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Trends, variability, and teleconnections of long-term rainfall in the Terai region of India

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Abstract

This study examined the long-term (1951–2015) spatio-temporal trends, variability, and teleconnections of rainfall of 15 districts in the Terai region of Uttar Pradesh, India. Gridded rainfall data of the India Meteorological Department (IMD) were analyzed using both parametric and non-parametric approaches, and teleconnections of seasonal and annual rainfall with Indian Ocean Dipole (IOD) and El Niño/Southern Oscillation (ENSO) were investigated. Lag-1 autocorrelation coefficient was calculated and tested at 5% level of significance. Our analysis revealed significantly declining trends in monthly rainfall for most of the districts in all the months, except February, April, May, and December which had increasing trends. Monthly rainfall values of the region as a whole had significantly decreasing trends in January, July, August, and October, while February and April had significantly increasing trends. In seasonal and annual rainfall data, only decreasing trends were significant. Monsoon, post-monsoon, and annual rainfall were decreasing in 6, 9, and 7 districts, respectively. The study area as a whole had a significant decrease in monsoon, post-monsoon, and annual rainfall with significantly negative Sen's slope (-2.7, -0.39, and -3.75), Spearman's rho (-0.25, -0.21, and -0.30), and slope of simple linear regression (-2.67, -0.98, and -3.49). CV for annual rainfall of the whole region was 19% with maximum variability recorded in post-monsoon rainfall (CV = 99.81%). Our results also revealed that the monsoon, post-monsoon, and annual rainfall of the whole region had significant teleconnections with both IOD and ENSO events. The results herein suggests decreasing rainfall trends in the Terai region of India with monsoon and annual rainfall having higher ENSO teleconnections while the post-monsoon rainfall teleconnection, dominated by IOD.

1 Introduction

Water is one of the most important and basic natural resources for sustaining all aspects of agriculture. Indian agriculture is predominantly rainfed which encompasses 68% of the total cultivated area (Meshram et al. 2017). So, any variability in the rainfall will have major consequences on food production as well as on the economy of the country. Hence, the study of variations in occurrence and distribution of rainfall is important for sustainable water management.

Moreover, for a better understanding of rainfall variations, it is important to know whether it has any teleconnections with Indian Ocean Dipole (IOD) and El Niño/Southern Oscillation (ENSO) events. About 80% of the total rainfall in India occur in the monsoon months (June to September) with large variability in its spatial as well as temporal distribution (Islam and Uyeda 2007; Malik et al. 2019). Recent studies also indicated that the contribution of monsoon rainfall may reach upto 85% of the total rainfall in the region (Dikshit et al. 2019). Such a huge concentration in 4 months leads to the crunch of water for agriculture and allied activities in the rest of the year. Also, the uneven distribution of rainfall is a major concern of Indian agriculture. Climate change has also affected the amount of rainfall and its distribution which is being felt in India. Rainfed agriculture is becoming more and more uncertain under the changing climate, as the agricultural sector output is strongly governed by timely supply of water. The only way to mitigate is to provide adequate irrigation facilities which require knowledge of rainfall pattern and variability. Hence, it

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is important to assess the trends, variability, and teleconnections of the rainfall.

There are many trend analyses for the whole Indian region but none have shown a clear positive or negative trend in the average annual and seasonal rainfall for the region as whole (Chakraborty et al. 2013; Swain et al. 2015; Saha et al. 2018). Studies at regional scales have also been conducted for detecting rainfall trends. But they cover only a few parts of India like Delhi and Mumbai city (Rana et al. 2012), Cuttack (Mondal et al. 2012), Chhattisgarh (Meshram et al. 2017), Uttar Pradesh (Kumar et al. 2018), and Uttarakhand (Malik and Kumar 2020), and only a few of them have extensive statistics.

In recent years, many attempts have been made to establish large scale teleconnections with climatic parameters using several indices (Xu et al. 2015). There are many circulation modeling studies showing the impacts of large scale atmospheric circulations on the Indian summer monsoon rainfall (Ashok et al. 2001, 2004; Cherchi and Navarra 2013; Andraju et al. 2019; Umakanth et al. 2019; Gusain et al. 2020) as well as for rainfall of different regions in the world (Almazroui et al. 2017, 2020a, b; Ongoma et al. 2019; Akinsanola and Zhou 2019). Both ENSO and IOD events are well correlated with Indian summer monsoon rainfall, and many studies showed their significant impacts on different parts of India (Saji and Yamagata 2003; Ashok et al. 2004; Ashok and Saji 2007; Pervez and Henebry 2015; Jha et al. 2016; Sreekala et al. 2018; Revadekar et al. 2018). To the best of our knowledge, the teleconnections for the Terai region has not been studied yet. The seasonal and annual trends of rainfall in the Terai region of India may also have teleconnections with ENSO and IOD events, which needs to be investigated. The districts of Terai region of Uttar Pradesh are predominantly rice-wheat zone with high productivity and are major contributors to food grain production of the country. Water scarcity due to rainfall variability can have a major impact on the rice-wheat productivity and economy of the Terai belt and hence the micro-level analysis of the rainfall variability will play a vital role in planning relief measures in response to weather aberrations like erratic rainfall. No detailed statistical analysis and teleconnections of rainfall have been studied for this region, which is important for efficient water management planning under the changing climatic conditions. Therefore, the objective of the study is to analyze the trends and variability of district-wise long-term rainfall data of the Terai region in Uttar Pradesh, India, along with the teleconnections of rainfall with IOD and ENSO events.

2 Material and methods

2.1 Study area

The study was conducted for 15 districts in the Terai region of Uttar Pradesh as shown in Fig. 1. Terai region spreads in a belt of around 670 km from Kushinagar to Saharanpur districts in Uttar Pradesh. Terai is an ill-drained narrow tract of 30–50 km which lies on the south of Bhabar running parallel to it. The average elevation of the region varies from 100 to 300 m above MSL. The region comes under monsoon type of climate and most of the Terai region in Uttar Pradesh is converted into agricultural land which is highly productive for rice, wheat, and sugarcane crops. The selected 15 districts viz. Bijnor, Bahraich, Balrampur, Bareilly, Gonda, Kushinagar, Lakhimpur Kheri, Maharajganj, Moradabad, Pilibhit, Rampur, Saharanpur, Shravasti, Siddharth Nagar, and Sitapur covers a total geographical area of 58,111 km^2.

2.2 Data used

Daily rainfall for the period of 1951–2015 (65 years) generated by the India Meteorological Department (IMD) at a grid size of 0.5° latitude × 0.5° longitude was used for this study. The dataset provided by IMD was developed using quality-controlled rainfall data collected from a network of more than 3000 rain gauge stations over India. The details of the gridded data generation are explained in Rajeevan and Bhate (2008). The daily rainfall data of each district were converted to the monthly rainfall data. According to the IMD, four meteorological seasons over India are winter season, January–February; pre-monsoon season, March–May; monsoon season, June–September; post-monsoon season, October–December (India Meteorological Department 2019). The monthly data were further cumulated over the winter, pre-monsoon, monsoon, and post-monsoon seasons to obtain the total seasonal and annual rainfall of all the districts. The analysis was performed on all 15 districts and the region as whole. The district-wise monthly and seasonal data was averaged to obtain monthly and seasonal data for the study area as a whole.

2.3 Spearman's rank correlation

Spearman's rank correlation (SRC) coefficient or Spearman's Rho (ρ) is a non-parametric method commonly used to verify the presence or absence of trends. The details about its statistic ρ (SR) and the standardized test statistic Z_ρ can be found in Lehmann and D'Abrera (1975) and Sneyers (1990). The positive value of Z_ρ indicates increasing trends, while negative Z_ρ shows decreasing trends. The null hypothesis of no trend in the time series against the alternate hypothesis of there is a trend in the time series were tested at three different significance levels (α), i.e., α = 10% with Z = ± 1.645, α = 5% with Z = ± 1.96, and α = 1% with Z = ± 2.58.

