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Assessment of water resources and crop yield under future climate scenarios: A case study in a Warangal district of Telangana, India

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In the present study, assessment of the impact of climate change on the availability of water resources and crop yield of Warangal district of Telangana state, India has been carried out using Soil and Water Assessment Tool (SWAT). The importance of bias correction methods in regional forecasts with multiple Regional Climate Models (RCMs) along with projected uncertainties have been emphasized, and regionalization of parameters in ungauged watersheds have been dealt with. SWAT model was run using observed data and then calibrated using observed streamflow of Akeru watershed, Warangal district, India. The R^2 and *NSE* values for calibration (0.72 and 0.84, respectively) and validation periods (0.7 and 0.56, respectively) indicated a significant correlation between observed and simulated streamflow. Then the model was run for historical and future scenarios (early, mid, and end of the 21st century) for four RCMs. Variables such as rainfall, surface runoff, water yield, evapotranspiration, and intensity of rainfall showed an increasing trend under future scenarios, while crop yields (corn, cotton and rice) showed a decreasing trend. The models predicted an increase in the extremity of rainfall events, especially in the months of July and August, for the mid and end of the 21st century. The results showed that the production of cotton is under threat in the district in future. The results obtained can be used to plan the mitigation and adaptation strategies for the region.

Keywords. Climate change impact; climate model; rainfall; runoff; SWAT.

1. Introduction

An increase in greenhouse gas (GHG) emissions alter hydrologic conditions such as increase in global temperature, initiating a chain of events, affecting rainfall patterns, runoff, evapotranspiration, soil moisture, stream flows and its frequency, severity of floods and droughts (Zierl and Bugmann 2005; Gosain *et al.* 2006; Oki and Kanae 2006; Zhang *et al.* 2006; Guhathakurta *et al.* 2011; Raneesh and Thampi Santosh 2011; Uniyal *et al.* 2015; Djebou 2017; Tavakolifar *et al.* 2017). Apart from global warming, climate change may add additional pressure on water resources and it is evident that climate change would impact the hydrology of a basin profoundly. Impacts have been reported in snowmelt and glaciers (Scherler *et al.* 2011; Khadka *et al.* 2014), green and blue water resources (Kundzewicz *et al.* 2008; Faramarzi *et al.* 2013; Shrestha *et al.* 2017b; Zhuang

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et al. 2018), crop yield and irrigation water requirement (Deb *et al.* 2016; Shrestha *et al.* 2017b), hydropower production (Shrestha *et al.* 2014; Tarroja *et al.* 2016; De Jong *et al.* 2018; Zhang *et al.* 2018), sediment yield and transport (Samaras and Koutitas 2014; Shrestha *et al.* 2016), water quality (Trang *et al.* 2017), reservoir capacity (Shrestha *et al.* 2016; Ehsani *et al.* 2017), marine ecosystems (Harley *et al.* 2006; Doney *et al.* 2012), economy (Moore and Diaz 2015; Auffhammer 2018; Tol 2018) and, fisheries (Ficke *et al.* 2007; Allison *et al.* 2009; Plagányi 2019). Impacts are region-specific, especially the arid and semi-arid regions are more vulnerable to climate change (Al-Hasan and Mattar 2014) and may have significant implications on agricultural production (Abbaspour *et al.* 2009; Mengistu 2011; Byakatonda *et al.* 2018; Makuvaro *et al.* 2018). Therefore, there is a need to assess the impact in this part of the basin in order to help formulate different management actions (Zierl and Bugmann 2005; Gosain *et al.* 2006; Zhang *et al.* 2006; Peddinti and Kambhammettu 2019; Tavakolifar *et al.* 2017; Chanapathi *et al.* 2018). Various adaptation and management strategies have been reported in agriculture (Howden *et al.* 2007; Elliott *et al.* 2014; Karimi *et al.* 2018; Khanal *et al.* 2018), water management (Abbas *et al.* 2018; Huang *et al.* 2018; Liu *et al.* 2018; Pearce *et al.* 2018; Tan and Foo 2018), livestock (Hristov *et al.* 2018), hydropower (Da Silva and Freitas 2011; Lucena *et al.* 2018), nutrients loading (Huttunen *et al.* 2015; Kondolf *et al.* 2018) and water quality (Whitehead *et al.* 2009). However, it is a rigorous task due to uncertainties (Lioubimtseva *et al.* 2005; Ficklin *et al.* 2013) and needs projected emission scenarios from various global and regional circulation models. The available RCPs are RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 (IPCC 2013). In the present study, the RCP 4.5 scenario has been used, as it stabilizes the radiative forcing at a modest value of 4.5 W/m^2 at the end of the century.

In the present study, Warangal district of Telangana state, India is considered for the study due its semi-arid nature. Small and erratic distribution of rainfall, along with intense solar radiation and extreme temperatures makes this region as one of the most vulnerable and drought-prone regions in Telangana state, India (Reddy *et al.* 2016). In the past, out of 15 years from 1997–2012, Warangal district was declared as a drought-affected region by the Government of India for 8 years (EPTRI 2015). In these regions, the intensity and distribution of rainfall pattern maintain a dynamic relationship with the crop water balance components, such as irrigation water requirement, effective rainfall, and crop evapotranspiration. This balance is most vulnerable to be disrupted by the impacts of climate change. Therefore, there is a growing need to understand the impact of climate change on the water resources and crop yield of this district for better planning and management.

However, there is limited research in these (semi-arid) regions due to data limitation. Thus, the present study focuses on providing a robust framework in modelling the data scare regions. The present work divides the administrative units of the district into different watersheds, while most of the researchers addressed this issue for river basins (Gosain *et al.* 2006; Zhang *et al.* 2006; Srinivasan *et al.* 2010; Liu *et al.* 2011; Uniyal *et al.* 2015), Most of the previous studies paid less attention towards bias correction methods (Gosain *et al.* 2011; Liu *et al.* 2011; Narsimlu *et al.* 2013; Kulkarni *et al.* 2014; Molina-Navarro *et al.* 2016). Whereas this study emphasizes the importance of bias correction methods in regional forecasts using multiple RCMs, in addition to the regionalization of the parameters (Blöschl and Sivapalan 1995; Fernandez *et al.* 2000; Hundecha *et al.* 2008; Samuel *et al.* 2011) in ungauged watersheds.

Thus, the present research work focuses on the assessment of surface water availability under present and future scenarios and its influence on crop yield of Warangal district, Telangana state, India, which is achieved through following specific objectives: (1) evaluation of bias correction methods, (2) hydrological modelling setup of Warangal district along with calibration and validation of the model, (3) regionalization of parameters with the help of calibrated (Akeru watershed) model, the regionalization of parameters to the other watersheds in the district has been carried out, and (4) assessment of water resources and crop yields of Warangal district under present and future climate scenarios. Finally, discussed the implications of climate change on water resources and water yield of the district.

2. Methodology

In the present study, a preliminary analysis of rainfall and runoff has been carried out, followed by bias correction of climate models (MIROC-MIROC5, GFDL-ESM2M, ICHEC-ESM, and

CNRM-CM5). To estimate water balance components of the study area, SWAT model was set up, the calibration and validation of the model were done with SWAT-CUP, using observed streamflow data and mean crop yield values from the available reports. Then the model was further run for historical and future scenarios to assess the impact of climate change on available water resources and crop yields of the study region.

