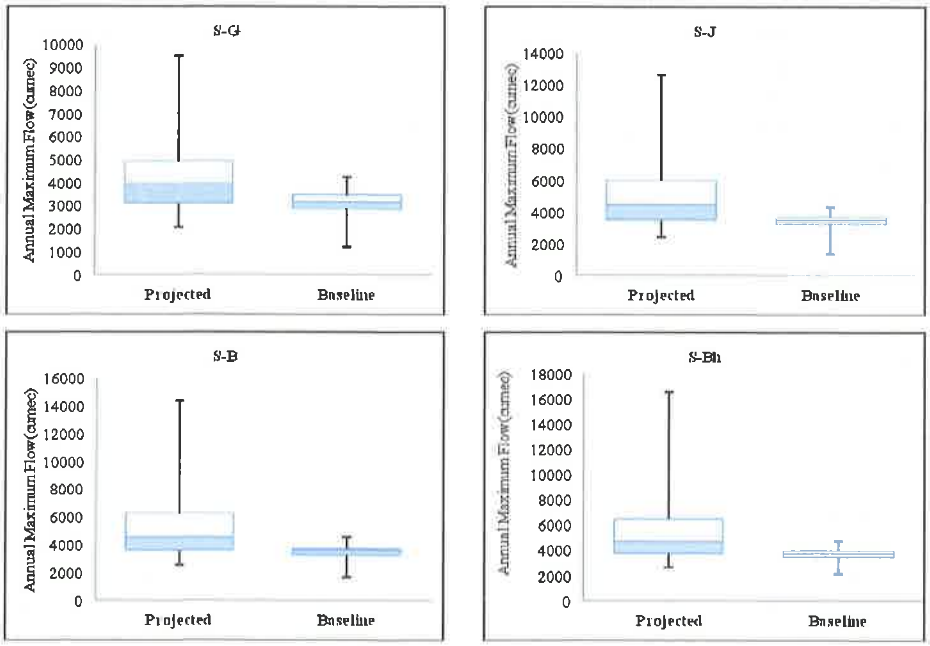
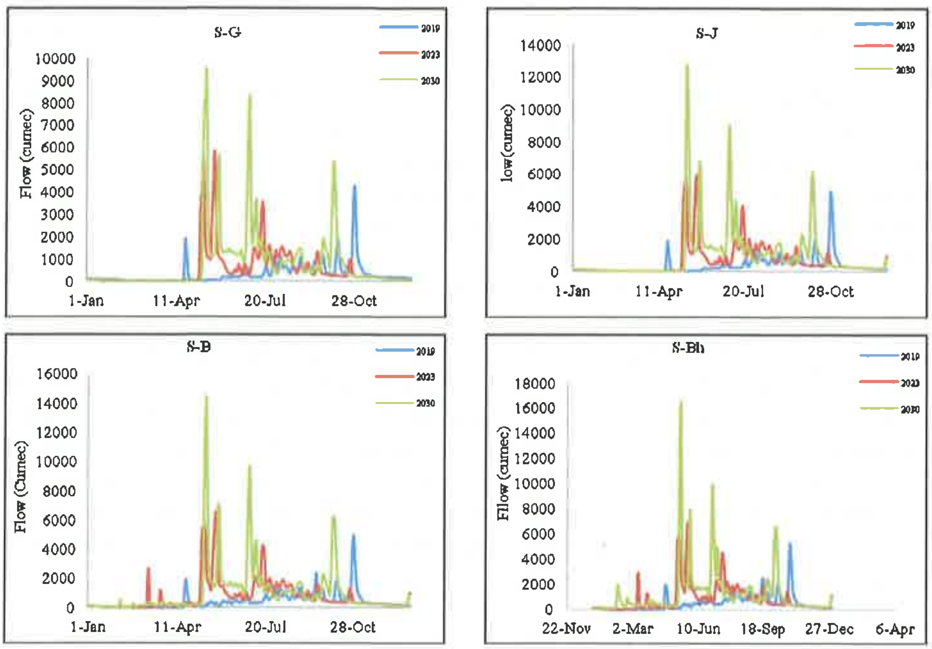


Figure 13 Hydrographs for sub-basins for future years (see online version for colours)