2.4 Mann–Kendall test

The Mann–Kendall (MK) test (Mann 1945; Kendall 1975) which is a rank-based non-parametric test, is used to detect
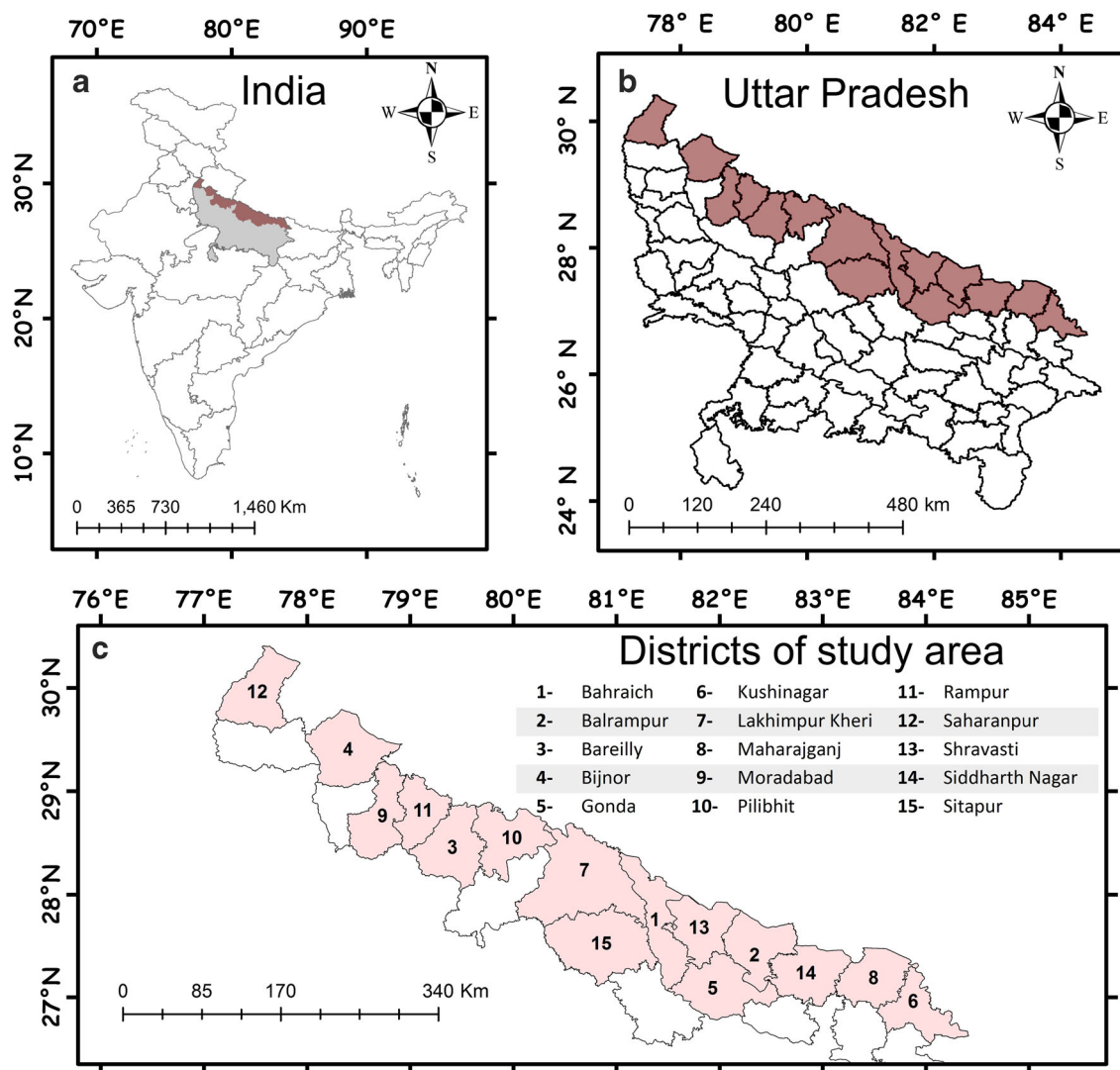
Fig. 1 Map showing districts of the study area in Terai region of Uttar Pradesh

significant trend in meteorological time series data (Tabari et al. 2011; Shifteh Some'e et al. 2012; Suryavanshi et al. 2014; Pingale et al. 2014; Gajbhiye et al. 2016; Kumar et al. 2017). The positive and negative values of standardized MK test statistic (Z_{MK}) indicate increasing and decreasing trend, respectively. The null hypothesis (no trend) and alternate hypothesis (trend) were tested at 1%, 5%, and 10% levels of significance.

2.5 Modified Mann–Kendall test

The modified Mann–Kendall (MMK) test for serially correlated data using the Hamed and Rao (1998) variance correction approach was used. The autocorrelation in the rainfall time series data was calculated using the expressions of Shahin et al. (1993) and Haan (2002). Anderson's test is used to calculate the upper and lower critical values of autocorrelation function (Anderson 1942). Lag-1 autocorrelation

coefficient which recognizes the serial correlation in the data series was calculated and tested at 5% confidence limits. If the lag-1 autocorrelation coefficient was found to be significant, MMK was applied to detect the trend (Kumar et al. 2017). The MMK test was not used for non-significant serial correlation time-series data. The null hypothesis (no trend) and alternate hypothesis (trend) are tested at 1%, 5%, and 10% significance levels. A positive value of the standardized MMK test statistic (Z_{MMK}) represents an increasing trend and a negative value of Z_{MMK} represents a decreasing trend in the time series data.

2.6 Sen's slope estimator

The Sen's slope estimator is a non-parametric statistic that is used to estimate the true slope (magnitude) of the trend (Theil 1950; Sen 1968). The Theil–Sen estimator has been used to estimate the slope of the trend line in hydrological time series (Yue et al. 2002; Mohsin and Gough 2010; Dinpashoh et al.

2011; Tabari et al. 2012; Tabari and Aghajanloo 2013). The magnitude of the trend was calculated by the slope (SS) of all data pairs. A positive value of SS indicates an upward or increasing trend, and a negative value of SS indicates a downward or decreasing trend in the time series.

2.7 Simple linear regression

Simple linear regression (SLR) is one of the most commonly used parametric models to detect the trend in a time series data. The method described by Meshram et al. (2017) was used in the current study. The positive and negative slope value (SL) indicates increasing and decreasing trends, respectively.

2.8 Teleconnections

The teleconnections with the IOD and ENSO were computed for the study area as a whole on seasonal as well as annual basis, for the duration 1951–2015 using two climatic (Dipole Mode Index (DMI) and Southern Oscillation Index (SOI)) and three sea surface temperature (SST) indices (Niño 3, Niño 4, and Niño 3.4). The monthly datasets were obtained from the Global Climate Observing System (GCOS) Working Group on Surface Pressure site (https://psl.noaa.gov/gcos_wgsp/). The intensity of the IOD is represented by the DMI. The SOI is calculated based on the method given by Ropelewski and Jones (1987) using CRU data source. The Niño 3, Niño 4, and Niño 3.4 indices were calculated from the HadISST1 based on the 1981–2010 climatology period. The monthly anomaly index data were averaged to obtain values for seasonal and annual scale. The teleconnections with IOD and ENSO with seasonal and annual rainfall was assessed using the Pearson linear correlation coefficient (CC).

3 Results and discussion

3.1 Statistical characteristics and variability of seasonal and annual rainfall

Descriptive statistical parameters including mean, standard deviation (SD), and coefficient of variation (CV) of seasonal and annual time series rainfall data for 15 districts of the Terai region of Uttar Pradesh are summarized in Table 1. The seasonal and annual rainfall variations of the region as a whole are depicted in Fig. 2. For winter rainfall events, the values of mean, SD, and CV ranged from 20.65 to 70.44 mm, 19.02 to 51.90 mm, and 73.69 to 96.13%, respectively. The values of mean, SD, and CV for the pre-monsoon rainfall ranged from 35.23 to 70.77 mm, 27.84 to 52.49 mm, and 59.85 to 86.83%, respectively. The mean rainfall of monsoon season varied from 803.03 to 1136.10 mm, with SD and CV varying

from 229.74 to 343.22 mm, and 22.81 to 33.51%, respectively. In post-monsoon season, mean rainfall values varied from 46.89 to 72.78 mm, with SD and CV varying from 55.40 to 88.98 mm and 99.41 to 150.58%, respectively. The maximum and minimum of mean annual rainfall in the region was found in Maharajganj (1306.83 mm) and Bareilly (926.03 mm), respectively. The standard deviation for the mean annual rainfall varied from 245.32 mm (Shravasti) to 358.64 mm (Siddharth Nagar). The upper limit of CV for mean annual rainfall was observed in Bareilly (34.18%) and the lower limit (20.85%) in Shravasti. Least variability in rainfall was found in Shravasti for monsoon (22.81%), post-monsoon (99.41%), and annual (20.85%) rainfall. Saharanpur and Maharajganj showed least variability in winter (73.69%) and pre-monsoon (59.85%) rainfall, respectively. The highest variability in pre-monsoon (86.83%), monsoon (33.51%), post-monsoon (150.58%), and annual (34.18%) rainfall was found in Bareilly, whereas in winter, Siddharth Nagar registered the highest variability (96.13%). The results also suggested that post-monsoon season recorded maximum variability in rainfall pattern of the region as a whole. The average annual rainfall of the study area as a whole was 1119 mm with SD and CV of 213 mm and 19%, respectively. Out of which 86.6%, 5.3%, 4.6%, and 3.5% of rainfall was received in monsoon, post-monsoon, pre-monsoon, and winter season, respectively.

