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Spatio-temporal analysis of rainfall along with trend analysis: A case study of Chhattisgarh state of East Central India

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सार – इस अध्ययनमें छत्तीसगढ़ राज्य के तीन एग्रो-जलवायु ज़ोन (ACZs) - उत्तरी पहाड़ियाँ, छत्तीसगढ़ मैदान और बस्तर पठार - के 27 ज़िलों में 50 वर्षों (1971-2021) की अवधि में वर्षा के स्थान और समय के हिसाब से परिवर्तन और प्रवृत्ति की जाँच की गई है। इसके लिए भारतीय मौसम विज्ञान विभाग (IMD) के लंबे समय के रोज़ाना के ग्रिडयुक्तडेटा का उपयोग किया गया है। वर्षा में बदलाव का विश्लेषण सालाना और मौसमी स्तर पर किया गया, और प्रवृत्ति का पता लगाने के लिए मैन-केंडल (MK), मॉडिफाइड मैन-केंडल (MMK), और थेल-सेन स्लोप एस्टीमेटर तरीकों का उपयोग किया गया। छत्तीसगढ़ में औसत सालाना वर्षा 1277.8 mm पाई गई, जिसमें से 80-85% वर्षा मॉनसून के मौसम (जून-सितंबर) में होती है। ACZs में, बस्तर पठार में अधिकांश औसत सालाना वर्षा (1488.7 mm) दर्ज की गई, जबकि छत्तीसगढ़ मैदान में सबसे कम (1200.6 mm) दर्ज की गई। ACZs के अंदर, छत्तीसगढ़ मैदान के कवर्धा ज़िले में वर्षा में सबसे ज़्यादा कोएफ़िशिएंट ऑफ़ वेरिएशन (CV) (31% तक) दिखा, इसके बाद बस्तर पठार के दंतेवाड़ा ज़िले में (30% तक), जो दूसरे ज़िलों की तुलना में ज़्यादा वर्षा में बदलाव दर्शाता है। प्रवृत्तिविश्लेषण से पता चला कि 14 ज़िलों में वर्षा में सकारात्मकप्रवृत्ति दिखी, जबकि 13 ज़िलों में नकारात्मकप्रवृत्ति दिखी, खासकर उत्तरी पहाड़ियाँ ACZ में। खास बात यह है कि सालाना और मॉनसून वर्षा की शृंखला में MK और MMK दोनों परीक्षण के प्रवृत्ति नतीजों में मज़बूत सहमति दिखी, जो नतीजों की सुदृढ़ता की पुष्टि करता है। सालाना सेन स्लोप का मैग्नीट्यूड जशपुर (उत्तरी पहाड़ियाँ ACZ) में -4.91 mm/वर्ष से लेकर सुकमा (बस्तर पठार ACZ) में 5.41 mm/वर्ष तक था, जो पूरे राज्य में बदलाव की अलग-अलग दरों को दर्शाता है। ये नतीजे क्षेत्रीय जलवायु व्यवहार के बारे में महत्वपूर्ण जानकारी देते हैं, जो वर्षा के वितरण और प्रवृत्ति में अनिश्चितताओं को उजागर करते हैं, जिसका पूर्वी-मध्य भारत में कृषि, जल संसाधन प्रबंधन और सूखे से निपटने की योजना पर असर पड़ता है।

ABSTRACT. This study examines the spatio-temporal variability and trends of rainfall across 27 districts within three Agro-Climatic Zones (ACZs) of Chhattisgarh State—namely, the Northern Hills, Chhattisgarh Plains, and Bastar Plateau—over a 50-year period (1971–2021), using long-term daily gridded rainfall data from the Indian Meteorological Department (IMD). Rainfall variability was analyzed at annual and seasonal scales, with trends detected using the Mann-Kendall (MK), Modified Mann-Kendall (MMK) and Theil-Sen slope estimator methods. The average annual rainfall in Chhattisgarh was found to be 1277.8 mm, with 80–85% of rainfall occurring during the monsoon season (June–September). Among the ACZs, the Bastar Plateau recorded the highest average annual rainfall (1488.7 mm), while the Chhattisgarh Plain recorded the lowest (1200.6 mm). Within the ACZs, Kawardha district in the Chhattisgarh Plains exhibited the highest coefficient of variation (CV) in rainfall (up to 31%), followed by Dantewara district in the Bastar Plateau (up to 30%), indicating greater rainfall variability compared to other districts. Trend analysis revealed that 14 districts exhibited positive rainfall trends, while 13 districts showed negative trends, particularly in the Northern Hills ACZ. Notably, annual and monsoon rainfall series exhibited strong agreement in trend results from both MK and MMK tests, confirming the robustness of the findings. The annual Sen's slope magnitude ranged from -4.91 mm/year in Jashpur (Northern Hills ACZ) to 5.41 mm/year in Sukma (Bastar Plateau ACZ), illustrating varying rates of change across the state. These findings offer significant insights into regional climatic behavior, highlighting uncertainties in rainfall distribution and trends, with implications for agriculture, water resource management, and drought mitigation planning in east-central India.

