Range Management and Agroforestry, 2026
ISSN 0971-2070 (Print); 2249-5231 (Online)
https://doi.org/10.59515/rma.2026.v47.i2.1374

Research Article

Rainfall Trends in the Bundelkhand Region of India over 121 Years

Amit K. Singh[1*], R. N. Singh[2*], Avijit Ghosh[1], Sonam Sah[2], Lata Vishnoi[3], Debashis Roy[3], Bappa Das[4] and J. P. Singh[1]

[1]ICAR-Indian Grassland and Fodder Research Institute, Jhansi-284003, India
[2]ICAR-National Institute of Abiotic Stress Management, Baramati-413115, India
[3]India Meteorological Department, New Delhi-110003, India
[4]ICAR-Central Coastal Agricultural Research Institute, Goa-403402, India
[*]Corresponding author email: amit09bhu@gmail.com, ramnsingh.icar@gmail.com

Received: 1st September, 2025 Accepted: 15th April, 2026

Abstract

This study examined the long-term (1901-2021) spatio-temporal rainfall trends across 13 districts in the Bundelkhand region of central India. Gridded rainfall data of the India Meteorological Department (IMD) were analyzed using both parametric (Mann-Kendall, Spearman's Rho) and non-parametric (Simple Linear Regression) approaches, to detect monthly, seasonal and annual rainfall trends. Statistical tests showed a significant decreasing trend of rainfall in the region. The months of April to June have significantly increasing trends, while in the rest of the months, only decreasing trends were significant. Also, only decreasing trends were significant in seasonal rainfall and annual rainfall. The study area as a whole had a significant decrease in monsoon and annual rainfall. The Sen's slope indicated declining monsoon and annual rainfall at the rate of -1.064 and -1.316 mm/year ($p < 0.001$), whereas the slope of linear regression depicted a declining monsoon and annual rainfall of the region at the rate of -0.894 mm/year ($p < 0.1$) and -1.031 mm/year ($p < 0.05$), respectively. The results reveal the growing vulnerability of agriculture and the need for climate-resilient adaptation strategies in the semi-arid region of Bundelkhand. The decline in rainfall observed highlights significant practical and policy implications for water and agricultural management and planning in this region.

Keywords: Mann-Kendall test, Seasonal rainfall, Sen's slope, Spearman's Rho.

Introduction

Rainfall has a significant impact on the amount of water availability for agriculture and surface/groundwater storage. Substantial climate change and variability have emerged as a significant cause affecting social, economic, and environmental circumstances (Dad *et al*., 2021; Rahaman *et al*., 2022). This pertains to fluctuations in the average state and various climate parameters across different scales, surpassing specific weather events (IPCC, 2018). Over the recent years, a surge in the occurrence and intensity of extreme weather events has been observed (Ahokpossi 2018; Masroor *et al*., 2022). The aftermath of insufficient rainfall extends to drought, giving rise to profound water scarcities that ripple through the realms of human welfare and the natural world. This triggers a cascade of repercussions, ranging from food insecurity and the depletion of biodiversity to catastrophic environmental outcomes and a surge in human mortality (Al-Habsi *et al*., 2014; Habte *et al*., 2021; Rahaman *et al*., 2022). As per the findings of IPCC (2021), the Earth's surface temperature took a leap of 1.09ºC in 2011-2020, in contrast to the period between 1850 and 1900. The repercussions of this temperature surge are significant: heightened heat, intensified precipitation, and more frequent droughts, each escalating with additional warming. The continued warming trend poses the risk of depleting the vital carbon sinks of our planet, housed within plants, soils, and the vast expanse of the ocean (IPCC, 2021).

For the sustenance of every dimension of agriculture, water stands out as an indispensable and foundational natural asset. Meshram *et al.* (2017) noted that 68% of India's cultivated land relies predominantly on rain-fed agriculture. Consequently, any fluctuation in rainfall patterns is poised to exert a profound influence on the country's economic landscape and the output of food production. Recent studies have shown that monsoon rainfall may account for up to 85% of the region's total rainfall (Dikshit *et al*., 2019). Climate change is now

having a significant impact on India's rainfall patterns and amount. Given that timely water availability has a significant impact on the agricultural sector's output, rainfed agriculture is becoming more and more uncertain as a result of climate change. The shift in precipitation trend, which may be either increasing or decreasing, is most likely to be the main effect of climate change. The rainfall pattern controls the overall cropping pattern, productivity, and sustainability of the agricultural industry. Intensity and frequency of rainfall have a significant impact on human welfare and quality of life (Kumar *et al*., 2017). Droughts often have a wide footprint and pose major agri-socio-economic risks. As highlighted by Liu and Chen (2021), India ranks among the top ten countries confronting considerable socioeconomic vulnerabilities due to anticipated rises in drought incidents in climate projections. The Bundelkhand region of Uttar Pradesh bears the brunt of severe impact, frequently grappling with drought episodes that result in substantial economic setbacks and trigger mass migration. Researchers have delved into scrutinizing annual and seasonal shifts in rainfall patterns across diverse regions in India, as evidenced by studies conducted by Singh *et al.* (2020), Panda and Sahu (2019), Malik *et al.* (2019), and Shree and Kumar (2018). Kumar *et al.* (1992) recognized a significant decline in summer monsoon rainfall in Madhya Pradesh and parts of the northwest peninsular region of India. Additionally, Jana *et al.* (2017) delved into investigations concerning seasonal and annual rainfall trends, along with periodicity analyses specific to the Bundelkhand region. While various trend assessments have been conducted for the entire Indian region, none have definitively revealed a positive or negative trend in the average annual and seasonal rainfall for this area, as indicated by Chakraborty *et al.* (2013), Swain et al (2015) and Saha *et al.* (2018). To analyze trends in hydro-meteorological time series, various statistical tests, including both parametric and non-parametric ones, are employed (Singh *et al*., 2021). To the greatest extent of our knowledge, the monthly and seasonal trends of rainfall patterns have not yet been explored for the Bundelkhand region, which is considered a high productivity zone (rice-wheat) and a major contributor of food grain to the nation. Water scarcity caused by rainfall variability can have a significant influence on food production and the economy; thus, micro-level monitoring of rainfall variability will be critical in developing relief measures in response to meteorological anomalies such as unpredictable rainfall. With this background, we undertook this work to analyze the long-term monthly, seasonal and annual rainfall trends in the Bundelkhand region of India.