3.2 Trend

3.2.1 Monthly trends

The results of the Mann–Kendall (Z_{MK})/modified Mann–Kendall (Z_{MMK}) and Spearman's rank correlation ($Z\rho$) test statistics for the monthly rainfall series are summarized in Table 2. In January, significantly decreasing trends of rainfall were observed for Bahraich, Balrampur, Gonda, Kushinagar, Maharajganj, Moradabad, Shravasti, Siddharth Nagar, and Sitapur as indicated by their Z_{MK}/Z_{MMK} and $Z\rho$ values, while for Pilibhit, it was indicated by $Z\rho$ only. In February, Balrampur, Bijnor, Saharanpur, Shravasti, and Sitapur recorded significantly increasing trends as indicated by the test statistics of Z_{MK}/Z_{MMK} and $Z\rho$, whereas Bahraich showed significantly increasing trend only through Z_{MK}. The results of Z_{MK} and $Z\rho$ indicated that in the month of March, only two districts viz. Gonda and Siddharth Nagar possessed significantly decreasing trends. In April, Bahraich, Bareilly, Lakhimpur Kheri, Pilibhit, Saharanpur, and Shravasti recorded significantly increasing trends as depicted by the values of Z_{MK}/Z_{MMK} and $Z\rho$ while in Sitapur, the increasing trend was confirmed by Z_{MK}. Bahraich and Shravasti reported an increasing trends with significantly positive Z_{MK} and $Z\rho$ in May. The test statistics of Z_{MK}/Z_{MMK} and $Z\rho$ showed that in June, out of 15 districts, only Bijnor showed a significantly increasing trend, whereas Maharajganj and Kushinagar

Table 1 Statistical summary of seasonal and annual rainfall time series

District	Winter			Pre-monsoon			Monsoon			Post-monsoon			Annual		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Bijnor	61.78	48.25	78.10	56.27	45.07	80.10	941.36	258.01	27.41	48.11	61.26	127.33	1107.51	279.74	25.26
Bahraich	37.57	28.17	74.97	55.49	45.03	81.15	983.13	249.19	25.35	61.22	67.23	109.83	1137.41	263.53	23.17
Balrampur	28.48	24.56	86.23	51.61	39.80	77.12	991.51	319.64	32.24	62.80	76.37	121.61	1134.40	342.95	30.23
Bareilly	37.21	29.50	79.28	35.23	30.59	86.83	803.03	269.13	33.51	50.55	76.12	150.58	926.03	316.49	34.18
Gonda	26.78	22.69	84.73	40.22	32.75	81.41	958.32	300.35	31.34	63.06	63.88	101.30	1088.39	317.15	29.14
Kushinagar	20.65	19.02	92.10	66.31	41.66	62.82	1025.42	317.75	30.99	63.50	68.39	107.70	1175.88	343.93	29.25
Lakhimpur Kheri	40.42	30.43	75.29	54.71	41.84	76.47	968.47	238.46	24.62	65.08	83.47	128.26	1128.67	274.39	24.31
Maharajganj	27.27	25.24	92.55	70.67	42.30	59.85	1136.10	319.21	28.10	72.78	73.73	101.31	1306.83	345.35	26.43
Moradabad	44.58	36.21	81.23	37.94	27.84	73.38	828.46	256.33	30.94	51.08	69.27	135.60	962.06	272.44	28.32
Pilibhit	41.71	31.69	75.97	48.77	41.93	85.98	1037.45	270.47	26.07	62.35	88.98	142.72	1190.28	318.34	26.75
Rampur	48.28	39.50	81.80	43.65	32.88	75.33	916.10	263.40	28.75	52.19	73.69	141.20	1060.22	293.09	27.64
Saharanpur	70.44	51.90	73.69	70.77	52.49	74.17	966.29	263.86	27.31	46.89	55.40	118.14	1154.39	280.98	24.34
Shravasti	35.23	27.97	79.39	54.20	40.81	75.30	1021.86	233.09	22.81	65.40	65.01	99.41	1176.69	245.32	20.85
Siddharth Nagar	25.89	24.89	96.13	51.11	32.95	64.48	1064.80	343.22	32.23	66.33	74.32	112.05	1208.12	358.64	29.69
Sitapur	34.93	27.73	79.39	39.79	31.51	79.20	897.39	229.74	25.60	60.05	77.55	129.14	1032.16	257.99	24.99

showed significantly decreasing trends. In July, Z_{MMK}/Z_{MK} and $Z\rho$ for Kushinagar and Siddharth Nagar were significantly negative, while in Balrampur and Gonda, Z_ρ had significantly negative values. Bareilly, Balrampur, Gonda, Kushinagar, Maharajganj, Pilibhit, and Siddharth Nagar reported decreasing trends with significantly negative Z_{MK} and Z_ρ in the month of August. In September, significantly decreasing trends were observed for Kushinagar and Maharajganj with negative Z_{MK}/Z_{MMK} and Z_ρ, while for Gonda, only the negative value of Z_ρ was significant. Z_{MMK} and Z_ρ of October showed significantly decreasing trends for Bijnor, Bareilly, Moradabad, Pilibhit, and Rampur. November and December did not record any significant trends in rainfall pattern. For the study area as whole, Z_{MK}/Z_{MMK} and $Z\rho$ indicated significantly decreasing trends in January and August, whereas they showed significantly increasing trends in February and April. In addition, May and October had increasing and decreasing trends of rainfall, respectively, with significant values of Z_{MK}/Z_{MMK}.

3.2.2 Seasonal and annual trends

In winter rainfall, only Siddharth Nagar showed significantly decreasing trend with negative values of Z_{MK} and $Z\rho$ (Table 3). The test statistic Z_{MK} and $Z\rho$ for pre-monsoon rainfall revealed significantly increasing trends for Bahraich and Shravasti. Decreasing trends in monsoon rainfall were observed in Balrampur, Gonda, Kushinagar, Maharajganj and Siddharth Nagar as indicated by Z_{MK}/Z_{MMK} and $Z\rho$, while for Bareilly the significant decrease in the monsoon rainfall

was confirmed only by $Z\rho$. Z_{MK}/Z_{MMK} and $Z\rho$ of post-monsoon rainfall showed significantly decreasing trends for Balrampur, Rampur, Moradabad, Pilibhit, Saharanpur, Bijnor and Bareilly. Significantly decreasing trends in annual rainfall were observed for Balrampur, Bareilly, Gonda, Kushinagar, Maharajganj, Pilibhit and Siddharth Nagar as indicated by the values of Z_{MK}/Z_{MMK} and $Z\rho$. Z_{MK}/Z_{MMK} and $Z\rho$ values of the study area as a whole revealed significantly decreasing trends for monsoon, post-monsoon and annual rainfall.

3.3 Magnitude of trend

The magnitude of the trend was analyzed by Sen's slope (SS), Spearman's Rho (SR), and slope of simple linear regression (SL) and summarized in Tables 2 and 3. The positive and negative values of these estimators represent increasing and decreasing magnitudes, respectively.

3.3.1 Magnitude of monthly trends

In January, all the districts showed a falling magnitude of trends, as reflected from all three magnitude estimators viz. SS, SR, and SL. In January, SS and SR were found significant in Balrampur (-0.15, -0.33) and Siddharth Nagar (-0.16, -0.37) at 1% level. The values were significant at 5% level in Bahraich (-0.24, -0.28), Gonda (-0.16, -0.30), and Maharajganj (-0.17, -0.31), whereas in Moradabad (-0.15, -0.21) and Shravasti (-0.14, -0.22), it was significant at 10% level. In Kushinagar, SS (-0.11) and SR (-0.32) were significantly decreasing at 1% and 5% level, respectively.

