Impact of climate change on the hydrology of a semi-arid river basin of India under hypothetical and projected climate change scenarios

Sujeet Desai, D. K. Singh, Adlul Islam and A. Sarangi

ABSTRACT

Climate change impact on the hydrology of the Betwa river basin, located in the semi-arid region of Central India, was assessed using the Soil and Water Assessment Tool (SWAT), driven by hypothetical scenarios and Model of Interdisciplinary Research on Climate version 5 (MIROC5) Global Circulation Model projections. SWAT-Calibration and Uncertainty Programs (SWAT-CUP) was used for calibration and validation of SWAT using multi-site streamflow data. The coefficient of determination, Nash–Sutcliffe efficiency, RMSE-observations standard deviation ratio and percent bias during calibration and validation period varied from 0.83–0.92, 0.6–0.91, 0.3–0.63 and −19.8–19.3, respectively. MIROC5 projections revealed an increase in annual mean temperature in the range of 0.7–0.9 °C, 1.2–2.0 °C and 1.1–3.1 °C during the 2020s, 2050s, and 2080s, respectively. Rainfall is likely to increase in the range of 0.4–9.1% and 5.7–15.3% during the 2050s and 2080s, respectively. Simulation results indicated 3.8–29% and 12–48% increase in mean annual surface runoff during the 2050s and 2080s, respectively. Similarly, an increase of 0.2–3.0%, 2.6–4.2% and 3.5–6.2% in mean annual evapotranspiration is likely during the 2020s, 2050s and 2080s, respectively. These results could be used for developing suitable climate change adaptation plans for the river basin.

Key words | adaptation measures, climate change, evapotranspiration, MIROC5, surface runoff, SWAT

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HIGHLIGHTS

- SWAT was calibrated at multi-site gauging stations in a semi-arid river basin.
- Hypothetical climate change scenarios of Rainfall, Temperature and CO_2 was used to assess the basin response.
- Surface runoff was sensitive to rainfall change and ET was sensitive to CO_2 change.
- Surface runoff and ET are projected to increase during the 2050s and 2080s under RCP scenarios.
- Climate change adaptation measures were suggested.

INTRODUCTION

The impact of climate change on water and agriculture is of major concern globally. Climate change may affect food and livelihood security, particularly in developing countries. It is a well-known fact that the increase in greenhouse gas (GHG) concentration in the atmosphere is the main cause of climate change (IPCC 2007). Globally, the mean surface temperature is expected to increase in the range of 0.3 °C to 0.7 °C for the period 2016–2035 with respect to 1986–2005 under various Representative Concentration Pathways

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(RCPs) (IPCC 2014). Climatic change is likely to affect the hydrological cycle, as climate and hydrology are complementary phenomena. The Coupled Model Intercomparison Project Phase 5 (CMIP5)-based model ensemble has projected 1.7 to 2.0 °C and 2.0 to 4.8 °C increase in all-India annual mean temperature during the 2030s and 2080s, respectively, under different Representative Concentration Pathways (RCPs) as compared to the pre-industrial base of the 1880s (1861–1900) (Chaturvedi *et al.* 2012). Similarly, precipitation is expected to increase by 1.2 to 2.4% and 3.5 to 11.3% during the 2030s and 2080s, respectively. In almost all regions of India, precipitation is projected to increase except for a few regions in short-term projections (2030s). Along with temperature and rainfall, changes in CO_2 concentrations in the atmosphere also influence the evapotranspiration and runoff. Several studies suggest that the effect of rising temperature on evapotranspiration is offset due to increased CO_2 concentrations (Rosenberg *et al.* 1989; Islam *et al.* 2012b). Thus, changes in the precipitation, temperature and other climatic variables would significantly change the surface and groundwater availability for agricultural crops, especially in arid and semi-arid regions. The semi-arid and water-scarce regions at regional levels are more susceptible to climate change and suffer from water shortage (Setegn *et al.* 2011). Therefore, it is extremely important to know the impact of climate change on water availability for planning and managing the water resources at the regional level (Islam *et al.* 2012a). Changes in the flow extremes due to climate change will also have serious consequences for the design and operation of water management structures (Vandana *et al.* 2019).

The Betwa river basin, which is a part of the Ganga basin, lies in the semi-arid and water-scarce region of Central India. It is one of the important tributaries of Yamuna river traversing the Bundelkhand region. Agriculture is the dominant land use in the basin, covering about 68% of the total geographical area and is predominantly rainfed due to poor irrigation facilities. This river basin also faces frequent droughts, affecting agricultural productivity. The Betwa and Ken, the two important rivers in the water-scarce Bundelkhand region, have been selected as a pilot project for interlinking of rivers by the National Water Development Agency (NWDA) of the Ministry of Water Resources, River Development & Ganga Rejuvenation (MoWR, RD & GR), Government of India to facilitate irrigation to the upstream water-scarce regions of Betwa basin to mitigate the water scarcity problem. As climate change is likely to further aggravate the water resource availability in the basin, it is very relevant to study the future impacts of climate change on water resource availability in the drought-affected Betwa river basin, especially from the agricultural point of view.

The assessment of climate change impact on the hydrology at river basin or watershed scale is carried out by using hydrological models that are driven by climate data from hypothetical scenarios or General Circulation Models' (GCMs) projections (Wu *et al.* 2012). The hypothetical climate change scenarios help in better understanding of how basins respond to changes in climate (Nash & Gleick 1991) in the absence of future climatic scenarios. They are generally used for estimating system sensitivity before applying more reliable, model-based scenarios (Mearns *et al.* 2001). Hydrologic simulation models translate GCM projections to hydrological projections. For assessment of climate change impact on water availability in large river basins, distributed, and semi-distributed hydrological models are preferred (Watts 2011) to account for the spatial heterogeneity of the river basin. The Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 1998) is one of the most commonly used semi-distributed, continuous time scale hydrological models, and has been widely used in different parts of the world (Parajuli 2010; Piniewski & Okruszko 2011; Lirong & Jianyun 2012; Ficklin *et al.* 2013). The SWAT model has successfully been applied for studying the impact of climate change on water resources in Indian river basins using various GCM projected climate change scenarios (Gosain *et al.* 2011; Narsimlu *et al.* 2013; Kumar *et al.* 2017). This model has many advantages due to its computational efficiency, auto-calibration, sensitivity and uncertainty analysis capability, and is available as an open-source tool (Islam *et al.* 2018).

GCMs are important tools for simulating the global climate response to increasing greenhouse gas concentrations (GHGs). However, mismatch between the coarse resolution of GCMs and fine resolution data requirements of hydrological models is one of the major obstacles in climate change impact assessment on water resources at the basin level using hydrological models. Most of the GCMs are capable of simulating average annual and seasonal climate over large geographical areas but are less reliable at smaller spatial and temporal scale or regional scale simulation, which is important for impact assessment studies (Grotch & MacCarcken 1991).

Over the past decades, there has been great advancement in GCM predictions. The CMIP5 climate change projections are driven by emission scenarios or concentration consistent with the Representative Concentration Pathways (RCPs) (Moss *et al.* 2010). The CMIP5 climate change scenarios assume a matrix approach to assess the impacts under various combinations of the rate of change and future socio-economic factors (Moss *et al.* 2010; van Vuuren *et al.* 2012). In CMIP5 models, there is an enhancement in the skills for simulating the seasonal cycle of temperature as compared to CMIP3 models (Sonali *et al.* 2017). Climate change impact assessment on the hydrology of river basins or sub-basins using various hydrological models under RCP scenarios has been studied in different parts of the world (Arnell & Lloyd-Hughes 2014; Gebre & Ludwig 2015; Ouyang *et al.* 2015; Yan *et al.* 2015; Basheer *et al.* 2016; Li *et al.* 2016). However, limited studies have been reported for Indian river basins or sub-basins using the CMIP5 projected climate scenarios (Mishra & Lilhare 2016; Saharia & Sarma 2018; Abeysingha *et al.* 2020). Understanding the hydrologic behaviour at the regional level under changing climatic scenarios would go a long way in resolving water resource management-related issues. Thus, the aim of this study was to assess the impact of climate change on the hydrology of the semi-arid Betwa river basin driven by RCP-based climate change scenarios using the SWAT hydrological model.

METHODS

Study area

The Betwa river basin is located in the Bundelkhand region of Central India and originates from Barkhera in Raisen district of Madhya Pradesh state, India (Figure 1). The river runs for more than 590 km prior to joining the Yamuna River in the Hamirpur district of Uttar Pradesh state. It flows in a north-eastern direction from Madhya Pradesh and enters Uttar Pradesh in Jhansi district. The Betwa river basin lies between latitude 22°59′57″ to 26°03′23″ N and longitude 77°05′51″ to 80°13′01″ E, covering five districts of Uttar Pradesh and nine districts of Madhya Pradesh. The total area drained by the basin is 43,946 km^2. The mean annual precipitation in the basin varies from 700 to 1,200 mm. The minimum temperature ranges from 8 to 12 °C and the maximum temperature ranges from 38 to 43 °C. The elevation of the river basin varies from 63 to 724 m above mean sea level (Desai *et al.* 2016). There are three major dams on the main Betwa River, namely, Rajghat dam, Matatila dam and Dhukwan dam for irrigation supply, mostly to the downstream part of the basin. The Dhukwan dam is the oldest among the three and was constructed in 1910, whereas Matatila dam and Rajghat dam were constructed in the years 1958 and 2000, respectively (India-WRIS 2014). A large portion of the basin is under the cultivation of millet, wheat and gram as major crops (Mali & Singh 2015).

Data

The input data required by the SWAT model are the Digital Elevation Model (DEM), land use, soil and daily weather data. The DEM (Figure 2(a)) was extracted from 90 m resolution Shuttle Radar Topographic Mission (SRTM) data (http://srtm.csi.cgiar.org). The land use (Figure 2(b)) map (1 km × 1 km resolution) was extracted from the FAO Global land use map (https://swat.tamu.edu/software/links). The soil map (Figure 2(c)) of the study basin with 78 m × 78 m resolution was extracted from the Ganga river basin management plan (GRBMP) portal (http://gisserver.civil.iitd.ac.in/grbmp accessed on 11 February 2015). In this study, daily minimum and maximum temperature data available at 1.0° × 1.0° resolution (Srivastava *et al.* 2009) and rainfall data available at 0.25° × 0.25° resolution (Pai *et al.* 2014) from 1998 to 2011 were obtained from the India Meteorological Department (IMD). The IMD gridded temperature and high-resolution rainfall data were regridded at 0.5° × 0.5° resolution (Figure 1). The streamflow data of four gauging sites, namely, Shahijina, Mohana, Garrauli and Basoda (Figure 1) for a 14-year (1998–2011) period were collected from the Yamuna Basin Organization (YBO) of Central Water Commission (CWC), Government of India.

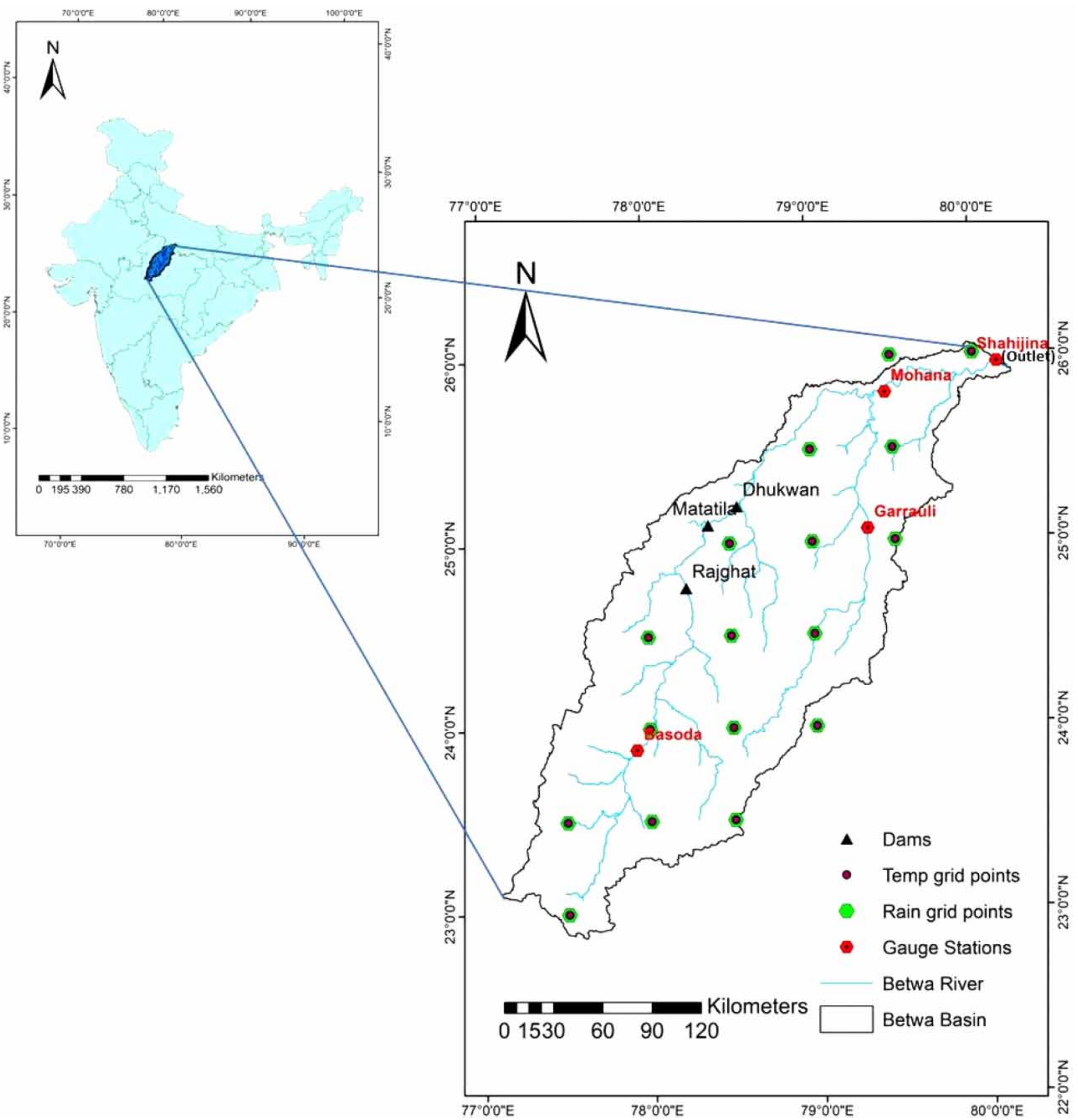


Figure 1 | Location of Betwa river basin and gauging stations.

