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ORIGINAL ARTICLE

An appraisal of flood events using IMD, CRU, and CCSM4-derived meteorological data sets over the Vaigai river basin, Tamil Nadu (India)

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Abstract
The study of the impact on climate change on water resources provides useful information for long-term trend analyses of important issues such as control of floods, management of drought, agricultural production, etc. This work is an attempt to assess the flood events in Vaigai watershed, Tamil Nadu (India). The Mann–Kendall test was performed to assess the rainfall and temperature trends on data extracted from Climatic Research Unit (CRU) and Community Climate System Model 4 (CCSM4) model for historical and future scenarios. The CCSM4 model was compared with India Meteorological Department and CRU data sets to analyze the performance and consistency of model data among the years of flood, viz., 1993, 2010, and 2015. The CCSM4 model was able to capture, in a few instances, the historical as well as future flood events over the region. The maximum rainfall (738.11 mm) was predicted for 2021 followed by 2038 and 2040, and the lowest rainfall (43.40 mm) was predicted for 2036. Besides, the temperature increased by 1 °C and rainfall was mostly maximum in September corresponding to the south-west monsoon (SWM) season. The predicted increases in rainfall can result in flash floods, which have serious implications on the agricultural sector and water resources of the basin, while the decreasing rainfall during the other seasons helps to reduce the flood severity.

Keywords Extreme events (floods) · IMD · CRU · CCSM4 · MK test · Vaigai river basin (Tamil Nadu)

Introduction

Nowadays, extreme weather events are occurring recurrently in the context of climate change and global warming (Asadi Zarch et al. 2015; Balaguru et al. 2016). Floods are one of the most significant natural hazards that cause extensive human misery and economic losses in the world (Kundu and Kundu 2011; Mall and Srivastava 2012; Kind et al. 2017; Lian et al. 2017; Mall et al. 2019). Climate change has an impact on the extreme events (flood/drought) over a basin. A number of studies corroborate the idea that the flood intensity is significantly sensitive to temperature variations in different places of the world (Panagoulia and Dimou 1997; Menzel et al. 2002; Hirabayashi et al. 2008; Fleming et al. 2012; Prudhomme et al. 2013; Chaubey et al. 2019). A heavy rainfall event is the most important factor for flooding and such flooding occurs when discharge exceeds a river's capability (Casale and Margottini 1999).

Trend analysis is a technical aspect or tool that helps to predict the future data based on past scenarios. Long-term analysis is usually the best method to get accurate results that are near to the actual values. The long-term trend analysis of a rainfall can be helpful for estimating the flood variability and watershed assessment. The hydrological cycle of a river basin is one of the most important factors influencing the frequency and intensity of flood and drought events triggered by climate variability. With India among one of the fastest-growing economies in the world, due consideration has to be given to the statement by the Inter-governmental Panel on Climate Change (IPCC) that anthropogenic emission of different gases has increased the planet's temperature by 1 °C. Since the 1950s, the average temperature and rainfall have been fluctuating in the Indian sub-continent (IPCC 2014). Some studies concentrated on the meteorological trend analysis for flood assessment using Coupled Model Intercomparison Project Phase 5

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(CMIP5)-based climate model (Taylor et al. 2012; Hirabayashi et al. 2013; Merz et al. 2014; Condon et al. 2015). Barnett et al. (2005) reported on water availability in snow-dominated regions influenced by warming climate of the world. The variability of water resources for long-term strategies and sustainable development at regional and national levels due to climate change effect was reviewed by Mall et al. (2006). Based on IMD gridded rainfall data, Goswami et al. (2006) illustrated a rising trend of rainfall over India in the last century. Guhathakurta et al. (2011) analyzed the possibility of excessive rainfall events for flood risk in India. Mall et al. (2011) described a variety of extreme weather incidents and climate change policies as well as their spatio-temporal and socio-economic impacts on communities over the Indian region. Singh and Kumar (2013) examined flood events and their losses from 1978 to 2006 for entire India. A few places in India (Jammu and Kashmir) and Pakistan (Azad Kashmir, Gilgit-Baltistan, and Punjab) experienced extreme flood disaster caused by intense rainfall (Najar and Masood 2014). Cho et al. (2016) described the effect of the floods in Uttarakhand (India), which resulted in excess of 5000 casualties and a massive loss of assets due to heavy rainfall. In their study, Thomas and Prasannakumar (2016) analyzed the rainfall pattern as well as the drought scenario over Kerala state in India. Using various climatic data sets and methods, they examined the temporal variation of rainfall and its concentration. Basha et al. (2017) studied the seasonal variability in India using CMIP5 models during the twentieth and twenty-first centuries. Mishra and Shah (2018) examined the basis of excessive rainfall and associated flooding in Kerala state.

Some other studies focused on the trend analysis over Tamil Nadu state in India. As per their study, Mialhe et al. (2008) quantified the water stocks in tiny irrigation reservoirs for proper planning, management in perspective of irrigation, land-use pattern, agricultural activities, and other water-related social concerns over the Vaigai–Periyar catchment area. Rafi et al. (2016) analyzed the seasonal and spatial rainfall distribution, frequency, and intensity at different rain gauge stations in and around Bangladesh. Kokilavani et al. (2017) studied the spatio-temporal variability of rainfall at Erode and Coimbatore districts using MK test over the period 1916–2015. Sathyanathan et al. (2018) revealed the long-term rainfall trend of Chennai city for 115 years (1901–2015) with data from CRU and State Ground and Surface Water Data Centre (SGSWDC), Chennai, India.

The main objective of the study was to assess the flood events using long-term meteorological parameters over the Vaigai river basin in India. The sub-objectives were (a) comparison of meteorological datasets, i.e., IMD, CRU, CCSM4 (model), and their trend analysis using MK test. (b) Prediction of flood events from 2006 to 2040 using CCSM4 (model) and (c) validation of CRU and CCSM4 model (historical)-derived data sets with IMD and raingauge station data.

Study area

Theni district in the state of Tamil Nadu, India, covers an area of 2889 km^2 at the foot of the Western Ghats. The district is bounded by Dindigul district in the north, Madurai district in the south, and Kerala state in the west. The catchment of Vaigai river spreads over an area of 7741 km^2 and the entire river flows in Tamil Nadu (Fig. 1). The Vaigai river starts at the east slope of the Varshanadu hills at an elevation of 1200 m near Kottaimalai in Madurai district with the geographical extension 9º28′46″N–10º19′50.68″N latitude and 77º8′24.68″E–78º55′2.89″E longitude. After traveling for 258 km, the river discharges into Ramanad big tank and, finally, reaches the Palk Bay near Mandapam. On the way, the major tributaries Suruliyar and Manjalar contribute water from the left bank of the Vaigai. Most of the agricultural fields get water from direct rainfall in Theni river basin. Theni district in Tamil Nadu has four seasons in a year, viz., winter (January and February), pre-monsoon (March, April, and May), south-west monsoon (SWM) (June, July, August, and September), and north-east monsoon (NEM) (October, November, and December).

Materials and methods

Data sets (rainfall and temperature)

CRU TS 4.0.1 (Climatic Research Unit Time Series) data sets for the monthly rainfall, and maximum and minimum temperatures corresponding to the study area were extracted. CRU data sets cover the Earth's land area with 0.5° × 0.5° gridded resolution for the period 1901–2015 (Table 1). The data were downloaded from the Centre of Environmental Data Archival (https://crudata.uea.ac.uk/cru/data/hrg/). In this study, one meteorological station with a regular grid 0.5° × 0.5° resolution falling within the Suruliyar catchment area in Theni district was considered. Besides, the Community Climate System Model 4 (CCSM4) coupled climate model was used for future flood events. The model is an ensemble of different segments, i.e., land, atmosphere, land-ice, sea-ice, and ocean plus one central coupler component. Moreover, it helps the researchers to conduct fundamental research on Earth's past, present, and future climate scenarios. The IMD-based gridded data sets were considered for validation at 0.25° × 0.25° resolution.