Fig. 2 Mean rainfall distribution of the study area in (**a**) winter, (**b**) pre-monsoon, (**c**) monsoon, (**d**) post-monsoon, and (**e**) annual time scale
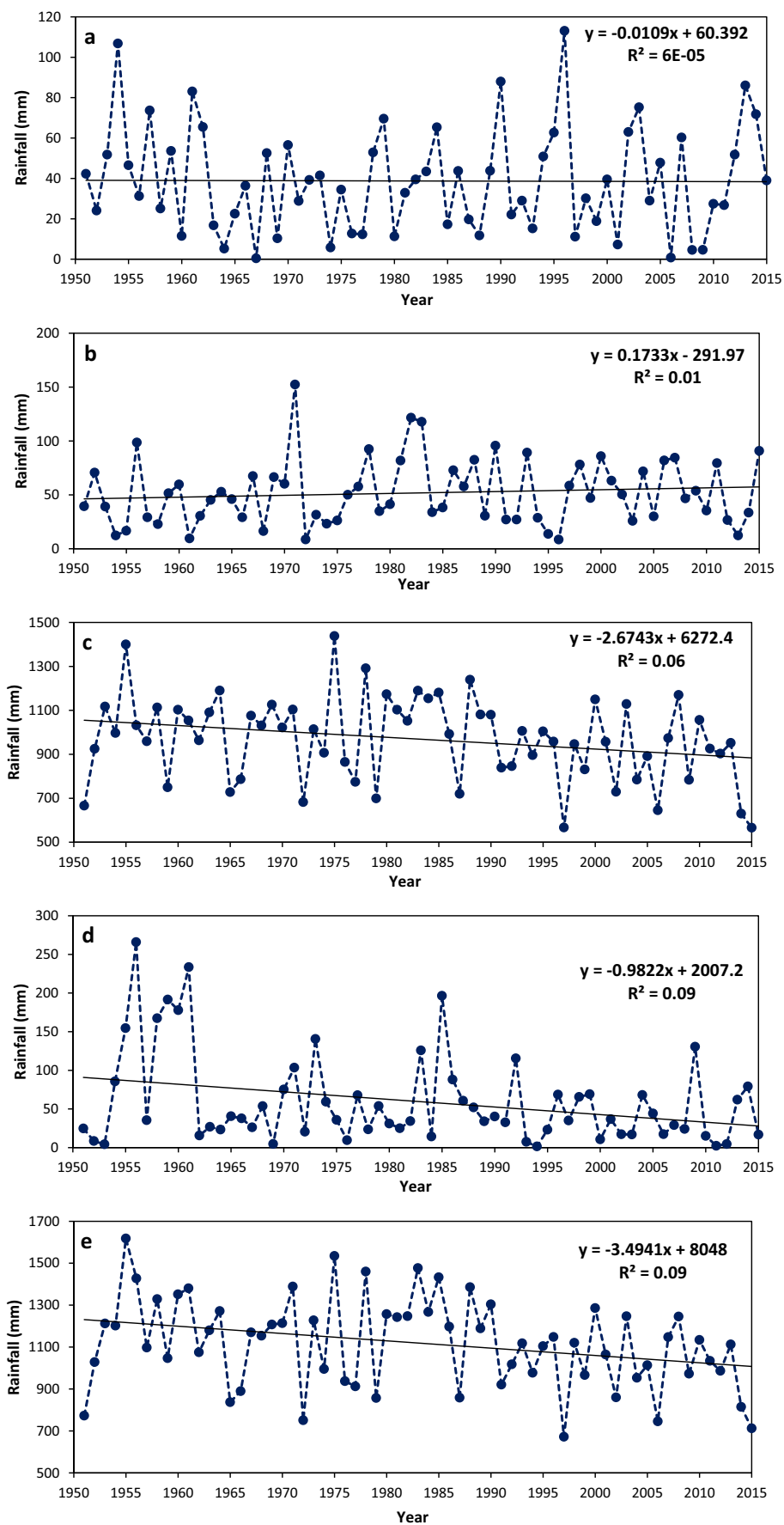
Table 2 Results of the statistical tests for the monthly rainfall

District	Test	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bijnor	Z_{MK}/Z_{MMK}	−1.52	5.59***	−0.78	0.86	1.56	1.85*	−1.16	−0.94	−0.07	−2.63***	−1.49	−0.16
	SS	−0.20	0.30	−0.06	0.01	0.17	0.89	−0.84	−0.77	−0.10	−0.21	0.00	0.00
	Z_ρ	−1.44	1.90**	−0.66	0.94	1.62	1.78*	−0.77	−1.02	−0.10	−1.96**	−1.44	−0.21
	SR	−0.18	0.23	−0.08	0.11	0.20	0.22	−0.09	−0.12	−0.01	−0.24	−0.18	−0.02
	SL	−0.16	0.52**	−0.02	0.06	0.28*	1.25*	−0.69	−0.69	−0.18	−1.23***	−0.07	−0.02
Bahraich	Z_{MK}/Z_{MMK}	−2.34**	1.67*	−1.03	2.78****	2.17**	0.37	0.06	0.14	0.83	−0.72	0.90	0.02
	SS	−0.24	0.11	−0.02	0.10	0.32	0.18	0.04	0.13	0.42	−0.11	0.00	0.00
	Z_ρ	−2.27**	1.64	−1.02	2.85****	2.20**	0.35	0.25	0.24	0.76	−0.72	0.12	0.05
	SR	−0.28	0.20	−0.12	0.35	0.27	0.04	0.03	0.03	0.09	−0.09	0.01	0.00
	SL	−0.29**	0.20	−0.10	0.09	0.44**	0.16	−0.18	0.05	0.27	−0.63	0.01	0.00
Balrampur	Z_{MK}/Z_{MMK}	−2.88****	2.23**	−1.19	1.04	1.06	0.09	−1.56	−2.11**	−1.34	−1.50	−0.05	−1.05
	SS	−0.15	0.14	−0.02	0.01	0.17	0.06	−1.67	−1.66	−0.77	−0.29	0.00	0.00
	Z_ρ	−2.66****	2.26**	−1.17	1.11	1.09	0.02	−1.68*	−2.18**	−1.25	−1.50	−0.06	−1.17
	SR	−0.33	0.28	−0.14	0.13	0.13	0.00	−0.21	−0.27	−0.15	−0.18	0.00	−0.14
	SL	−0.25**	0.24*	−0.08	0.02	0.13	0.07	−2.32**	−1.76**	−0.85	−1.03**	0.01	−0.05
Bareilly	Z_{MK}/Z_{MMK}	−1.54	1.22	−0.64	1.67*	1.09	−0.36	−1.27	−1.80*	−0.43	3.15***	0.52	0.96
	SS	−0.12	0.08	−0.01	0.03	0.06	−0.09	−0.96	−1.42	−0.37	−0.20	0.00	0.00
	Z_ρ	−1.59	1.04	−0.65	1.74*	1.15	−0.41	−1.34	−1.80*	−0.47	−2.27**	0.55	0.93
	SR	−0.19	0.13	−0.08	0.21	0.14	−0.05	−0.16	−0.22	−0.05	−0.28	0.06	0.11
	SL	−0.19*	0.11	−0.12	0.05	0.10	−0.03	−1.02	−1.67*	−0.41	−1.55***	−0.06	0.00
Gonda	Z_{MK}/Z_{MMK}	−2.53**	1.62	−1.82*	1.25	1.19	0.28	−1.62	−2.39**	−1.63	−1.41	0.01	−0.72
	SS	−0.16	0.07	−0.03	0.02	0.15	0.12	−1.55	−1.45	−1.11	−0.24	0.00	0.00
	Z_ρ	−2.41**	1.59	−1.81*	1.30	1.00	0.13	−1.87*	−2.45**	−1.67*	−1.34	−0.02	−0.89
	SR	−0.30	0.20	−0.22	0.16	0.12	0.01	−0.23	−0.30	−0.20	−0.16	0.00	−0.11
	SL	−0.23**	0.17*	−0.11	0.00	0.08	0.26	−2.01*	−1.61**	−1.19	−0.69*	0.09	−0.04
Kushinagar	Z_{MK}/Z_{MMK}	−2.52**	0.97	−0.93	0.60	0.61	−2.71***	−1.81*	−2.99****	−2.16**	−0.82	−0.94	−0.81
	SS	−0.11	0.03	−0.01	0.02	0.14	−1.64	−2.50	−2.27	−1.81	−0.15	0.00	0.00
	Z_ρ	−2.58****	0.93	−0.78	0.67	0.52	−2.69****	−2.29**	−2.93****	−2.14**	−0.69	−0.88	−0.88
	SR	−0.32	0.11	−0.09	0.08	0.06	−0.33	−0.28	−0.36	−0.26	−0.08	−0.11	−0.11
	SL	−0.20**	0.07	−0.09	0.02	0.10	−1.51***	−2.20**	−2.16***	−1.85*	−0.62	−0.06	−0.01
Lakhimpur Kheri	Z_{MK}/Z_{MMK}	−1.19	1.30	−0.91	2.17**	1.45	0.57	0.05	−0.92	0.15	−1.38	−0.44	0.70
	SS	−0.16	0.09	−0.03	0.07	0.23	0.33	0.03	−0.53	0.10	−0.21	0.00	0.00
	Z_ρ	−1.49	1.29	−0.89	2.22**	1.48	0.64	0.02	−0.99	0.18	−1.43	−0.54	0.86