Other climatic variables such as relative humidity, wind speed and solar radiation, estimated using long-term statistics through a weather generator model (WXGEN) available from the SWAT India database (https://swat.tamu.edu/data/india-dataset) were used in the study.

Soil and water assessment tool (SWAT)

SWAT is a semi-distributed, physically based, watershed scale, continuous model that can run at daily, monthly or yearly time steps. It simulates hydrological processes, and the impact of climate and land use changes on water, sediment and agricultural chemical yields (Arnold et al. 1998). In SWAT, soil water balance in each HRU is represented using Equation (1) (Arnold et al. 1998; Neitsch et al. 2011):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{Surf} - E_a - W_{seep} - Q_{gw}) \tag{1}$$

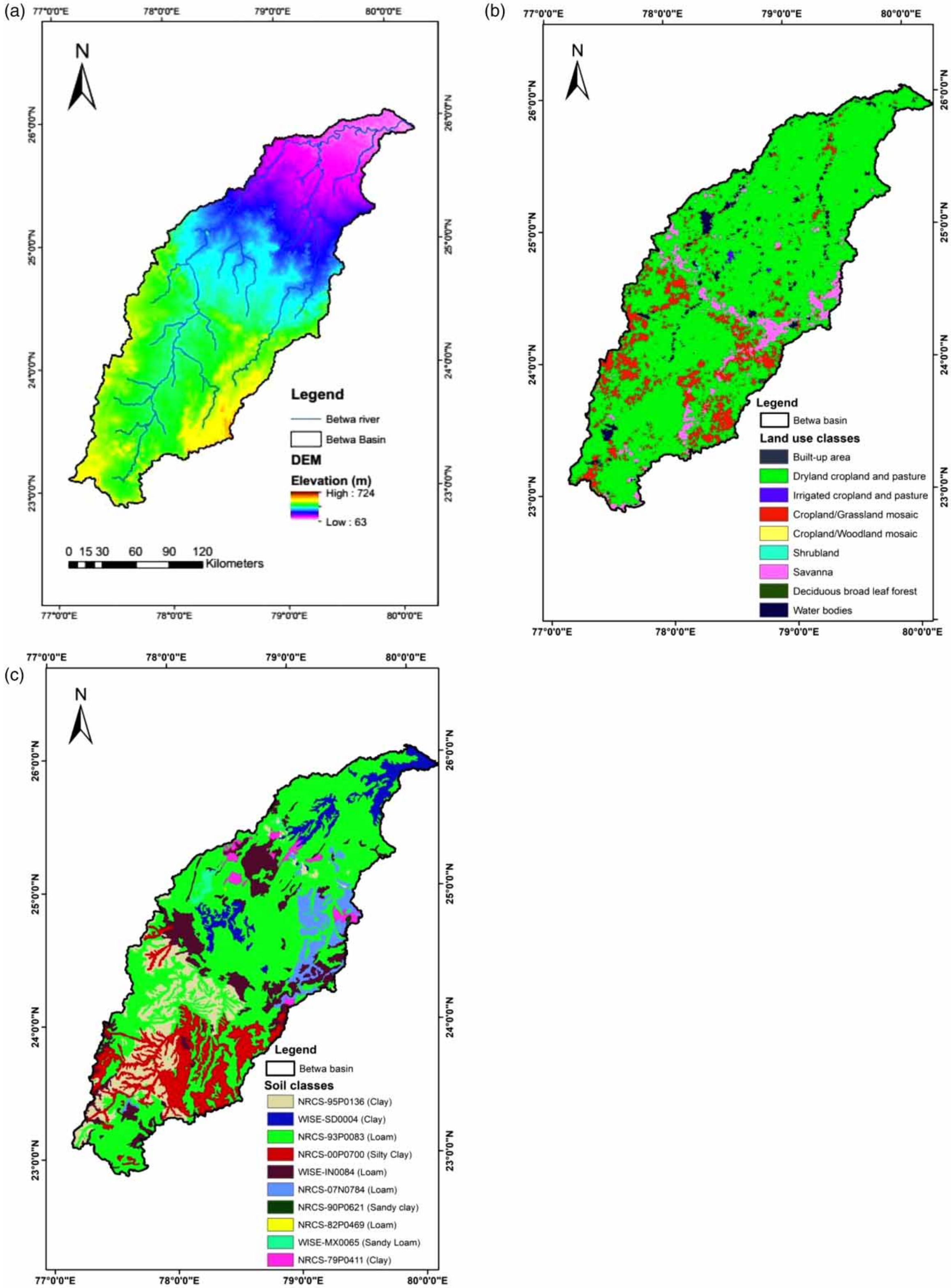


Figure 2 | Different thematic maps of Betwa river basin: (a) DEM, (b) land use, (c) soil map.

where, SW_t is the final soil water content (mm); SW_0 is the initial soil water content on day i (mm); R_{day} is the amount of precipitation on day i (mm); Q_{surf} is the amount of surface runoff on day i (mm); E_a is the amount of evapotranspiration (ET) on day i (mm); W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm); Q_{gw} is the amount of return flow on day i (mm).

In the present study, the Arc-SWAT 2009 version of the SWAT model with the ArcGIS 9.3.1 interface was used. The data of land use, soil and slope were imported into the SWAT model and overlaid to obtain the HRUs. Weather data at $0.5^\circ \times 0.5^\circ$ resolution for the Betwa basin were given as input to the SWAT model. A two-year warm-up period (1998–99) was considered before the model simulation to stabilize the model for initial conditions. SWAT was calibrated for the period 2000–2005 and validated for the period 2006–2011. The model calibration and validation were carried out by using the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm of SWAT-Calibration and Uncertainty Programs (SWAT-CUP) (Abbaspour 2014). The model performance was evaluated by using various statistical indicators such as coefficient of determination (R^2), NSE (Nash–Sutcliffe efficiency), RMSE-observations standard deviation ratio (RSR) and percent bias (PBIAS) (Moriasi *et al.* 2007).

Hypothetical climate change scenarios

The SWAT model has the facility to simulate change in precipitation, temperature and CO_2 to assess their impacts on hydrological response. The rainfall adjustment (RFINC) and the temperature adjustment (TEMPINC) variables in the Edit SWAT Input are used for the rainfall (% change) and temperature (°C) adjustment. The daily rainfall within a month is adjusted by the specified percentage and daily maximum temperature and minimum temperature are raised and lowered by a specified amount. The potential evapotranspiration in the SWAT model is calculated using the Penman–Monteith method. For estimating actual evapotranspiration (AET), using the Ritchie (1972) methodology, SWAT first evaporates any rainfall intercepted by the plant canopy. It then calculates the maximum amount of transpiration and the maximum amount of soil evaporation using an approach given by Ritchie (1972). While comparing AET data of flux tower and SWAT simulated AET using the Penman–Monteith method, Jung *et al.* (2016) reported that AET values modelled using SWAT were similar to the observed AET. The Penman–Monteith method has the provision to incorporate the effect of increased CO_2 on evapotranspiration. The effect of change in the CO_2 concentration on plant stomatal conductance in the SWAT model is computed from the equation developed by Easterling *et al.* (1992). The SWAT model considers a default value of 330 ppm CO_2 concentration. The sensitivity of the basin to changing climate was analysed for the observed period of the data and two scenarios were considered for carbon dioxide emissions, i.e., 330 ppm (default) and 660 ppm (doubled). The daily rainfall of the entire observed period was changed by (±) 10% and (±) 20%. The average daily temperature of the entire observed period was increased by 2 °C and 4 °C. The calibrated SWAT model was separately run with the combination of all the hypothetical scenarios to assess the response of the basin. Table 1 presents the hypothetical scenarios with different

Table 1 | Hypothetical climate change scenarios

Scenarios	Temperature (°C)	Rainfall (%)	CO_2 concentration (ppm)
1	2	+10	330
2	4	+10	330
3	2	−10	330
4	4	−10	330
5	0	+20	330
6	2	+20	330
7	4	+20	330
8	0	−20	330
9	2	−20	330
10	4	−20	330
11	2	0	330
12	4	0	330
13	0	0	660
14	2	0	660
15	4	0	660
16	0	+20	660
17	2	+20	660
18	4	+20	660
19	0	−20	660
20	2	−20	660
21	4	−20	660

combinations of temperature, rainfall and CO_2 used for simulating surface runoff and ET.

Climate change scenarios based on GCM projections

Uncertainty of GCMs in simulating climate change at regional levels is one of the major drawbacks for impact analysis. Since it is difficult for all the GCMs to reproduce observed data at regional scales, the selection of suitable GCMs becomes necessary to reduce the uncertainty in future predictions. The CMIP5-based Model of Interdisciplinary Research on Climate version 5 (MIROC5) GCM has been found to perform better in quantifying the expected future change in extreme rainfall events over India (Chaturvedi *et al.* 2012; Panjwani *et al.* 2019). Therefore, in this study, MIROC5 GCM output for climate change simulation was used. MIROC5 is a GCM jointly developed by the Center for Climate System Research (CCSR), University of Tokyo, National Institute for Environmental Studies (NIES) and Japan Agency for Marine-Earth Science and Technology. The detailed description of the model is described by Watanabe *et al.* (2010). In this study, bias-corrected and spatially downscaled monthly projections of MIROC5 GCM at $0.5° \times 0.5°$ resolution were used. The SWAT model, however, requires weather data input on the daily time step. The per cent changes in mean monthly rainfall and increase/decrease in temperature for the three future periods 2010–2039 (2020s), 2040–2069 (2050s) and 2070–2099 (2080s) were calculated from the output of MIROC5 GCM considering 1961 to 1990 as the baseline period. The change factors were estimated for weather points located in the basin and the future precipitation and temperature series were generated by multiplying the change factor to daily rainfall data and adding the change to daily temperature data for that particular month (delta change method). Thus, the maximum and minimum temperature and rainfall data series were prepared for the three future periods (2020s, 2050 and 2080s) and for four RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). A calibrated and validated SWAT model was run for these 12 scenarios. The different water balance components in the basin, such as rainfall, surface runoff and evapotranspiration under climate change, were estimated and the results expressed as percentage change over the baseline values.

RESULTS AND DISCUSSION

Model calibration and validation

The model performance was evaluated by comparing the observed and simulated streamflow at Shahijina, Mohana, Garrauli, and Basoda gauging stations. The coefficient of determination (R^2), NSE (Nash–Sutcliffe efficiency), RMSE-observations standard deviation ratio (RSR) and percent bias (PBIAS) for calibration and validation periods varied from 0.83 to 0.92, 0.6 to 0.91, 0.3 to 0.63 and −19.8 to 19.3, respectively (Table 2). The very good match between the observed and simulated hydrographs, and the values of model performance indicators revealed that SWAT could capture the monthly flows very well at Shahijina, Mohana, Garrauli and Basoda gauging stations during calibration and validation periods (Figure 3). Based on the criteria suggested by Moriasi *et al.* (2007) and Parajuli (2010), the overall performance of the model could be rated as 'very good' to 'satisfactory'. The poor performance of the model at some stations could be attributed to observed streamflow data quality (Mishra & Lilhare 2016; Abeysingha *et al.* 2020). The observed streamflow data for the major sub-continental river basins with trans-boundary water sharing issues

Table 2 | Calibration and validation statistics for monthly streamflow

	Calibration				Validation			
Stations	R^2	**NSE**	**RSR**	**PBIAS**	R^2	**NSE**	**RSR**	**PBIAS**
Shahijina	0.86	0.84	0.40	−19.8	0.83	0.75	0.50	7.5
Mohana	0.92	0.91	0.30	−13.5	0.88	0.79	0.45	19.3
Garrauli	0.91	0.60	0.63	2.1	0.88	0.65	0.59	11.6
Basoda	0.89	0.89	0.33	−0.9	0.87	0.85	0.39	14.9

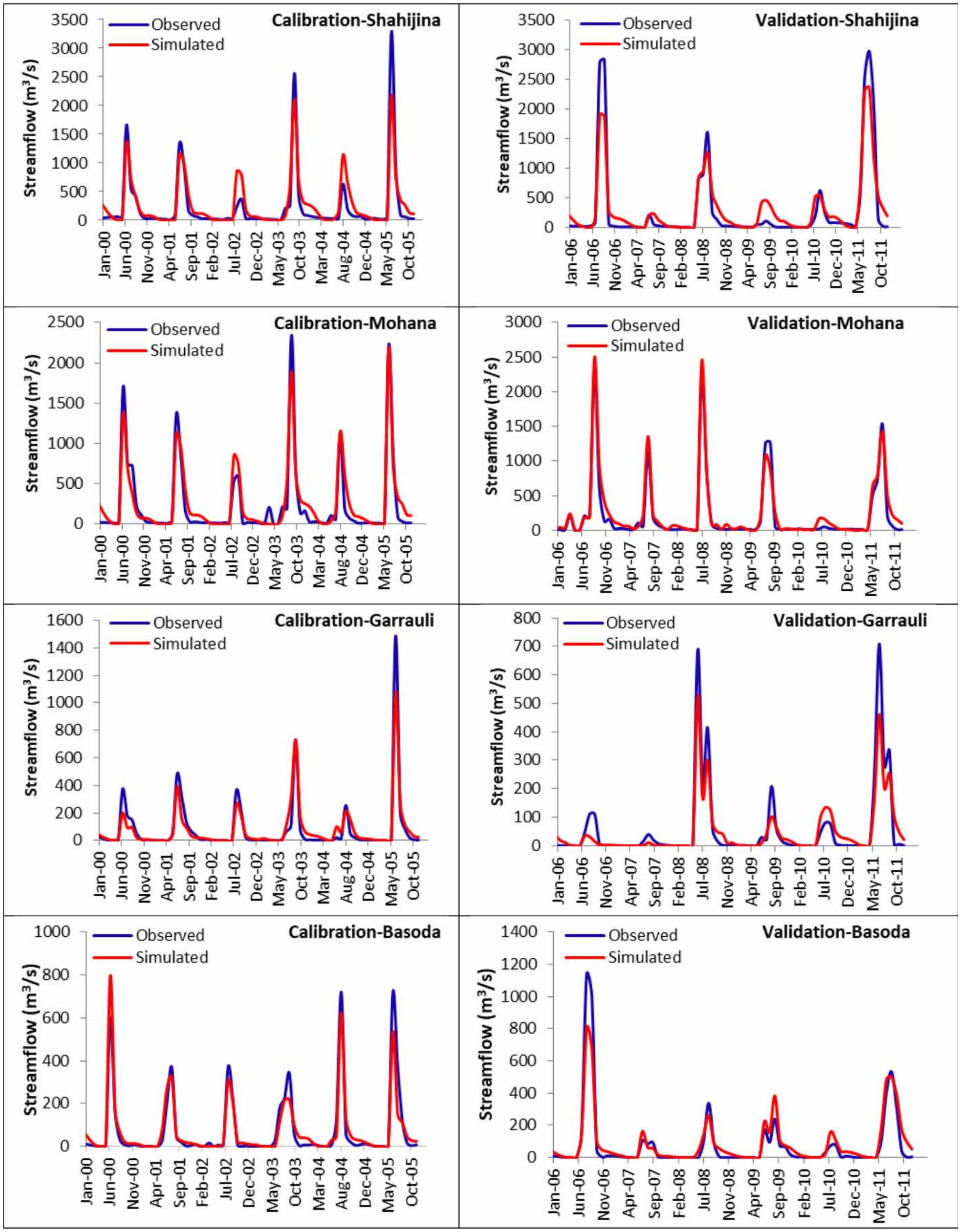


Figure 3 | Observed and simulated streamflow hydrographs for the calibration and validation period.