2.1 *Study area*

The Warangal district (figure 1) (17°19′–18°36′N, 78°49′–80°43′E) is a part of the Deccan Plateau of India, covering a geographical area of 12,846 km^2, with a population density of 273 people per km^2 (2011 census, India). The district falls in the drainage basins of both, Godavari and Krishna rivers, and is semi-arid in nature. Almost 51% of the district is utilized as agricultural land for growing cotton, rice, maize, groundnut, chillies, green gram, mangoes, and turmeric, employing rainfed tanks, irrigation canals, dug wells, and tube wells being the primary sources of irrigation. The dominant rock types in the district are granites, gneisses, sandstone, limestone, shale, and quartzites (Central Ground Water Board), with the dominant soils being red earth, forest soils and black soils. The minimum and maximum temperature of the district varies from 15.5° to 40.3°C. The mean annual rainfall is about 1050 mm, and most of the rain occurs during southwest monsoon (figure 2).

2.2 *Input data*

Geospatial data like Digital Elevation Model (DEM), soil data, land use data and slope map were used as input for the SWAT model. DEM is a digital representation of the earth's topography. It is used for topographic, geomorphological parameter estimation and also used for watershed delineation and stream network generation. A 90 m resolution Shuttle Radar Topography Mission (SRTM) DEM (http://www.usgs.gov/) was used to divide the district into different watershed units, and for preparation of the slope map. Both the land use and soil maps were obtained from the water base (http://www.waterbase.org/). Warangal district mainly consists of three soil types: Chromic Luvisols (86.9%), Pellic Vertisols (12.27%), and Eutric Nitosols (0.83%). Most of the district being covered by the Chromic Luvisols soil is of a boon to small farmers because of its ease of cultivation. However, since the soil has a tendency to be 50% saturated at all time, it is prone to erosion, leading to loss of nutrients and fertility. Vertisols, containing more than 30% clay, are active soils having high natural chemical fertility.

Land use map for Warangal district revealed it to be predominantly cropland/grassland mosaic (39.93%), followed by savanna (22.34%), dryland cropland and pasture (16.4%), irrigated crop pasture (15.5%), deciduous broadleaf forest (4.49%), water bodies (0.9%), residential medium density (0.173%), cropland/woodland mosaic (0.165%),

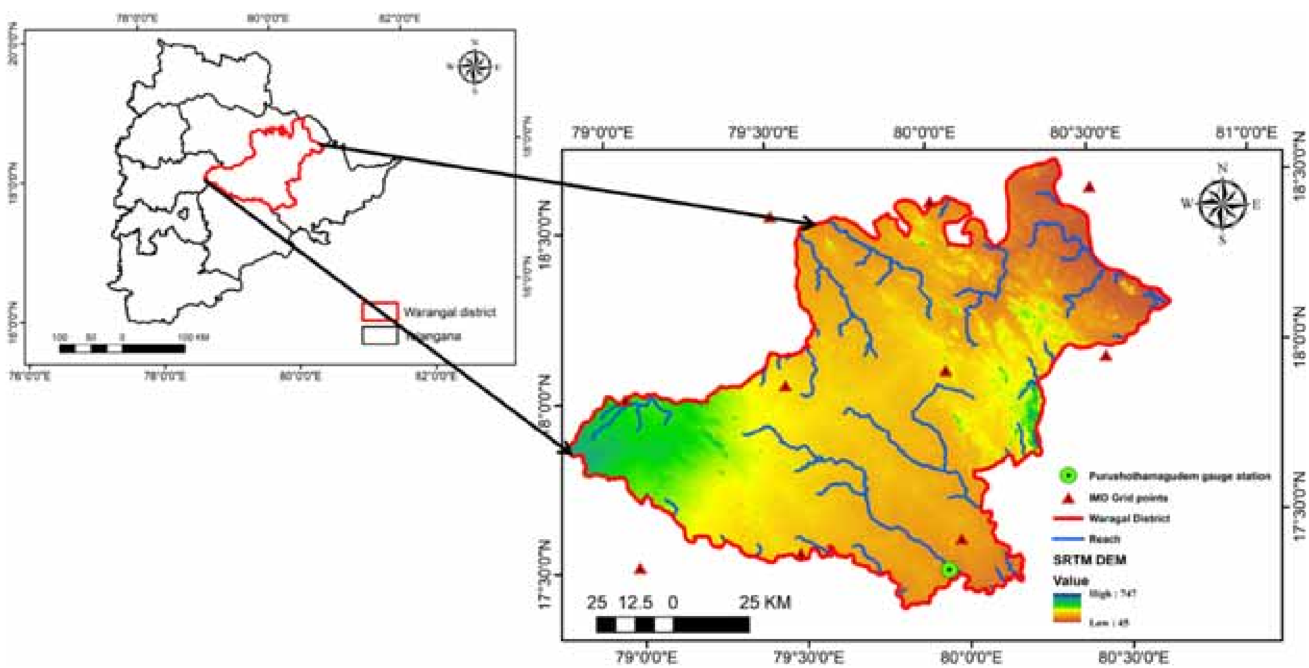

Figure 1. Location map of Warangal district along with IMD rainfall and streamflow gauge stations.

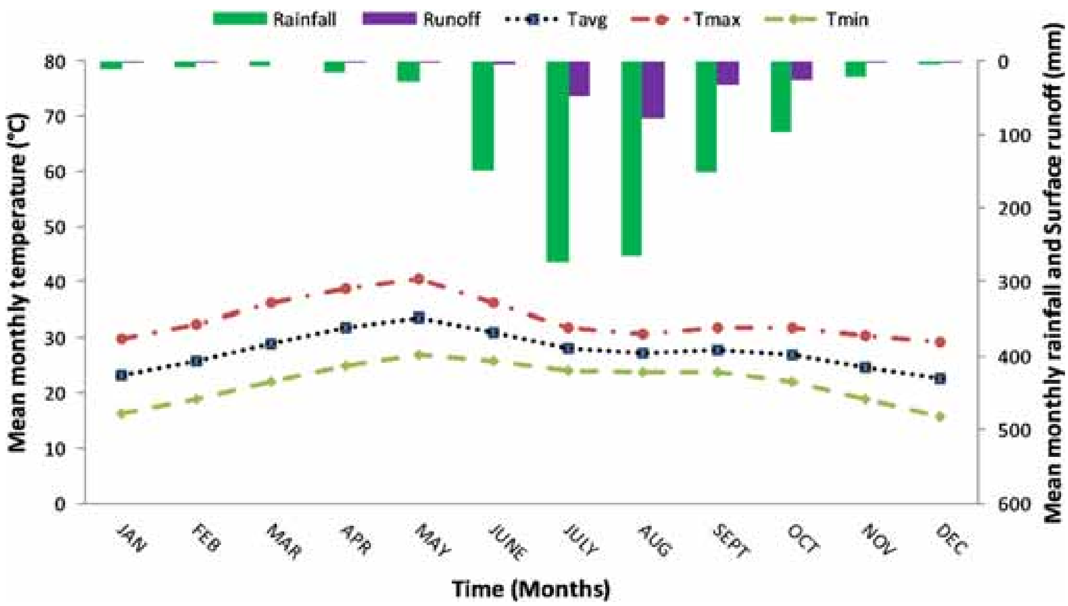

Figure 2. Mean monthly variation of rainfall temperature and simulated runoff over a period of 31 years (1975–2005).

shrubland (0.06%), and grassland (0.015%). the agriculture-based land use classes such as cropland/grassland mosaic (CRGR), irrigated cropland and pasture (CRIR) and dryland cropland and pasture (CRDY) were subclassified into three major agriculture crops (cotton, rice and corn respectively) in the district. Each crop needs specific management operations to include in the model. Therefore, mainly four management operations such as planting/growing season operation, auto irrigation, fertilizer application and, harvest and kill operation were used in the model run. The management operations were scheduled by date, which was based on the reports of Agriculture Contingency Plan for District Warangal (CRIDA 2012) and respective irrigation management schedules from TNAU agriculture portal (TNAU 2018).