Cartosat-1-derived DEM was downloaded from Bhuvan portal (http://bhuvan.nrsc.gov.in/data/download/index

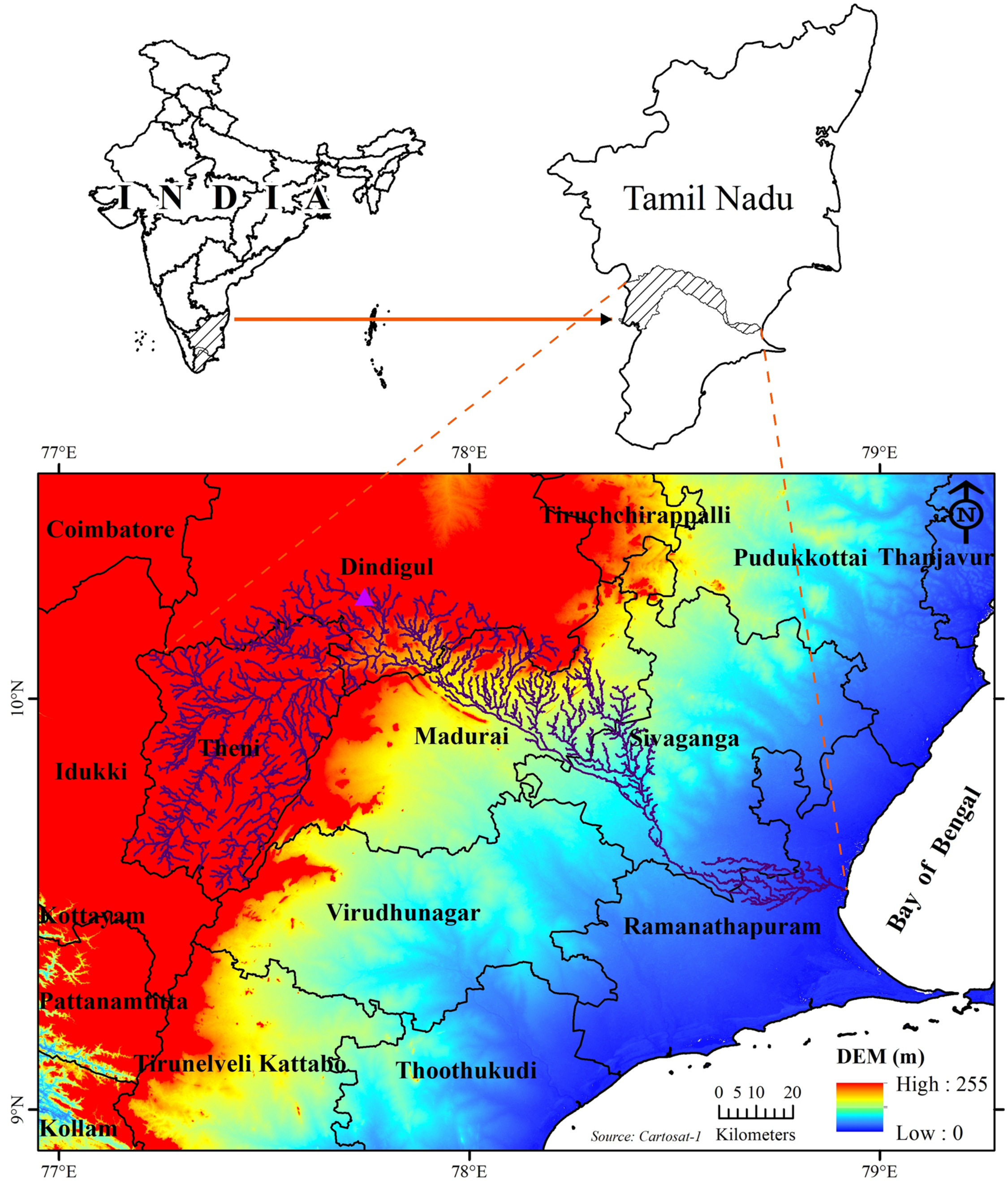


Fig. 1 Location of the study area (Vaigai basin)

Table 1 Specification of data sets

Data sets	Period	Time	Source
Rainfall data	1901–2015	Monthly	CRU TS4.0, IMD, CCSM4
Temperature data	1901–2015	Monthly	CRU TS4.0, IMD, CCSM4
Cartosat-1 DEM	2011	Yearly	Bhuvan, ISRO

.php) for generating slope and drainage networks (Table 1). The geo-processing activities were executed in the ArcGIS software. First, the different tiles (DEM) were combined by mosaic, clipped, and re-projected in GIS environment. Later, the drainage directions and stream segments were extracted. The coordinates of the outlet point (pour point) were marked for delineating the watershed. The area of the watershed came out to be approximately 780 km^2.

Methodology

Mann–Kendall (MK) trend tests

The non-parametric MK trend test is a tool for determining rank correlation between the rank observations and their time order for the long-term time series data such as agricultural, meteorological, and hydrological data (Mann 1945; Kendall 1955). The MK test has been used as a tool for long-term trend of climatic variation (Hirsch et al. 1982; Burn and Hag Elnur 2002; Yue et al. 2002; Duhan and Pandey 2013; Suryavanshi et al. 2014; Kundu et al. 2014, 2015; Kumar et al. 2016). The null hypothesis, H0, is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, HA, is that the data follow a monotonic trend. The Mann–Kendall test, formulated by Mann (1945) and Kendall (1955), statistic S is given as follows (Eq. 1):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}(xj - xi), \quad (1)$$

where S is Mann–Kendall statistic and sgn is the signum function. The application of trend test is done to a time series xi that is ranked from $i = 1, 2, \ldots n-1$ and xj and which is ranked from $j = i+1, 2, \ldots n$. For $n < 10$, then value of $|S|$ is compared directly to the theoretical distribution of S derived by Mann and Kendall.

The variance statistic is given as follows (Eq. 2):

$$Var(S) = \left[n(n-1)(2n+5) - \sum_{i=1}^{m} t(i)(i-1)(2i+5)\right]/18, \quad (2)$$

where t is considered as the number of ties up to sample i.

The Z test statistics is given by the following equation (Eq. 3):

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \end{cases}. \quad (3)$$

Table 2 Rainfall trend of SW monsoon (CRU)

Variable	Kendall's tau	p value	Minimum	Maximum	Std. deviation
Jun	−0.151	0.0163	17.000	133.000	28.599
Jul	0.016	0.1084	22.900	235.800	41.622
Aug	−0.117	0.062	30.400	251.900	49.005
Sep	0.072	0.250	21.100	367.900	59.619