are restricted to public sharing (Mishra & Lilhare 2016; Abeysingha et al. 2020). In the present study, mean monthly streamflow data (computed from 10 days' average streamflow data) were used for calibration and validation of SWAT due to the non-availability of daily streamflow data. The other reason for poor performance of the model at some stations could be attributed to the presence of dams on the main stream. These dams capture a huge volume of water affecting natural runoff. Some studies reported slightly lower average annual flow/peak, but even distribution of annual flow with cascade of reservoirs (Yijian & Wu 1996; Liu et al. 2019). However, due to the non-availability of operational data of dams/reservoirs, simulation of streamflow at some gauging stations affected by the presence of dams/reservoirs is difficult. It is worth mentioning here that out of four gauging stations in the Betwa river basin, two gauging stations (Basoda and Garrauli) are located at the upstream part of the basin and on the tributary (North East Side) of the Betwa river, respectively, and are not directly impacted by the presence of dams. Mishra & Lilhare (2016) recommended selection of gauging stations located in the upstream regions that are least affected by the location of dams and reservoirs for model calibration and evaluation. Further, while assessing the impact of dams on streamflow in Huai river basin of China using SWAT, Wang & Xia (2010) suggested a multi-site calibration strategy considering the spatial distribution and different characteristics of dams. In this study, multi-site calibration of the SWAT model revealed 'very good' to 'satisfactory' model performance on monthly time step for the Betwa river basin. As the aim of this study is to provide an assessment of climate change impact on streamflow with respect to baseline climate forcing, the calibrated model can be applied for assessing relative changes in water balance components based on long-term simulations.

Climate change simulations

Response of surface runoff to hypothetical scenarios

The response of the basin's surface runoff to rainfall, temperature and CO_2 changes annually and in different seasons is shown in Figure 4(a)–4(e). The results showed that an increase in temperature alone resulted in a decrease in surface runoff, if rainfall remains unchanged. An increase in temperature by 4 °C with precipitation remaining unchanged resulted in a decrease in surface runoff by 6%. An increase in rainfall generally resulted in increased surface runoff, even though there was an increase in temperature. For example, increase in rainfall by 10 and 20% coupled with 2 °C increase in temperature resulted in 30 and 66% increase in annual surface runoff whereas decrease in the rainfall by 10 and 20% resulted in decrease in the annual surface runoff by 30 and 69%, respectively (Figure 4). Similarly, increase in rainfall by 20% coupled with 4 °C increase in temperature resulted in 62, 68.2, 24.4, 55.3 and 30.8% increase in annual, monsoon (JJAS), pre-monsoon (MAM), post-monsoon (OND) and winter season (JF) surface runoff, respectively. On the other hand, a 4 °C increase in temperature and 20% decrease in rainfall resulted in 72, 76, 37.4, 62.4 and 55% decrease in surface runoff, whereas under doubled CO_2 condition there was an 61, 63.4, 35.9, 56.8 and 45.9% decrease in annual, monsoon, pre-monsoon, post-monsoon and winter season surface runoff, respectively. If temperature remains unchanged, increase in rainfall alone by 20% resulted in increased surface runoff by 70.1, 75.3, 29.9, 63.5 and 33.3%, whereas annual, monsoon, pre-monsoon, post-monsoon and winter season surface runoff increased by 80.2, 87.2, 34.8, 70.8 and 36.01%, respectively, with doubling of CO_2 concentrations. Keeping the temperature and rainfall constant, doubling the CO_2 alone resulted in 12.1, 13.6, 5.2, 10.9 and 7.7% increase in the annual, monsoon, pre-monsoon, post-monsoon and winter season surface runoff, respectively. In general, under doubled CO_2 condition there was an increase in surface runoff (Figure 4) as doubling of CO_2 resulted in a decrease in evapotranspiration, as discussed in the subsequent section. Since the river basin mainly falls in the semi-arid region, changes in surface runoff might have a significant impact on the basin hydrology.

Response of evapotranspiration to hypothetical scenarios

The response of the basin's annual and seasonal evapotranspiration demand to rainfall, temperature and CO_2 changes is shown in Figure 5(a)–5(e). In general, it was found that doubled CO_2 condition resulted in a decrease in the evapotranspiration demand. For example, increasing the temperature by 4 °C increased the annual ET by 3.9%, whereas under doubled CO_2 level the ET decreased by

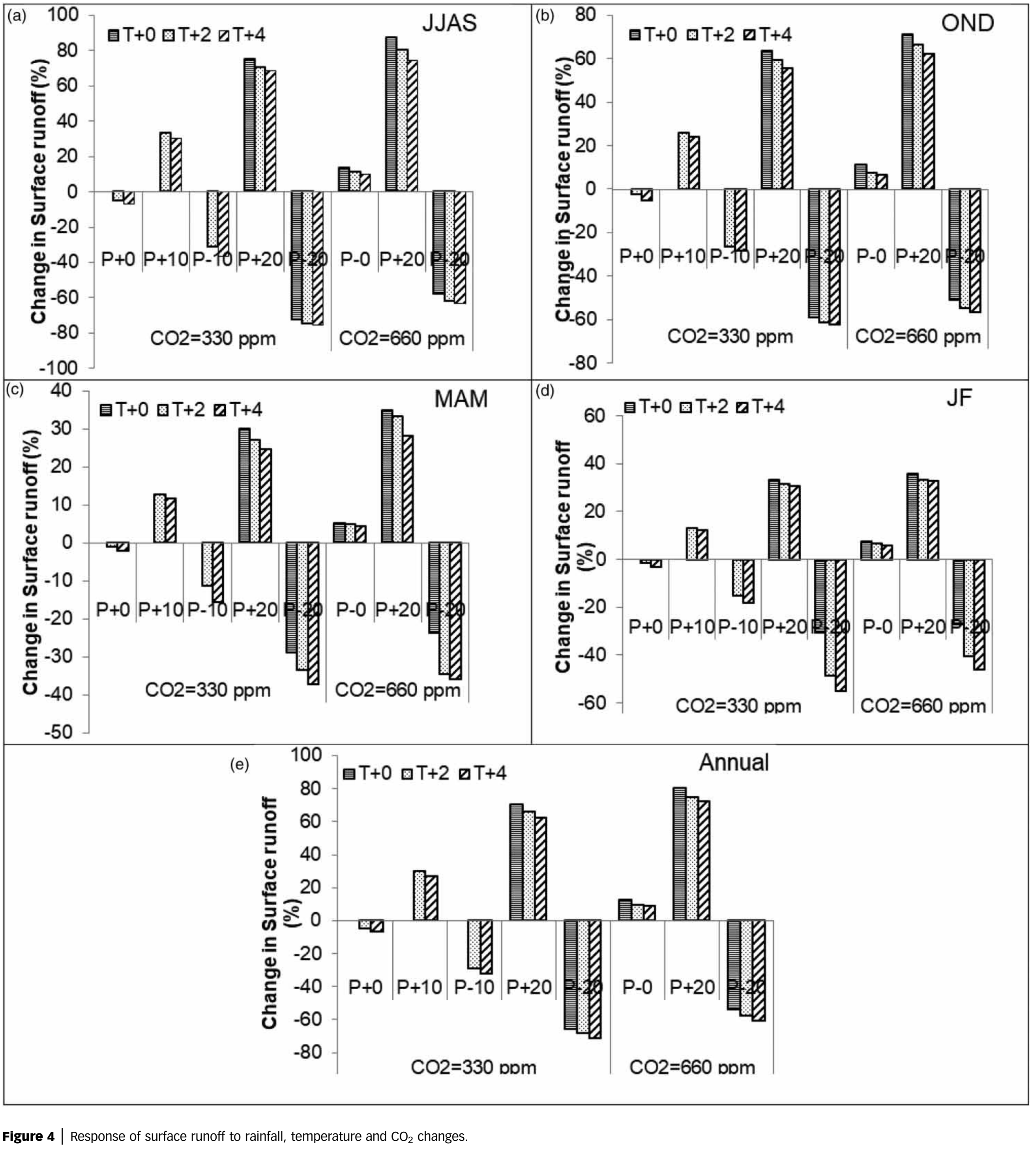


Figure 4 | Response of surface runoff to rainfall, temperature and CO_2 changes.

4.07%. The combined effect of increase in temperature and rainfall by 2 °C and 20%, respectively, resulted in increase in annual ET by 4.2%, whereas this effect was offset by doubling the CO_2 level as the ET decreased by 4.8%. The combined effect of an increase in temperature by 2 °C and a decrease in rainfall by 20% decreased the annual ET by 1.8%, whereas doubling the CO_2 under the same condition further decreased the ET by 3.5%. The effect of increase in

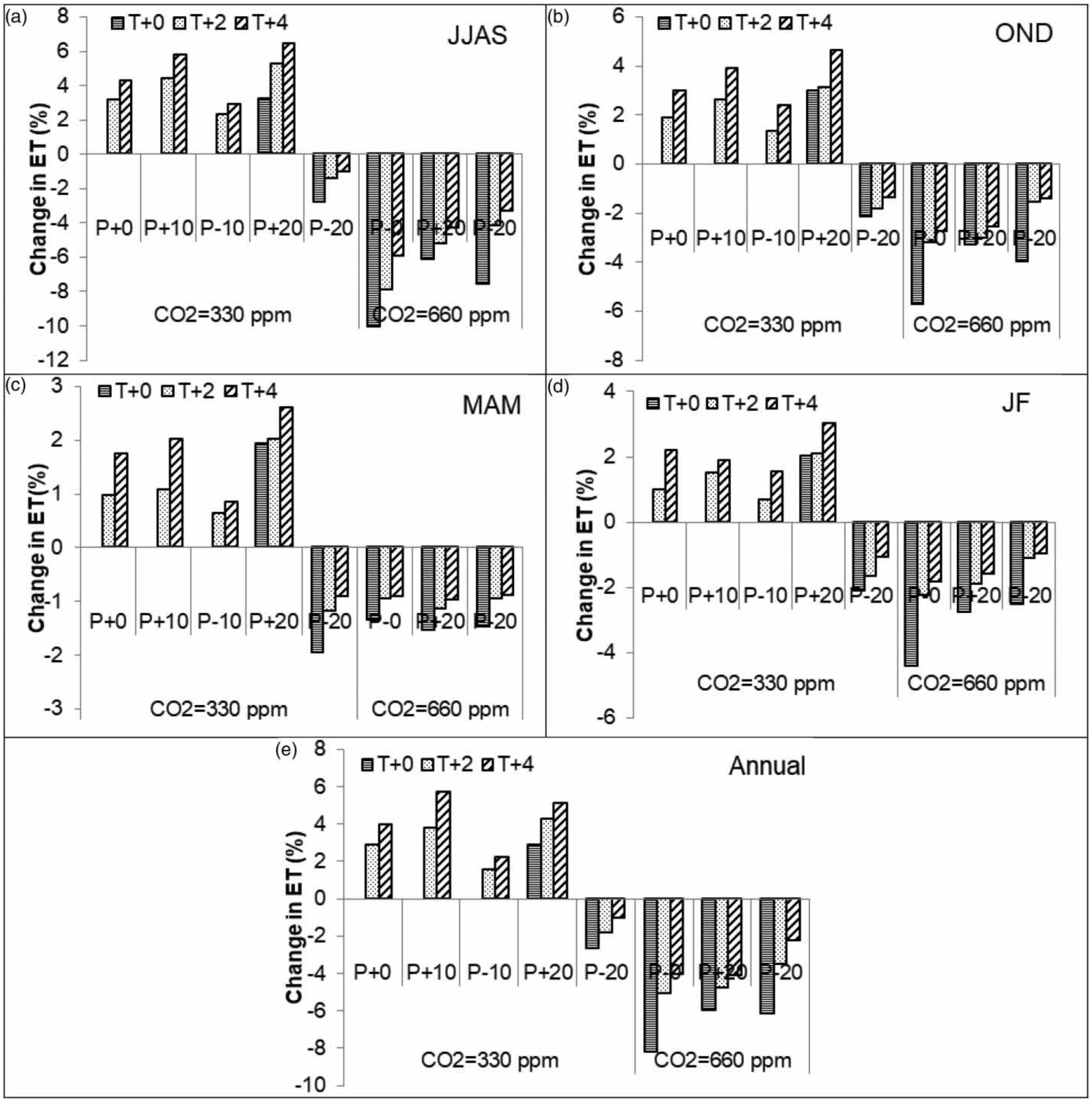


Figure 5 | Response of evapotranspiration to rainfall, temperature and CO_2 changes.

temperature by 4 °C and rainfall by 20% resulted in 5.1, 6.4, 2.6, 3.4 and 3% increase in annual, monsoon (JJAS), pre-monsoon (MAM), post-monsoon (OND) and winter season (JF) ET, respectively. However, this effect of increased temperature was offset when the CO_2 was doubled, resulting in a decrease in annual, monsoon (JJAS), pre-monsoon (MAM), post-monsoon (OND) and winter season (JF) ET by 4.1, 4.3, 1.0, 2.5 and 1.5%, respectively (Figure 5). Keeping the rainfall and temperature constant, doubling the CO_2 alone resulted in a decrease in ET by 8.2, 10.0, 2.3, 5.7, and 4.3% in the annual, monsoon, pre-monsoon, post-monsoon and winter season, respectively (Figure 5). In general, the effect of increased temperature was moderated by doubling the CO_2 concentration (660 ppm). Thus, the crop water demand in the basin may not increase significantly in future under climate change scenarios due to a decrease in the evapotranspiration under increased CO_2 concentration.