In this district, rice is grown in both Kharif and Rabi seasons, which is generally irrigated. The major source of irrigation for the rice are canals, tanks and irrigation projects. Therefore, in the auto irrigation schedule, the water is supplied to the rice from the respective reaches. The other two major crops in the district were cotton and corn and the major sources of irrigation for these two crops are groundwater from dug and tube wells. Therefore, in the auto irrigation schedule, the water is supplied to the cotton and corn are from the aquifer (notably from shallow aquifer). The beginning of the planting season, amount and duration of irrigation, fertilizer application for these crops (cotton, rice and corn) is specified based on the reports of CRIDA (2012), the detailed schedule of the management operations of these crops was provided in table 1.

2.2.1 *Climate data*

Observed climate data such as rainfall, maximum and minimum temperatures for a 0.5° × 0.5° resolution of the study area was obtained from India Meteorological Department (IMD), Pune for a period of 36 years (1970–2005). However, the first 5 years were used as the warm-up period in the model setup and are subsequently excluded from the analysis to make the analysis uniform throughout the manuscript. Therefore, the analysis has been carried out for a duration of 31 years (1975–2005). From the rainfall data, it was observed that June–October were the critical months, including almost 91.2% of total rainfall, with the maximum rainfall occurring between July and August (figure 2). While the temperature data reported the annual mean, maximum and minimum temperatures of the region to be 27.6, 33.3, and 21.9°C during this period. The climate models used in the present study were obtained from the Earth System Grid Federation (ESGF) (esg-dn1.nsc.liu.se) for a 0.5° × 0.5° resolution (table 2). The data were collected for four time periods such as baseline data (1970–2005), early-century (2006–2040), mid (2041–2070), and end of the 21st century (2071–2100).

Table 1. *Schedule of management operations for the major crops in Warangal district.*

Crop	Planting date	Auto irrigation initialization	Fertilizer application	Harvest and kill operation	Duration (days)
Rice (Kharif)	15th June	21st June	30th June, 21st July, and 30th July	12th November	150
Rice (Rabi)	20th November	21st November	22nd November, 23rd November, and 20th December	18th April	150
Cotton (Kharif)	15th June	21st June	30th June, 21st July, and 30th July	22nd November	160
Corn (Kharif)	15th June	17th June	19th June, 21st June, and 15th August	3rd October	110
Corn (Rabi)	15th October	17th October	19th October, 21st October, and 15th December	2nd February	110

Table 2. *List of climate models used in the present study.*

Experiment name	RCM	Driven GCM	Resolution
RCA4 (ICHEC-ESM)	RCA4 (Samuelsson *et al.* 2011)	EC-EARTH (Hazeleger *et al.* 2012)	$\sim 0.5° \times 0.5°$
RCA4 (MIROC-MIROC5)	RCA4 (Samuelsson *et al.* 2011)	MIROC-MIROC5 (Watanabe *et al.* 2010)	$\sim 0.5° \times 0.5°$
RegCM4 (GFDL)	RegCM4 (Giorgi *et al.* 2012)	GFDL-ESM2M-LR (Dunne *et al.* 2012)	$\sim 0.5° \times 0.5°$
CCAM (CNRM)	CCAM (McGregor and Dix 2001)	CNRM-CM5 (Voldoire *et al.* 2013)	$\sim 0.5° \times 0.5°$

RCM: Regional Climate Model; GCM: Global Climate Model; RCA 4: Rossby Centre regional atmospheric model version 4; RegCM4: The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4; CCAM: Commonwealth Scientific and Industrial Research Organisation (CSIRO) Conformal-Cubic Atmospheric Model; ICHEC-ESM: Irish Centre for High-End Computing(ICHEC) European Consortium ESM; MIROC-MIROC5: Model for Interdisciplinary Research On Climate (MIROC) Japan Agency for Marine-Earth Sci & Tech, Japan; GFDL-ESM: Geophysical Fluid Dynamics Laboratory USA Earth System Model; CNRM-CM5: Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique.

2.2.2 *Streamflow data*

In the entire Warangal district, only one streamflow gauge station data was available (at Purushothamgudem, figure 1), which is an outlet of Akeru watershed a sub-tributary of Krishna river basin, covering an area of about 2163 km^2. The available data from 1st September 1987 to 31st May 2006 obtained from Central Water Commission (CWC), Hyderabad, reported 93.5% of total streamflow was covered between the months of July and October, with the peak flow occurring in August (figure 2).

2.3 *Selection of bias correction method*

Rainfall analysis for Warangal district was carried out using rainfall data from various climate models. Four RCM models, driven by MIROC-MIROC5, GFDL-ESM2M, ICHEC-ESM, and CNRM-CM5 GCM models were used in the analysis. It was observed that climate models predicted lesser rainfall than the observed value (i.e., IMD grid rainfall). Also, the seasonal rainfall trend of climate models (June–October) differed with IMD grid rainfall, emphasizing the need for bias correction. Data from the climate models were bias-corrected via linear scaling, precipitation local intensity scaling, power transformation, and distribution mapping for the study area (CMhyd tool; Rathjens *et al.* 2016). Among all bias correction methods, linear scaling method was selected for further analysis, based on its performance in terms of statistical parameters on a seasonal basis (June to October) (table 3). Linear scaling method adjusted the simulated RCM data with a multiplicative correction factor for precipitation, as shown in equations (1 and 2). For temperature

Table 3. *Model evaluation using statistical parameters for various models.*

	RMSE		MAE		NSE		Coefficient of correlation (r)	
Climate model	Before BC	After BC	Before BC	After BC	Before BC	After BC	Before BC	After BC
CNRM-CM5_LS	140.9	127	99.27	90.2	–0.16	0.06	0.17	0.38
GFDL-ESM2M_LS	154	137.9	115.8	98.6	–0.38	–0.11	0.05	0.27
MIROC-MIROC5_LS	154	135.4	119.2	102.7	–0.38	–0.07	0.17	0.35
ICHEC-ESM_LS	149.8	125.1	110.3	91.63	–0.31	0.09	–0.01	0.41
CNRM-CM5_LOCI	140.9	128.7	99.27	91.5	–0.16	0.03	0.17	0.37
GFDL-ESM2M_ LOCI	154	140.2	115.8	100.6	–0.38	–0.15	0.05	0.25
MIROC-MIROC5_ LOCI	154	136.9	119.2	104.2	–0.38	–0.09	0.17	0.35
ICHEC_ESM_ LOCI	149.8	128.5	110.3	95	–0.31	0.04	–0.01	0.38
CNRM-CM5_PTF	140.9	141.5	99.27	102.1	–0.16	–0.17	0.17	0.3
GFDL-ESM2M_PTF	154	167.6	115.8	113.4	–0.38	–0.45	0.05	0.19
MIROC-MIROC5_PTF	154	147.3	119.2	118.9	–0.38	–0.44	0.17	0.26
ICHEC_ESM_PTF	149.8	156.9	110.3	109.6	–0.31	–0.27	–0.01	0.28
CNRM-CM5_DM	140.9	153	99.27	110.7	–0.16	–0.37	0.17	0.26
GFDL-ESM2M_DM	154	158.5	115.8	114.6	–0.38	–0.47	0.05	0.19
MIROC-MIROC5_DM	154	154.5	119.2	118.5	–0.38	–0.39	0.17	0.28
ICHEC_ESM_DM	149.8	159.7	110.3	118.6	–0.31	–0.49	–0.01	0.2