Keywords – Agro-climatic zones, Spatio-temporal analysis, Rainfall trends, Rainfall variability, Mann-Kendall, Modified Mann-Kendall, Theil-Sen slope.

1. Introduction

Precipitation is one of the most vital components of the hydrological cycle, and its patterns typically fluctuate across time and space due to both anthropogenic influences and global warming caused by the increase in atmospheric gas concentrations (Dickinson and Cicerone, 1986). Climate change, being a long-term phenomenon, has become one of the most pressing issues worldwide. From a measurement perspective, quantifying climate change is a complex and challenging task (Bárdossy and Pegram, 2014). Researchers and policymakers are actively engaged in studying climate change and its quantification using various climatic models (Murphy *et al.*, 2004; Boorman and Sefton, 1997; Seidenfaden *et al.*, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), industrialization has led to a 1 °C rise in global temperature due to anthropogenic emissions of gases and fossil fuels. Both average temperature and rainfall have been fluctuating since the 1950s, particularly across India (Peterson *et al.*, 2008; Khan *et al.*, 2022). Carbon dioxide emissions in India are rising as a result of rapid urbanization, which is expected to have a substantial impact on the hydrological cycle (IPCC, 2007).

The historical monitoring of climatic variables has garnered increasing attention as scientists seek to determine whether the greenhouse effect has resulted in a clear signal of climate change (Easterling *et al.*, 2000). Goswami *et al.* (2006) demonstrated an increase in rainfall across India over the past century using IMD gridded rainfall datasets. Micro-level rainfall is a critical factor in local hydrological, agricultural, and economic activities (Singh and Mal, 2014; Singh and Roy, 2002). Understanding rainfall trends is essential for planning and managing water supplies. Trend analysis is a key technique used to understand the temporal and spatial variations of climate-related factors. This is particularly important for a country like India, where the economy is heavily dependent on agriculture, which relies on the monsoon rains (Kumar *et al.*, 2015; Srivastava *et al.*, 2016). Any changes to the timing or distribution of rainfall could significantly impact agricultural conditions and, consequently, the economy, posing a threat to the nation’s food security.

India's climate variability is higher than the global average (Cooper *et al.*, 2008). Therefore, addressing the challenges associated with water resources requires the collaborative efforts of hydrologists, agriculturalists, meteorologists, and industrialists. Using the temporal and spatial variability of precipitation is essential for sustainable water and agricultural resource planning and mitigation strategies (Brunsell *et a*l., 2010; Sushant *et al.*, 2015; Rajeevan *et al.*, 2006; Hammouri *et al.*, 2015). Kumar and Jain (2010) examined the impact of changes in rainfall patterns on runoff, soil moisture, groundwater reserves, and the frequency of droughts and floods (Wang and Xie, 2018). Changes in mean rainfall can affect the severity and frequency of extreme rainfall events (Zwiers *et al.*, 2013). Gumus *et al.* (2022) applied the Mann-Kendall test to detect trends in streamflow in the Tigris River Basin, and similar methods have been used in southern Turkey to detect trends in meteorological time series, including precipitation (Gümüş *et al.*, 2023), and to analyze hydrological droughts in Mediterranean river basins (Simsek, 2021).