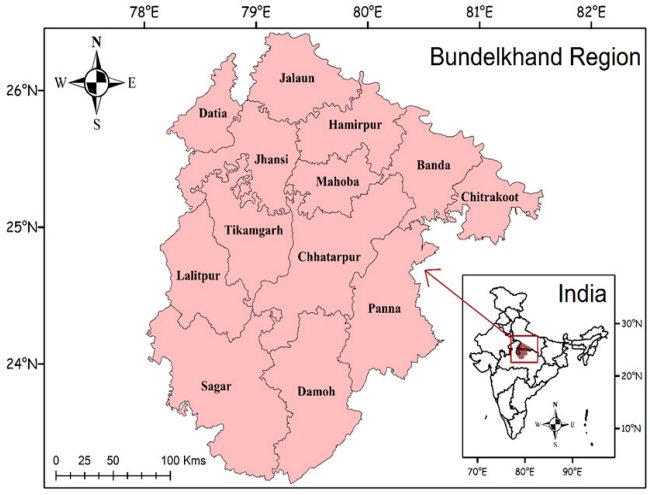

Fig 1. Districts of Bundelkhand region

Materials and Methods

Study site: The study was conducted in 13 districts in the Bundelkhand region of India (Fig 1). It is part of the central zone of India, situated between latitudes 23°20′ N and 26°20′ N and longitudes 78°20′ E and 81°40′ E. The area in Uttar Pradesh and Madhya Pradesh spans over 7.08 million hectares (Mha) and is characterized by hard rocks, undulating topography, and a variety of slopes. More than 80% of the population depends on the agriculture, livestock, and forestry sectors, making it mostly an agrarian economy. Under typical rainfall years, cereals make up the majority (54.6%) of the food grain production, followed by pulses (32.4%), oilseeds (8.0%), sugarcane (0.2%), and other crops (4.8%). According to historical data, the Bundelkhand region experiences an average annual rainfall of about 800 to 1000 mm over 40-42 rainy days. About 25% of the cropland in this rain-fed region is double-cropped.

Data sets: For this investigation, we utilized daily rainfall data from 1901-2021 (121 years), provided by the India Meteorological Department (IMD) at a grid size of 0.25° latitude × 0.25° longitude. The methodology for generating gridded data is elaborated in Pai *et al.* (2014). The daily rainfall records for each district were transformed into monthly data. There are four meteorological seasons in India: winter (January-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-December) as per the India Meteorological Department classifications (Singh *et al.*, 2020). The monthly data were cumulated across winter, pre-monsoon, monsoon, and post-monsoon

seasons to determine the total seasonal and annual rainfall for all districts. The analysis encompassed all 13 districts in the Bundelkhand region, where district-wise daily data were averaged to derive monthly, seasonal and annual data for the entire study area (Sah *et al.*, 2021).

Trend analysis: Methods, such as Mann-Kendall (MK), modified Mann-Kendall (MMK), Sen's slope (SS) estimator, Spearman's rank correlation, and simple linear regression (SLR), were employed to evaluate the trends and magnitudes of the seasonal and annual rainfall data. The rank-based non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) is employed to identify substantial trends 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; Singh *et al.*, 2021, Singh *et al.*, 2024). The standardized MK test statistic (Zmk) values may be positive or negative, indicating an increasing and decreasing trend, respectively. In contrast, the Hamed and Rao (1998) variance correction approach is implemented to analyze serially correlated data using the modified Mann-Kendall (MMK) test. The autocorrelation in the rainfall time series data was determined by employing the expressions of Shahin *et al.* (1993) and Haan (2002). The upper and lower critical values of the autocorrelation function have been identified using Anderson's test (Anderson, 1942). The Lag-1 autocorrelation coefficient, which acknowledges the serial correlation in the data series, was calculated and evaluated at 5% confidence level. MMK was implemented to identify the trend in the event that the lag-1 autocorrelation coefficient was significant (Kumar *et al.*, 2017). The null hypothesis (no trend) and alternate hypothesis (trend) were evaluated at significance levels of 10, 5 and 1%. A positive value of the standardized MMK test statistic (Zmmk) indicates an upward trend in the time series data, while a negative value of Zmmk indicates a downward trend. The Sen's slope estimator, a non-parametric statistical test, is implemented to determine the precise magnitude of trend (Theil, 1950; Sen, 1968). The Theil-Sen estimator has been frequently employed by hydrologists to ascertain the slope of trend lines in time series associated with water systems (Yue *et al.*, 2002; Mohsin and

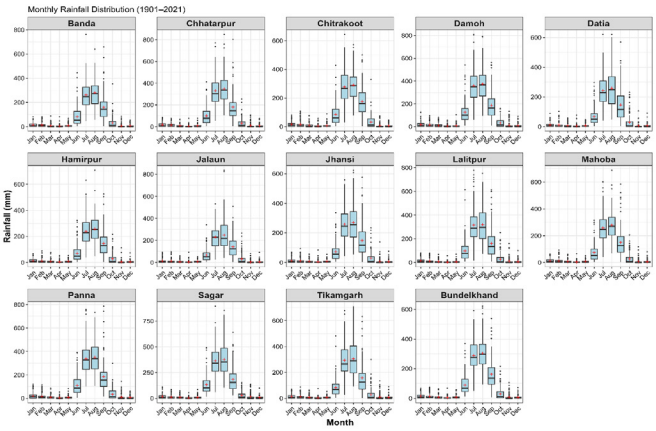

Fig 2. Monthly rainfall distribution during the period 1901-2021 in the study area

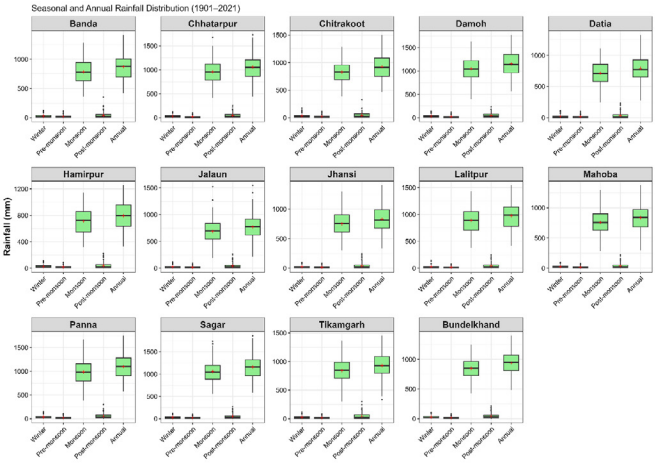

Fig 3. Seasonal and annual rainfall distribution during the period 1901-2021 in the study area

Gough, 2010; Dinpashoh *et al.*, 2011; Tabari *et al.*, 2012; Tabari and Aghajanloo, 2013). The slope of all data pairings is the determinant of the strength of the trend. One of the non-parametric methods commonly employed to confirm the existence or absence of trends is Spearman's rank correlation coefficient, or Spearman's Rho. One of the most frequently employed parametric models for identifying trends in time series data is simple linear regression. The positive and negative slope values (SLR) represent tendencies that are increasing and decreasing, respectively.

Results and Discussion

Summary of rainfall distribution: The monthly rainfall pattern in Bundelkhand is strongly dominated by the monsoon months (June-September) (Fig 2). The onset of the southwest monsoon in June leads to a sharp rise in rainfall, with peaks in July and August, which contribute

Table 1. Summary of monthly rainfall variations in Bundelkhand region.