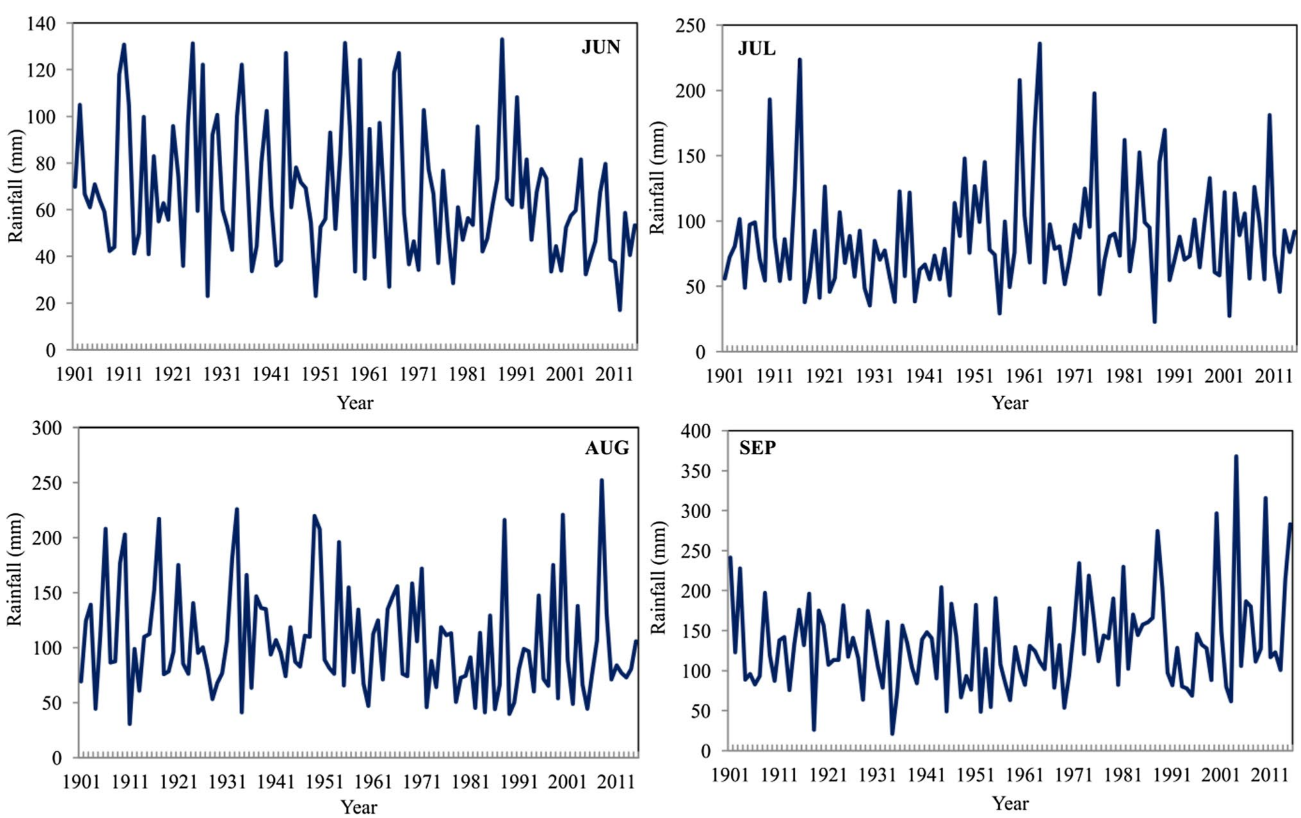


Fig. 2 Rainfall trend of SW monsoon (CRU)

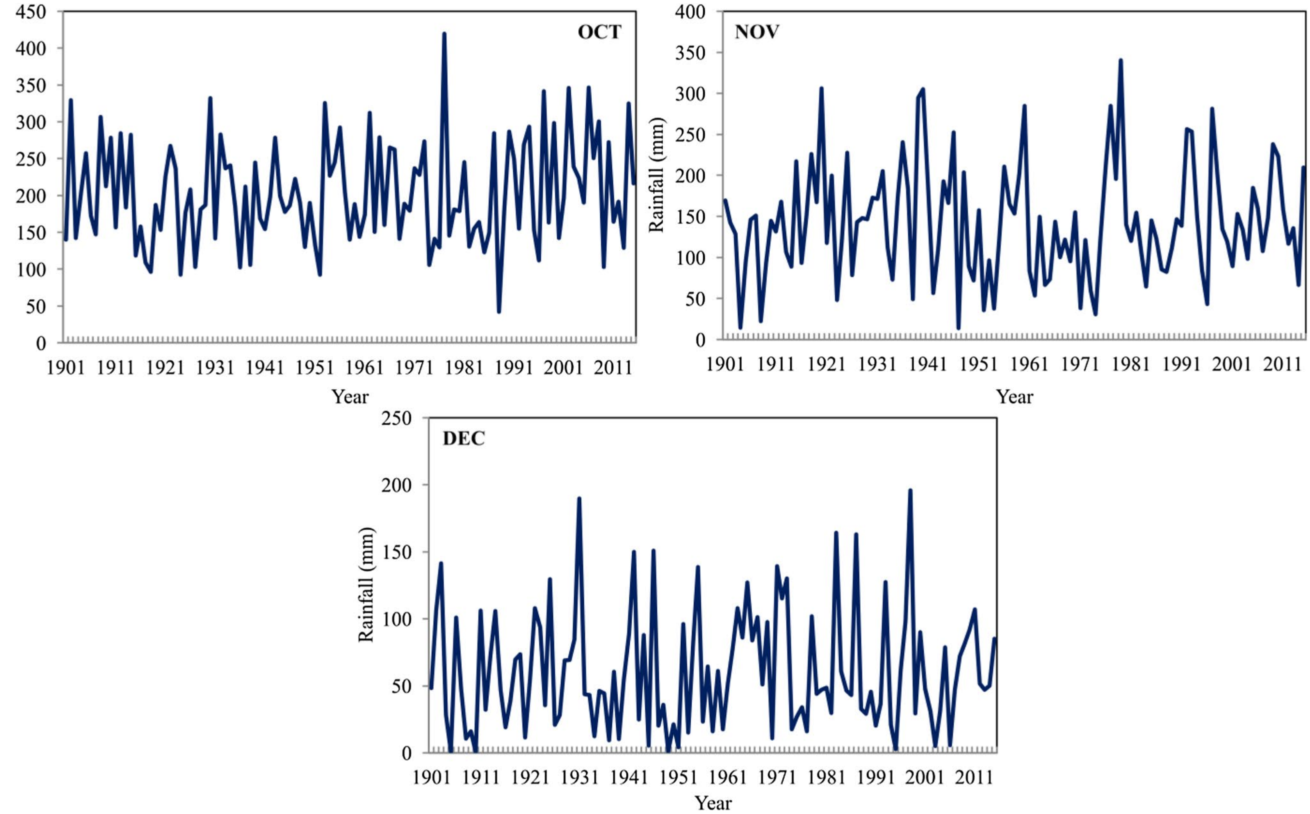


Fig. 3 Rainfall trend of NE monsoon (CRU)

Table 3 Rainfall trend of NE monsoon (CRU)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Oct	0.063	0.315	42.300	419.300	70.406
Nov	0.018	0.783	13.700	340.000	68.473
Dec	0.042	0.509	0.600	195.800	44.408

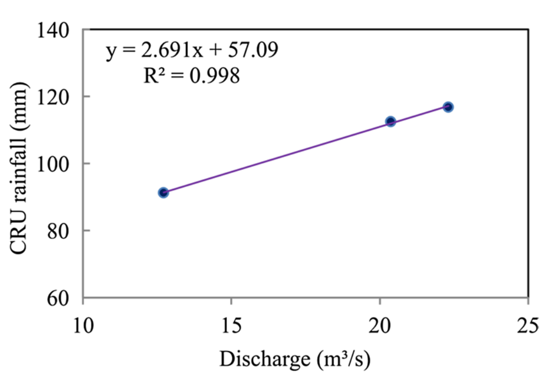


Fig. 4 Correlation between CRU-based rainfall and discharge data for flood years (1993, 2010, and 2015)

A positive value of Z indicates an increasing trend and negative value indicates decreasing trend. It is normally distributed.

Sen's slope

It is a non-parametric procedure to estimate slope of trend in a time series. For sample size of N, the slope (Q) is given by the following equation (Eq. 4):

$$Q = (xj - xi)/((j - k)) \quad i = 1, 2, \ldots \ldots, N, \tag{4}$$

where xj and xk are the data values at times j and k ($j > k$), respectively (Sen 1968).

Results and discussion

Rainfall analysis based on CRU

The MK test was performed on both the rainfall and temperature data derived from the CRU data sets for the period 1901–2015. The test was performed at 5% and 1% level of significance. However, the focus of this study was on SWM