Correlation between climatic and hydrologic parameters

Multi-correlation analysis for three climatic parameters, namely, temperature, CO_2 and rainfall, and two hydrologic parameters, namely, surface runoff and evapotranspiration were carried out to identify the most significant parameters affecting the surface runoff and evapotranspiration. The comparison of the magnitude of the correlation indicated that rainfall changes had a significant effect on monsoon (0.992), post-monsoon (0.994), pre-monsoon (0.986), winter (0.975) and annual (0.992) changes in surface runoff at 0.01 level of significance (Table 3). Similarly, comparison of magnitude of the correlation analysis on evapotranspiration revealed that CO_2 level had a significant effect on monsoon (−0.864), post-monsoon (−0.856), pre-monsoon (−0.672), winter (−0.736) and annual (−0.843) ET at 0.01 level of significance (Table 4), and rainfall had a significant effect at 0.05 level of significance in the pre-monsoon season only.

MIROC5 projected change in rainfall

The annual and seasonal changes in rainfall for the future periods from baseline (1961–1990) in the Betwa basin are shown in Figure 6(a) and 6(b). There is a decrease in the mean annual rainfall during the 2020s for all the scenarios except RCP4.5. The decrease in rainfall during the 2020s ranged from 0.9 to 3.2% under different RCPs (Figure 6(a)), but a 2.1% increase in annual rainfall is observed under RCP4.5. The mean annual rainfall is projected to increase in the range of 0.4–9.1% and 5.7–15.3% during the 2050 and 2080s, respectively, under different RCPs. The monsoon rainfall followed a similar trend to that of annual rainfall. In monsoon season (JJAS), rainfall is projected to decrease in the range of 4.2–6.3% during the 2020s whereas it is projected to increase in the range of 1–7% and 0.3–11% during the 2050s and 2080s, respectively. The seasonal rainfall shows slightly different changes as compared to annual changes (Figure 6(b)). In general, seasonal rainfall showed an increase during post-monsoon season (OND) for all the scenarios and future periods due to projected increase in

Table 3 | Correlation between changes in temperature, rainfall, CO_2 and changes in surface runoff

Seasons	Changes in temperature	Changes in CO_2	Changes in rainfall
Monsoon (JJAS)	−0.060	0.639	0.992**
Post-monsoon (OND)	−0.061	0.703	0.994**
Pre-monsoon (MAM)	−0.098	0.738	0.986**
Winter (JF)	−0.125	0.621	0.975**
Annual	−0.063	0.643	0.992**

**Correlation is significant at the 0.01 level (two-tailed).

Table 4 | Correlation between changes in temperature, rainfall, CO_2 and changes in ET

Seasons	Changes in temperature	Changes in CO_2	Changes in rainfall
Monsoon (JJAS)	0.385	−0.864**	0.262
Post-monsoon (OND)	0.392	−0.856**	0.273
Pre-monsoon (MAM)	0.343	−0.672**	0.469*
Winter (JF)	0.401	−0.736**	0.360
Annual	0.413	−0.843**	0.262

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

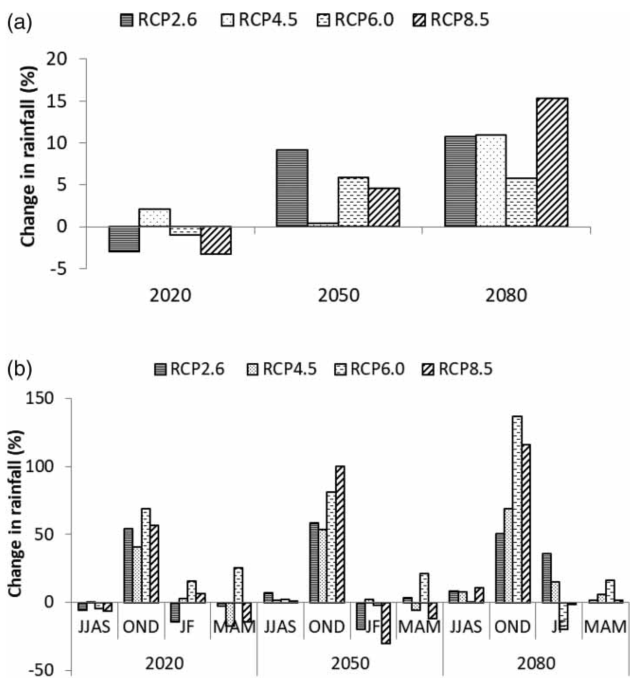


Figure 6 | Projected changes in rainfall in the basin: (a) annual and (b) seasonal.

the rainfall, especially in the months of October and November. The projected increase in the rainfall from baseline (1961–1990) in post-monsoon season was in the range of 41–69%, 53–100% and 50–137% during the 2020s, 2050s and 2080s, respectively. During the winter (JF) and summer season (MAM) there is considerable variation in rainfall change in future periods under different scenarios.

MIROC5 projected change in temperature

The annual mean temperature (T_{mean}) in the basin is projected to increase during the 2020s, 2050s and 2080s. Increase in annual mean temperature under different RCPs varied in the range of 0.7–0.9 °C, 1.2–2.0 °C and 1.1–3.1 °C during the 2020s, 2050s and 2080s, respectively (Figure 7). The trend analysis of time series data of annual mean temperature for the period 1971–2007 also showed an increasing trend in most of the districts falling under the Betwa river basin (Desai *et al.* 2019). The monthly analysis showed increase in the mean temperature in the different months under different RCPs and future periods. The increase in mean temperature during different months varied in the range of 0.1–1.6 °C, 0.4–3.2 °C and 0.2–4.1 °C during the 2020s, 2050s and 2080s, respectively (Table 5). The increase in mean temperature is found to be maximum in the months of April and May and minimum in the months of July and September. This increase in mean temperature during different months will increase the evapotranspiration demand, thereby affecting streamflow and water resource availability in the basin.

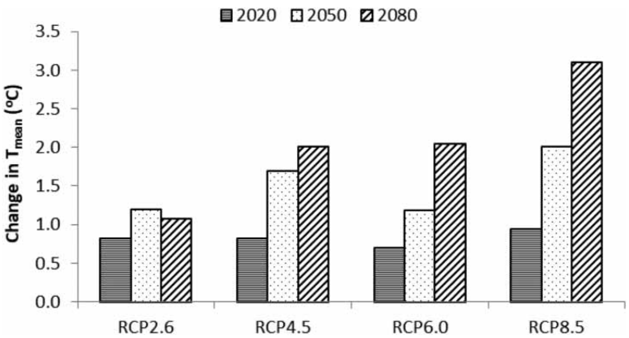


Figure 7 | Projected changes in annual mean temperature under different scenarios.

Average annual water balance for baseline period

The calibrated SWAT model was used to simulate the hydrological response of the Betwa river basin for the baseline period (1961–1990). Based on the recommendations of the World Meteorological Organization (WMO), the period 1961–1990 was used as a representative of the present-day climate. This period incorporates some of the natural alterations in climate, containing both dry and wet periods (Wigley & Jones 1987). The sub-basin-wise spatial variation of average

Table 5 | Projected changes in monthly mean temperature under different scenarios

	2020s (2010–2039)				2050s (2040–2069)				2080s (2070–2099)			
Mon	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Jan	1.0	0.9	0.9	0.9	1.6	2.1	1.4	2.3	1.6	2.4	2.4	3.9
Feb	0.8	0.8	0.3	0.9	1.5	1.7	1.7	2.4	1.1	2.5	2.6	3.8
Mar	0.9	1.0	0.1	0.9	1.0	2.4	1.3	2.4	0.6	2.6	2.5	3.5
Apr	1.6	1.4	0.9	1.3	1.7	2.8	1.6	3.2	1.6	3.1	3.0	4.2
May	0.9	1.3	1.0	1.4	1.6	2.4	1.2	2.8	1.5	2.4	2.5	3.9
Jun	1.1	0.7	1.2	1.6	1.4	1.2	1.4	2.0	1.6	1.3	1.6	2.0
Jul	0.4	0.2	0.6	0.6	0.5	0.6	0.8	1.1	0.3	0.4	1.2	2.2
Aug	0.8	0.7	1.1	0.9	1.2	1.5	1.1	1.4	1.4	1.9	1.8	2.6
Sep	0.4	0.5	0.4	0.8	0.6	1.1	0.6	1.2	0.5	1.4	1.5	1.6
Oct	0.6	0.5	0.6	0.7	0.8	1.3	0.9	1.5	0.8	1.6	1.5	2.8
Nov	0.8	1.1	0.7	0.8	1.2	1.5	0.9	1.9	0.9	2.2	2.0	3.2
Dec	0.6	0.7	0.7	0.6	1.1	1.5	1.3	1.8	1.1	2.4	2.0	3.4

annual rainfall, surface runoff and evapotranspiration for the baseline period (1961–1990) is shown in Figure 8(a)–8(c). The spatial variation of average annual rainfall and surface runoff during the baseline period ranged between 905–1,224 mm and 133–453 mm, respectively. The rainfall and surface runoff were found to be greater in the upstream part of the basin mainly covering the sub-basins of Basoda catchment. The rainfall and surface runoff were found to be lower in the downstream part of the basin. The spatial variation of average annual evapotranspiration during the baseline period ranged between 570 and 787 mm with a maximum and minimum annual evapotranspiration occurring in the upstream and downstream part, respectively.

Climate change impact on surface runoff

The model simulation for the 2020s (2010–2039) period showed a decrease in the mean annual surface runoff in the range of 4.7–12.4% under different scenarios except for RCP4.5 where surface runoff increased by 4.5% as compared to the baseline period. The increase in the surface runoff for the RCP4.5 scenario is attributed to the projected increase in rainfall by 2.1%. The increase in the mean annual surface runoff varied in the range of 3.8–29% and 12–48% for the 2050s (2040–2069) and 2080s (2070–2099) under different scenarios (Figure 9(a)). This increase in surface runoff during the 2050s and 2080s is mainly due to the projected increase in rainfall, as runoff is more sensitive to rainfall changes as compared to temperature change (Islam *et al.* 2012a). Seasonal analysis revealed that surface runoff in monsoon season (JJAS) would decrease during the 2020s in the range of 8.7–15.1% under different scenarios, except for RCP4.5 where the surface runoff increases by 2.7% due to increase in the rainfall. During the 2050s and 2080s, the increase in mean annual surface runoff varied in the range of 3.8–29.1% and 12.2–48.9%, respectively. In the post-monsoon season (OND), surface runoff is projected to increase in the range of 42.3–61.5%, 60.4–117.4%, and 77.2–163.7% during the 2020s, 2050s and 2080s, respectively (Figure 9(b)). However, in the winter season (JF) and pre-monsoon season (MAM) there is considerable variation in surface runoff under different RCPs in future periods.

The sub-basin-wise spatial variation of average annual surface runoff under different RCPs during the 2020s, 2050s and 2080s is shown in Figure 10(a)–10(d). The surface runoff under RCP2.6 for the 2020s, 2050s and 2080s period ranged between 120–409 mm, 170–581 mm and 173–589 mm, respectively. Surface runoff in the different sub-basins under the baseline period varied in the range of 133–453 mm (Figure 8(b)). The decrease in the surface runoff during the 2020s as compared to the baseline is due to projected decrease in rainfall. The spatial variation of average annual surface runoff under RCP4.5 varied from 139 to 472 mm, 138–470 mm and 170–578 mm. Similarly, under RCP6.0, average annual surface runoff ranged between 127–432 mm, 150–511 mm and 148–503 mm during the 2020s, 2050s and 2080s, respectively. The model simulated average annual surface runoff under RCP8.5 during the 2020s, 2050s and 2080s varied from 117 to 398 mm, 151–514 mm and 186–634 mm, respectively. The surface runoff is expected to decrease during the 2020s, whereas it increases under all scenarios during the 2050s and 2080s due to projected increase in rainfall. Further, surface runoff will be maximum on the upstream part on the southwestern side, covering sub-basins 27–33 of Basoda catchment and minimum on the downstream part on the northeastern side covering sub-basins 1, 2, 7 and 11 and sub-basins 12, 17 and 22 on the middle part during the 2020s, 2050s and 2080s. Most of the rainfall flows down as surface runoff due to which the surface water resources would not be available in the upper part of the basin. In the middle part of the basin, there are major irrigation projects like Rajghat dam, Dhukwan dam and Matatila dam which catch huge amounts of surface runoff coming from the upstream part of the basin. Due to the presence of these dams, the surface runoff on the downstream side might reduce significantly.