District		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Banda	Mean ± SD	14.2 ± 17.1	12.5 ±17.7	7 ± 12.6	4.3 ± 9.5	8.8 ± 13.1	80.6 ± 79.7	261.7 ± 121	280.5 ± 110.3	159.3 ±109.3	30.3 ± 48.9	5.1 ±13.9	5.6 ± 10.2
	CV	120.4	142	180.8	218.9	149.9	98.9	46.3	39.3	68.6	161.5	272.9	181.7
Chhatarpur	Mean ± SD	16.7 ± 20.2	13.7 ±18.2	7.9 ± 12.4	4.4 ± 9.2	7.4 ±11.5	99.1 ± 81.2	330.1 ± 140.9	348.1 ± 141	181 ± 131.8	32 ± 47.6	10 ± 23.7	6.5 ±13
	CV	121.1	133	156.3	209.8	155.3	82	42.7	40.5	72.8	148.7	236.8	198.9
Chitrakoot	Mean ± SD	16.1 ± 19.2	15.6 ± 24	8.8 ± 14.4	4.1 ± 8.2	7.9 ± 12.8	85.6 ± 78	277.6 ± 116.8	290.1 ± 102.8	175.9 ± 102.5	32.1 ± 45.7	6.3 ± 15.8	5.5 ± 9.4
	CV	119.3	153.9	163.8	197.9	162	91.2	42.1	35.5	58.3	142.1	251.7	171.6
Damoh	Mean ± SD	18 ± 24.2	14.4 ± 19.6	10.3 ± 16.4	4.9 ± 9	7.3 ±12.8	126.9 ± 95.9	361.1 ±142.7	374.9 ± 140.6	186.5 ± 117.7	31.5 ± 38.1	11.6 ± 25.5	7.5 ± 14.6
	CV	134.5	135.6	159	183.9	175.8	75.5	39.5	37.5	63.2	121.1	219.9	196.2
Datia	Mean ± SD	10.7 ± 14.6	10 ± 18	5.8 ± 10.7	4 ± 10.2	7.2 ± 10.3	67.5 ± 58.5	242.8 ± 107.3	258 ± 122.6	145.6 ± 112.7	27.5 ± 48.3	5.1 ± 14.2	5.4 ±11.8
	CV	136.3	179.9	183.2	258.2	143	86.6	44.2	47.5	77.4	175.6	279.2	218.3
Hamirpur	Mean ± SD	13.5 ± 16.8	11.6 ± 17.7	7 ± 12.2	3.6 ± 7.5	7.5 ± 9.7	70.8 ± 65.6	238.9 ± 105.4	257.5 ± 109.3	145.2 ± 97.6	28.3 ± 43.2	4.6 ± 13.9	5.5 ±10.1
	CV	124.3	152.2	174.8	208.6	129.9	92.5	44.1	42.4	67.2	152.9	306.2	185.9
Jalaun	Mean ± SD	13.4 ± 18.2	11.7 ± 19.5	6.5 ± 11.1	4.2 ± 10.5	7.7 ± 9.4	66.9 ± 58.6	230.1 ± 103.1	248 ± 133.9	141.9 ± 95.1	30.3 ± 48.6	4.4 ± 12.5	5.3 ± 11.4
	CV	136	166.5	170.9	248.6	123.5	87.7	44.8	54	67	160.2	287.9	216.3
Jhansi	Mean ± SD	11.9 ± 15.5	11.1 ± 17.2	6.5 ± 11.1	4.1 ± 9.8	7.1 ± 9.3	73.4 ± 61.6	258.6 ± 112.9	270.7 ± 125	148 ± 112.5	28.6 ± 46.9	6.1 ± 17.2	5.5 ± 10.8
	CV	130.1	155.4	169.9	239.2	131.8	84	43.7	46.2	76	164.1	284.5	198.7
Lalitpur	Mean ± SD	15.2 ±19.5	11.5 ± 17.2	6.9 ± 11.6	2.9 ±6.6	5.9 ±9.9	96.9 ± 89.1	314.6 ± 146.9	319.6 ± 142.3	159.5 ± 125.8	27 ± 44.3	11.3 ± 28.1	6.6 ± 13.6
	CV	128.5	150	167.8	226.5	168.2	92	46.7	44.5	78.8	164.2	248.7	205.8
Mahoba	Mean ± SD	13.4 ±16.5	11.7 ± 18.2	6.6 ± 11.6	3.3 ±7.5	6.7 ± 9.3	72.9 ± 65.2	258 ± 111	279 ± 117.5	148.8 ± 109	26.6 ±40.2	6.4 ± 17.4	5.7 ± 11.8
	CV	123.2	155.2	176.9	223.5	139.4	89.5	43	42.1	73.3	151.1	273.4	206
Panna	Mean ± SD	20.2 ± 24.9	16.4 ± 21.9	9.9 ± 15.2	4.3 ± 7.9	7.5 ± 12.1	110.6 ± 85.5	338.8 ± 138.4	350.2 ± 133.5	185.8 ± 131.9	34.2 ± 46.3	9.9 ± 23	6.7 ± 12.2
	CV	123.4	133.9	154.2	182.9	160.6	77.3	40.9	38.1	71	135.4	231.6	181.7
Sagar	Mean ± SD	16.7 ± 22.6	12.6 ± 18.6	9.7 ± 15.4	4 ± 7.3	8.4 ± 13.2	131.4 ± 96.6	365.1 ± 145.3	377.6 ± 142.9	183.5 ± 121.3	28 ± 37.3	13.9 ± 30.1	8 ± 17.2
	CV	134.9	147.3	158.3	185.3	157.1	73.5	39.8	37.9	66.1	133	216.4	215.5
Tikamgarh	Mean ± SD	13.7 ± 17.1	12 ± 17	7.1 ± 11.9	3.8 ± 8.3	6.2 ± 9.4	85.2 ± 73.9	294.1 ± 124.8	306.3 ± 132	157.5 ± 125.2	28.2 ± 47.1	9.3 ± 22.8	6.3 ± 12.8
	CV	124.7	141.8	168.1	218.9	152.5	86.8	42.4	43.1	79.5	167.3	246.9	202.8
Bundelkhand	Mean ± SD	14.9 ± 16.7	12.7 ± 17.1	7.7 ± 11.3	4 ± 7.7	7.3 ± 9.4	89.8 ± 67.8	290.1 ± 103.9	304.7 ± 108.5	163 ±101.9	29.6 ± 40.7	8 ± 18	6.2 ± 10.8
	CV	112.2	135	147.4	192.9	127.7	75.5	35.8	35.6	62.5	137.7	225.3	176.1