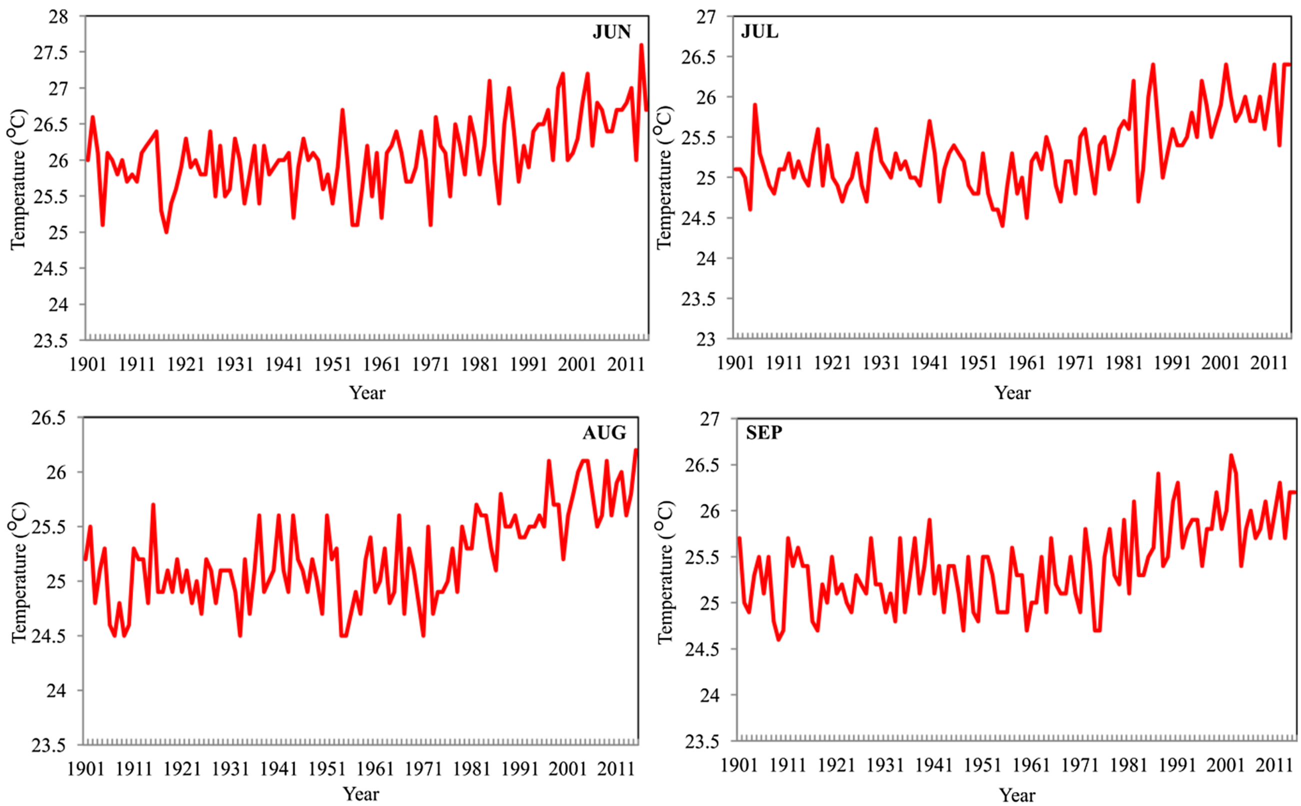


Fig. 5 Temperature trend of SW monsoon (CRU)

Table 4 Temperature trend of SW monsoon (CRU)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Jun	0.349	0.0001	25.000	27.600	0.500
Jul	0.423	0.0001	24.400	26.400	0.452
Aug	0.446	0.0001	24.500	26.200	0.415
Sep	0.399	0.0001	24.600	26.600	0.447

Table 5 Temperature trend of NE monsoon (CRU)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Oct	0.446	0.0001	23.800	26.100	0.429
Nov	0.397	0.0001	22.900	25.000	0.434
Dec	0.480	0.0001	21.900	24.500	0.484

and NEM seasons, as the watershed receives the maximum amount of rainfall in these two seasons.

In SWM, September received maximum rainfall of 367.90 mm, with a standard deviation (SD) of 59.60 mm and June received less rainfall (133 mm) (Table 2). The month of June showed a decreasing trend with $p < 0.05$ (Fig. 2).

The maximum rainfall during NEM occurred in October and was 419.30 mm, with an SD of 70.40 mm. No trend was observed for NEM season (Fig. 3). Similar studies were previously done by Kokilavani et al. (2017) and Sathyanathan et al. (2018). In general, the NEM season contributes more rainfall than the SWM season over Tamil Nadu region (Table 3). However, being close to the Western Ghats and at high elevation, the study area receives almost an equal amount of rainfall from both monsoons. The relationship between rainfall (CRU) and station-based (Suruliyar) discharge (Q) data (Integrated Hydrological Data Book 2016) was strongly positive ($R^2 = 0.998$) and statistically significant at ($p < 0.05$) for flood years over the region (Fig. 4).

Temperature analysis based on CRU

The present study reveals that there was a significant rise in temperature in all the months. There is, thus, significant increasing trend of temperature in all seasons too. The maximum temperature was 27.60 °C and minimum 24.4 °C in SWM season (Fig. 5). For NEM, the max was 26.1 °C and minimum was 21.9 °C (Tables 4, 5).

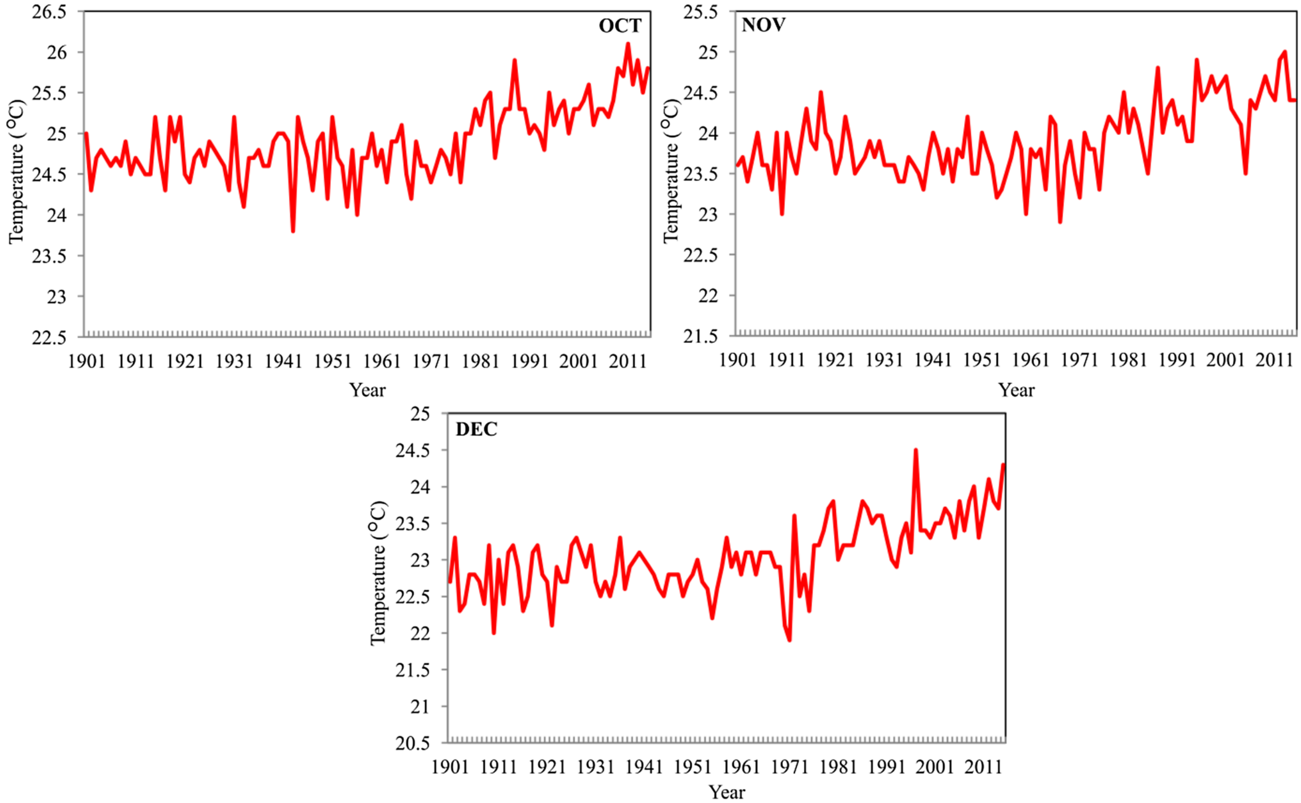


Fig. 6 Temperature trend of NE monsoon (CRU)

Table 6 Rainfall trend of SW monsoon (CCSM4)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Jun	0.079	0.514	25.521	266.709	47.933
Jul	−0.059	0.629	34.577	513.760	104.079
Aug	−0.055	0.650	52.448	382.509	66.336
Sep	−0.247	0.038	47.332	494.334	86.028

Thus, as per CRU data, there was no significant trend in rainfall for SWM or NEM season, but there was a significant increasing trend in temperature for all seasons (Fig. 6).