Table 2 (continued)

District	Test	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	SR	−0.18	0.16	−0.11	0.27	0.18	0.08	0.00	−0.12	0.02	−0.17	−0.06	0.10
	SL	−0.19*	0.20	−0.07	0.10	0.20	0.52	−0.02	−0.72	0.05	−0.96*	0.00	0.06
Maharajganj	Z_{MK}/Z_{MMK}	−2.43**	1.40	−1.44	−0.05	*0.67*	−2.44**	*−1.17*	−2.54**	−1.97**	−0.44	−0.56	−0.9
	SS	−0.17	0.06	−0.04	0.00	0.17	−1.21	−1.81	−2.10	−1.41	−0.10	0.00	0.00
	Z_ρ	−2.49**	1.36	−1.53	−0.14	1.00	−2.36**	−1.42	−2.63***	−1.97**	−0.44	−0.53	−0.96
	SR	−0.31	0.17	−0.19	−0.01	0.12	−0.29	−0.17	−0.32	−0.24	−0.05	−0.06	−0.12
	SL	−0.26**	0.13	−0.11	−0.06	0.21	−1.17*	−1.54	−2.08**	−1.25	−0.54	−0.03	−0.03
Moradabad	Z_{MK}/Z_{MMK}	−1.71*	1.37	−1.31	0.51	0.77	*0.02*	−0.96	−0.96	−0.62	−2.74***	−0.51	0.43
	SS	−0.15	0.11	−0.06	0.00	0.03	0.01	−0.81	−1.03	−0.40	−0.22	0.00	0.00
	Z_ρ	−1.71*	1.28	−1.12	0.58	0.81	0.09	−0.92	−1.06	−0.74	−2.02**	−0.53	0.37
	SR	−0.21	0.16	−0.14	0.07	0.10	0.01	−0.11	−0.13	−0.09	−0.25	−0.06	0.04
	SL	−0.22*	0.24	0.00	0.03	0.09	0.08	−0.68	−0.71	−0.37	−1.21***	−0.04	0.04
Pilibhit	Z_{MK}/Z_{MMK}	−1.62	0.90	−1.49	1.95*	0.76	0.50	−1.11	−2.12**	−0.92	−2.77***	−0.04	0.05
	SS	−0.15	0.08	−0.06	0.04	0.08	0.22	−0.94	−1.87	−0.69	−0.19	0.00	0.00
	Z_ρ	−1.80*	0.73	−1.44	2.11**	0.73	0.58	−1.12	−2.11**	−0.98	−1.89*	0.00	0.00
	SR	−0.22	0.09	−0.18	0.26	0.09	0.07	−0.14	−0.26	−0.12	−0.23	0.00	−0.02
	SL	−0.26**	0.08	−0.08	0.04	0.03	0.54	−0.67	−1.69**	−0.70	−1.32**	−0.04	−0.02
Rampur	Z_{MK}/Z_{MMK}	−0.96	1.26	−1.21	*1.44*	1.38	0.24	−0.86	−0.51	*−0.25*	−2.28**	−0.09	0.66
	SS	−0.08	0.12	−0.04	0.02	0.11	0.12	−0.71	−0.51	−0.21	−0.21	0.00	0.00
	Z_ρ	−0.98	1.21	−1.05	1.39	1.37	0.41	−0.79	−0.54	−0.23	−2.18**	−0.10	0.54
	SR	−0.12	0.15	−0.13	0.17	0.17	0.05	−0.09	−0.06	−0.02	−0.27	−0.01	0.06
	SL	−0.13	0.19	−0.06	0.05	0.15	0.66	−0.40	−0.30	−0.05	−1.14**	−0.02	0.02
Saharanpur	Z_{MK}/Z_{MMK}	−1.41	5.76***	−0.49	2.09**	0.85	1.00	−1.31	−0.97	−0.19	*1.25*	−0.26	*−0.36*
	SS (	−0.23	0.47	−0.05	0.09	0.09	0.51	−1.11	−0.87	−0.09	−0.10	0.00	0.00
	Z_ρ	−1.38	2.24**	−0.47	2.17***	0.81	1.09	−1.31	−1.00	−0.19	−1.36	−0.35	−0.53
	SR	−0.17	0.28	−0.05	0.27	0.10	0.13	−0.16	−0.12	−0.02	−0.17	−0.04	−0.06
	SL	−0.25	0.50**	0.06	0.28*	0.19	0.87	−1.07	−1.00	0.28	−0.70**	−0.11**	−0.10
Shravasti	Z_{MK}/Z_{MMK}	−1.90*	2.76***	−1.02	2.62***	2.46**	1.29	0.25	0.14	*−0.43*	−1.06	*0.09*	−0.32
	SS	−0.14	0.20	−0.01	0.10	0.44	0.78	0.21	0.12	−0.26	−0.18	0.00	0.00
	Z_ρ	−1.80*	2.67***	−0.97	2.49***	2.28**	1.26	0.10	0.17	−0.44	−1.00	0.03	−0.47
	SR	−0.22	0.33	−0.12	0.31	0.28	0.15	0.01	0.02	−0.05	−0.12	0.00	−0.05
	SL	−0.21*	0.29**	−0.05	0.15***	0.42*	0.83	−0.35	−0.07	−0.42	−0.72*	0.03	−0.01

Table 2 (continued)

District	Test	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Siddharth. Nagar	Z_{MK}/Z_{MMK}	−2.96***	1.02	−1.78*	0.84	1.29	−1.35	−1.76*	−2.57**	−1.36	−1.12	−0.66	−1.36
	SS	−0.16	0.04	−0.05	0.01	0.26	−0.78	−2.13	−2.47	−1.25	−0.24	0.00	0.00
	Z_ρ	−2.98***	1.09	−1.80*	0.74	1.18	−1.39	−1.89*	−2.45**	−1.48	−1.29	−0.69	−1.42
	SR	−0.37	0.13	−0.22	0.09	0.14	−0.17	−0.23	−0.30	−0.18	−0.16	−0.08	−0.17
	SL	−0.28**	0.09	−0.16**	0.01	0.18	−0.62	−2.68**	−2.20**	−1.06	−0.91*	0.01	−0.02
Sitapur	Z_{MK}/Z_{MMK}	−1.67*	1.75*	−1.10	1.70*	1.46	0.74	−0.45	−1.35	−0.11	−1.24	−0.10	0.06
	SS	−0.18	0.11	−0.03	0.03	0.12	0.42	−0.22	−0.81	−0.08	−0.16	0.00	0.00
	Z_ρ	−2.08**	1.76*	−1.08	1.79	1.39	0.79	−0.60	−1.39	−0.22	−1.19	−0.21	0.05
	SR	−0.26	0.22	−0.13	0.22	0.17	0.09	−0.07	−0.17	−0.02	−0.14	−0.02	0.00
	SL	−0.27**	0.21*	−0.09	0.05	0.12	0.32	−0.68	−0.98	−0.23	−0.92*	−0.01	0.00
Study area	Z_{MK}/Z_{MMK}	−2.02**	1.76*	−1.31	1.77*	1.78*	−0.13	−1.35	−2.14**	−0.9	−2.18**	−0.44	−0.07
	SS	−0.19	0.16	−0.06	0.07	0.27	−0.03	−0.99	−1.09	−0.49	−0.27	0.00	0.00
	Z_ρ	−2.01**	1.69*	−1.27	1.86*	1.62	−0.08	−1.47	−2.14**	−0.88	−1.56	−0.36	−0.22
	SR	−0.25	0.21	−0.15	0.23	0.20	−0.01	−0.18	−0.26	−0.11	−0.19	−0.04	−0.02
	SL	−0.23**	0.22*	−0.07	0.06	0.18	0.15	−1.11*	−1.17**	−0.53	−0.94**	−0.01	−0.01

*Significance at $p \leq 0.1$; **significance at $p \leq 0.05$; ***significance at $p \leq 0.01$, Unit of SS and SL : mm/year