Table 2. Summary of seasonal rainfall variations in Bundelkhand region

District		Winter	Pre Monsoon	Monsoon	Post Monsoon	Annual
Banda	Mean ± SD	26.6 ± 26	20.1 ± 22.4	782.1 ± 211.3	40.9 ± 52.1	869.8 ± 220.2
	CV	97.9	111.4	27	127.3	25.3
Chhatarpur	Mean ± SD	30.4 ± 27.9	19.7 ± 21	958.3 ± 244.4	48.6 ± 53.6	1056.9 ± 253.7
	CV	91.9	106.7	25.5	110.4	24
Chitrakoot	Mean ± SD	31.7 ± 32.3	20.8 ± 23.7	829.2 ± 208.2	43.9 ± 48.6	925.6 ± 222.6
	CV	102	113.5	25.1	110.7	24.1
Damoh	Mean ± SD	32.4 ± 30.8	22.5 ± 24.1	1049.4 ± 247.4	50.5 ± 49.7	1154.8 ± 262.7
	CV	95.1	107.2	23.6	98.3	22.8
Datia	Mean ± SD	20.7 ± 23.5	17 ± 18.5	713.9 ± 201.4	38 ± 50.5	789.6 ± 212.5
	CV	113.5	109.1	28.2	132.8	26.9
Hamirpur	Mean ± SD	25.2 ± 25.5	18.1 ± 18.3	712.5 ± 202	38.3 ± 46.5	794 ± 214.2
	CV	101.2	101.4	28.4	121.5	27
Jalaun	Mean ± SD	25.1 ±27.8	18.4 ± 18.6	686.8 ± 222.7	40 ± 49.6	770.3 ± 237
	CV	110.7	101.2	32.4	124.2	30.8
Jhansi	Mean ± SD	23 ± 24.3	17.7 ± 18.4	750.6 ±207.3	40.1 ± 50.3	831.3 ± 223
	CV	105.9	103.8	27.6	125.6	26.8
Lalitpur	Mean ± SD	26.6 ± 28.1	15.7 ± 17.3	890.6 ± 234.5	44.9 ± 52.3	977.9 ± 251.6
	CV	105.4	110	26.3	116.5	25.7
Mahoba	Mean ± SD	25.1 ± 25.1	16.6 ± 17.2	758.6 ± 211	38.7 ± 45.4	839 ± 218.7
	CV	100.1	103.8	27.8	117.3	26.1
Panna	Mean ± SD	36.6 ± 34.3	21.7 ± 23	985.3 ± 249.7	50.9 ±52.4	1094.5 ± 260.9
	CV	93.7	105.9	25.3	103	23.8
Sagar	Mean ± SD	29.4 ± 29.1	22.1 ± 21.8	1057.6 ± 245.5	49.9 ± 52.6	1159 ± 262.3
	CV	99.1	98.8	23.2	105.4	22.6
Tikamgarh	Mean ± SD	25.7 ± 25.8	17 ± 18.3	843 ± 218.8	43.7 ± 52.9	929.5 ± 234
	CV	100.2	107.2	26	121	25.2
Bundelkhand	Mean ± SD	27.6 ± 24.9	19 ± 17.6	847.5 ±187.4	43.7 ± 45	937.8 ± 199.1
	CV	90.2	92.5	22.1	103	21.2

the largest share of annual rainfall. Mean rainfall during July (230–365 mm) and August (248–378 mm) is relatively stable, with lower variability (CV 35–55%), underscoring their importance for kharif agriculture. September shows declining rainfall with higher variability, indicating increased risk during crop reproductive stages.

On average, Bundelkhand receives 290 mm in July and 305 mm in August, highlighting reliance on a narrow monsoon window. In seasonal analysis (Fig 3), monsoon rainfall dominates (687–1058 mm), while winter and pre-monsoon rainfall remain low (15–37 mm). Post-monsoon rainfall is modest (38–51 mm) but highly variable. Variability is highest in winter and pre-monsoon seasons (CV > 90–110%), whereas monsoon rainfall is relatively stable (CV: 22–32%).

Annual rainfall ranges from 770 to 1159 mm across districts, with moderate variability (CV: 21–31%). Overall, the region receives 938 mm annually, of which 90% (848 mm) occurs during the monsoon season. Detailed data of all districts and the whole region are provided in Tables 1 and 2.

Monthly rainfall trends: The results of statistical tests, including the Mann-Kendall (Zmk)/modified Mann-Kendall (Zmmk), Spearman's rank correlation (Zspear), and simple linear regression (SLR) applied to monthly rainfall data are summarized in Table 3. Trends analysis indicated decreasing trends in January and February rainfall across all the districts of the Bundelkhand region, except for Mahoba. Significant decreases were observed in Damoh (Zmk, Zspear) in January, as well as in Chitrakut (Zmk), Damoh (Zmk, Zspear), Jalaun (Zmk, Zspear), and Panna (Zspear) in February. March exhibited non-significant positive trends in five districts, while the remaining districts showed non-significant negative trends. During April, rainfall trends varied among the districts, with six districts showing an increase while the remaining seven exhibited a decrease. Out of these, significant increases were observed in Chhatarpur (Zmk,

Table 3. Results of the statistical tests for the monthly rainfall (1901-2021) in different districts

District	Test	Month											
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Banda	Zmk/Zmmk	-0.376	-0.701	0.063	0.907	2.190**	2.131**	-1.557	-2.561**	-0.365	-0.19	0.027	0.343
	SS	0	0	0	0	0.014	0.296	-0.558	-0.898	-0.097	0	0	0
	Zspear	-0.318	-0.736	0.123	0.984	2.150**	2.129**	-1.362	-2.425**	-0.506	-0.202	-0.035	0.344
	SR	-0.029	-0.067	0.011	0.09	0.196	0.194	-0.124	-0.221	-0.046	-0.018	-0.003	0.031
	SLR	-0.033	-0.01	0.031	0.005	0.086**	0.42*	-0.446	-0.688*	-0.107	-0.144	-0.071	0.004
Chhatarpur	Zmk/Zmmk	-0.719	-0.389	0.797	1.791*	0.922	0.544	-2.009**	-0.652	0.365	1.139	-0.733	0.048
	SS	-0.004	0	0	0	0.003	0.076	-0.659	-0.239	0.086	0.005	0	0
	Zspear	-0.683	-0.42	0.672	1.737*	1.115	0.566	-1.38	-0.685	0.417	1.062	-0.636	0.032
	SR	-0.062	-0.038	0.061	0.159	0.102	0.052	-0.126	-0.063	0.038	0.097	-0.058	0.003
	SLR	-0.037	0.013	0.015	0.005	0.058*	0.133	-0.784**	-0.137	0.095	0.083	-0.093	0.013
Chitrakut	Zmk/Zmmk	-0.585	-1.82*	-0.59	-0.595	-1.271	1.687*	-1.969**	-2.659***	-0.081	-0.373	-0.124	0.315
	SS	-0.002	-0.01	0	0	0	0.233	-0.774	-0.931	-0.023	0	0	0
	Zspear	-1.127	-1.498	-0.654	-0.623	-1.072	1.740*	-2.008**	-2.697	-0.056	-0.239	-0.112	0.131
	SR	-0.103	-0.137	-0.06	-0.057	-0.098	0.159	-0.183	-0.246	-0.005	-0.022	-0.01	0.012
	SLR	-0.047	-0.01	0.007	0.005	0.052	0.339	-0.737**	-0.873***	0.055	-0.119	-0.025	-0.013
Damoh	Zmk/Zmmk	-1.8*	-1.865*	-1.285	-0.087	-1.131	0.759	-1.593	-1.382	-1.705*	-0.414	-1.649*	-0.868
	SS	-0.011	-0.016	0	0	0	0.133	-0.608	-0.574	-0.479	0	0	0
	Zspear	-1.940*	-1.909*	-1.279	-0.085	-1.115	0.73	-1.693*	-1.369	-1.641	-0.384	-1.649*	-0.94
	SR	-0.177	-0.174	-0.117	-0.008	-0.102	0.067	-0.155	-0.125	-0.15	-0.035	-0.151	-0.086
	SLR	-0.05	-0.012	-0.051	-0.015	0.038	0.397	-0.478	-0.607	-0.37	-0.107	-0.088	-0.014
Datia	Zmk/Zmmk	-0.577	-0.874	-0.58	1.528	2.053**	1.279	-0.41	-0.67	0.562	0.794	-0.032	0.518
	SS	0	0	0	0	0.011	0.132	-0.104	-0.186	0.128	0	0	0
	Zspear	-0.623	-0.845	-0.626	1.555	2.329**	1.281	-0.338	-0.725	0.518	0.672	-0.101	0.527
	SR	-0.057	-0.077	-0.057	0.142	0.213	0.117	-0.031	-0.066	0.047	0.061	-0.009	0.048
	SLR	0.011	0.038	-0.018	0.02	0.067**	0.204	-0.093	-0.284	0.1	0.099	-0.021	0.026
Hamirpur	Zmk/Zmmk	-0.586	-0.977	0.083	1.97**	2.71***	0.697	-1.727*	-2.76***	-1.682*	0.533	0.726	1.364
	SS	0	-0.002	0	0	0.021	0.065	-0.609	-1.188	-0.444	0	0	0
	Zspear	-0.461	-1.04	0.109	1.902	2.71***	0.672	-1.799*	-3.73	-1.767*	0.504	0.699	1.276
	SR	-0.042	-0.095	0.01	0.174	0.247	0.061	-0.164	-0.34	-0.161	0.046	0.064	0.116
	SLR	-0.028	-0.08	-0.006	-0.031	0.05	0.053	-0.71**	-1.31***	-0.562*	-0.1	-0.023	0.01
Jalaun	Zmk/Zmmk	-1.611	-1.941*	-1.194	-0.545	0.378	0.181	-1.998**	-3.605***	-2.027**	0.42	-1.322	0.105
	SS	-0.019	-0.015	0	0	0	0.022	-0.668	-1.13	-0.469	0	0	0
	Zspear	-1.639	-1.918*	-1.164	-0.542	0.37	0.188	-2.380**	-3.562***	-2.044**	0.31	-1.302	0.079
	SR	-0.15	-0.175	-0.106	-0.05	0.034	0.017	-0.217	-0.325	-0.187	0.028	-0.119	0.007