Rainfall analysis based on CCSM4 model data

In SWM, the months of July and September received the maximum rainfall of 513.76 mm and 494.33 mm, respectively, with SD of 104.07 and 86.02 mm (Table 6). This is similar to the values for the CRU data. June received lesser rainfall (266.70 mm) (Fig. 7). There was no trend in all months except September, which had a decreasing trend, and there was no trend in SWM season also.

During NEM, the month of November received the maximum amount of rainfall (666.87 mm) with SD of 143.29 (Table 7). The CRU and model data differ, since October had the highest rainfall as per CRU model. In both observations, December month had less rainfall, i.e., 195.80 mm for CRU and 211.06 mm for CCSM4 model-derived data (Fig. 8). Both CRU and model did not show any trend for NEM season.

Temperature analysis based on CCSM4 model data

All months showed an increasing trend. In both model and CRU observations, June recorded the highest temperature (29.67 °C) and August recorded the lowest temperature (24.9 °C) (Tables 8, 9). Comparing with CRU data, the model maximum temperatures for June and July were higher by 2 °C (Fig 9). In NEM season, October had maximum temperature (27.44 °C) and December had minimum temperature (22 °C) (Table 9).

Again, as for SWM, the NEM temperatures of model were higher than the corresponding CRU values (Fig. 10). Basha et al. (2017) worked on the CMIP5 climate model, CRU and IMD data sets and showed a similar pattern among

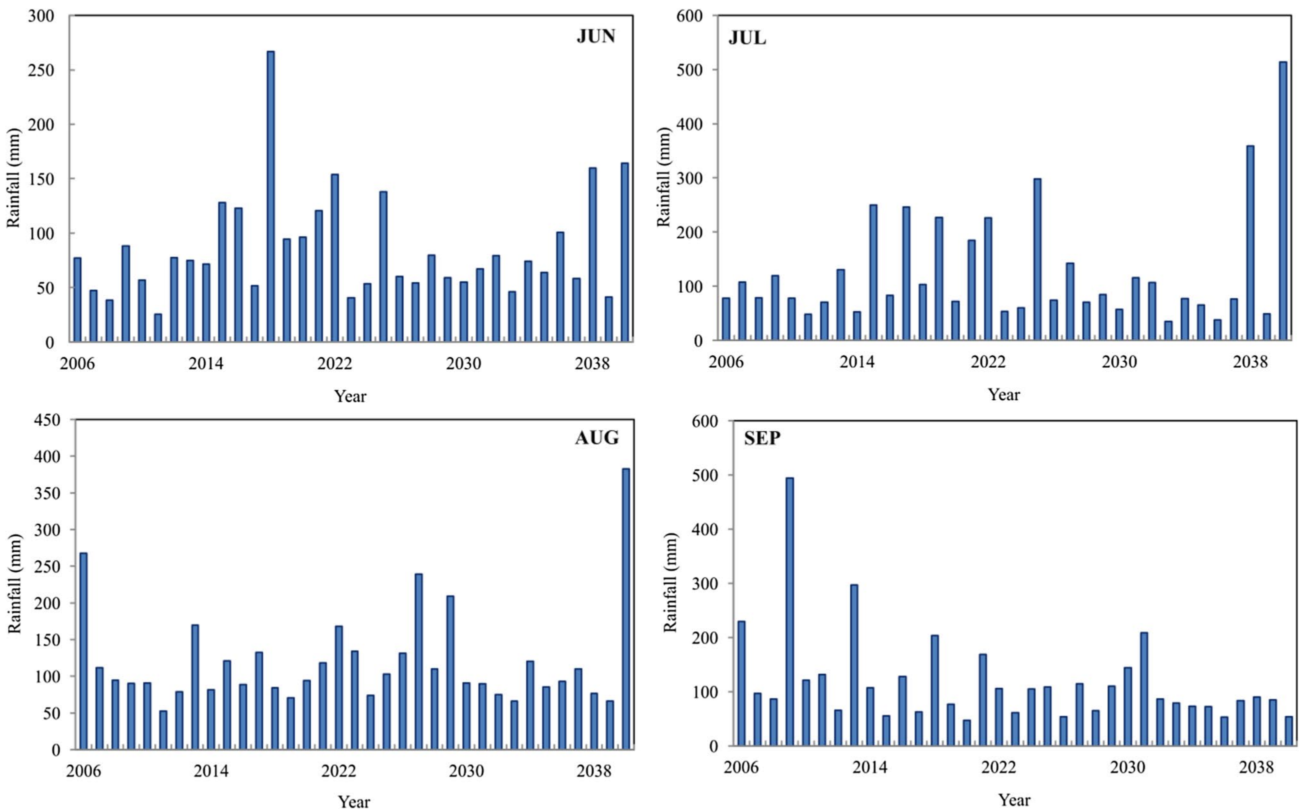


Fig. 7 Rainfall trend of SW monsoon (CCSM4)

Table 7 Rainfall trend of NE monsoon (CCSM4)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Oct	0.012	0.932	18.137	245.312	50.4
Nov	0.062	0.609	27.240	666.873	143.296
Dec	−0.055	0.268	6.005	211.065	60.29

the data sets. As per their observation, the projected temperatures increased up to 2050. This study also agrees with the increasing trend of temperature in CCSM4 model data.

Figure 11 shows the seasonal variation of rainfall in the flood years from the IMD, CRU, and CCSM4 data sets. In 1993, the maximum amount of rainfall occurred but the CRU and CCSM4 data did not capture it. In 1993, CRU and IMD showed a similar trend, even though the CRU values for NEM were lesser. The maximum rainfall values for 1993, 2010, and 2015 were 1263, 1160, and 979 mm as per IMD. Whereas, for the same years CRU and model data (CCSM4) showed 1094.80, 1349.20, and 1400.90 mm and 855.59, 776.42, and 858.28 mm rainfall, respectively. September, October, and November have historically received maximum rainfall in this watershed area.

Figure 12 shows the temperatures for the years 1993, 2010, and 2015. Both model and CRU data had an increasing trend. As per IMD data, average temperatures for the years 1993, 2010, and 2015 were 26.85 °C, 27.60 °C, and 27.54 °C, respectively, which shows the increasing trend of temperature. As per CRU and model observations, the average temperatures were 24.64 °C, 25.95 °C, and 25.86 °C and 26.13 °C, 25.74 °C, and 25.95 °C correspondingly for the years of 1993, 2010, and 2015 (Fig. 12).

Figure 13 illustrates that March and April recorded maximum temperatures in the year 1993, which gradually decreased as rainfall started. November recorded maximum rainfall and minimum temperature for CCSM4 model data. Both IMD and CRU showed maximum rainfall in the months of October and November (Fig. 13).

For the year 2010, IMD data and CRU data mostly followed similar patterns in temperature and rainfall. In November, high rainfall was recorded in all the three data sets. In the case of temperature, the maximum value was 30.8 °C and minimum 24 °C. All three data sets have the same trend for temperature, but the variation is seen in rainfall (Fig. 14).

Figure 15 shows that both IMD and CRU data sets share a similar pattern but not the model for 2015. There is some difference from IMD temperature also (Fig. 15).