4.9 Annual maximum flow

An increasing trend of annual peak flows for all the sub-basins in future periods in comparison to baseline period has been observed (Figure 12). Increase in the annual flood maxima was simulated (range being 12 to 17%) with the time of occurrence shifting from monsoon to month of October in future years of 2015, 2019, 2020 and in month of May for 2023 and 2030 for all sub-basins. Remarkable increase (range 37 to 48.7%) in the annual flood maxima was simulated for the year 2030 for all the sub-basins. High flow in May, 2030 may be attributed to three day heavy rainfall in May, 2030 for the sub-basin. Increase of annual maximum flow with the time of occurrence shifting from monsoon to month of March or May (as the case may be) for some of the future years for sub-basins of Damoder River has been noted (Chatterjee et al., 2014). However, reduction of peak flow was reported by Dhar (2010) for Ajay River catchment (West Bengal, India) for future period of 2040–2050.

The stream-flow hydrographs for some future years for the sub-basins have been shown in Figure 13.

5 Conclusions

The HEC-HMS catchment simulation model (using distributed modelling approach thereby explicitly accounting for response of individual sub-catchments) has been applied to Subarnarekha River basin in Eastern India for assessment of impact of climate change on the water arena (on phases of the hydrologic cycle) of the basin. Further SMA algorithm which accounts for a watershed's soil moisture balance over a long-term period, takes explicit account of all runoff components including direct runoff (surface flow) and indirect runoff (interflow and groundwater flow) has been used to compute losses from the basin. The projected climate scenario is based on simulated projections of climate over India, generated by a high-resolution regional climate model PRECIS (Providing Regional Climates for Impacts Studies) developed by the Hadley Centre, UK and run at the Indian Institute of Tropical Meteorology (IITM), Pune, India at 50 km × 50 km horizontal resolution over the South Asian domain for A1B scenario (Special Report on Emissions Scenarios (SRES) prepared under the IPCC coordination (IPCC, 2007).

The impact analysis revealed decrease of projected rainfall by for month of August for all sub-basins and high increase in the rainfall for the months of March, April, May and December for the sub-basins. High increase in flow (median) by (79 to 950%) for sub-basins for the months of January to May and marked increase of flow (median) (1495 to 3367%) for sub-basins S-B and S-Bh for the months of March and April were noted.

Change in seasonal distribution of rainfall (decrease of rainfall in the JJAS period) for almost half of the future years was noted for all the sub-basins; this decrease turned out to be marked for four years (including 2030). Correspondingly, change in seasonal distribution of stream flow (decrease of stream flow in the JJAS period by 29% to 39%) for almost half of the future years was noted.

Increase of annual 24-h maximum rainfall and associated increase in the annual flood maxima (12 to 17%) were noted with time of occurrence of peak rainfall and flood shifting from monsoon period to the months of October and May. Marked increase in the annual 24-h maximum rainfall (and associated annual flood maxima – range 37 to 48.7%)

was simulated for the year 2030 for all the sub-basins. Higher PET values for February to June and lower PET values for the remaining months were noted. Increase of annual flow (21.5 to 22.5%) for all the sub-basins in conformity with annual rainfall was noted. An increasing trend of annual 24-h maximum rainfall, annual peak flows and annual streamflow for all the sub-basins was predicted.

Seasonal change in rainfall pattern might affect crop production. Again, seasonal shift in stream flow pattern might have significant negative effects on ecosystem. This may jeopardise economy of people associated with fishing trade and agriculture. Thus, the outcome of the study would facilitate to work out the policy options related to sustainable development under changed climate scenario (change in precipitation and flow pattern) at local level and this may include motivating the stakeholders to adapt to changed scenario (change of crop pattern, adoption of efficient irrigation practice and upgradation of existing flood warning system) foregoing the conventional practices.

It may be noted that this study has been carried out using a single hydrological model (including adoption of single method for phases of hydrological cycle and unchanged land use pattern in future) using single projection (among ensemble of Projections) generated by a regional climate model (viz., PRECIS derived from the Hadley Center Coupled Model HadCM3) for a single emission scenario. Thus other climate projections (ensemble projection and other climate models) and other greenhouse gas emission scenarios (A1, A2, B1 etc. related to various aspects of future development) may be considered for this basin for investigation beyond 2030 with other hydrological models (considering changed land use pattern) and the associated uncertainties may be addressed.

It may also be noted that to the best of our knowledge, no work related to such detailed simulation of impact of climate change in the Subarnarekha River basin has been carried out.

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