BC: Bias correction; LS: Linear scaling; LOCI: Local intensity scaling; PT: Power transformation of precipitation; DM: Distribution mapping.

correction, an additive correction term was used, as shown in equations (3 and 4). The main advantage of this method is that it maintains consistency between the variability of corrected data, with the original RCM data (Lenderink *et al.* 2007; Teutschbein and Seibert 2012).

$$P^*_{\mathrm{contr}}(d) = P_{\mathrm{contr}}(d)\left[\frac{\mu_m(P_{\mathrm{obs}}(d))}{\mu_m(P_{\mathrm{contr}}(d))}\right] \quad (1)$$

$$P^*_{\mathrm{scen}}(d) = P_{\mathrm{scen}}(d)\left[\frac{\mu_m(P_{\mathrm{obs}}(d))}{\mu_m(P_{\mathrm{contr}}(d))}\right] \quad (2)$$

$$T^*_{\mathrm{contr}} = T_{\mathrm{contr}}(d) + \mu_m(T_{\mathrm{obs}}(d)) - \mu_m(T_{\mathrm{contr}}(d)) \quad (3)$$

$$T^*_{\mathrm{scen}} = T_{\mathrm{scen}}(d) + \mu_m(T_{\mathrm{obs}}(d)) - \mu_m(T_{\mathrm{contr}}(d)) \quad (4)$$

where P = precipitation; T = temperature; (d) = daily; * = final bias corrected value; μ_m = monthly mean; obs = observed; contr = Historic RCM simulated (controlled scenario); scen = RCM simulated (future scenarios).

The Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Nash–Sutcliff Efficiency (NSE), and correlation coefficient (R) were used as parameters for model evaluation (Willmott *et al.* 1985; Terink *et al.* 2010; Fang *et al.* 2015).

2.4 *Hydrological modelling of Akeru watershed using SWAT model*

The SWAT model was used for the hydrological modelling of Warangal district since it functions well in expansive watersheds for long-term impact assessments (Perrin *et al.* 2012). It can also be efficiently used for the evaluation of climate change impacts on the water resources of a region (Gosain *et al.* 2011; Wang *et al.* 2018). In the present study, based on the drainage network and DEM, Warangal district which is divided into 37 watersheds using a threshold of 2000 cells ($\approx$16.2 km^2 area), is considered for subbasin delineation. However, for the analysis purpose, only major sub-watersheds have been considered. The significant watersheds of the district are the Akeru watershed (2163 km^2), Munneru watershed (1770 km^2), Parkhal watershed (1111 km^2), Lakhnavaram watershed (1093 km^2), Ramappa watershed (817 km^2), Gollapally watershed (690 km^2), Kamalapur watershed (540 km^2), and Dhoolmitta watershed (317 km^2) (figure 3). The total number of HRUs present in this study is 951, which were defined by considering the 10% of land use, soil and slope thresholds. The SWAT model was simulated with observed weather data obtained from IMD, Pune, while the first 5 years were used as the warm-up period and are subsequently excluded from the analysis.

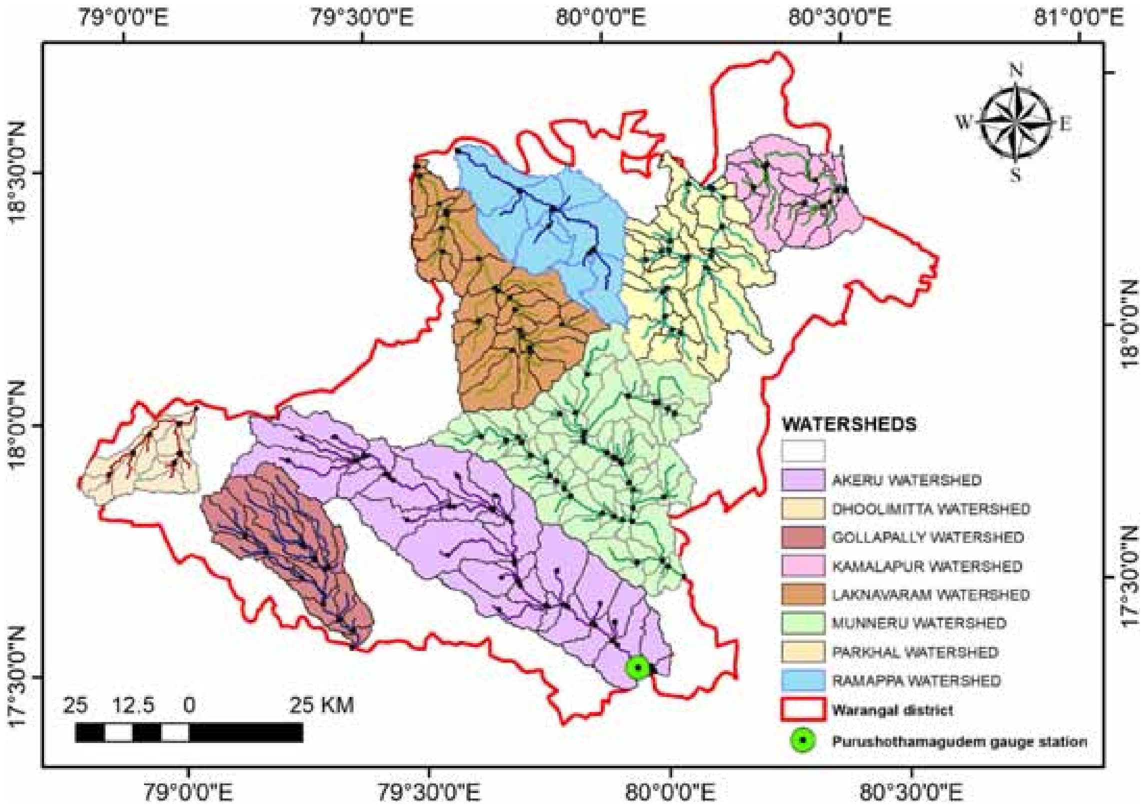

Figure 3. Major watersheds of Warangal district.

SWAT-CUP (SWAT-Calibration and Uncertainty Program) was used for calibration (1988–1995) and validation (1996–2005) of the model. It enables the uncertainty and sensitivity analysis, and can also be used for calibration and validation purposes (Guo *et al.* 2002; Schuol *et al.* 2008; Yang *et al.* 2008; Arnold *et al.* 2012; Narsimlu *et al.* 2013; Chanapathi *et al.* 2018). In the present study, the SUFI-2 (Sequential Uncertainty Fitting Algorithm) optimization algorithm was used for the evaluation of SWAT model performance.

Using SWAT-CUP, sensitivity analysis of model parameters was carried out, and the eight most sensitive parameters were identified. Calibration and validation of the model were carried out using these sensitive parameters. The best parameter values after calibration and validation of the model are shown in table 4. Calibrated parameters were applied to SWAT, to predict the impact of climate change on water resources of the Akeru watershed for climate data, i.e., historical (1975–2005), and future periods such as beginning of the century (2009–2040), mid (2044–2070), and end centuries (2074–2100), excluding the warm-up period. The calibration and validation graphs are shown in figure 4.

SWAT model using a regionalized parameter set gives satisfactory results for ungauged watersheds (Heuvelmans *et al.* 2006; Gitau and Chaubey 2010; Sellami *et al.* 2014; Athira *et al.* 2016). Therefore, SWAT parameters were regionalized based on the Purushothamgudem gauge station data of Akeru watershed, and then water availability was assessed for all other watersheds of the entire district since the geomorphological and physical characteristics (such land use and soil classes) of the other watersheds were quite similar to the Akeru watershed.