Cont...

	SLR	-0.055	-0.013	-0.039	-0.042	0.007	-0.09	-0.675**	-1.012***	-0.448*	0.036	-0.039	-0.017
Jhansi	Zmk/Zmmk	-1.164	-0.553	0.591	1.736*	1.794*	1.001	-1.755*	-0.603	-0.184	0.674	-0.398	0.178
	SS	-0.003	0	0	0	0.008	0.122	-0.354	-0.215	-0.053	0	0	0
	Zspear	-1.148	-0.633	0.653	1.751*	1.930*	1.023	-0.961	-0.52	-0.17	0.669	-0.392	0.163
	SR	-0.105	-0.058	0.06	0.16	0.176	0.093	-0.088	-0.047	-0.015	0.061	-0.036	0.015
	SLR	-0.029	0.01	0.005	0.018	0.072*	0.373	-0.516	-0.372	-0.025	0.026	-0.031	0.025
Lalitpur	Zmk/Zmmk	-1.249	-1.305	-0.514	-1.558	-0.403	0.092	-2.955***	0.052	-0.701	-0.87	-1.860*	-0.67
	SS	0	-0.001	0	0	0	0.011	-0.73	0.015	-0.162	0	0	0
	Zspear	-1.187	-1.241	-0.568	-1.613	-0.433	0.069	-1.839*	-0.063	-0.682	-0.924	-2.132**	-0.737
	SR	-0.108	-0.113	-0.052	-0.147	-0.04	0.006	-0.168	-0.006	-0.062	-0.084	-0.195	-0.067
	SLR	-0.046	-0.003	-0.014	-0.028*	-0.015	0.191	-0.772*	-0.125	-0.182	-0.07	-0.112	-0.005
Mahoba	Zmk/Zmmk	0.578	0.127	1.297	2.183**	3.270***	1.947*	-0.481	-0.267	0.141	1.870*	0.119	1.5
	SS	0	0	0	0	0.007	0.22	-0.129	-0.096	0.028	0.008	0	0
	Zspear	0.591	0.059	1.267	2.121**	3.245***	1.887*	-0.402	-0.36	0.087	1.875*	0.11	1.064
	SR	0.054	0.005	0.116	0.194	0.296	0.172	-0.037	-0.033	0.008	0.171	0.01	0.097
	SLR	-0.016	0.031	0.03	-0.006	0.068**	0.315*	-0.289	-0.098	0.125	0.023	-0.038	0.004
Panna	Zmk/Zmmk	-1.501	-1.597	-1.414	-0.587	-2.814***	1.078	-3.106***	-1.808*	-0.612	-0.304	-1.896*	-1.04
	SS	-0.02	-0.024	0	0	-0.016	0.186	-0.685	-0.61	-0.164	0	0	0
	Zspear	-1.582	-1.706*	-1.462	-0.613	-2.746***	1.043	-1.419	-1.422	-0.806	-0.36	-1.904*	-1.195
	SR	-0.144	-0.156	-0.133	-0.056	-0.251	0.095	-0.13	-0.13	-0.074	-0.033	-0.174	-0.109
	SLR	-0.073	-0.04	-0.026	-0.034	-0.038	0.209	-0.655	-0.423	-0.173	-0.213	-0.072	-0.032
Sagar	Zmk/Zmmk	-1.359	-1.379	-0.315	-0.294	-0.616	0.607	-0.77	0.276	-1.324	-0.138	-0.984	-0.422
	SS	-0.007	-0.007	0	0	-0.001	0.121	-0.431	0.119	-0.366	0	0	0
	Zspear	-1.365	-1.42	-0.225	-0.332	-0.775	0.525	-1.076	0.256	-1.316	-0.222	-1.028	-0.512
	SR	-0.125	-0.13	-0.021	-0.03	-0.071	0.048	-0.098	0.023	-0.12	-0.02	-0.094	-0.047
	SLR	-0.054	0.01	-0.016	-0.014	-0.009	0.488*	-0.224	0.092	-0.115	-0.036	-0.068	0.001
Tikamgarh	Zmk/Zmmk	-1.112	-1.292	-0.263	-0.924	-0.485	-0.123	-1.965	0.15	-0.665	-1.117	-2.118	-1.031
	SS	0	-0.001	0	0	0	-0.017	-0.698	0.077	-0.145	0	0	0
	Zspear	-1.118	-1.237	-0.207	-0.897	-0.485	-0.069	-1.635	0.064	-0.65	-0.662	-2.183**	-1.081
	SR	-0.102	-0.113	-0.019	-0.082	-0.044	-0.006	-0.149	0.006	-0.059	-0.06	-0.199	-0.099
	SLR	-0.043	-0.012	-0.007	-0.031*	-0.021	0.169	-0.743*	-0.116	-0.137	-0.065	-0.122	0.002
Bundelkhand	Zmk/Zmmk	-1.008	-1.051	-0.186	0.884	1.275	1.181	-2.005**	-1.602	-0.733	0.444	-0.898	0.104
	SS	-0.018	-0.015	0	0.002	0.015	0.169	-0.64	-0.516	-0.175	0.007	0	0
	Zspear	-0.833	-1.096	-0.165	0.863	1.361	1.166	-1.871*	-1.534	-0.812	0.433	-0.868	0.119
	SR	-0.076	-0.1	-0.015	0.079	0.124	0.106	-0.171	-0.14	-0.074	0.039	-0.079	0.011
	SLR	-0.038	-0.006	-0.007	-0.011	0.032	0.246	-0.548**	-0.458	-0.134	-0.045	-0.062	0