Long-term rainfall variability studies are crucial for evaluating the effectiveness of water conservation measures. Given the geography of India, assessing rainfall variability using Geographic Information Systems (GIS) is vital. Rainfall variability has significant implications for various sectors, including agriculture, water resource management, disaster management, urban planning, biodiversity, and ecosystems (Gebremichael *et al.*, 2014; Conway *et al.*, 2005; Gouda *et al.*, 2023; Chiang *et al.*, 2014; Senanayake *et al.*, 2022). However, several challenges need to be addressed, such as data availability, the quality of historical datasets, spatial and temporal variability, data integration, climate change studies, complex system modeling, capacity and expertise, climatic uncertainty and financial constraints (Ayanlade *et al.*, 2018; Mkuhlani *et al.*, 2020; Xie *et al.*, 2015; Sylla *et al.*, 2013).

Chhattisgarh, a central Indian state, relies heavily on monsoon rainfall for its agricultural activities, making the understanding of rainfall patterns vital for effective water resource management and agricultural planning. The state’s vulnerability to climate change is exacerbated by shifting monsoon patterns and increased rainfall variability, which can lead to droughts or floods. Meshram *et al.* (2017) examined long-term decadal trends and variability of precipitation in the state, revealing a significant decrease in annual monsoon rainfall, particularly in the central and southern regions. The state's diverse geography, with areas like the Bastar Plateau receiving more rainfall than the Chhattisgarh Plains, adds complexity to managing water

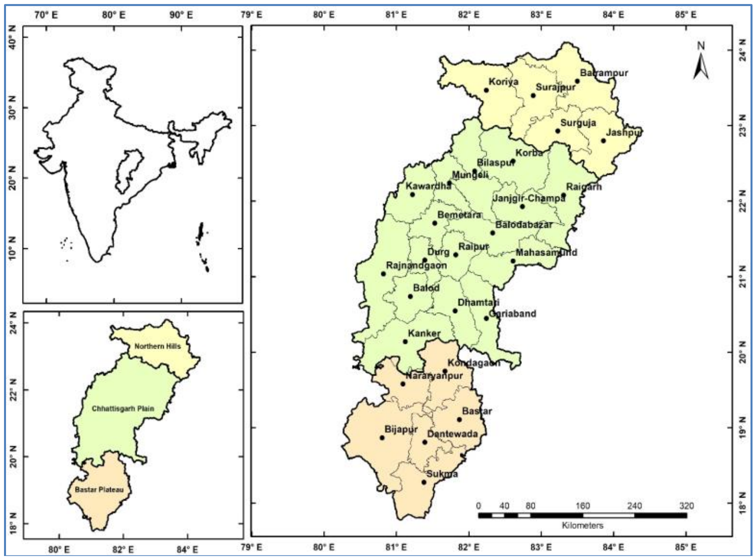

Fig. 1. Location map of study area

resources. This study aims to analyze the spatio-temporal variability of rainfall trends in Chhattisgarh over the past five decades, using advanced trend detection methods like Mann-Kendall & Theil-Sen. The findings will offer valuable insights into the state's climate change vulnerability, informing agricultural and water resource planning. Finally, leveraging GIS for rainfall variability assessment, though challenging, is essential for informed decision-making and requires enhanced data collection and technological advancements.

2. Data and methodology

2.1. *Study area*

Chhattisgarh, known as the "Rice Bowl" of India, is a central Indian state with abundant natural resources and minerals. It spans 27 districts over 135,192 km², divided into three agro-climatic zones: Northern Hills, Chhattisgarh Plains, and Bastar Plateau. The state's tropical, humid climate, influenced by the Tropic of Cancer and ample water resources, supports rain-fed agriculture, the primary livelihood and economic backbone. The Mahanadi River is its lifeline, with an average annual rainfall of 1279 mm. Forests cover about 44% of the region, enriching biodiversity and resources. Fig. 1 presents the location map of the study area.

2.2. *Data collection*

Daily observed rainfall data was collected from the Department of Agricultural Meteorology, College of Agriculture, Raipur (Chhattisgarh). Additionally, daily gridded rainfall data (0.25º x 0.25º) for the period 1971–2021 was obtained from the official website of the Indian Meteorological Department (IMD), Pune, India. The shapefile (.shp) of the study area was downloaded from the Diva-GIS open-access portal. The ASTER Digital Elevation Model (DEM) was accessed from the Earth Explorer website (https://earthexplorer.usgs.gov/).