Climate change impact on evapotranspiration

The mean annual evapotranspiration is projected to increase in the range of 0.2–3.0%, 2.6–4.2% and 3.5–6.2% during the 2020s, 2050s and 2080s, respectively, under different scenarios (Figure 11(a)). This increase in ET during all the future periods is attributed to the projected increase in the mean temperature. The seasonal analysis also revealed increase in ET during all the seasons. In the monsoon season (JJAS), ET increases in the range of 0.4–

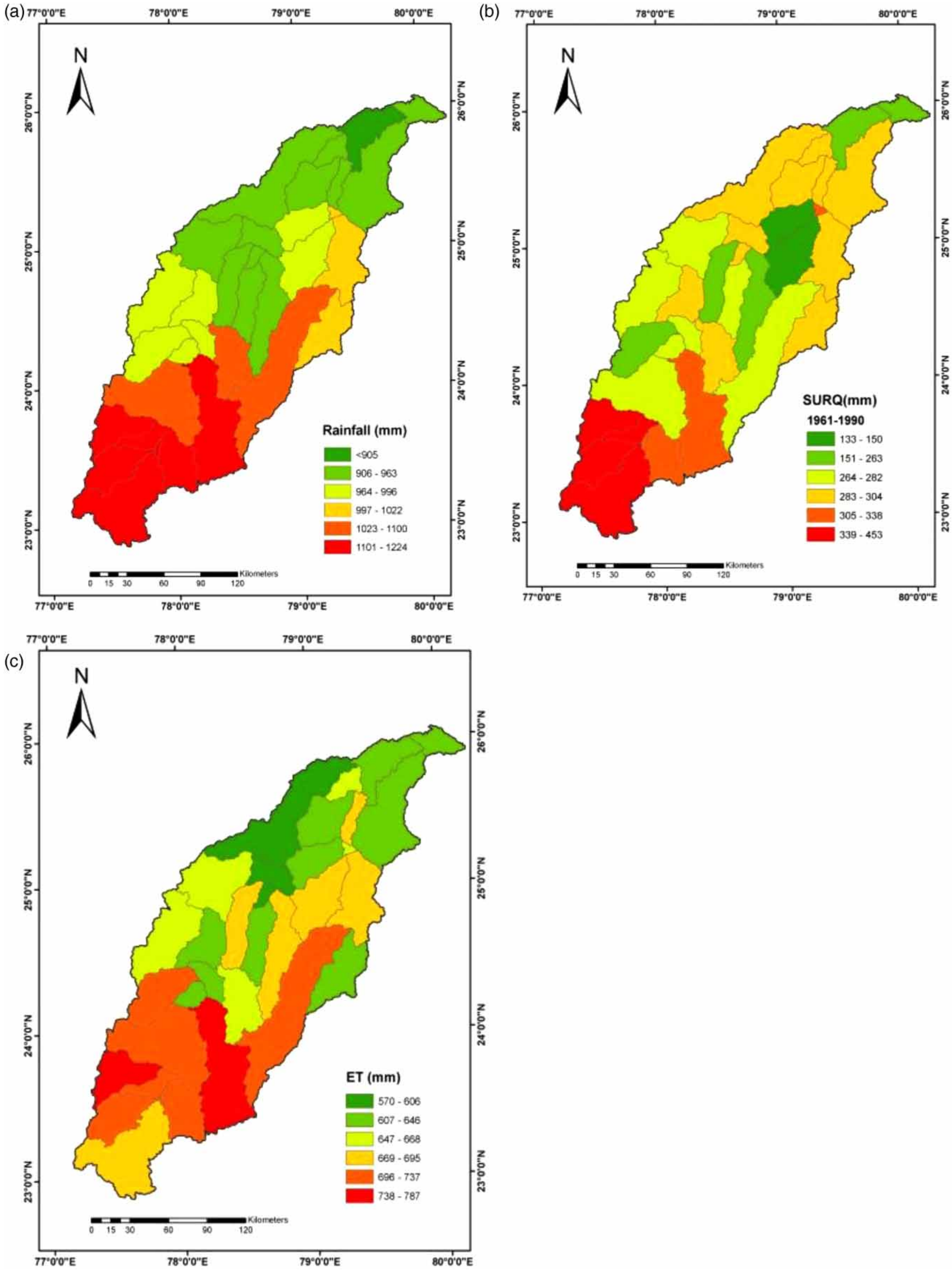


Figure 8 | Sub-basin wise average annual: (a) rainfall, (b) surface runoff and (c) ET for baseline period (1961–1990).

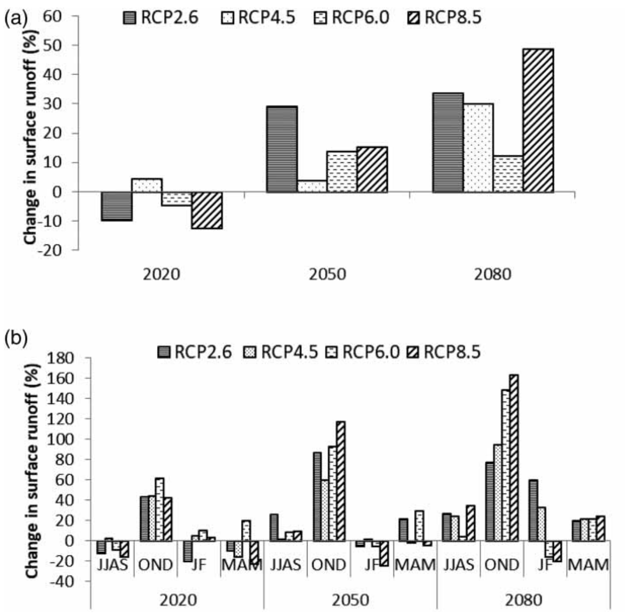


Figure 9 | Projected changes in (a) mean annual and (b) seasonal surface runoff under different scenarios.

1.1%, 1.2–2.6% and 1.4–6.3% during the 2020s, 2050s and 2080s, respectively (Figure 11(b)). The projected increase in ET in the winter season (JF) varied in the range of 0.2–5.0%, 1.0–6.4% and 5.5–8.6% during the 2020s, 2050s and 2080s, respectively. The increase in ET during pre-monsoon season (MAM) ranged between 0.1–4.1%, 0.6–3.8% and 0.4–4.1%. However, the percentage change in ET in post-monsoon season (OND) is higher as compared to other seasons, and it ranged from 2.3 to 4.7%, 5.3–7.6% and 4.4–12.5% during the 2020s, 2050s and 2080s, respectively. This increase in ET in the post-monsoon season could be attributed to significant increase in precipitation during October and November and substantial rise in mean monthly air temperature during October–December. An increase in the evapotranspiration in future in post-monsoon season might result in increased crop water demand.

The sub-basin-wise spatial variation of average annual evapotranspiration in the basin, showed that the ET varied from 588 to 889 mm, 601–885 mm and 609–924 mm during the 2020s, 2050s and 2080s, respectively, under different RCPs (Figure 12(a)–12(d)) as compared to baseline ET of 570–787 mm (Figure 8(c)). The ET was found to be maximum in the upstream part of the basin covering sub-basins 25–32 and minimum in the downstream part covering sub-basins 1, 2, 8 and 10 and sub-basins 15, 19 and 20 in the middle part of the basin. The upper part of the basin receives good rainfall but most of it is lost as evapotranspiration, due to which this region might experience acute water shortage during the remaining months of the year. Among all four RCPs, and future periods, the maximum increase in ET would be under RCP8.5 during the 2080s. Increase in evapotranspiration in future would, thus, increase the crop water demand in the river basin.

The Betwa River is one of the important tributaries of the Yamuna River in the Bundelkhand region of central India and part of the Ganga river basin. It plays an important role in the agriculture and socio-economic development of the Bundelkhand region. The river basin is mostly rainfed with water availability only during monsoon season and faces acute water scarcity during non-monsoon months. Although the upstream part of the basin receives a good amount of rainfall, most of it flows as surface runoff or is lost as evapotranspiration, due to which, this region experiences acute water shortage during the remaining months of the year. Owing to poor rainfall distribution in the region, irrigation and water management is a challenging task in the basin. This river basin also faces frequent drought events affecting agricultural productivity. There are major irrigation projects along this river like Rajghat dam, Matatila dam and Dhukwan dam, but they supply irrigation mostly to the downstream part of the basin, due to which, the upper part remains water stressed.

The analysis of MIROC5 GCM data revealed that both maximum and minimum temperatures are projected to increase in the basin. This increase in temperature will increase the evapotranspiration and, as a result, the crop water demand will also increase. Our analysis revealed that rainfall is projected to decrease during the 2020s whereas it is projected to increase during the 2050s and 2080s under all four RCPs. Shrestha *et al.* (2017) also reported that MIROC5 showed a decrease in annual precipitation under RCP4.5 and RCP8.5 during the 2020s and 2030s and a gradual increase for the 2040s in Bago River of Myanmar. The rainfall is likely to increase during post-monsoon months during near-, mid- and end-century in the basin as projected by MIROC5. Pechlivanidis *et al.* (2016) reported an extended monsoon period, lasting until the start of the post-monsoon season in October, during end-century under RCP8.5 for the Indian subcontinent.

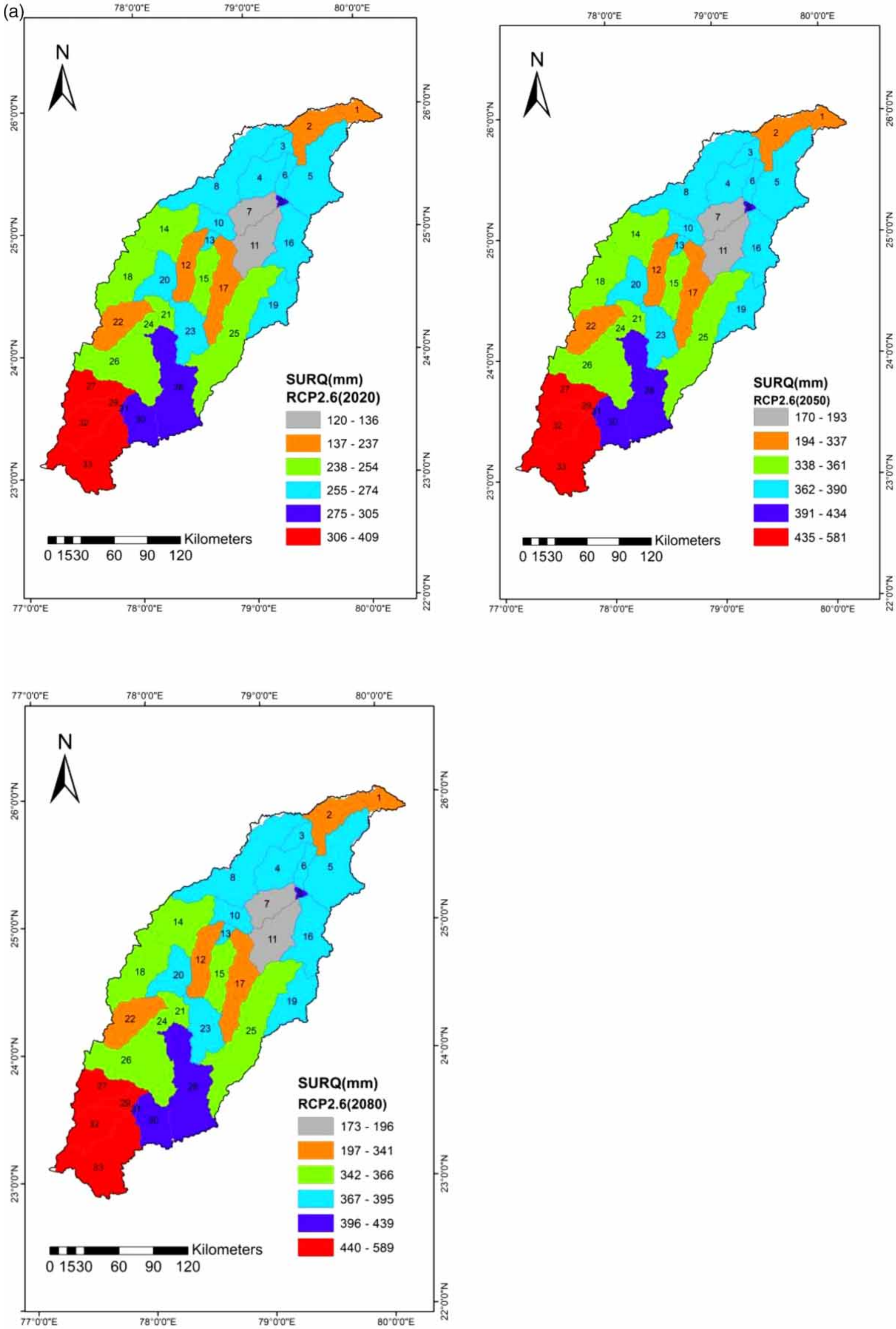
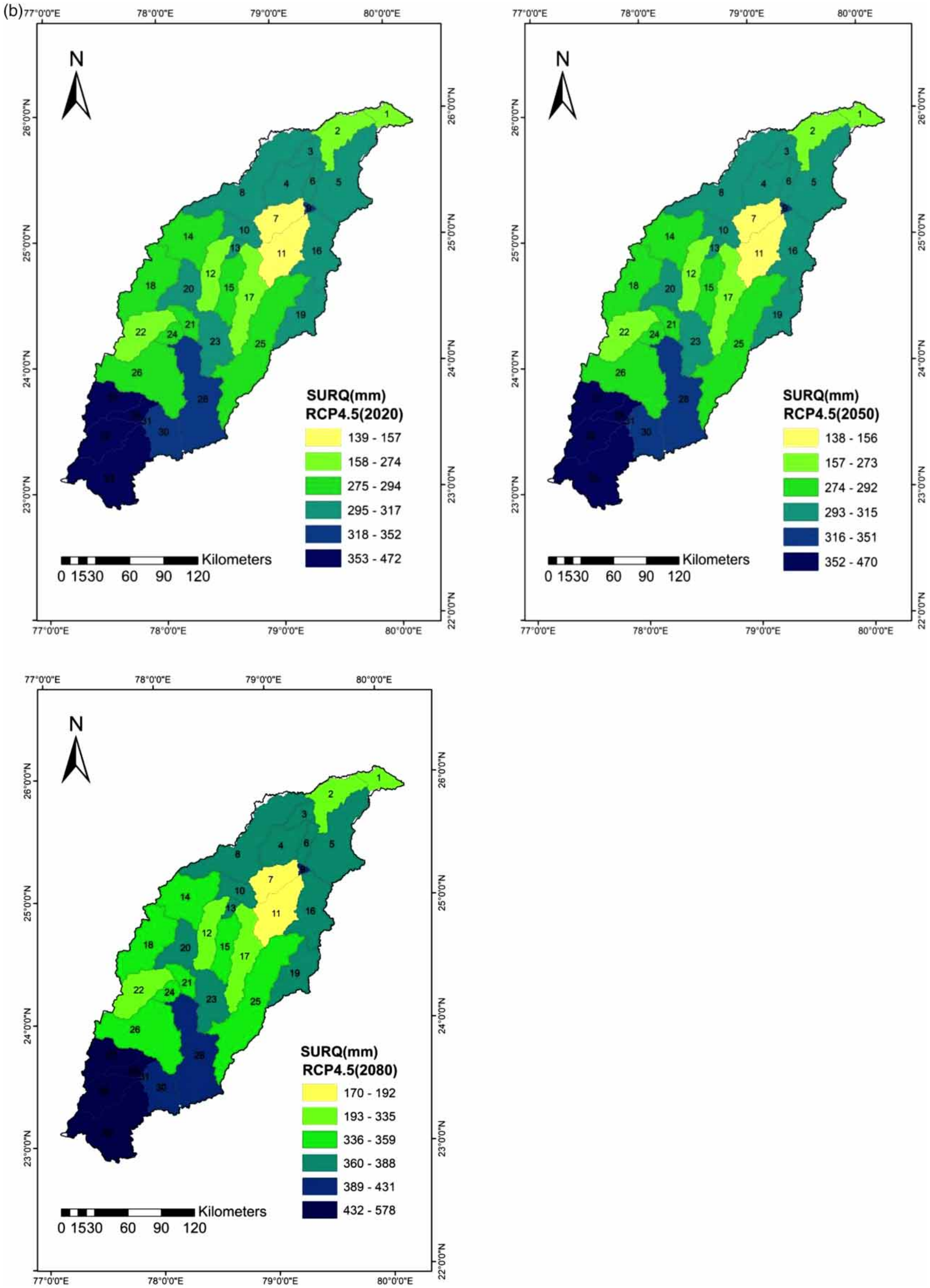