***Significant at 1% ; **Significant at 5% ; *Significant at 10% ; Bold numbers denote Zmmk results

Zspear), Hamirpur (Zmk), Jhansi (Zmk, Zspear), and Mahoba (Zmk, Zspear), whereas significant decreasing trends were only found in Lalitpur (SLR) and Tikamgarh (SLR) districts. The long-term monthly rainfall analysis during the month of May revealed significant positive trends in six districts, except for Panna, which displayed a significant negative trend. Similarly, June displayed increasing trends in all districts except Tikamgarh, with significant increases noted in Banda (Zmk, Zspear, m), Chitrakut (Zmk, Zspear), Mahoba (Zmk, Zspear, m), and Sagar (SLR). In July, all 13 districts experienced decreasing rainfall trends, with nine districts showing statistically significant trends as indicated by at least one of the three tests. Similarly, only negative trends of monthly precipitation were found significant in the months of August and September across the districts. Negative values demonstrate a declining trend in the data, which is particularly evident in the monsoon months (July, August, and September) in the districts of the Bundelkhand region. October showed increasing trends in six districts, with significant positive values observed in Mahoba. November displayed increasing trends in all districts except three, with significant trends found in Damoh (Zmk, Zspear), Lalitpur (Zmk, Zspear), Panna (Zmk, Zspear), and Tikamgarh (Zspear). For the month of December, the trends were found non-significant across all the 13 districts. Overall, long-term monthly rainfall trends across the entire region indicated decreases in January, February, March, July, August, September, and November, while increases were observed in April, May, June, October, and December. However, out of all the 12 months, only the decreasing trend of July rainfall was found to be statistically significant. July represents the core month for monsoon onset and crop establishment in the region; therefore, its significant declining trend poses risks of delayed sowing, poor crop germination, and early-season moisture stress, especially in predominantly rainfed farming systems. This reduction in July rainfall can affect kharif crop growth, increasing the likelihood of early to mid-season droughts even in years with near-normal total monsoon rainfall. To mitigate risk associated with declining July rainfall, agricultural strategies must emphasize flexible and rainfall-contingent sowing windows, promotion of short-duration and drought-tolerant crop varieties, and strengthened contingency crop planning. Greater emphasis is also required on promotion of in-situ soil moisture conservation practices and prioritization of protective and supplemental irrigation during crop establishment and early vegetative stages.

Seasonal and annual rainfall trends: The analysis of seasonal winter rainfall through three distinct tests revealed a prevalent decreasing trend in the majority of the districts (12 out of 13), as indicated by negative values of Zmk/Zmmk, Zspear tests, and SLR, except for the Mahoba district, which showed an increase in rainfall (Table 4). Present findings for pre-monsoon rainfall patterns revealed increasing trends in Banda, Chattarpur, Datia, Hamipur, Jhansi, and Mahoba districts, Chitrakut, Damoh, Jalaun, Lalitpur, Panna, Sagar and Tikamgarh recorded decreasing trends in the pre-monsoon rainfall, respectively. Furthermore, analysis of seasonal long-term trends in monsoon rainfall indicated decreases across all 13 districts. Similarly, post-monsoon rainfall exhibited decreasing trends in Banda, Chattarpur, Chitrakut, Damoh, Jalaun, Lalitpur, Panna, Sagar, and Tikamgarh districts, while trends were observed to be increasing for Datia, Hamirpur, Jhansi, and Mahoba districts. Consistent with monsoon seasonal rainfall, all districts showed declining trends in annual rainfall as indicated by Zmk/Zmmk, Zspear, and m values. Overall, statistical analyses confirmed the significance of decreasing trends in winter, monsoon, post-monsoon, and annual rainfall. However, in the case of pre-monsoon rainfall, four districts displayed significant increases, while two exhibited significant decreases. Furthermore, the three tests indicated significant decreasing trends in both monsoon and annual rainfall across the entire Bundelkhand region.

The long-term rainfall trend analysis shows declining trends in monsoon months (July–September) and increasing trends during pre-monsoon and post-monsoon months. The significant decline in July rainfall critically affects the kharif crop establishment phase. During this period, risks of delayed sowing and early-season moisture stress increase. The increased rainfall in the May-June period, although it supports the pre-sowing soil moisture, could not correlate with agronomic utility in July. The consistent reduction in rainfall during the monsoon months indicates increasing uncertainty in rainfed agriculture, necessitating a shift toward climate-resilient cropping systems. The localized increase in pre-monsoon rainfall in some districts highlights opportunities for strengthening rainwater harvesting and in-situ soil moisture conservation to buffer monsoon deficits. These changing rainfall trends are also likely to influence the change in existing cropping systems, sowing strategies and overall farm management. A transition from long-duration water intensive crop towards short-duration and drought-tolerant crops like pulses and millets may become essential to survive these trends. Declining trends in winter, post-monsoon and annual rainfall in the area increase dependence on irrigation and limited groundwater resources. Policies should prioritize supplemental and micro-irrigation, particularly during critical crop growth stages, and promote district-specific adaptation strategies rather than uniform regional planning. To increase the resilience of agriculture and sustainable management of water resources in the Bundelkhand region, the inclusion of

Table 4. Results of the statistical tests for the seasonal rainfall over the period 1901-2021