3. Results and discussions

3.1 *Analysis of climate models data*

Bias correction by linear scaling method (Leander and Buishand 2007; Terink *et al.* 2010; Bordoy and Burland 2013) improved the model evaluation parameter values of RMSE, MAE, NSE and R from 140.9, 99.27, −0.16, 0.17 before bias correction, to 125.1, 90.2, 0.09 and 0.41, respectively (table 3).

The long term average annual rainfall predicted by the climate models MIROC-MIROC5, CNRM-CM5, GFDL-ESM2M, and ICHEC-ESM showed a

Table 4. *The sensitive parameters and their values.*

Parameter name	Description	Best parameter value	Parameter range
A__GWQMN gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	–91.05	–100 to 100
V__GW_REVAP gw	Groundwater "revap" coefficient	0.1398	0.1 to 0.15
R__CN2 mgt	SCS runoff curve number	–0.0997	–0.1 to 0.05
V__GW_DELAY gw	Groundwater delay (days)	103.69	30 to 120
R__SOL_K sol	Saturated hydraulic conductivity (mm/hr)	0.195	–0.2 to 0.3
A__REVAPMN gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	51.69	–60 to 60
V__ALPHA_BF gw	Base flow alpha factor (days)	0.556	0.45 to 0.65
V__ESCO bsn	Soil evaporation compensation factor	0.41	0.4 to 0.6

GWQMN: Threshold depth of water in the shallow aquifer required for return flow to occur; GW_REVAP: Groundwater "revap" coefficient; CN2: SCS Curve Number II; GW_DELAY: Groundwater delay; SOL_K: Saturated hydraulic conductivity (mm/hr); REVAPMN: Threshold depth of water in the shallow aquifer for "revap" to occur (mm); ALPHA_BF: Base flow alpha factor; ESCO: Soil Evaporation Compensation Factor.

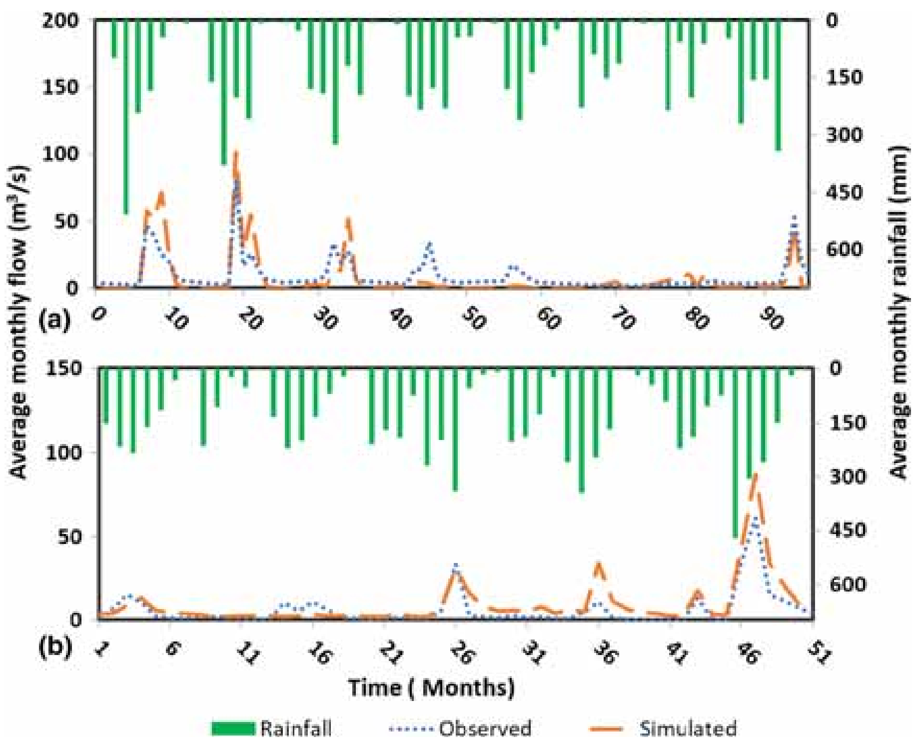

Figure 4. Simulated hydrograph for Akeru watershed for (**a**) calibration and (**b**) validation periods.

minor negative deviation from the observed (IMD) rainfall values by 2.6, 4.87, 4.78, and 6.9% respectively for the historical period (1975–2005), which was carried to the water balance components (figure 5). For the monsoon season (July–October), it was observed that the historical rainfall data as predicted by the four climate models deviated by −2 to +21% for the 10th percentile, and −13 to −19% for the 90th percentile values of the observed (IMD) rainfall. The climate model MIROC-MIROC5 showing the least deviation for both the percentile values, also gave a satisfactory prediction for the mean monthly rainfall compared to the other models.

3.2 *Calibration and validation of the model*

For the model evaluation, 15 parameters were selected, which may potentially influence the water balance components (Arnold *et al.* 2012; Shrestha *et al.* 2012; Narsimlu *et al.* 2013; Singh *et al.* 2013;

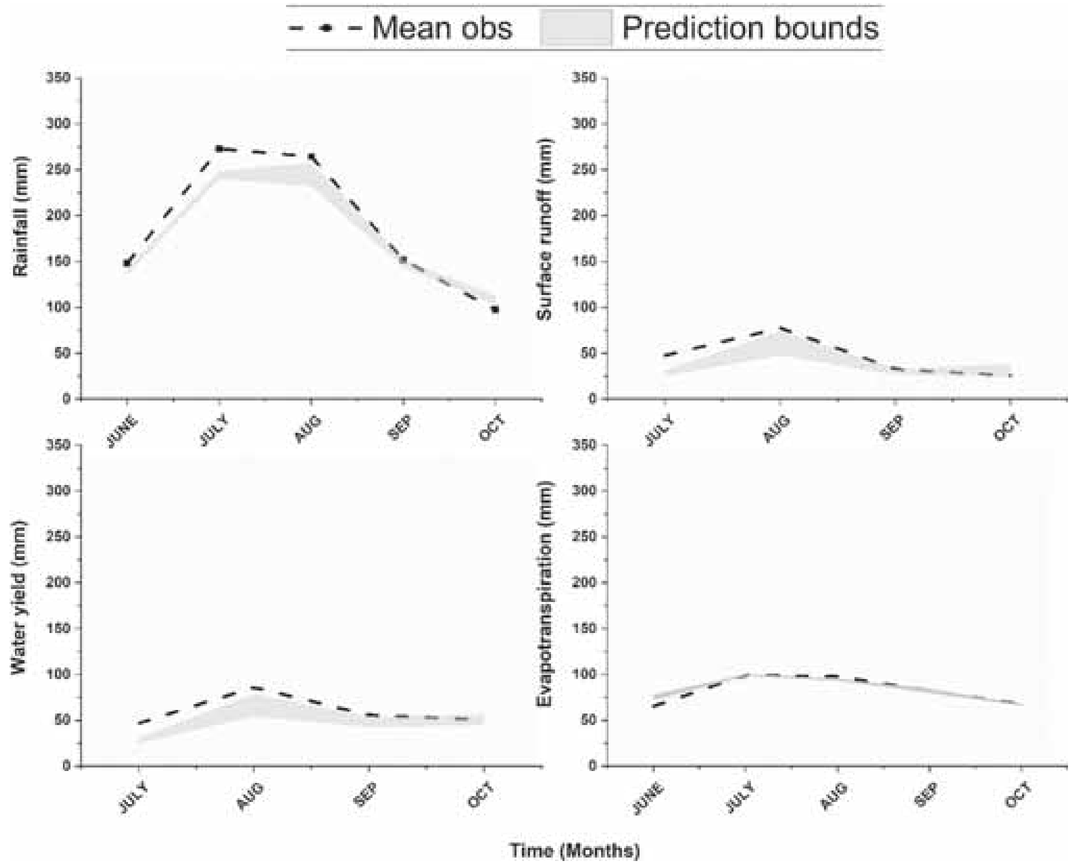

Figure 5. Projected rainfall and water balance components of climate models (baseline scenario) along with IMD data.