Figure 10 | Sub-basin-wise average annual surface runoff for future periods: (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5. *(continued.)*



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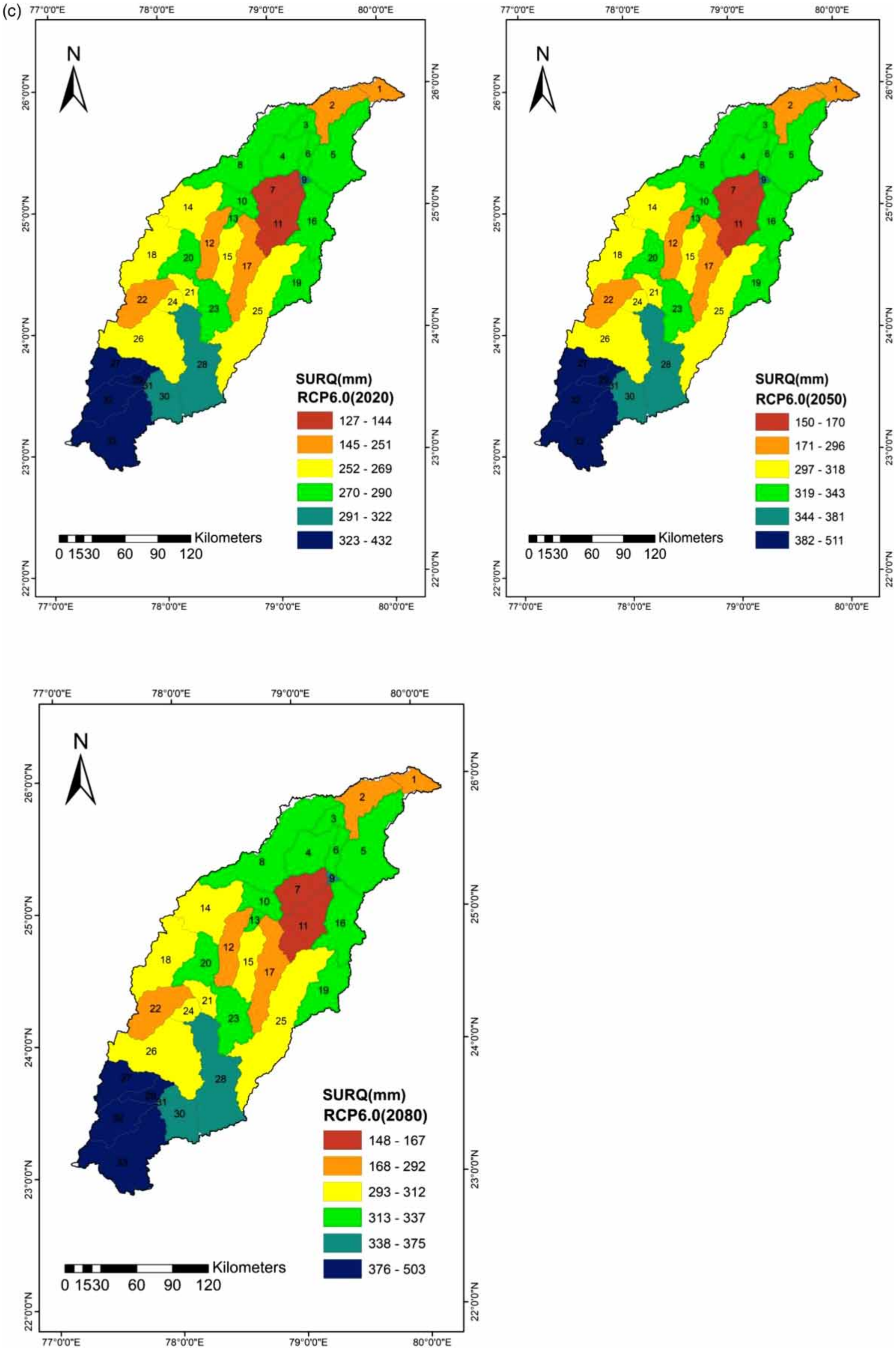

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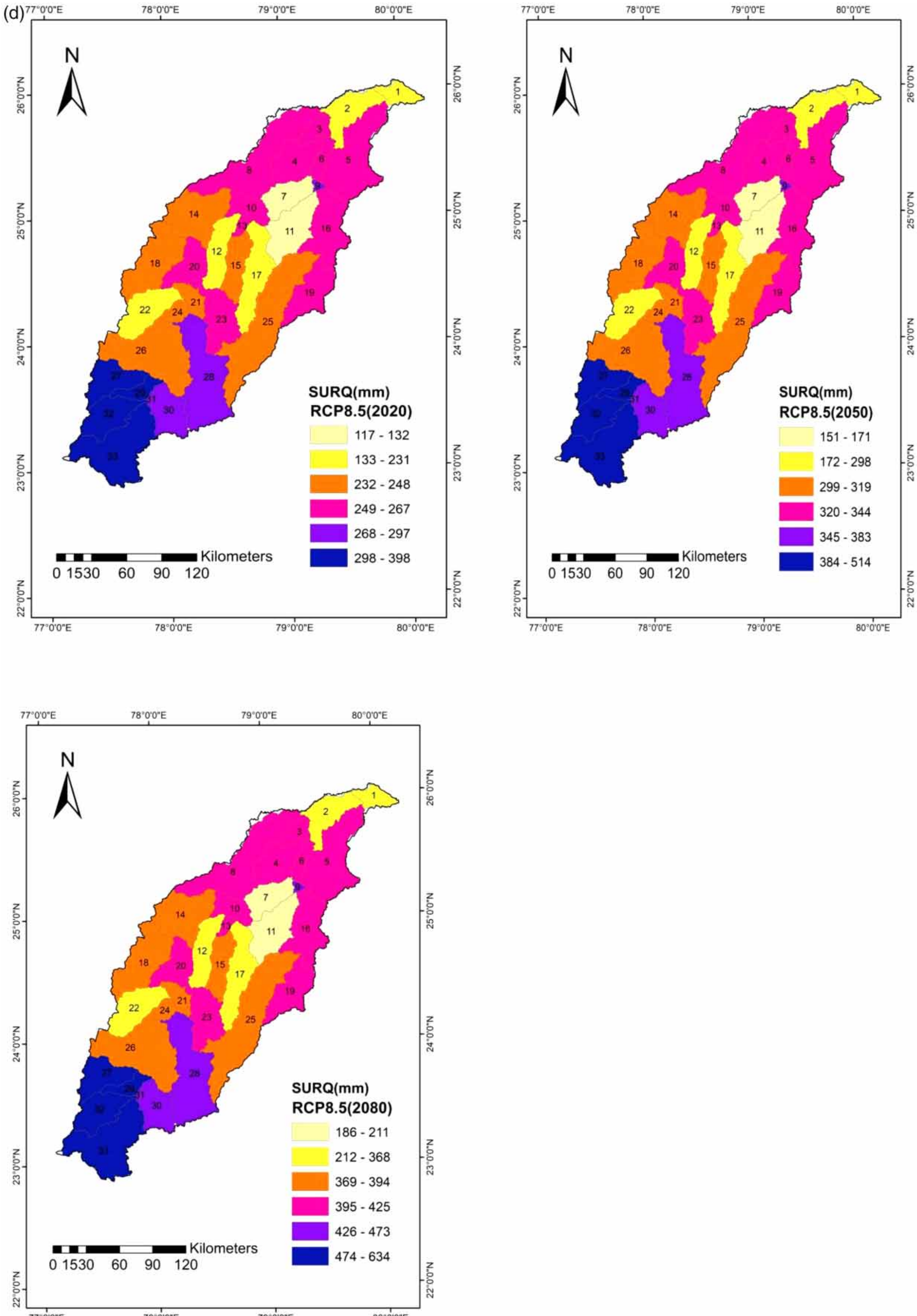

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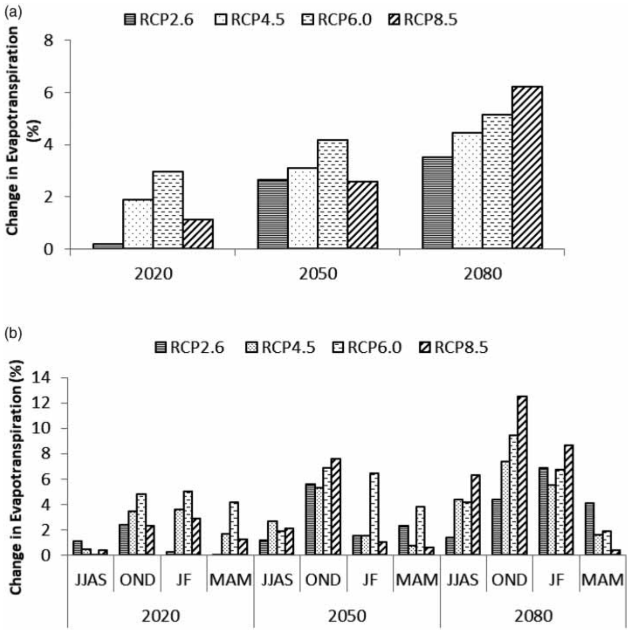


Figure 11 | Projected changes in (a) annual and (b) seasonal evapotranspiration under different scenarios.

Kumar *et al.* (2011) also reported an extended monsoon season for India in the future with ensemble mean annual cycle of rainfall increase by nearly 20% during May and October in the future period (2070–2098). Our analysis showed increase in the post-monsoon season surface runoff in the basin during the 2020s, 2050s and 2080s as a result of increase in the post-monsoon season rainfall.

The SWAT simulation showed a decrease in the mean annual surface runoff during the 2020s and an increase during the 2050s and 2080s. An increase in the surface runoff during the 2050s and 2080s is consistent with an increase in the rainfall in the basin. These results were in line with Kumar *et al.* (2017), who reported similar results for the upper Kharun catchment of Central India. The upper and middle parts of the basin are affected by flooding during monsoon and post-monsoon seasons during the 2050s and 2080s. Increase in the streamflow due to climate change would further increase frequency of floods and cause water stagnation. The Ganga river basin is more sensitive to change in rainfall than temperature and this increase in the rainfall will result in increased surface runoff in all the sub-basins (Mishra & Lilhare 2016). The ET is projected to increase in the basin as a result of projected increase in the temperature. These results were consistent with previous studies in the Bundelkhand region of Central India reported by Narsimlu *et al.* (2013) in the Sind river basin, which is adjacent to the Betwa river basin. Mishra & Lilhare (2016) also reported an increase in evapotranspiration by 10% in the majority of river basins in India under RCP4.5 and RCP8.5 scenarios. It was observed that rainfall, surface runoff and ET increased more in the upstream part of the basin as compared to the downstream part. The major reason for variation between upstream and downstream parts of the basin could be due to spatial variation of rainfall and other anthropogenic activities. The anthropogenic factors which result in significant alteration in hydrology are changes in land use and land cover, soil water infiltration, deforestation, construction of new dams, city expansion, etc. (Wei & Zhang 2010).

The results obtained from climate change simulation of the SWAT model could be useful in planning adaptation measures for the Betwa river basin for the short term (2020s), medium term (2050s) and long term (2080s). In the short term, adaptation measures such as creation of additional water storage facilities, adjustment in cropping patterns and growing of drought-tolerant varieties would be helpful as the rainfall and surface runoff in the basin is likely to decrease. In order to overcome the water scarcity problem during non-monsoon months, suitable water conservation measures like farm ponds, check dams and percolation ponds as an adaptation measure will help to store excess rainwater in the sub-basins receiving higher rainfall and further utilize this water during rabi (post-monsoon) and summer season for irrigation. In the medium and long term, focus should be on management of flood and waterlogging by enhancing the capacity of existing reservoirs and creation of additional storage reservoirs to attenuate the flood and provide water during post-monsoon and summer seasons as the rainfall and surface runoff is projected to increase. Improvement in drainage efficiency and growing flood-tolerant crop varieties are some long-term adaptation strategies to overcome the impact of climate change on water and agriculture under flood situation.