Italic values are Z_{MMK}

Table 3 Results of the statistical tests for the seasonal and annual rainfall

District	Test	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Bijnor	Z_{MK}/Z_{MMK}	0.74	1.08	− 0.02	− 2.12**	− 0.44
	SS	0.20	0.21	− 0.07	− 0.60	− 0.97
	Z_ρ	0.65	1.07	− 0.04	− 2.49**	− 0.47
	SR	0.08	0.13	0.00	− 0.31	− 0.06
	SL	0.35	0.33	− 0.31	− 1.33***	− 0.96
Bahraich	Z_{MK}/Z_{MMK}	− 0.57	1.82*	0.10	− 0.82	− 0.01
	SS	− 0.10	0.42	0.16	− 0.19	− 0.04
	Z_ρ	− 0.49	1.82*	0.19	− 0.85	0.04
	SR	− 0.06	0.22	0.02	− 0.10	0.00
	SL	− 0.09	0.43	0.30	− 0.63	0.01
Balrampur	Z_{MK}/Z_{MMK}	− 0.31	0.56	− 2.41**	− 1.94*	− 2.81***
	SS	− 0.04	0.11	− 4.82	− 0.47	− 6.15
	Z_ρ	− 0.33	0.56	− 2.34**	− 1.76*	− 2.76***
	SR	− 0.04	0.07	− 0.29	− 0.22	− 0.34
	SL	− 0.01	0.06	− 4.87**	− 1.07**	− 5.89***
Bareilly	Z_{MK}/Z_{MMK}	− 0.22	0.40	− 1.62	− 3.42***	− 2.11**
	SS	− 0.02	0.05	− 3.09	− 0.48	− 4.18
	Z_ρ	− 0.18	0.34	− 1.71*	− 2.48**	− 2.22**
	SR	− 0.02	0.04	− 0.21	− 0.31	− 0.27
	SL	− 0.08	0.03	− 3.15*	− 1.61***	− 4.81**
Gonda	Z_{MK}/Z_{MMK}	− 1.04	0.41	− 2.10**	− 1.43	**− 2.37**
	SS	− 0.12	0.06	− 3.99	− 0.30	− 4.92
	Z_ρ	− 0.93	0.43	− 2.06**	− 1.36	− 2.41**
	SR	− 0.11	0.05	− 0.25	− 0.17	− 0.30
	SL	− 0.05	− 0.02	− 4.56**	− 0.64	− 5.28**
Kushinagar	Z_{MK}/Z_{MMK}	− 1.12	0.44	− 2.90***	− 0.68	− 3.04***
	SS	− 0.10	0.15	− 8.32	− 0.16	− 9.37
	Z_ρ	− 1.18	0.44	− 3.57***	− 0.54	− 3.61***
	SR	− 0.14	0.05	− 0.44	− 0.06	− 0.45
	SL	− 0.13	0.02	− 7.82***	− 0.70	− 8.63***
Lakhimpur Kheri	Z_{MK}/Z_{MMK}	0.04	1.39	− 0.06	− 1.23	− 0.10
	SS	0.00	0.31	− 0.07	− 0.32	− 0.20
	Z_ρ	− 0.01	1.47	− 0.06	− 1.35	− 0.12
	SR	0.00	0.18	0.00	− 0.16	− 0.01
	SL	0.01	0.23	− 0.17	− 0.9	− 0.82
Maharajganj	Z_{MK}/Z_{MMK}	− 1.22	− 0.07	− 2.57**	− 0.68	− 2.71***
	SS	− 0.15	− 0.02	− 6.18	− 0.19	− 7.02
	Z_ρ	− 1.23	0.00	− 2.69***	− 0.61	− 2.78***
	SR	− 0.15	0.00	− 0.33	− 0.07	− 0.34
	SL (mm/year)	− 0.13	0.03	− 6.07***	− 0.61	− 6.77***
Moradabad	Z_{MK}/Z_{MMK}	0.15	0.53	− 0.87	− 2.87***	− 1.61
	SS	0.04	0.10	− 1.69	− 0.42	− 3.27
	Z_ρ	0.17	0.43	− 1.01	− 2.14**	− 1.62
	SR	0.02	0.05	− 0.12	− 0.26	− 0.20
	SL	0.01	0.13	− 1.69	− 1.21***	− 2.75
Pilibhit	Z_{MK}/Z_{MMK}	− 0.78	0.13	− 1.35	− 2.98***	− 1.79*
	SS	− 0.14	0.03	− 2.76	− 0.45	− 3.96
	Z_ρ	− 0.75	0.16	− 1.41	− 2.20**	− 1.80*
	SR	− 0.09	0.02	− 0.17	− 0.27	− 0.22

Table 3 (continued)

District	Test	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
	SL	−0.17	0.00	−2.53	−1.39**	−4.11**
Rampur	Z_{MK}/Z_{MMK}	0.47	0.60	−0.48	−1.86*	−0.92
	SS	0.11	0.12	−0.78	−0.38	−1.66
	Z_ρ	0.48	0.56	−0.44	−1.91*	−0.92
	SR	0.06	0.07	−0.05	−0.24	−0.11
	SL	0.06	0.14	−0.10	−1.14**	−1.04
Saharanpur	Z_{MK}/Z_{MMK}	0.74	1.26	−0.58	−3.02***	−0.64
	SS	0.22	0.36	−1.00	−0.43	−1.36
	Z_ρ	0.59	1.48	−0.64	−2.10**	−0.65
	SR	0.07	0.18	−0.08	−0.26	−0.08
	SL	0.24	0.54	−0.92	−0.92**	−1.05
Shravasti	Z_{MK}/Z_{MMK}	0.19	2.20**	0.35	−0.89	0.01
	SS	0.03	0.60	0.45	−0.24	0.06
	Z_ρ	0.24	2.05**	0.32	−0.84	0.13
	SR	0.03	0.25	0.04	−0.10	0.01
	SL	0.08	0.52*	−0.02	−0.70	−0.12
Siddharth. Nagar	Z_{MK}/Z_{MMK}	−1.74*	0.35	−2.80***	−1.37	−3.27***
	SS	−0.21	0.07	−5.73	−0.24	−6.96
	Z_ρ	−1.76*	0.31	−2.70***	−1.48	−3.13***
	SR	−0.22	0.03	−0.33	−0.18	−0.39
	SL	−0.19	0.02	−6.58***	−0.92*	−7.66***
Sitapur	Z_{MK}/Z_{MMK}	−0.31	0.67	−1.43	−1.60	−1.51
	SS	−0.05	0.1	−2.02	−0.34	−2.25
	Z_ρ	−0.36	0.7	−1.43	−1.51	−1.59
	SR	−0.04	0.08	−0.17	−0.18	−0.19
	SL	−0.06	0.07	−1.57	−0.92*	−2.48
Study area	Z_{MK}/Z_{MMK}	−0.09	1.01	−2.15**	−2.85***	−2.41 **
	SS	−0.01	0.21	−2.7	−0.39	−3.75
	Z_ρ	−0.16	1.05	−2.07**	−1.71*	−2.44**
	SR	−0.02	0.13	−0.25	−0.21	−0.30
	SL	−0.01	0.17	−2.67**	−0.98**	−3.49**

*Significance at $p \leq 0.1$; **significance at $p \leq 0.05$; ***significance at $p \leq 0.01$, Unit of SS and SL : mm/year

Italic values are Z_{MMK}

Statistically significant values of SL at 5% level were observed in Bahraich (−0.29), Balrampur (−0.25), Gonda (−0.23), Kushinagar (−0.20), Maharajganj (−0.26), Pilibhit (−0.26), Siddharth Nagar (−0.28), and Sitapur (−0.27), whereas it was found statistically significant at 10% level in Bareilly (−0.19), Lakhimpur Kheri (−0.19), Moradabad (−0.22), and Shravasti (−0.21). In February, all the districts showed a rising magnitude of the trend. Significant values were found for SS (0.11) in Bahraich, SS (0.11), SR (0.22), and SL (0.21) in Sitapur, SL in Balrampur (0.24) and Gonda (0.178) at 10% level. SS and SR of Balrampur (0.14, 0.28), SL of Shravasti (0.29), SR and SL of Bijnor (0.23, 0.52) and Saharanpur (0.28, 0.50) were found significant at 5% level. SS and SR of Shravasti (0.20, 0.334) and SS of Bijnor (0.30) and Saharanpur (0.47) were significant at 1% level. As revealed from the values of SS, SR, and SL in the month of March, except Moradabad and Saharanpur, all other districts showed a decreasing magnitude of the trends in rainfall. The significant decreasing values of SS and SR were observed only in Gonda (−0.03, −0.22) and Siddharth Nagar (−0.05, −0.22) at 10% level, whereas SL was found to be significant only in Siddharth Nagar (−0.16) at 5% level. In April, all the districts showed an increasing magnitude of rainfall trends except Maharajganj. SS and SR in Bareilly (0.03, 0.21), SS in Pilibhit (0.04) and Sitapur (0.03), and SL in Saharanpur (0.28) were found significant at 10% level, whereas SR in Pilibhit (0.26), SR and SL in Shravasti (0.31, 0.15), SS and SR in Lakhimpur Kheri (0.07, 0.27) and Saharanpur (0.09, 0.27) were significant at 5% level.