District	Test	Season				
		Winter	**Pre- Monsoon**	**Monsoon**	**Post- Monsoon**	**Annual**
Banda	Zmk/**Zmmk**	**-0.734**	2.395**	-1.871*	**-0.607**	-1.947*
	SS	-0.037	0.087	-1.102	-0.029	-1.375
	Zspear	-0.838	2.344**	-1.741*	-0.512	-1.875*
	SR	-0.077	0.214	-0.159	-0.047	-0.171
	SLR	-0.043	0.123*	-0.822	-0.212	-0.954
Chhatarpur	Zmk/**Zmmk**	-0.585	1.176	**-2.616*** **	-0.448	**-2.347****
	SS	-0.026	0.03	-1.022	-0.016	-1.167
	Zspear	-0.65	1.122	-1.461	-0.386	-1.524
	SR	-0.059	0.102	-0.133	-0.035	-0.139
	SLR	-0.024	0.078	-0.693	0.003	-0.636
Chitrakut	Zmk/**Zmmk**	**-1.455**	-0.39	**-1.528**	**-0.803**	**-1.58**
	SS	-0.079	-0.002	-1.293	-0.029	-1.428
	Zspear	-1.576	-0.358	-1.771	-0.534	-1.912*
	SR	-0.144	-0.033	-0.162	-0.049	-0.175
	SLR	-0.057	0.063	-1.216*	-0.157	-1.367*
Damoh	Zmk/**Zmmk**	-1.636	**-1.592**	-1.803	**-1.838***	-2.050**
	SS	-0.077	-0.061	-1.307	-0.135	-1.535
	Zspear	-1.721*	-1.686*	-1.794	-2.033**	-2.069**
	SR	-0.157	-0.154	-0.164	-0.186	-0.189
	SLR	-0.062	-0.028	-1.058	-0.209	-1.357*
Datia	Zmk/**Zmmk**	-0.159	**1.648***	**-0.365**	0.516	**-0.242**
	SS	0	0.046	-0.236	0.008	-0.133
	Zspear	-0.226	2.036**	-0.385	0.466	-0.297
	SR	-0.021	0.186	-0.035	0.043	-0.027
	SLR	0.049	0.068	-0.074	0.104	0.148
Hamirpur	Zmk/**Zmmk**	**-2.528****	1.566	**-3.892**	0.253	**-3.625*****
	SS	-0.088	0.047	-2.306**	0.009	-2.593***
	Zspear	-1.753*	1.489	-3.804	0.272	-3.888***
	SR	-0.16	0.136	-0.347	0.025	-0.355
	SLR	-0.108	0.014	-2.531***	-0.112	-2.737***
Jalaun	Zmk/**Zmmk**	**-2.353****	-0.887	**-3.341*****	**-0.271**	**-2.420****
	SS	-0.07	-0.028	-2.427**	-0.003	-2.669***
	Zspear	-2.121**	-0.912	-3.974***	-0.243	-3.791***
	SR	-0.194	-0.083	-0.363	-0.022	-0.346
	SLR	-0.067	-0.073	-2.225***	-0.02	-2.386***
Jhansi	Zmk/**Zmmk**	-0.663	1.981**	-1.476	0.217	**-1.341**
	SS	-0.018	0.056	-1.071	0.003	-0.956
	Zspear	-0.788	1.889*	-1.384	0.198	-1.338
	SR	-0.072	0.172	-0.126	0.018	-0.122
	SLR	-0.019	0.096	-0.54	0.02	-0.443
Lalitpur	Zmk/**Zmmk**	-1.19	-0.8	-1.539	**-1.543**	-1.880*
	SS	-0.051	-0.017	-1.018	-0.1	-1.358
	Zspear	-1.201	-0.869	-1.643	-1.724*	-2.092**
	SR	-0.11	-0.079	-0.15	-0.157	-0.191
	SLR	-0.049	-0.057	-0.888	-0.188	-1.181*

Cont...

Mahoba	Zmk/**Zmmk**	**0.198**	2.760***	-0.293	**0.715**	-0.289
	SS	0.005	0.047	-0.212	0.014	-0.234
	Zspear	0.217	2.761***	-0.319	0.621	-0.259
	SR	0.02	0.252	-0.029	0.057	-0.024
	SLR	0.015	0.091*	0.053	-0.01	0.149
Panna	Zmk/**Zmmk**	**-1.556**	-2.218**	**-1.784***	**-1.726***	**-3.049*****
	SS	-0.103	-0.076	-1.414	-0.165	-2.054**
	Zspear	-1.920*	-2.222**	-1.777*	-1.809*	-2.531**
	SR	-0.175	-0.203	-0.162	-0.165	-0.231
	SLR	-0.113	-0.098	-1.043	-0.317**	-1.571**
Sagar	Zmk/**Zmmk**	-1.488	-1.087	-0.002	**-1.353**	-0.002
	SS	-0.064	-0.046	-0.001	-0.121	-0.002
	Zspear	-1.636	-1.055	-0.1	-1.578	-0.229
	SR	-0.149	-0.096	-0.009	-0.144	-0.021
	SLR	-0.045	-0.039	0.242	-0.103	0.055
Tikamgarh	Zmk/**Zmmk**	-1.119	-1.038	-1.427	-1.737*	-1.848*
	SS	-0.048	-0.017	-1.0	-0.098	-1.341
	Zspear	-1.142	-1.044	-1.434	-1.766*	-1.940*
	SR	-0.104	-0.095	-0.131	-0.161	-0.177
	SLR	-0.055	-0.059	-0.827	-0.185	-1.126
Bundelkhand	Zmk/**Zmmk**	-1.08	0.706	**-2.591*****	**-0.694**	-2.274**
	SS	-0.049	0.022	-1.064	-0.051	-1.316
	Zspear	-1.144	0.68	-2.061**	-0.701	-2.365**
	SR	-0.104	0.062	-0.188	-0.064	-0.216
	SLR	-0.044	0.014	-0.894*	-0.107	-1.031**

***Significant at 1%; **Significant at 5% ; *Significant at 10% ; Bold numbers denote Zmmk results

long-term rainfall trend information into agro-advisory services and drought preparedness, as well as watershed development program will be a necessity.

Conclusion

In summary, our investigation brought to light considerable variations in monthly, seasonal, and annual rainfall patterns within the Bundelkhand region of Uttar Pradesh and Madhya Pradesh, India, spanning over a period of 121 years. The comprehensive analysis revealed decreasing trends in the monthly rainfall values for January, February, March, July, August, September, and November, contrasting with slightly increasing trends observed in April, May, June, October and December. The seasonal results highlight the decreasing winter, monsoon, post-monsoon and annual rainfall over the region. These findings underscore the dynamic and noteworthy shifts in precipitation trends over the studied period in the districts of the Bundelkhand region as well as the region as a whole. Overall, this study highlights the urgent need for integrated, climate-resilient agricultural and water management strategies that take into account the changing rainfall patterns to sustain agricultural productivity in the region.

Acknowledgement

The authors gratefully acknowledge the Indian Council of Agricultural Research, New Delhi, for providing institutional support necessary for conducting this research.

References

Ahokpossi, Y. 2018. Analysis of the rainfall variability and change in the Republic of Benin (West Africa). Hydrological Sciences Journal 63(15-16): 2097-2123.

Al-Habsi, M., L. Gunawardhana and G. Al-Rawas. 2014. Trend analysis of climate variability in Salalah, Oman. International Journal of Studies in Research Technology and Management, 2: 168-171.

Anderson, R. L. 1942. Distribution of the serial correlation coefficient. The Annals of Mathematical Statistics 13(1): 1-13.

Chakraborty, S., R. P. Pandey, U. C. Chaube and S. K. Mishra. 2013. Trend and variability analysis of rainfall series at Seonath River Basin, Chhattisgarh (India). International Journal of Applied Sciences and Engineering Research 2(4): 425-434.

Dad, J. M., M. Muslim, I. Rashid and Z. A. Reshi. 2021. Time series analysis of climate variability and trends

in Kashmir Himalaya. Ecological Indicators 126: 107690.

Dikshit, A., N. Satyam and B. Pradhan. 2019. Estimation of rainfall-induced landslides using the TRIGRS model. Earth Systems and Environment 3: 575-584.