Results of sensitivity analysis showed that surface runoff in the basin is sensitive to change in rainfall, whereas evapotranspiration demand is sensitive to change in the CO_2 level. CO_2 plays a significant role in controlling the basin hydrology as it results in increased surface runoff and decreased evapotranspiration due to decreased stomatal conductance (Rosenberg *et al.* 1989; Islam *et al.* 2012b). Simulation results

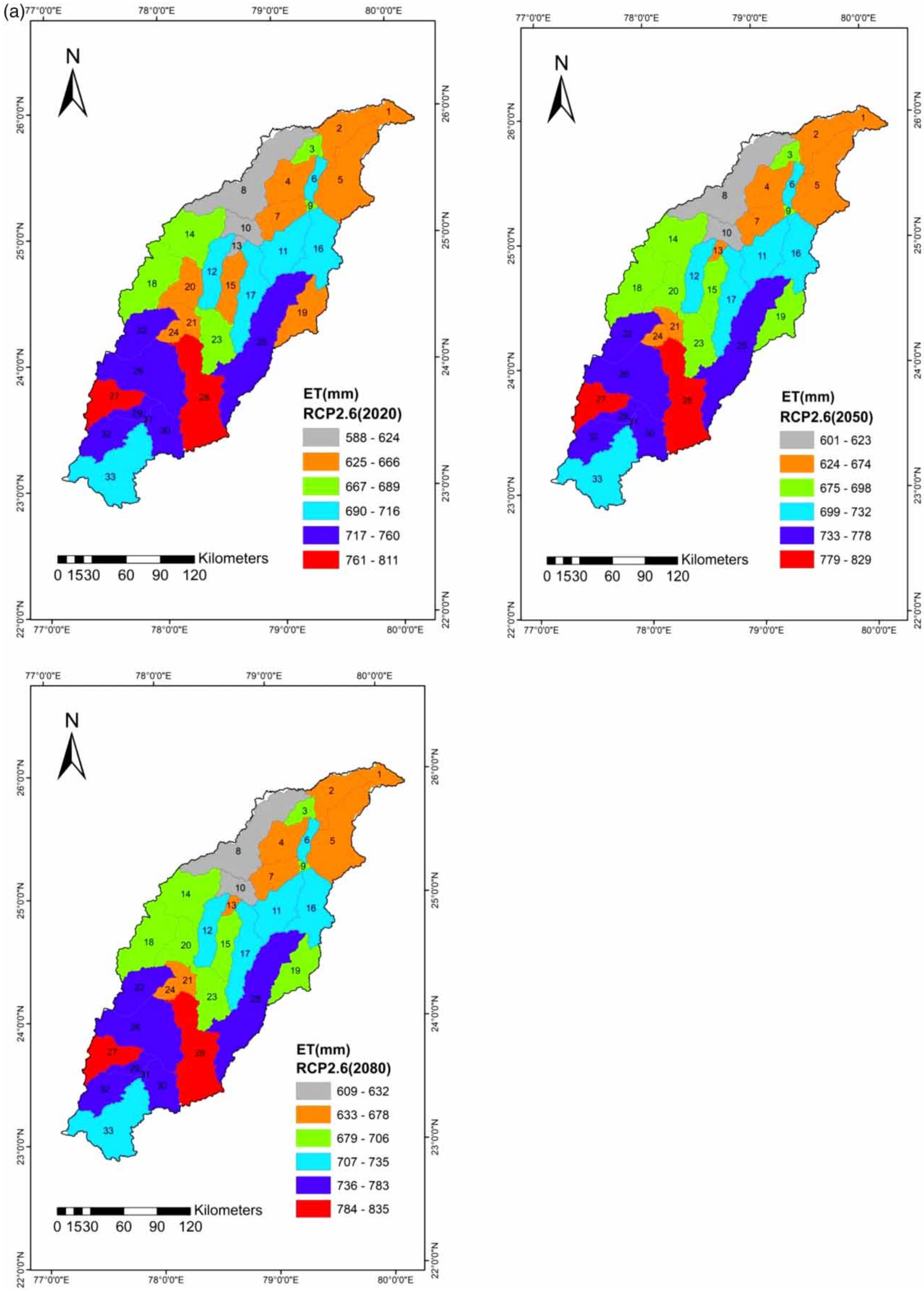
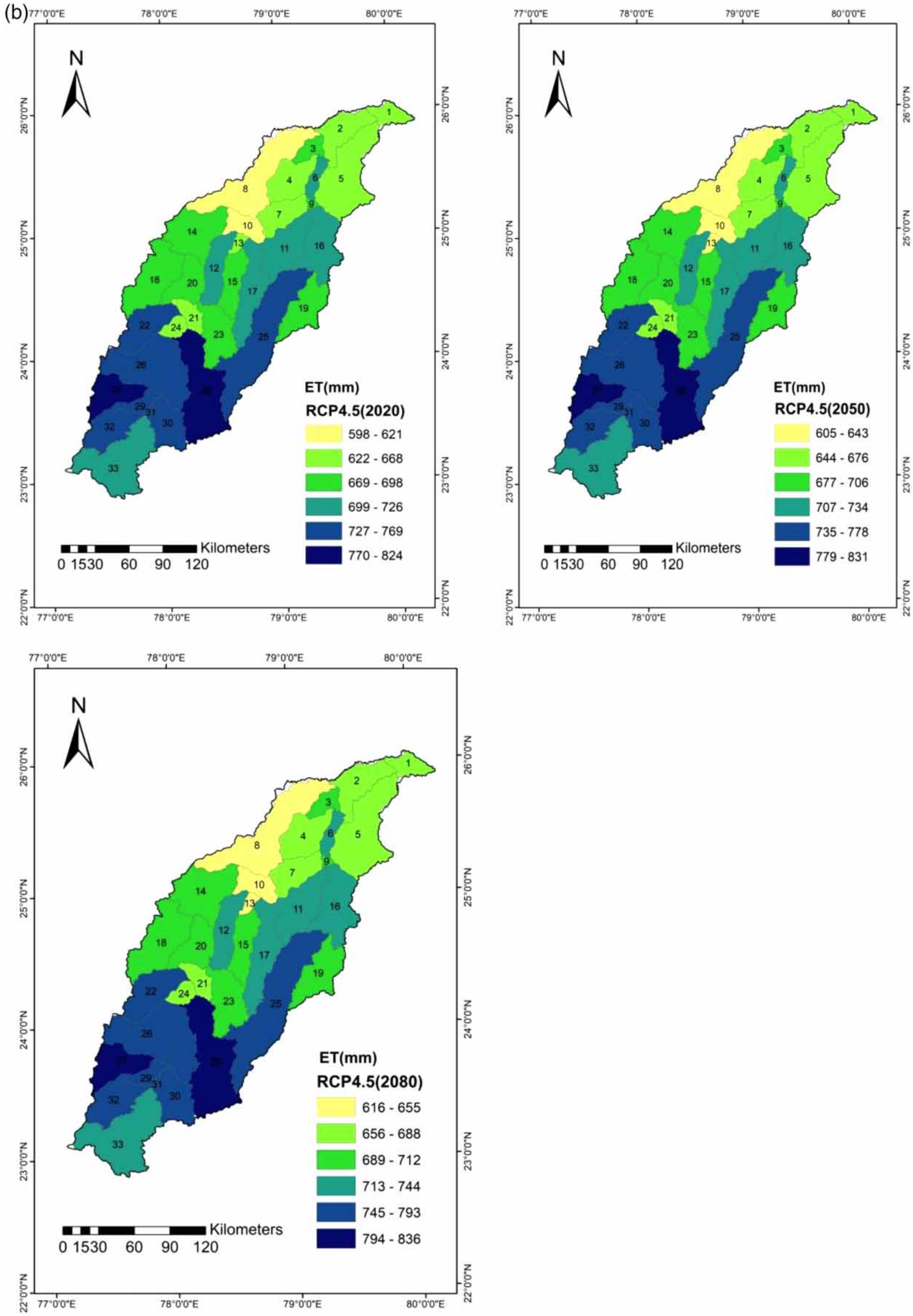


Figure 12 | Sub-basin-wise average annual evapotranspiration for future periods: (a) RCP2.6, (b) RCP4.5, (c) RCP6.0 and (d) RCP8.5. *(continued.)*



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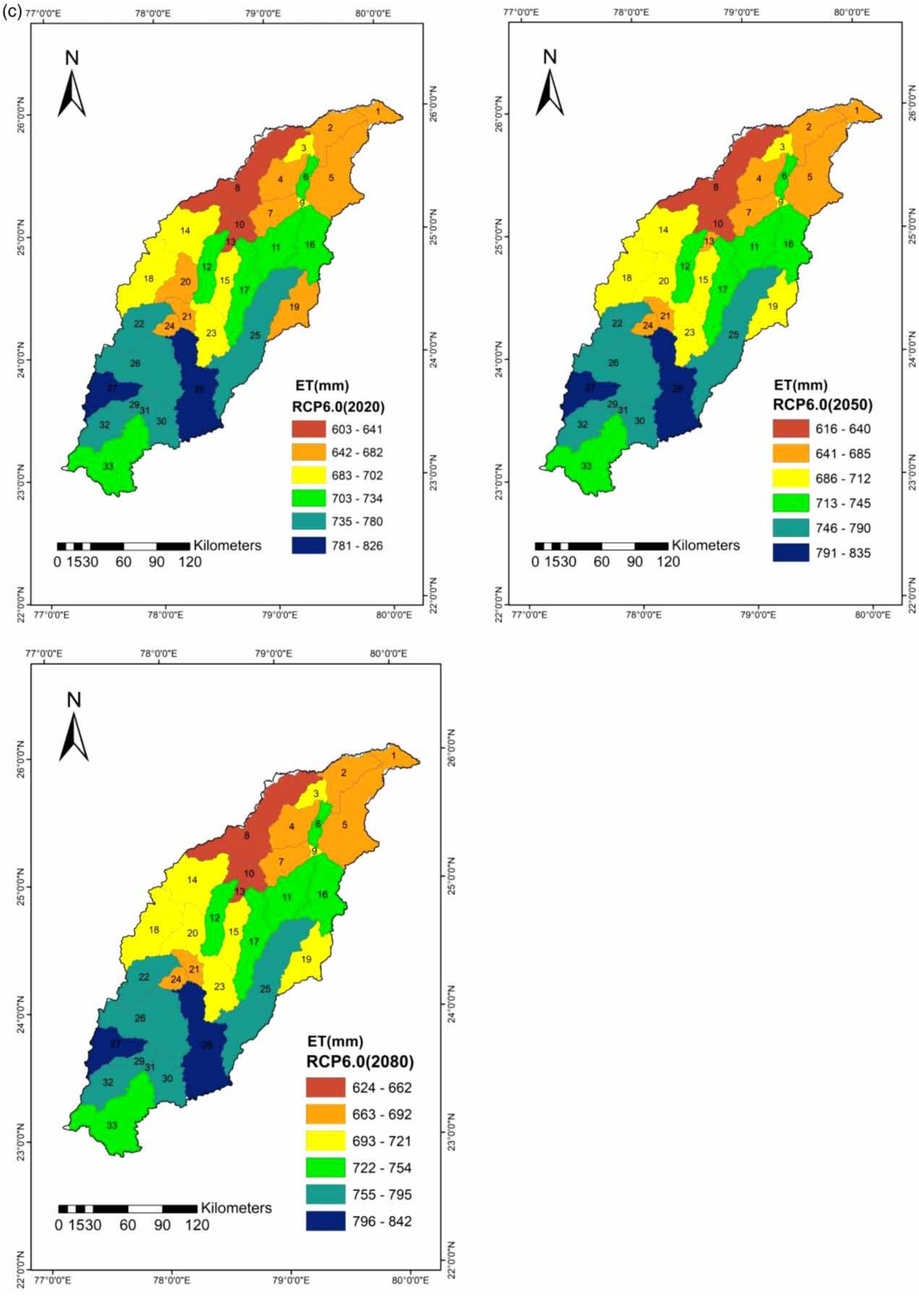

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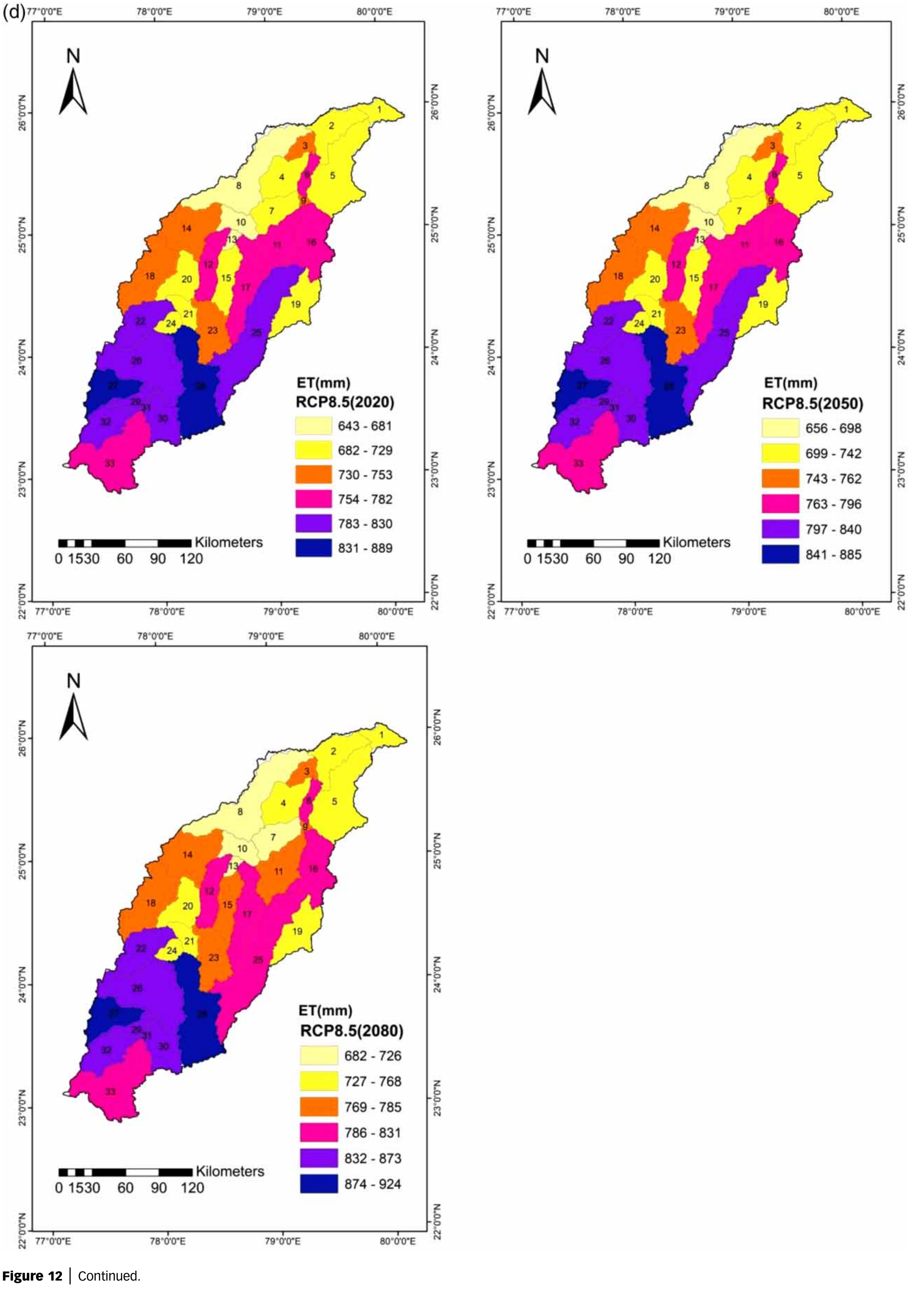

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showed that increased CO_2 concentration combined with increased rainfall may further increase surface water availability in future. However, the crop water demand may not increase due to decrease in evapotranspiration. This may again lead to a flood-like situation during monsoon season in future. Under such situations, adaptation strategies such as improving drainage efficiency in flood-prone areas, growing flood-tolerant crop varieties, use of improved planting methods like broad bed furrow, ridge and furrow, raised bed and sunken furrow as suggested by Sikka *et al.* (2018) are likely to mitigate the effect of flooding and excess runoff during monsoon season. In the present context, the study gives a good insight into the impact of climate change, which will be helpful for planning water management strategies in the basin. However, the results are based on single GCM output, which is one of the limitations of the study. The GCM projections are always associated with uncertainty which can be minimized by using multiple climate models' data. Therefore, further studies using multi-model ensemble climate change scenarios would be helpful in developing more robust adaptation measures for sustainable water resource management of the Betwa river basin.