Molina-Navarro *et al.* 2016). However, sensitivity analysis reduced the number of parameters to eight. The calibration and validation of the model were then carried out using these parameters. Table 4 gives the parameter range for the sensitive parameters, along with the best fit value. The goodness-of-fit of the model was evaluated using R^2 and *NSE* values (figure 4). R^2 and NSE values of 0.72 and 0.7, respectively were obtained for calibration, with the values for validation being 0.84 and 0.56, respectively. Nash and Sutcliffe (1970) concluded that any hydrological model correlates significantly with the observed data, provided, the R^2 value is more than 0.65, and *NSE* value is more than 0.6.

3.2.1 *Calibration of the crop yield*

Due to the lack of specific crop yield data on yearly basis, the calibration of the model (crop yield) was carried out using mean yield values from the available reports of DESMOA (Directorate of Economics and Statistics, Government of Telangana) (DESMOA 2016a, b) by manual calibration procedure using crop parameters from literature (Palazzoli *et al.* 2015; Rafiee and Shourian 2016; Chen *et al.* 2017). The initial and final values of crop parameters are given in table 5.

The mean crop yield values of corn, cotton and rice obtained from the reports of DESMOA were compared with simulated yield driven from observed (IMD) data. The observed values from the reports are in good agreement with simulated crop yields, indicates good performance of the model. The mean observed crop yield values (2009–2014) of the corn, cotton and rice are approximately 3.7, 0.8 and 2.91 t/ha respectively, whereas the simulated crop yields of respective crops (1975–2005) were 3.4, 0.76 and 2.8 t/ha respectively (figure 6).

3.3 *Analysis of water balance components*

A rainy day was defined as the day with an amount of rainfall realised is about 2.5, mm or more (as per IMD). The average number of rainy days was found to be 77 days for the season (June–October) with the IMD observed data over a period of 31 years (1975–2005). While all climate models project more number of rainy days than the observed rainfall, they

Table 5. *Initial and final crop parameters.*

	Cotton		Rice		Corn	
Parameter	Initial	Final	Initial	Final	Initial	Final
BIO_E	15	15	22	30	39	40
BLAI	4	5	5	5	6	6
HVSTI	0.4	0.3	0.5	0.8	0.5	0.45
WSYF	0.3	0.3	0.25	0.7	0.3	0.3
T_{base}	15	15	10	10	8	8
T_{opt}	30	30	25	25	25	25

BIO_E: Biomass/energy ratio; BLAIR: Max leaf area index; HVSTI: Harvest index; WSYF: Lower limit of harvest index; T_BASE: Min temperature plant growth; T_OPT: Optimal temperature for plant growth.

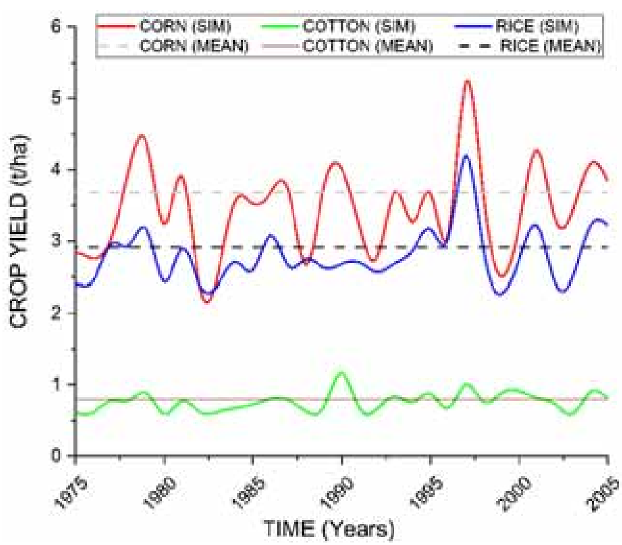

Figure 6. Simulated crop yields of corn cotton and rice compared with the mean observed yield.

are 100, 99, 96 and 90 days respectively for the climate models ICHEC-ESM, CNRM-CM5, GFDL-ESM2M, and MIROC-MIROC5. However, MIROC-MIROC5 showing the least deviation compared with the other models, which was considered for further study.

In this study, historical climate model data (baseline scenario) was considered as a reference for the evaluation of future scenarios. For the beginning of the century (2009–2040), the climate models predicted a 0.66, 8, 15.7 and 2.6% increase in average annual rainfall, surface runoff, water yield, and evapotranspiration, compared to their corresponding baseline scenario values respectively (figure 7a). The maximum and minimum temperatures as predicted by the models were 0.88°C and 1°C higher than their corresponding baseline values respectively, for the same time period. From the climate model predictions for the mid-century (2044–2070), the rainfall, overall average surface runoff, water yield, and evapotranspiration may increase by 6.9, 22.3, 21.6, and 4.5% compared to the baseline scenario. The average annual maximum and minimum temperatures were also predicted to increase by 1.7°C and 1.9°C for the same time period. Similarly, for the end century (2074–2100), an increase in the values of all the above variables was predicted. An increase of 9.4, 35.5, 33.8 and 5.7% is predicted for the rainfall, overall average surface runoff, water yield, and evapotranspiration. While the average annual maximum and minimum temperatures are expected to increase by 1.73° and 2.3°C compared to the baseline scenario. It was observed that prediction bound (uncertainty range) of climate models followed an increasing trend and moves away from the baseline scenario, indicates an increasing trend in both the quantity and uncertainty of water balance components in future would be crucial for the planning and management. These fluctuations in the water balance components are likely to affect the crop productivity by affecting the water availability of the crops. The uncertainty ranges of rainfall, along with other water balance components for future scenarios are shown in figure 7(a, b, c) and table 6.

From the model predictions, it was found that the maximum amount of rainfall may shift towards August and also the amount of rainfall in the month of August may increase (9.5, 29 and 49.5 mm for early, mid and end century respectively). There may not be any change in the average number of rainy days for early, mid and end centuries, but the 75th, 95th, and 99th percentile rainfall values were increasing (8.5, 20.3 and 31.5 mm for early century, 9.2, 20.7 and 33.5 mm for mid-century and 10.1, 20.3 and 37.8 mm for end century respectively) compared with historical values (8.4, 19.7 and 29.9 mm respectively). From these results, we can conclude that the long-term average seasonal rainfall and its intensity showed an increasing trend, may lead to more extreme events in the future scenarios (Molina-Navarro *et al.* 2016), such as too wet or dry days would influence cropping area, intensity and yields by affecting field workability and work calendar (Sawano *et al.* 2008).