SS and SR of Bahraich (0.10, 0.35) and SS of Shravasti (0.10) showed significantly increasing magnitude of trends at 1% level. All the 15 districts showed an increasing magnitude of rainfall trends in May. Significant values at 5% level were found for SS (0.32), SR (0.27), SL (0.44) in Bahraich and for SS (0.44) and SR (0.28) in Shravasti. SL for Bijnor (0.28) and Shravasti (0.42) were found significant at 10% level. As reflected from the values of SS, SR, and SL of Bijnor, Balrampur, Gonda, Moradabad, Pilibhit, Rampur, and Sitapur showed the increasing magnitude of trends for June and decreasing magnitude of trends for July, August, September, and October. Bijnor's SS, SR, and SL for June (0.89, 0.22, 1.25) were significant at 10% level, SR for October (−0.24) at 5% level and SS, SL for October (−0.21, −1.23) at 1% level. In Balrampur, SL (−2.32) of July, SS (−1.66), SR (−0.27), and SL (−1.76) of August and SL (−1.03) of October were significant at 5% level, whereas SR (−0.210) of July was significant at 10% level. Gonda showed significantly decreasing values of SS (−1.45), SR (−0.30), and SL (−1.61) at 5% level in August. Gonda's SR (−0.23) and SL (−2.01) in July, SR (−0.20) in September, and SL (−0.69) in October were found significant at 10% level. Significant decreasing magnitude of trend in October was observed for Rampur and Moradabad with Rampur registering significant SS (−0.21), SR (−0.27), and SL (−1.14) at 5% level, whereas Moradabad showing significant SS (−0.22), SL (−1.21) at 1% level, and SR (−0.25) at 5% level. Considering the months from June to October, Pilibhit revealed significant SS (−1.87), SR (−0.26), and SL (−1.69) at 5% level in August and significant SS (−0.19) at 1%, SR (−0.23) at 10%, and SL (−1.32) at 5% level in October. Sitapur showed a decrease in the magnitude of rainfall in October with significant SL (−0.92) at 10% level. Bareilly showed a decreasing magnitude of trends from June to October. In August, SS (−1.42), SR (−0.22), and SL (−1.67) were found significant at 10% level, while in October, SS (−0.20), SL (−1.55) were significant at 1% level, and SR (−0.28) at 5% level. Kushinagar and Maharajganj had the negative magnitude of the trends continuously from June to October. In Kushinagar, the SS, SR, and SL of June (−1.64, −0.33, −1.51) and August (−2.27, −0.36, −2.16) were significant at 1% level. SR (−0.28) and SL (−2.28) of July, SS (−1.81) and SR (−0.26) of September were significant at 5% level. SS (−2.50) of July and SL (−1.85) of September were significant at 10% level. The significant negative magnitude in Maharajganj for SS and SR were observed in June (−1.21, −0.29) and September (−1.41, −0.24) at 5% level. SS and SR of August (−2.10, −0.32) were significantly negative at 5% and 1% level, respectively. SL in Maharajganj was found significant in June (−1.17) and August (−2.08) at 10% and 5% level, respectively. Lakhimpur Kheri, Shravasti, and Saharanpur possessed insignificant magnitudes of SS and SR from June to September. The only significant value was observed for SL (in October) which was found to be −0.96 in Lakhimpur

Kheri, −0.72 in Shravasti at 10% level, and −0.70 in Saharanpur at 5% level. The results obtained indicated decreasing magnitude of the trends in Siddharth Nagar from June to October. In July, SS (−2.13) and SR (−0.23) were found significant at 10% level and SL (−2.68) at 5% level. SS (−2.47), SR (−0.30), and SL (−2.20) of August showed significantly decreasing magnitude at 5% level. October possessed significant SL (−0.91) at 10% level for this district. For November and December, the only significant trend was found in Saharanpur for SL (−0.11) during November at 5% level.

Magnitude of monthly trends for the study area The overall change and variations in the whole study area, i.e., Terai region of Uttar Pradesh for seasonal and annual trend using the simple linear regression method are shown in Fig. 2. As listed in Table 2, SS, SR, and SL indicated that the study area as a whole, showed increasing magnitude of trends in February, April, and May, whereas for the remaining months (except June's SL), it showed a decreasing magnitude of trends for rainfall over 65 years. The rise in the magnitude of trends as revealed by SS, SR, SL for Feb (0.16, 0.21, 0.22), SS and SR for April (0.07, 0.23), and SS for May (0.27) were significant at 10% level. The values of SS, SR, and SL for January (−0.19, −0.25, −0.23) and August (−1.09, −0.26, −1.17) were significant at 5% level. The SS and SL for October (−0.27, −0.94) were also significant at 5% level, whereas SL for July (−1.11) showed significantly decreasing magnitude at 10% level.

3.3.2 Magnitude of seasonal and annual trends

It is evident from the results that in winter, only Siddharth Nagar showed a significant magnitude of the trend in rainfall at 10% level with SS and SR values of −0.21 and −0.22, respectively. The number of districts showing positive values for SS, SR, and SL in pre-monsoon season was found to be 14, 15, and 13, respectively, while rest of districts showed decreasing magnitude of trends. The values of SS and SR were found significant in Bahraich (0.42, 0.22) at 10% level and in Shravasti (0.60, 0.25) at 5% level. SL was found significant only in Shravasti (0.52) at 10% level.

The analysis revealed that most of the districts were showing a strong fall in magnitude of monsoon rainfall. The SS, SR, and SL of Gonda (−3.99, −0.25, −4.56) and Balrampur (−4.82, −0.29, −4.87) were found significant at 5% level, while that of Kushinagar (−8.32, −0.44, −7.82) and Siddharth Nagar (−5.73, −0.33, −6.58) at 1% level. Maharajganj had significantly negative SS (−6.18) at 5% level, while the SR (−0.33) and SL (−6.07) were significant at 1% level. SR (−0.21) and SL (−3.15) of Bareilly were statistically significant at 10% level.

For post-monsoon rainfall, all the districts showed decreasing magnitude of trends with negative values of SS, SR, and SL. Both SS and SR values were found significant in

Balrampur (− 0.47, − 0.22) and Rampur (− 0.38, − 0.24) at 10% level, while in Bareilly (− 0.48, − 0.31) at 1% level. The SS values were significant in Bijnor (− 0.60) at 5% level, while in Moradabad (− 0.42), Pilibhit (− 0.45), and Saharanpur (− 0.43) at 1% level. Negative SR values were significant in Bijnor (− 0.31), Moradabad (− 0.26), Pilibhit (− 0.27), and Saharanpur (− 0.26) at 5% level. SL indicated falling slope of trends in Siddharth Nagar (− 0.920) and Sitapur (− 0.92) at 10% level, while it was significant at 5% level in Balrampur (− 1.07), Pilibhit (− 1.39), Rampur (− 1.14), and Saharanpur (− 0.92). Bijnor (− 1.33), Bareilly (− 1.61), and Moradabad (− 1.21) possessed significantly falling SL values at 1% level. SS, SR, and SL of annual rainfall in 14, 13, and 14 districts, respectively, showed decreasing magnitude of rainfall trends (Fig. 3). Annual rainfall followed

a significant decrease in magnitude of trend with SS, SR, and SL values of − 4.18, − 0.27, − 4.81 in Bareilly at 5% level and − 6.15, − 0.34, − 5.89 in Balrampur, − 9.37, − 0.45, − 8.63 in Kushinagar, − 7.02, − 0.34, − 6.77 in Maharajganj and − 6.96, − 0.39, − 7.66 in Siddharth Nagar at 1% level, respectively. Pilibhit showed a significant value of SS (− 3.96) and SR (− 0.22) at 10% level and Gonda showed a significant value of SS (− 4.92) and SR (− 0.30) at 5% level. Both Pilibhit (− 4.11) and Gonda (− 5.28) showed a statistically significant value of SL at 5% level.