CONCLUSIONS

In this study, climate change impact on the hydrology and water resources availability in the Betwa basin was assessed using the SWAT model and CMIP5-based MIROC5 GCM projections. Multi-site calibration of the SWAT model was carried out in the basin using the SUFI-2 algorithm of SWAT-CUP. The model performance indicators revealed that SWAT could capture the monthly flows very well at four spatially distributed gauging stations. SWAT simulation results using hypothetical climate change scenarios revealed that surface runoff is sensitive to rainfall change and evapotranspiration is sensitive to change in CO_2 concentration. The analysis of MIROC5 GCM projected changes in mean annual temperature revealed increase in mean temperature in the range of 0.7–0.9 °C, 1.2–2.0 °C and 1.1–3.1 °C during the 2020s, 2050s and 2080s, respectively, over the baseline (1961–1990) period under different RCPs. Annual rainfall analysis revealed decrease in the range of 0.9–2.9% during the 2020s and increase in the range of 0.4–9.1% and 5.7–15.3% during the 2050 and 2080s, respectively. The simulation results showed decrease in mean annual surface runoff in the range of 4.7–12.4% in the basin under different RCPs during 2020s, and increase in mean annual runoff in the range of 3.8–29% and 12–48% during the 2050s and 2080s, respectively. Increase in the post-monsoon season rainfall and surface runoff was maximum (as compared to the baseline period) under all RCPs and future periods. The mean annual evapotranspiration is projected to increase in the range of 0.2–3.0%, 2.6–4.2% and 3.5–6.2%, during the 2020s, 2050s and 2080s, respectively. The results of this study indicate that the surface water resources, as well as evapotranspiration, are projected to increase in future in the basin as a result of increase in rainfall and temperature. However, CO_2 also plays a significant role in controlling the basin hydrology as it results in increased surface runoff and decreased evapotranspiration. Results of the present study can be used to suggest the climate change adaptation measures based on short-term, medium-term and long-term availability of surface water resources in the Betwa river basin.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abbaspour, K. C. 2014 *SWAT-CUP 2012 SWAT Calibration and Uncertainty Programs*. A User Manual. Dübendorf, Switzerland.

Abeysingha, N. S., Islam, A. & Singh, M. 2020 Assessment of climate change impact on flow regimes over the Gomti River basin under IPCC AR5 climate change scenarios. *J. Water Clim. Change* **11** (1), 303–326.

Arnell, N. W. & Lloyd-Hughes, B. 2014 The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Clim. Change* **122** (1–2), 127–140.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. 1998 Large area hydrologic modeling and assessment part I: model development. *J. Am. Water Resour. Assoc.* **34** (1), 73–89.

Basheer, A. K., Ali, A. B. & Abdelgader, A. M. 2016 Impacts of climate change under CMIP5 RCP scenarios on the streamflow in the Dinder River and ecosystem habitats in Dinder National Park, Sudan. *Hydrol. Earth Syst. Sci.* **20** (4), 1331–1353.

Chaturvedi, R. K., Joshi, J., Jayaraman, M., Bala, G. & Ravindranath, N. H. 2012 Multi-model climate change projections for India under representative concentration pathways. *Curr. Sci.* **103** (7), 791–802.

Desai, S., Singh, D. K., Sarangi, A., Khanna, M., Sahoo, R. N. & Pathak, H. 2016 Extraction of geomorphological parameters of Betwa basin using GIS and Watershed Morphology Estimation Tool (WMET). *Indian J. Soil Conserv.* **44** (3), 241–248.

Desai, S., Singh, D. K., Islam, A., Sarangi, A. & Khanna, M. 2019 Trend analysis of climatic variables in Betwa river basin. *Indian J. Agric. Sci.* **89** (6), 1033–1038.

Easterling, W. E., Rosenberg, N. J., McKenney, M. S., Jones, C. A., Dyke, P. T. & Williams, J. R. 1992 Preparing the erosion productivity impact calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO_2. *Agric. For. Meteorol.* **59** (1–2), 17–34.

Ficklin, D. L., Stewart, I. T. & Maurer, E. P. 2013 Climate change impacts on streamflow and subbasin-scale hydrology in the upper Colorado river basin. *PloS One* **8** (8), e71297.

Gebre, S. L. & Ludwig, F. 2015 Hydrological response to climate change of the Upper Blue Nile River Basin: based on IPCC Fifth Assessment Report (AR5). *J. Climatol. Weather Forecast.* **3** (1), 1–15.

Gosain, A. K., Rao, S. & Arora, A. 2011 Climate change impact assessment of water resources of India. *Curr. Sci.* **101** (3), 356–371.

Grotch, S. L. & MacCarcken, M. C. 1991 The use of General Circulation Models to predict regional climate change. *J. Clim.* **4** (3), 286–303.

India-WRIS. 2014 Ganga Basin. http://indiawris.gov.in/wris/#/Basin (accessed 04 02 2019).

IPCC. 2007 *Climate Change 2007: The Physical Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Inter-Governmental Panel on Climate Change*. Cambridge University Press, New York, US. http://www.ipcc.ch

IPCC. 2014 *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.)]*. IPCC, Geneva, Switzerland.

Islam, A., Sikka, A. K., Saha, B. & Singh, A. 2012a Streamflow response to climate change in the Brahmani River Basin, India. *Water Resour. Manage.* **26** (6), 1409–1424.

Islam, A., Ahuja, L. R., Garcia, L. A., Ma, L. & Saseendran, A. S. 2012b Modeling the effect of elevated CO_2 and climate change on reference evapotranspiration in the semi-arid Central Great Plains. *Trans. ASABE* **55** (6), 2135–2146.

Islam, A. K. M., Paul, S., Mohammed, K., Billah, M., Fahad, M., Rabbani, G., Hasan, M., Islam, G. M. & Bala, S. K. 2018 Hydrological response to climate change of the Brahmaputra basin using CMIP5 general circulation model ensemble. *J. Water Clim. Change* **9** (3), 434–448.

Jung, C. G., Lee, D. R. & Moon, J. W. 2016 Comparison of the Penman-Monteith method and regional calibration of the Hargreaves equation for actual evapotranspiration using SWAT-simulated results in the Seolma-cheon basin, South Korea. *Hydrolog. Sci. J.* **61** (4), 793–800.

Kumar, K. K., Kamala, K., Rajagopalan, B., Hoerling, M. P., Eischeid, J. K., Patwardhan, S. K., Srinivasan, G., Goswami, B. N. & Nemani, R. 2011 The once and future pulse of Indian monsoonal climate. *Clim. Dyn.* **36** (11–12), 2159–2170.

Kumar, N., Tischbein, B., Kusche, J., Laux, P., Beg, M. K. & Bogardi, J. J. 2017 Impact of climate change on water resources of upper Kharun catchment in Chhattisgarh, India. *J. Hydrol. Reg. Stud.* **13**, 189–207.

Li, F., Zhang, G. & Xu, Y. J. 2016 Assessing climate change impacts on water resources in the Songhua River basin. *Water* **8** (10), 420.

Lirong, S. & Jianyun, Z. 2012 Hydrological response to climate change in Beijiang River basin based on the SWAT model. *Procedia Eng.* **28**, 241–245.

Liu, X., Yang, M., Meng, X., Wen, F. & Sun, G. 2019 Assessing the impact of reservoir parameters on runoff in the Yalong River Basin using the SWAT Model. *Water* **11** (4), 643.

Mali, S. S. & Singh, D. K. 2015 Mapping spatial variability in crop evapotranspiration and defining spatial resolution units for crop water footprint assessment at river basin scale. *Ecoscan* **9** (1–2), 75–79.

Mearns, L. O., Hulme, M., Carter, T. R., Leemans, R., Lal, M., Whetton, P., Hay, L., Jones, R. N., Kittel, T., Smith, J. & Wilby, R. 2001 Climate scenario development. In: *Climate Change 2001: The Science of Climate Change* (J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson, eds.). Cambridge University Press, New York, US, pp. 739–768.

Mishra, V. & Lilhare, R. 2016 Hydrologic sensitivity of Indian sub-continental river basins to climate change. *Glob. Planet. Change* **139**, 78–96.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Binger, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **50**, 885–900.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T. & Meehl, G. A. 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463** (7282), 747–756.

Narsimlu, B., Gosain, A. K. & Chahar, B. R. 2013 Assessment of future climate change impacts on water resources of upper sind river basin, India using SWAT model. *Water Resour. Manage.* **27** (10), 3647–3662.

Nash, L. L. & Gleick, P. H. 1991 Sensitivity of streamflow in the Colorado basin to climatic changes. *J. Hydrol.* **125** (3–4), 221–241.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. 2011 *Soil and Water Assessment Tool. Theoretical Documentation, Version 2009*. Soil and Water Research Laboratory, Agricultural Research Service, Temple, TX, USA.

Ouyang, F., Zhu, Y., Fu, G., Lü, H., Zhang, A., Yu, Z. & Chen, X. 2015 Impacts of climate change under CMIP5 RCP scenarios on streamflow in the Huangnizhuang catchment. *Stoch. Env. Res. Risk A* **29** (7), 1781–1795.

Pai, D. S., Sridhar, L., Badwaik, M. R. & Rajeevan, M. 2014 Analysis of the daily rainfall events over India using a new long period (1901–2010) high resolution (0.25×0.25) gridded rainfall data set. *Clim. Dyn.* **45** (3–4), 755–776.

Panjwani, S., Kumar, S. N., Ahuja, L. & Islam, A. 2019 Prioritization of global climate models using fuzzy analytic hierarchy process and reliability index. *Theor. Appl. Climatol.* **137** (3–4), 2381–2392.

Parajuli, P. B. 2010 Assessing sensitivity of hydrologic responses to climate change from forested watershed in Mississippi. *Hydrol. Process.* **24** (26), 3785–3797.

Pechlivanidis, I. G., Olsson, J., Bosshard, T., Sharma, D. & Sharma, K. C. 2016 Multi-basin modelling of future hydrological fluxes in the Indian subcontinent. *Water* **8** (5), 177.

Piniewski, M. & Okruszko, T. 2011 Multi-site calibration and validation of the hydrological component of SWAT in a large lowland catchment. In: *Modelling of Hydrological Processes in the Narew Catchment* (D. Świątek & T. Okruszko, eds). Springer, Berlin, Heidelberg, pp. 15–41.

Ritchie, J. T. 1972 Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* **8** (5), 1204–1213.

Rosenberg, N. J., McKenney, M. S. & Martin, P. 1989 Evapotranspiration in a greenhouse-warmed world: a review and a simulation. *Agric. Forest Meteorol.* **47** (2–4), 303–320.

Saharia, A. M. & Sarma, A. K. 2018 Future climate change impact evaluation on hydrologic processes in the Bharalu and Basistha basins using SWAT model. *Nat. Hazards* **92** (3), 1463–1488.

Setegn, S. G., Rayner, D., Melesse, A. M., Dargahi, B. & Srinivasan, R. 2011 Impact of climate change on the hydroclimatology of Lake Tana Basin, Ethiopia. *Water Resour. Res.* **47** (4), W04511.

Shrestha, M., Shrestha, S. & Datta, A. 2017 Assessment of climate change impact on water diversion from the Bago River to the Moeyingyi wetland, Myanmar. *Curr. Sci.* **112** (2), 377–384.

Sikka, A. K., Islam, A. & Rao, K. V. 2018 Climate-smart land and water management for sustainable agriculture. *Irrig. Drain.* **67** (1), 72–81.

Sonali, P., Kumar, D. N. & Nanjundiah, R. S. 2017 Intercomparison of CMIP5 and CMIP3 simulations of the 20th century maximum and minimum temperatures over India and detection of climatic trends. *Theor. Appl. Climatol.* **128** (1–2), 465–489.

Srivastava, A. K., Rajeevan, M. & Kshirsagar, S. R. 2009 Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. *Atmos. Sci. Lett.* **10** (4), 249–254.

Vandana, K., Islam, A., Sarthi, P. P., Sikka, A. K. & Kapil, H. 2019 Assessment of potential impact of climate change on streamflow: a case study of the Brahmani River Basin, India. *J. Water Clim. Change* **10** (3), 624–641.

Van Vuuren, D. P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A. & Rose, S. K. 2012 A proposal for a new scenario framework to support research and assessment in different climate research communities. *Global Environ. Change* **22** (1), 21–35.

Wang, G. & Xia, J. 2010 Improvement of SWAT2000 modelling to assess the impact of dams and sluices on streamflow in the Huai River basin of China. *Hydrol. Process.* **24** (11), 1455–1471.

Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., Takemura, T., Chikira, M., Ogura, T., Sekiguchi, M. & Takata, K. 2010 Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *J. Clim.* **23** (23), 6312–6335.

Watts, G. 2011 Water for people: Climate change and water availability. In: *Modelling the Impact of Climate Change on Water Resources* (F. Fung, A. Lopez & M. New, eds). Wiley-Blackwell, Chichester, UK, pp. 86–127.

Wei, X. & Zhang, M. 2010 Quantifying streamflow change caused by forest disturbance at a large spatial scale: a single watershed study. *Water Resour. Res.* **46** (12), 1–15.

Wigley, T. M. L. & Jones, P. D. 1987 England and Wales precipitation: a discussion of recent changes in ariability and an update to 1985. *Int. J. Climatol.* **7** (3), 231–246.

Wu, Y., Liu, S. & Gallant, A. L. 2012 Predicting impacts of increased CO_2 and climate change on the water cycle and water quality in the semiarid James River Basin of the Midwestern USA. *Sci. Total Environ.* **430**, 150–160.

Yan, D., Werners, S. E., Ludwig, F. & Huang, H. Q. 2015 Hydrological response to climate change: The Pearl River, China under different RCP scenarios. *J. Hydrol. Reg. Stud.* **4**, 228–245.

Yijian, D. & Wu, Y. 1996 Effect of water resource projects along caoe river basin on ecological environments. *Adv Water Sci.* **7** (3), 260–267.

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