3.4 *Analysis of crop yield*

In this study, two climate models (CNRM-CM5 and ICHEC-ESM) among the four were selected for the

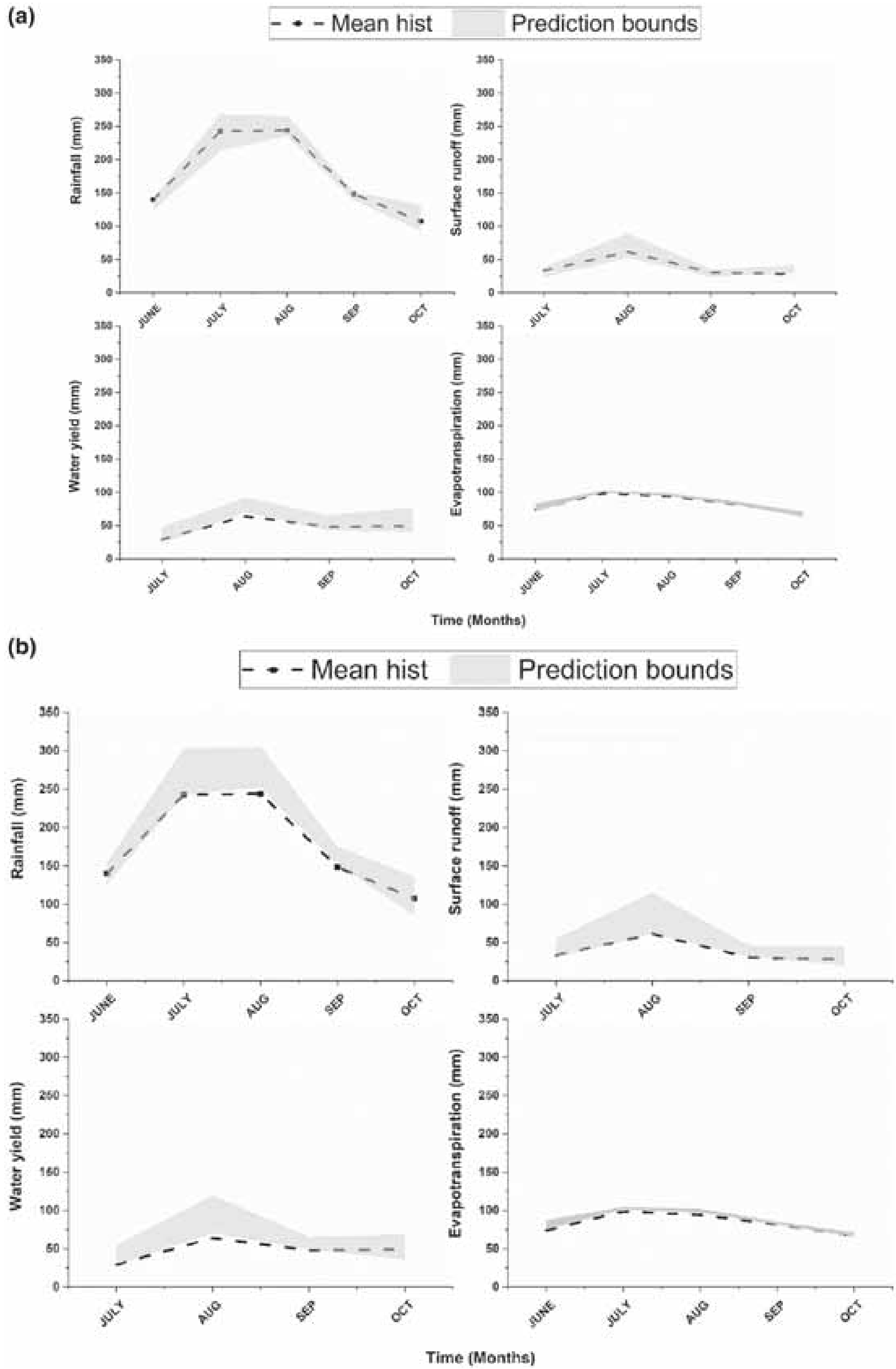

Figure 7. Projected rainfall and water balance components of climate models for (**a**) early (2009–40), (**b**) mid (2044–70), and (**c**) end (2074–2100) along with average baseline scenario.

analysis of crop yield under future climate scenarios. The results projected that the average historical crop yields predicted by the two climate models for a period of 31 years (1975–2005) are relatively close to the observed data (IMD) driven crop yields. The historical average crop yields of the corn, cotton and rice are 3.5,

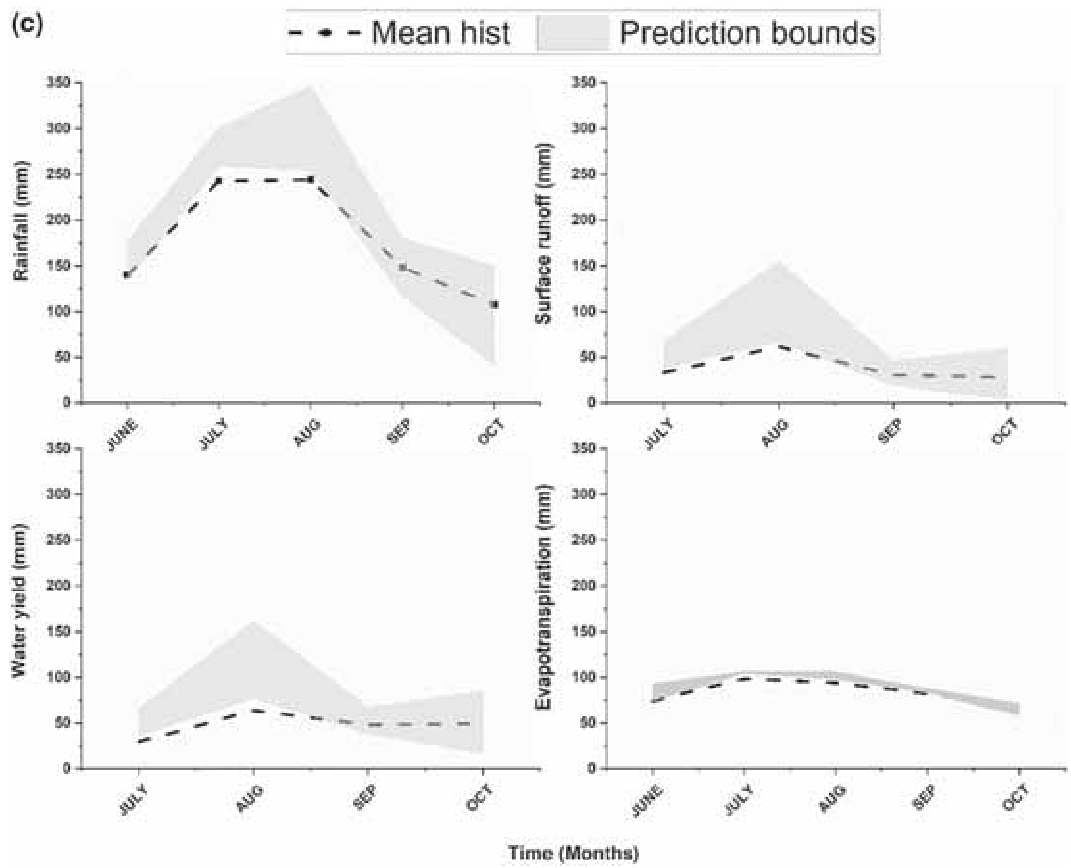

Figure 7. *(Continued)*

Table 6. *Seasonal water balance components variation of the Warangal district under climate change scenarios.*