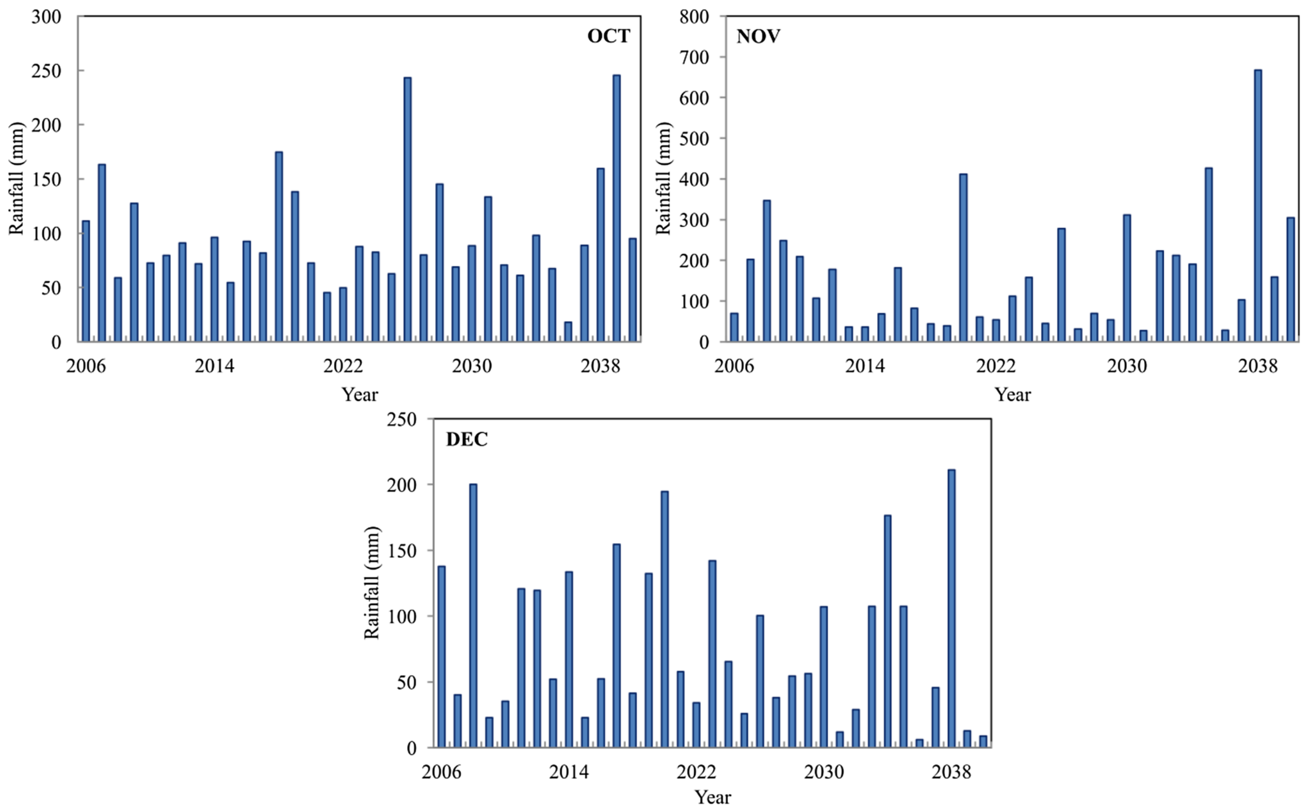


Fig. 8 Rainfall trend of NE monsoon (CCSM4)

Table 8 Temperature trend of SW monsoon (CCSM4)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Jun	0.291	0.015	25.665	29.670	1.072
Jul	0.308	0.01	25.030	29.038	0.901
Aug	0.439	0	24.905	27.927	0.713
Sep	0.459	0	25.091	27.572	0.649

Table 9 Temperature trend of NE monsoon (CCSM4)

Variable	Kendall's tau	*p* value	Minimum	Maximum	Std. deviation
Oct	0.442	0	24.960	27.442	0.515
Nov	0.435	0	23.310	25.938	0.554
Dec	0.207	0.083	22.400	25.343	0.586

Future prediction using CCSM4 model (rainfall and temperature)

The CCSM4 model data (2006–2018) reveal that the month of September is likely to receive maximum rainfall. However, there is an irregular pattern with heavy rain in summer in a few years (Fig. 16).

The months of April and May recorded the highest temperatures in all the observed years. There was an increasing trend of temperature over the years (Figs. 17, 18).

Conclusions

The highest average rainfall was predicted for 2038 (160 mm) and the lowest annual average rainfall was predicted for 2036 (43 mm). The highest average annual temperature of 27.65 °C was predicted for 2030 and the lowest average annual temperature of 24.85 °C was predicted for 2021. In this study, the long-term (115 years) CRU derived rainfall was compared with the IMD and CCSM4 data sets for historical and future meteorological trend analysis in the context of flood hazard. IMD-derived data sets were compared with station-based discharge data which validate flood occurrence over the basin. As per the trend analysis, there was an increasing trend of temperature over the study area. The temperature increased by up to 1 °C and rainfall was maximum in the months of SWM season especially in the month of September. The maximum amounts of rainfall were predicted for 2021, 2038,

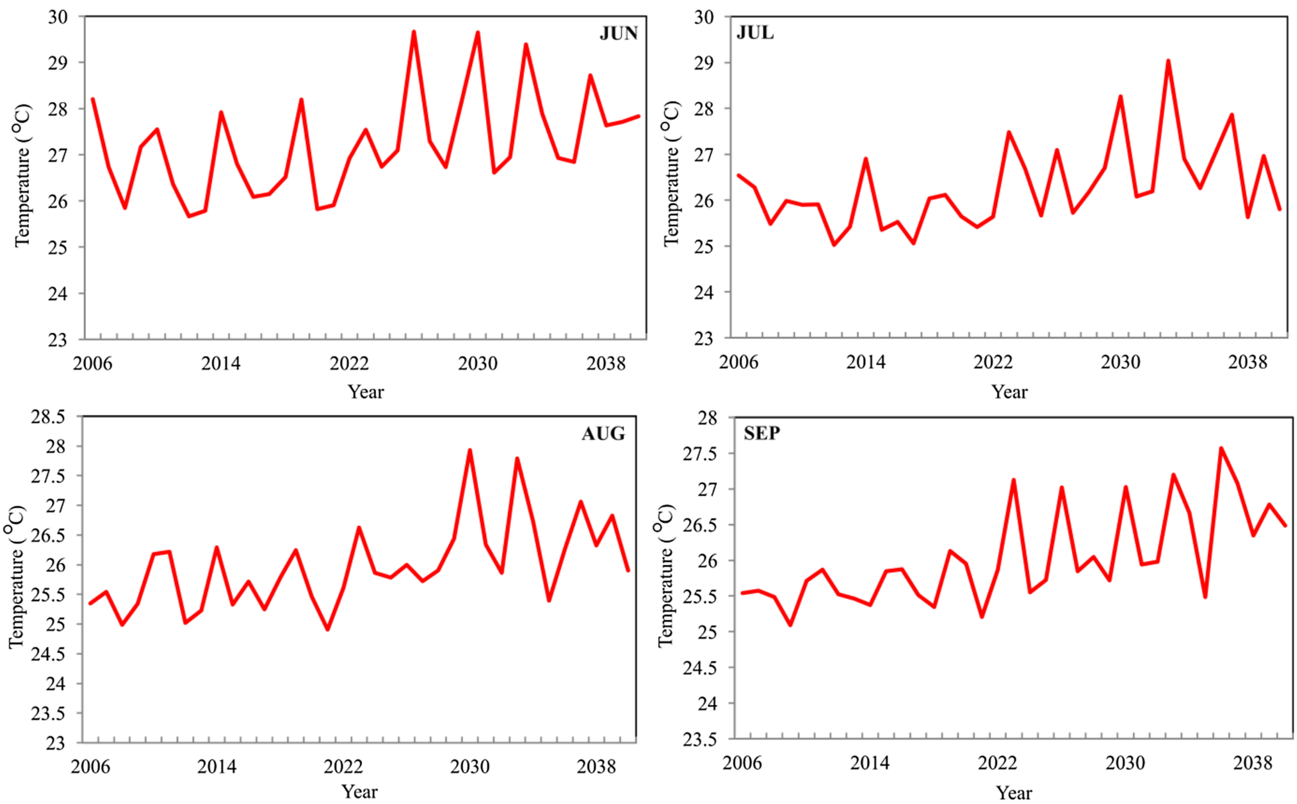


Fig. 9 Temperature trend of SW monsoon (CCSM4)