Dinpashoh, Y., D. Jhajharia, A. Fakheri-Fard, V. P. Singh and E. Kahya. 2011. Trends in reference crop evapotranspiration over Iran. Journal of Hydrology 399(3-4): 422-433.

Gajbhiye, S., C. Meshram, R. Mirabbasi and S. K. Sharma. 2016. Trend analysis of rainfall time series for Sindh River Basin in India. Theoretical and Applied Climatology 125(3-4): 593-608.

Haan, C. 2002. Statistical Methods in Hydrology. 2nd edn. Iowa State University Press.

Habte, A., G. Mamo, W. Worku, D. Ayalew and S. Gayler. 2021. Spatial variability and temporal trends of climate change in southwest Ethiopia. Advances in Meteorology 2021(2): 1-13. DOI: 10.1155/2021/3863530.

Hamed, K. H. and A. Ramachandra Rao. 1998. A modified Mann-Kendall trend test for autocorrelated data. Journal of Hydrology 204(1-4): 182-196.

IPCC. 2018. Summary for policymakers. In: V. Masson-Delmotte and Associates (eds.). Global warming of 1.5 °C. Cambridge University Press, Cambridge, UK. pp. 3-24.

IPCC. 2021. Summary for policymakers. In: V. Masson-Delmotte and Associates (eds.). Climate Change 2021: the Physical Science Basis. Cambridge University Press, Cambridge, UK. pp. 3-32.

Jana, C., N. M. Alam, D. Mandal, M. Shamim and R. Kaushal. 2017. Spatio-temporal rainfall trends in the twentieth century for Bundelkhand region, India. Journal of Water and Climate Change 8(3): 441-455.

Kendall, M. G. 1975. Rank Correlation Methods. 4th edn. Charles Griffin.

Kumar, K. R., G. B. Pant, B. Parthasarathy and N. A. Sontakke. 1992. Spatial and subseasonal patterns of long-term trends of Indian summer monsoon rainfall. International Journal of Climatology 12(3): 257-268.

Kumar, N., C. C. Panchal, S. K. Chandrawanshi and J. D. Thanki. 2017. Analysis of rainfall using Mann-Kendall trend, Sen's slope and variability in south Gujarat, India. Mausam 68(2): 205-222.

Liu, Y. and J. Chen. 2021. Future global socioeconomic risk to droughts under climate change. Science of the Total Environment 751: 142-159.

Malik, A., A. Kumar, P. Guhathakurta and O. Kisi. 2019. Spatial-temporal trend analysis of rainfall using innovative trend analysis. Arabian Journal of Geosciences 12: 1-23.

Mann, H. B. 1945. Non-parametric tests against trend. Econometrica 13(3): 245-259.

Masroor, M., H. Sajjad, S. Rehman, R. Singh, M. H. Rahaman, M. Sahana, R. Ahmed and R. Avtar. 2022. Relationship between drought and soil erosion in the Godavari middle sub-basin, India. Geoscience Frontiers 13(2): 101312.

Meshram, S. G., V. P. Singh and C. Meshram. 2017. Long-term trend and variability of precipitation in Chhattisgarh State, India. Theoretical and Applied Climatology 129: 729-744.

Mishra, A. K. and V. P. Singh. 2010. A review of drought concepts. Journal of Hydrology 391(2): 202-216.

Mohsin, T. and W. A. Gough. 2010. Trend analysis of long-term temperature time series in the Greater Toronto area. Theoretical and Applied Climatology 101(3): 311-327.

Pai, D. S., L. Sridhar, M. Rajeevan, O. P. Sreejith, N. S. Satbhai and B. Mukhopadhyay. 2014. Development of high-resolution daily gridded rainfall data over India. Mausam 65(1): 1-18.

Panda, A. and N. Sahu. 2019. Trend analysis of seasonal rainfall and temperature pattern in Odisha, India. Atmospheric Science Letters 20(10): e932.

Pingale, S. M., D. Khare, M. K. Jat and J. Adamowski. 2014. Spatial and temporal trends of rainfall and temperature in Rajasthan, India. Atmospheric Research 138: 73-90.

Rahaman, M. H., M. Masroor, S. Rehman, R. Singh, R. Ahmed, M. Sahana and H. Sajjad. 2022. Climate variability and water resources: Bridging knowledge gaps. Water Resources 49(4): 699-710.

Sah, S., R. N. Singh, G. Chaturvedi and B. Das. 2021. Trends, variability and teleconnections of long-term rainfall in the Terai region of India. Theoretical and Applied Climatology 143: 291-307.

Saha, S., D. Chakraborty, R. K. Paul, S. Samanta and S. B. Singh. 2018. Disparity in rainfall trends across India. Theoretical and Applied Climatology 134: 381-395.

Sen, P. K. 1968. Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association 63(324): 1379-1389.

Shahin, M., H. J. L. van Oorschot and S. J. de Lange. 1993. Statistical analysis in water resources engineering. A. A. Balkema Pulishers, Lisse. pp. 1-394.

Shifteh Some'e, B., A. Ezani and H. Tabari. 2012. Spatio-temporal trends of precipitation in Iran. Atmospheric Research 113: 1-12.

Shree, S. and M. Kumar. 2018. Seasonal and annual rainfall trends for Ranchi district, India. Environmental Earth Sciences 77(19): 693.

Singh, R. N., S. Sah, B. Das, L. Vishnoi and H. Pathak. 2020. Spatio-temporal trends and variability of rainfall in Maharashtra, India. Theoretical and Applied Climatology 142: 1-16.

Singh, R. N., S. Sah, B. Das, R. Jaiswal, A. K. Singh, K. S. Reddy and H. Pathak. 2024. Innovative and polygonal trend analysis of temperature in agro-climatic zones of India. Scientific Reports 14: 29914.

Singh, R. N., S. Sah, B. Das, S. Potekar, A. Chaudhary and H. Pathak. 2021. Innovative trend analysis of rainfall in India during 1901-2019. Theoretical and Applied Climatology 145: 821-838.

Suryavanshi, S., A. Pandey, U. C. Chaube and N. Joshi. 2014. Long-term climatic changes in Betwa Basin, India. Theoretical and Applied Climatology 117(4): 403-418.

Swain, S., M. Verma and M. K. Verma. 2015. Statistical trend analysis of monthly rainfall for Raipur District, Chhattisgarh. International Journal of Advanced Engineering Research Studies 4(2): 87-89.

Tabari, H. and M. B. Aghajanloo. 2013. Temporal pattern of aridity index in Iran. International Journal of Climatology 33(2): 396-409.

Tabari, H., B. S. Some'e and M. R. Zadeh. 2011. Testing for long-term trends in climatic variables in Iran. Atmospheric Research 100 (1): 132-140.

Tabari, H., H. Abghari and P. Hosseinzadeh Talaee. 2012. Temporal trends of drought and rainfall in Iran. Hydrological Processes 26(22): 3351-3361.

Theil, H. 1950. A rank-invariant method of linear and polynomial regression. Mathematics 392: 387-392.

Yue, S., P. Pilon, B. Phinney and G. Cavadias. 2002. Influence of autocorrelation on the detection of trend in hydrological series. Hydrological Processes 16(9): 1807-1829.