	Water balance components (mm)				% Variation			
Period	Rainfall (Jun–Oct)	Surface runoff (Jul–Oct)	Water yield (Jul–Oct)	ET (Jun–Oct)	Rainfall (Jun–Oct)	Surface runoff (Jul–Oct)	Water yield (Jul–Oct)	ET (Jun–Oct)
IMD data (1975–2005)	935	184	239	413	–	–	–	–
Historic data (1975–2005)	883 (881 to 906)	146 (131 to 176)	191 (174 to 220)	416 (415 to 417)	–5.6 (–3 to 7.8)	–20.7 (–4.3 to .–28.8)	–20.2 (–8 to –27.3)	0.93 (0.48 to 1.1)
Beginning of the Century (2009–2040)	888 (824 to 930)	166. (156 to 188)	221 (183 to 271)	427 (425 to 431)	0.7 (–6.6 to 5.3)	8.(2 to 22.6)	15.7 (–4.2 to 41.8)	2.6 (2 to 3.6)
Mid Century (2044–2070)	944 (941 to 974)	188 (175 to 207)	232 (213 to 242)	435 (429 to 443)	6.9 (1.8 to 10.3)	22.3 (14.3 to 35)	21.6 (11.6 to 26.9)	4.5 (3 to 6.5)
End Century (2074–2100)	966 (835 to 1028)	208 (162 to 271)	356 (192 to 314)	440 (427 to 451)	9.4 (–5.4 to 16.5)	35.5 (5.9 to 77)	33.8 (0.5 to 64.4)	5.7.(2.7 to 8.2)

Symbol "negative" indicates that it is decreasing and the values in () indicate prediction bounds of climate models (MIROC-MIROC5 GFDL-ESM2M ICHEC-ESM and CNRM-CM5).

0.79 and 2.9 t/ha respectively, while IMD driven crop yields are 3.4, 0.76 and 2.8 t/ha respectively, indicate good agreement between baseline and observed driven crop yield data (figure 8a). From here onwards, the historical driven crop yield data (baseline scenario) was considered as a reference for the evaluation of future scenarios.

For the beginning of the century (2009–2040), the climate models predicted a 7.2, 7.9 and 12.8% decrease in average annual crop yields of corn,

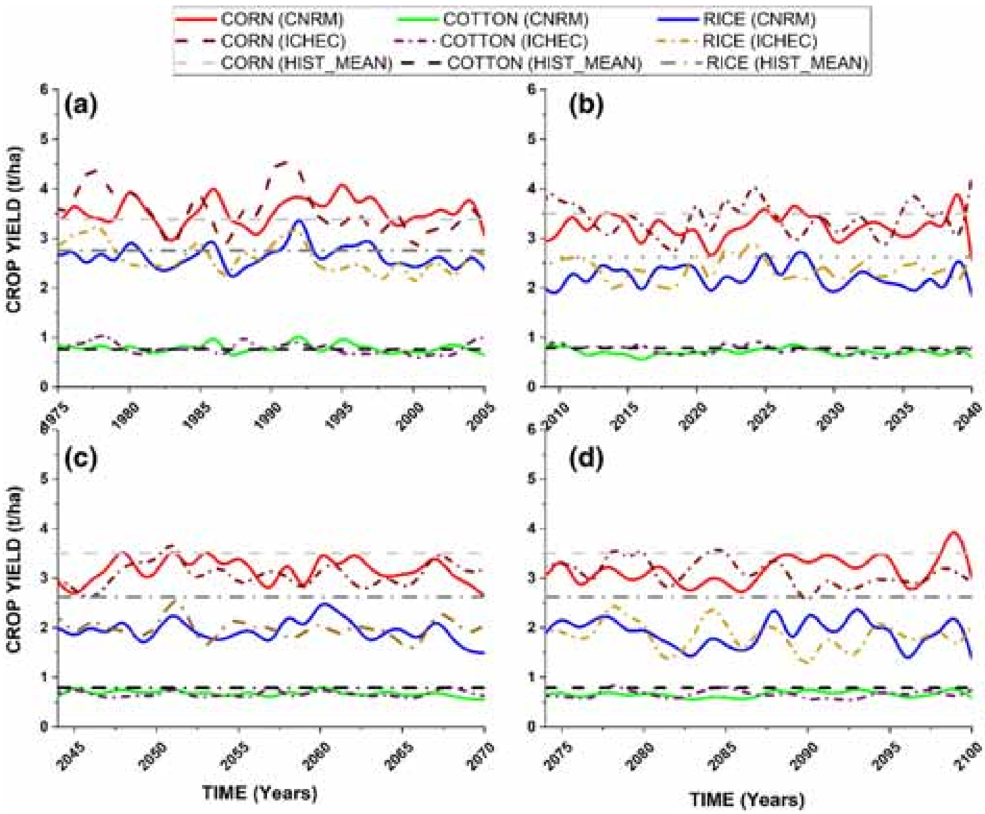

Figure 8. Projected crop yield of corn cotton and rice under present and future scenarios. (**a**) Observed (simulated), (**b**) early (2009–40), (**c**) mid (2044–70), and (**d**) end (2074–2100) compared with the average baseline scenario.

Table 7. *Variation of Crop yield (t/ha) in Warangal district under climate change scenarios.*

	Corn		Rice		Cotton	
Parameter	Mean	% Variation	Mean	% Variation	Mean	% Variation
IMD data (1975–2005)	3.4		2.8		0.76	
Historic data (1975–2005)	3.5	–	2.6	–	0.79	–
Beginning of the Century (2009–2040)	3.2	–7.2	2.3	–7.9	0.73	–12.8
Mid Century (2044–2070)	3.1	–12.2	2	–15.7	0.67	–25.1
End Century (2074– 2100)	3.1	–11.1	1.88	–16.5	0.66	–28.3

Symbol 'negative' indicates that it is decreasing.

cotton, and rice, compared to their corresponding baseline driven values respectively (figure 8b). Which can be attributed to a decrease in rainfall and increasing temperature. From the climate model predictions for the mid-century (2044–2070), the average crop yields of corn, cotton, and rice may decrease by 12, 15.7 and 25% compared to the baseline scenario even though the mean rainfall is increased by 7% (figure 8c). In this scenario, the change in the crop yields may be driven by high temperature (around 1.8°C rise) changes along with fluctuations in rainfall. The average crop yields of corn, cotton, and rice may further decrease by 14, 16.5 and 28.3% compared to the baseline scenario in case of end century (2074–2100) (figure 8d), due to further rise in temperature (around 2.3°C). The model projected that the mean crop yields for corn, cotton and rice were followed decreasing trend under future scenarios irrespective of changes in rainfall (table 7). From the model projections, it was observed that the crop yields of all three major crops (rice, corn and cotton) in the district followed the decreasing trend, would be attributed to the increasing temperature and fluctuations in the rainfall. The production of cotton is seemingly highly influenced by rainfall change in this district, while rice and corn are less likely affected. In future perspective, rice and cotton are important crops in this district, potential adaptation strategies have to be taken to cope up with climate change.

4. Conclusions

In this study, assessment of surface water availability under present and future scenarios and its influence on crop yield of Warangal district, Telangana state, India has been carried out. The SWAT model can predict the runoff well in the semi-arid region such as Warangal district. The rainfall, maximum and minimum temperatures, surface runoff, water yield, and evapotranspiration showed increasing trend, while crop yield showed a decreasing trend in future climate scenarios. From the model predictions, it was found that the maximum amount of rainfall may shift towards August from July and also the amount of rainfall in the month of August may increase in future scenarios. Extreme rainfall events may follow an increasing trend under future scenarios especially in the months of July and August for mid and end centuries, which may lead to the risk of floods or droughts. The magnitude and uncertainty of water balance components were projected to increase in future would be crucial for the planning and management. The results showed that the production of cotton is under threat in the view of climate change. In light of this, it is necessary to revise the water budget and water management strategies of the Warangal district to consider climate change. Further, the government should frame policies and strategies to adapt the future climate changes in the district.

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