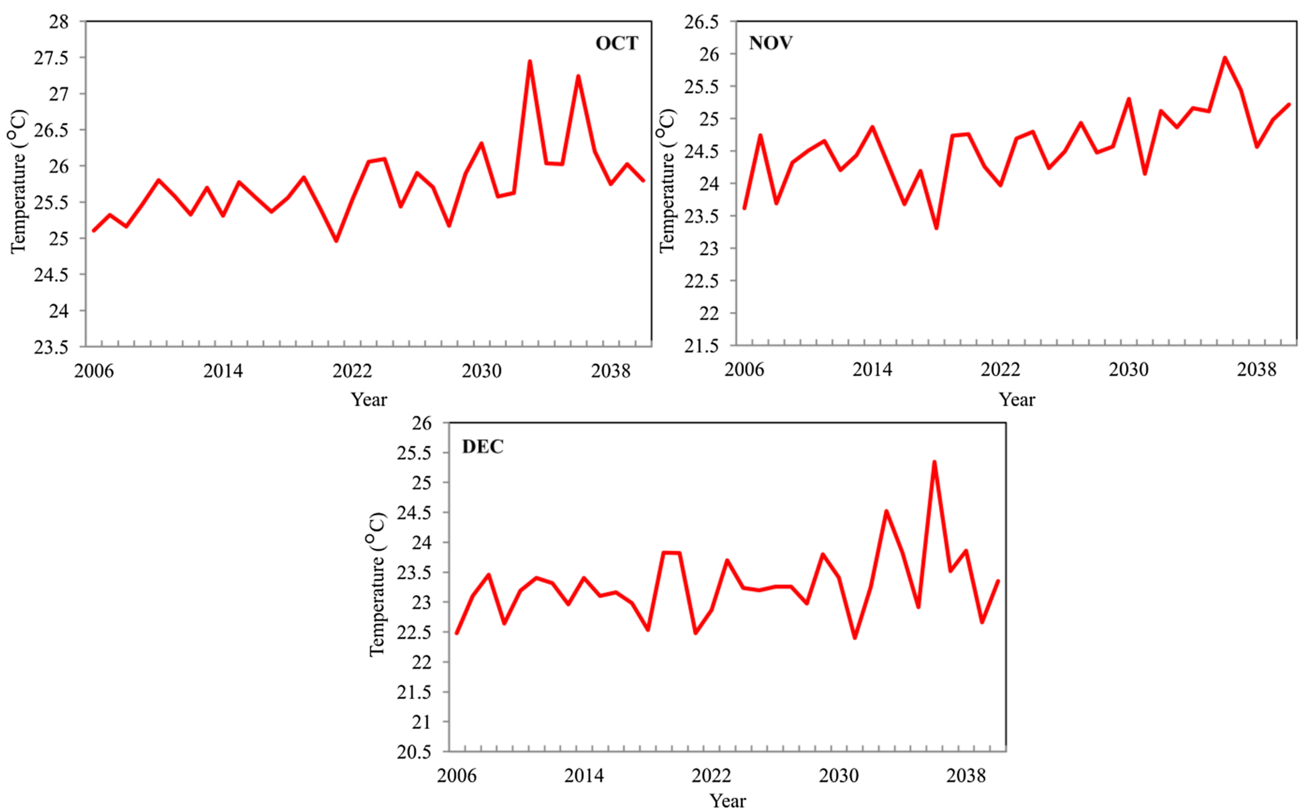


Fig. 10 Temperature trend of NE monsoon (CCSM4)

Fig. 11 Seasonal variation of rainfall (1993, 2010, and 2015)

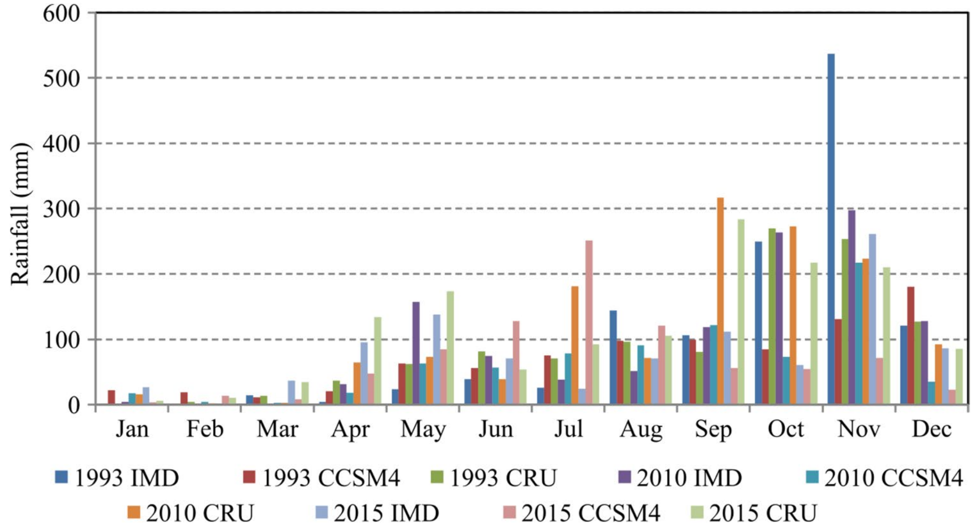


Fig. 12 Seasonal variation of temperature (1993, 2010, and 2015)

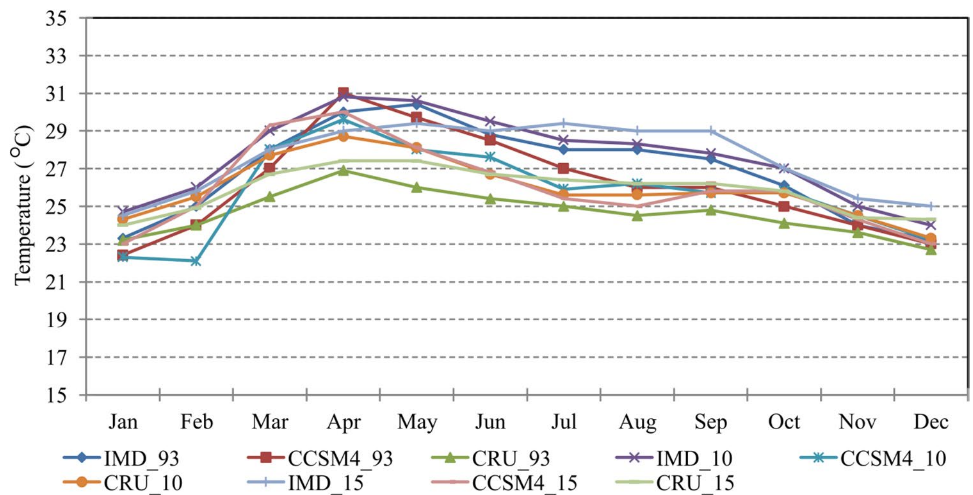
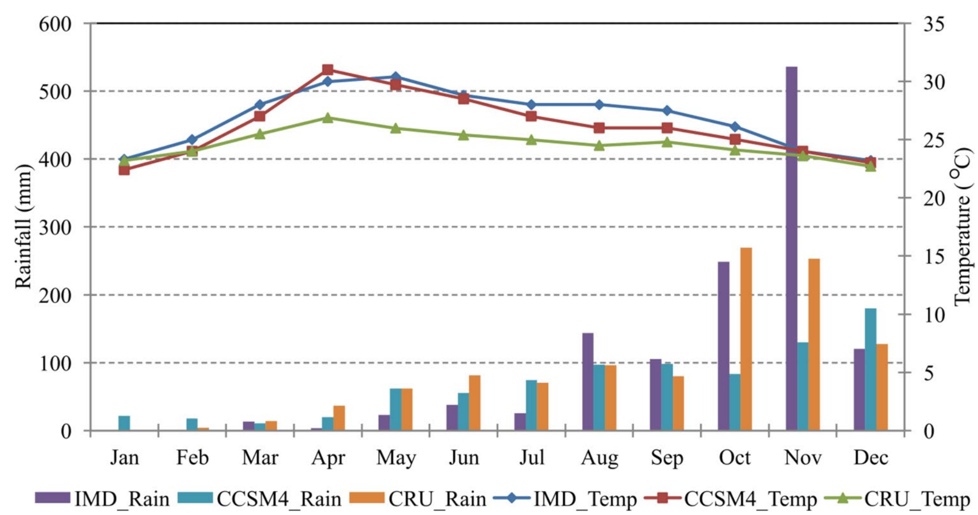


Fig. 13 Rainfall and temperature variation (1993)