Magnitude of seasonal and annual trends for the study area
Analysis of the Terai region of Uttar Pradesh on seasonal scale revealed that in the study area except for pre-monsoon, all other seasons showed a continuous decreasing

Fig. 3 Spatial variation of annual rainfall trends and magnitude based on (**a**) MK/MMK test (values are SS), (**b**) SRC test (values are SR), (**c**) SLR (values are SL)

Map of district wise annual rainfall trends and magnitude.
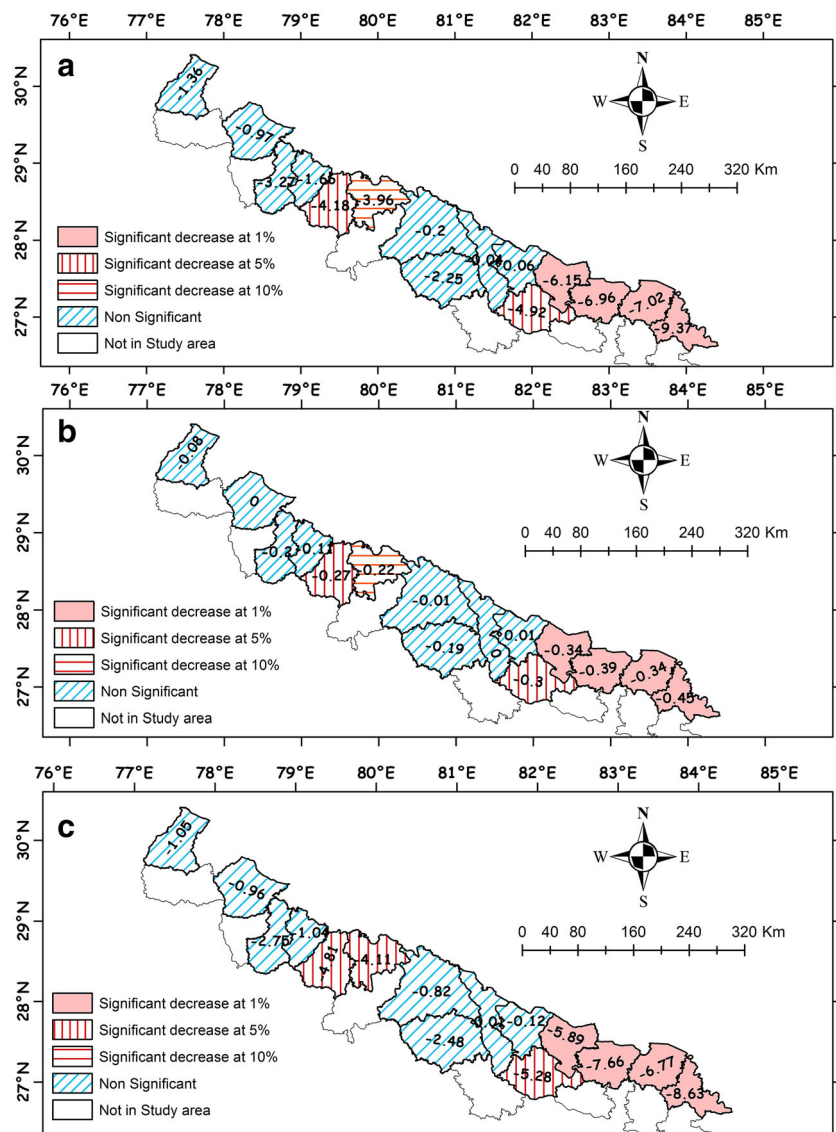
trends of rainfall. Significant values of SS (− 2.70), SR (− 0.25), and SL (− 2.67) were obtained for monsoon season at 5% level which indicated a decreasing magnitude of the rainfall. In post-monsoon season, SS (− 0.39) was found to be significant at 1% level, SR (− 0.21) at 10% level, and SL (− 0.98) at 5% level. Annual rainfall in the Terai region of UP also showed a strong decreasing magnitude of the trends with SS (− 3.75), SR (− 0.30), and SL (− 3.49) values significant at 5% level. Therefore, from this study, it is evident that, in general, the magnitude of rainfall events in the districts of the Terai region of Uttar Pradesh has been decreasing over 65 years (1951 to 2015).

We compared results of our analysis with similar studies for the region. Kumar et al. (2010) reported decreasing trends using 135 years (1871–2005) of sub-divisional data. Kumar et al. (2018) also reported decreasing trends of rainfall in the Uttar Pradesh in their analysis for the period 1981–2012 using MK test. On the contrary, Guhathakurta and Rajeevan (2008) reported increasing monsoon rainfall trends in the western UP for the period of 1901–2003. Subash and Sikka (2014) did not find any significant trends in the sub-divisional rainfall data for the period of 1904–2003 in Uttar Pradesh.

3.4 Seasonal and annual teleconnections

The significant correlations of monsoon, post-monsoon and annual rainfall were depicted in Table 4. Except for the winter, all the seasonal and annual indices were significantly correlated with monsoon as well as the annual rainfall of the region. None of the IOD and ENSO indices were significantly correlated with the winter and pre-monsoon rainfall (data not presented).

It can be seen that the correlation coefficients (CC) of monsoon and annual rainfall were at par for all the four indices. The SST indices (Niño 3.4,Niño 3 and Niño 4) have higher correlation with both monsoonal and annual rainfall followed by the climatic indices (SOI and DMI). Niño 3.4 of monsoon season had the highest correlation with monsoon (− 0.64), while the annual rainfall had the highest correlation (− 0.66) with Niño 3.4 over the study area. The CC for the post-monsoon rainfall was having the highest correlations with the DMI. This implies the dominance of ENSO in monsoon and annual rainfall, while that of IOD in the post-monsoon rainfall. Similar findings on higher impacts of ENSO on rainfall in India have been reported by Kumar et al. (1995) and Whitaker et al. (2001). The correlation coefficients are approximately similar to the findings of

Table 4 Correlation analysis of seasonal and annual indices of ENSO and IOD with monsoon, post-monsoon and annual rainfall

Rainfall	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
DMI					
Monsoon	−0.15	−0.14	−0.33**	−0.50***	−0.39**
Post-monsoon	−0.21	−0.47***	−0.41***	−0.28*	−0.45***
Annual	−0.19	−0.26*	−0.41***	−0.52***	−0.48***
Niño 3.4					
Monsoon	0.02	−0.31*	−0.64***	−0.61***	−0.57***
Post-monsoon	0.07	−0.04	−0.27*	−0.22	−0.19
Annual	0.05	−0.27*	−0.66***	−0.62***	−0.57***
Niño 3					
Monsoon	0	−0.32**	−0.59***	−0.60***	−0.57***
Post-monsoon	0.06	−0.06	−0.25*	−0.25*	−0.21
Annual	0.04	−0.29*	−0.61***	−0.61***	−0.57***
Niño 4					
Monsoon	−0.05	−0.33**	−0.63***	−0.61***	−0.54***
Post-monsoon	−0.02	−0.12	−0.25*	−0.21	−0.2
Annual	−0.03	−0.32**	−0.64***	−0.60***	−0.53***
SOI					
Monsoon	−0.13	0.32**	0.62***	0.46***	0.49***
Post-monsoon	−0.13	0.15	0.25*	0.2	0.19
Annual	−0.19	0.34**	0.62***	0.47***	0.48***

*Significance at $p \leq 0.1$; **significance at $p \leq 0.05$; ***significance at $p \leq 0.01$

Ashok et al. (2001, 2019) and Jha et al. (2016) for monsoon rainfall over India. On the contrary, ENSO effects over Bangladesh are much remarkable which was reported by Ahmed et al. (2017) who illustrated weak teleconnections of ENSO and significant correlation of IODs with rainfall in Bangladesh, while in Saudi Arabia, both ENSO and IOD have almost equal teleconnections (Athar 2015). It can be concluded that monsoonal and annual rainfall amount over the Terai region seems to be better correlated with the ENSO, whereas the post-monsoon rainfall have higher correlations with the IOD. The increasing trend of IOD events and its higher correlations with the post-monsoon rainfall may lead to increase in extreme rainfall events in the post-monsoon season (Ajayamohan and Rao 2008). These findings may have implications for the seasonal as well as annual rainfall predictions. Further research can be extended on the evaluation of the recent climate models (Jain et al. 2019; Almazroui et al. 2020b) for the region to strengthen the rainfall predictions which will help in improving the adaptation strategies to climate change.

4 Conclusion

Our study revealed significant changes in monthly, seasonal, and annual rainfall series in the Terai region of UP, India during the past 65 years. None of the districts showed a significant increasing trends of rainfall in January, March, and July to December. The months of February, April, May, and December did not have any significant decrease in rainfall, rather they had a significant increase in some of the districts. Similarly, none of the seasonal and annual rainfall values (except pre-monsoon at Bahraich and Shravasti) showed any significant increasing trends of rainfall. In seasonal and annual rainfall data, only decreasing trends were significant. The overall average of the study area depicted a significant decrease in the long-term monthly (January, July, August, and October), seasonal (monsoon, post-monsoon), and annual rainfall. Monsoon, post-monsoon, and annual rainfall of the region were significantly correlated with both IOD and ENSO events. The teleconnections for monsoon and annual rainfall were higher with ENSO, whereas the post-monsoon rainfall had more correlations with IOD events. The findings would be useful for researchers, planners, and managers for planning efficient use of water resources.

Compliance with ethical standards

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