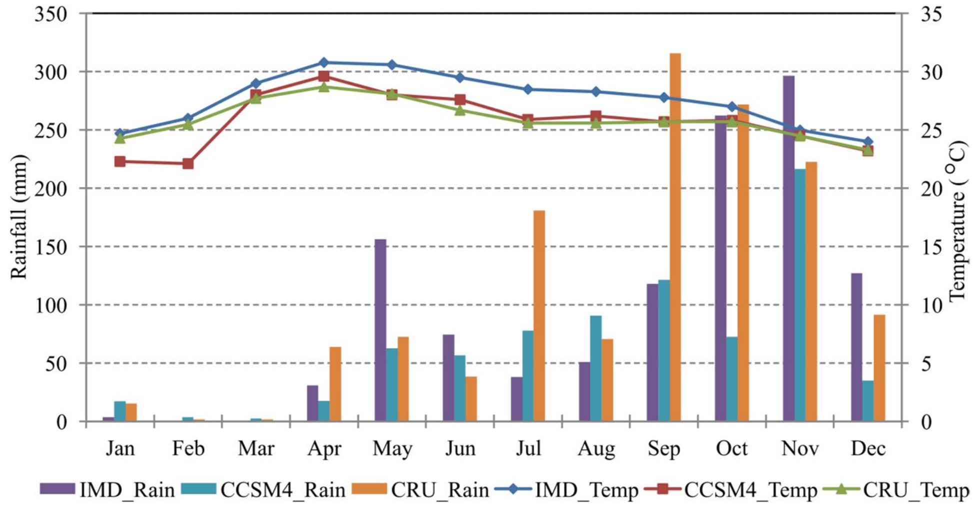


Fig. 14 Rainfall and temperature variation (2010)

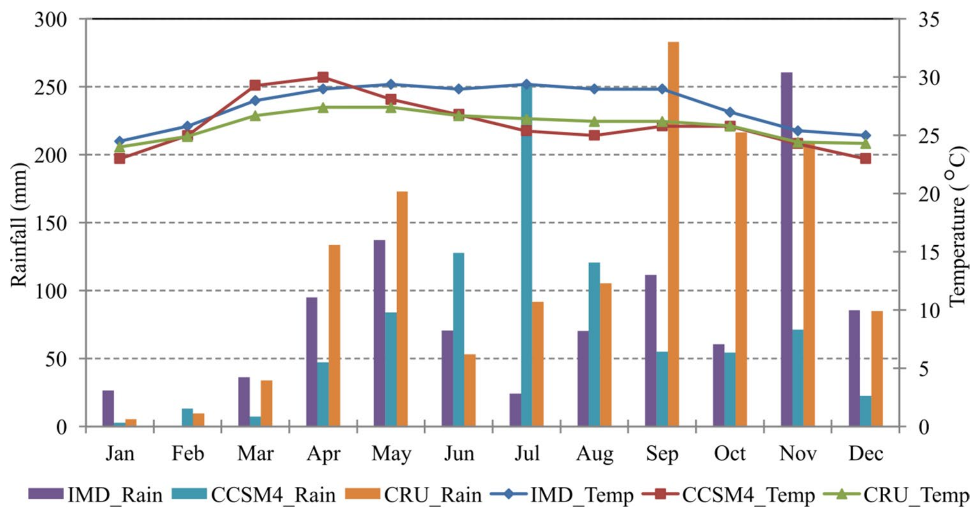


Fig. 15 Rainfall and temperature variation (2015)

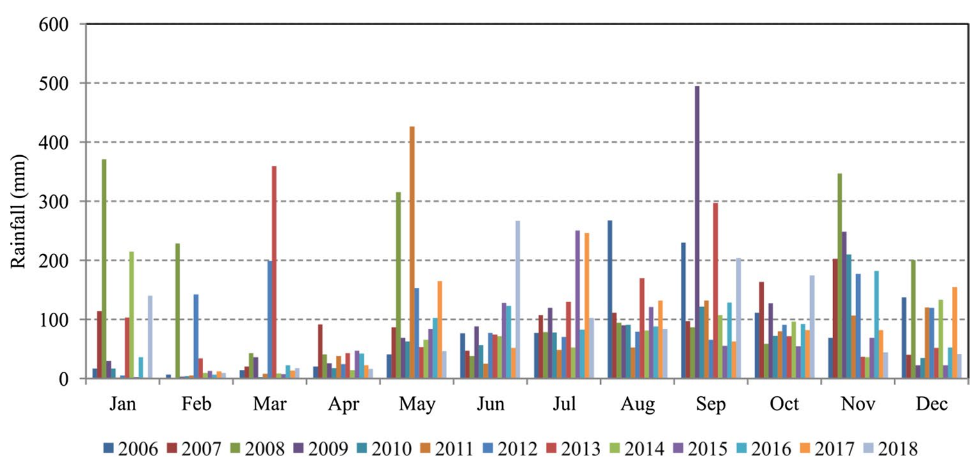


Fig. 16 CCSM4-based seasonal rainfall pattern (2006–2018)

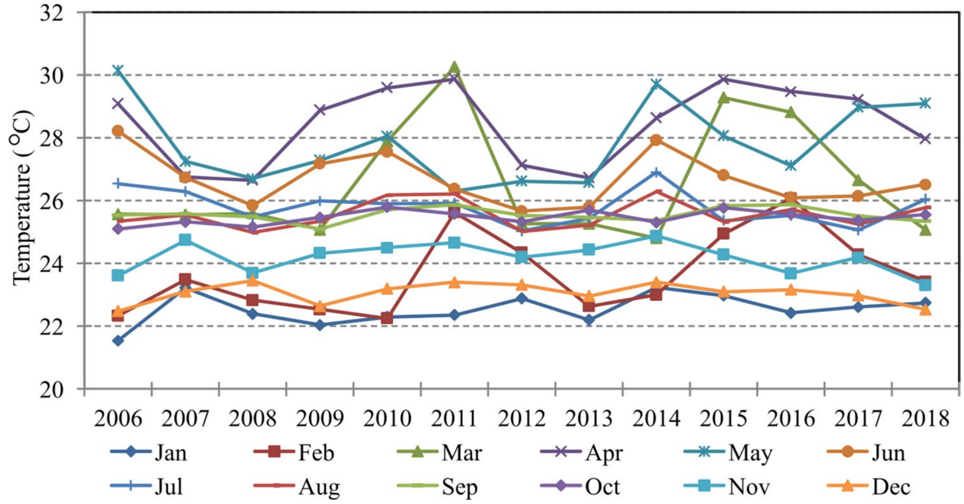


Fig. 17 CCSM4-based seasonal temperature pattern (2006–2018)

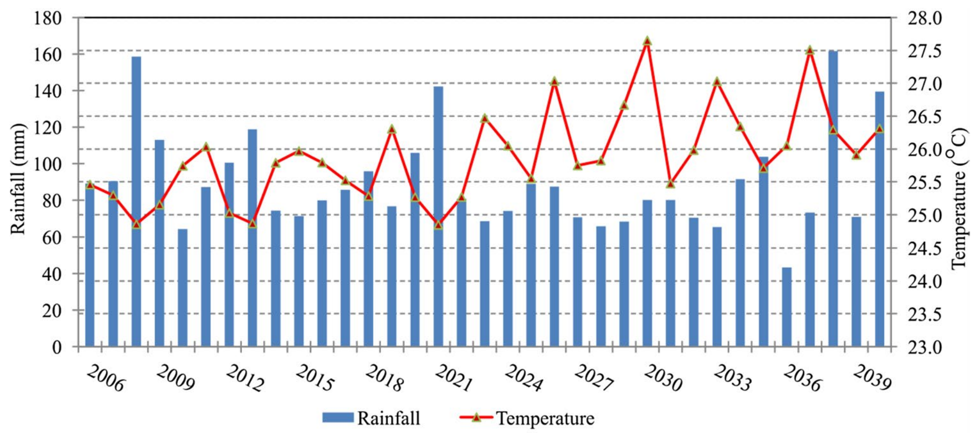


Fig. 18 CCSM4-based rainfall and temperature pattern (2006–2040)

and 2040. The years 2028, 2033, and 2036 were predicted as low rainfall years. However, this study has been scientifically conducted using authentic data sets and also has the potential to help in establishing an early warning of the flood situation over the basin.

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