2.3. *Software/ Programme*

Python was used for coding to extract the daily gridded (.grd extension) rainfall data. MATLAB software was then employed for converting the data from daily to monthly and from monthly to seasonal formats. MS Office (Excel) was utilized for data processing, statistical analysis, and preparing input data for trend analysis. MATLAB was also used for the calculations of the Mann-Kendall (MK) test, Modified Mann-Kendall (MMK) test, and Sen's slope. Finally, ArcGIS 10.5 software was used for data point interpolation and the preparation of spatio-temporal maps.

2.4. *Long-term rainfall variability and trend analysis*

Long-term rainfall variability and trend analysis in Chhattisgarh's ACZs involved statistical measures like mean, standard deviation (SD), and percentage coefficient of variation (CV) for monthly, annual, and seasonal time series (Landsea and Gray, 1992). Trend analysis was conducted using the MK test, MMK test, and Theil-Sen's slope estimator (Kendall, 1975; Theil, 1950; Choudhury *et al.*, 2012, Hamed and Rao, 1998), implemented through MATLAB. Rainfall datasets were categorized into time series based on IMD-defined seasons: pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November) and winter (December-February).

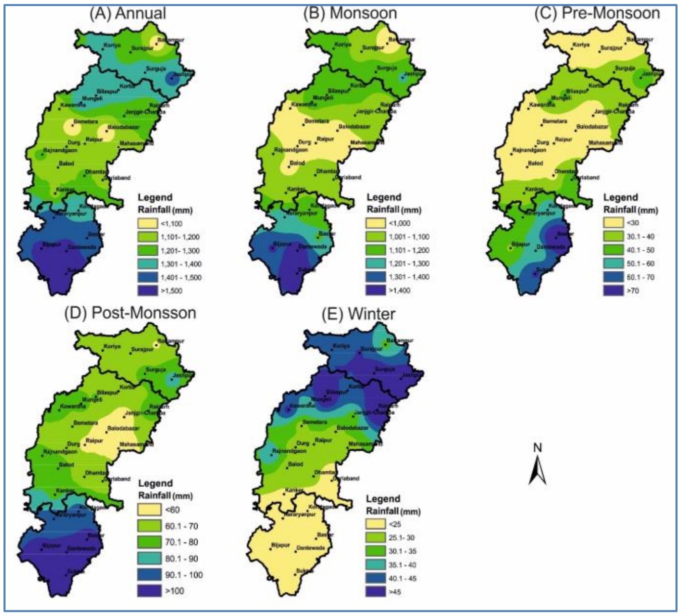

Fig. 2. Annual and seasonal rainfall pattern in different districts of Chhattisgarh

Spatial maps of rainfall trends were generated using the Inverse Distance Weighted (IDW) interpolation technique in ArcGIS 10.5, aiding visualization and analysis of rainfall patterns over time.

3. Results and discussions

3.1. *Rainfall patterns and variability across Agro-climatic zones*

Rainfall patterns and variability play a vital role in Chhattisgarh's hydrological cycle, influencing agriculture and water management. This section examines the spatial and temporal distribution of rainfall across the state's three Agro-Climatic Zones (Northern Hills, Chhattisgarh Plains, and Bastar Plateau) during 1971-2021, using metrics such as mean rainfall, standard deviation (SD), and coefficient of variation (CV). Chhattisgarh receives most of its rainfall during the monsoon season (June–September), while other seasons exhibit significant variability. Table 1 summarizes annual and seasonal rainfall statistics across the districts and ACZs.

In the Northern Hills, districts like Balrampur, Jashpur, and Koriya receive annual rainfall between 1113.8 mm (Balrampur) and 1387.4 mm (Jashpur). Monsoon rainfall is relatively stable (CV = 24-26%), while Pre-Monsoon and Winter rainfall are highly variable, with CVs exceeding 100%. For example, Balrampur has a Pre-Monsoon CV of 134%. SD for monsoon rainfall ranges from 244.6 mm (Surguja) to 294.0 mm (Jashpur), highlighting moderate inter-annual variation.

The Chhattisgarh Plains experience the lowest annual rainfall, with Balodabazar (1082.1 mm) and Bemetra (1079.5 mm) receiving the least in the state. Monsoon rainfall shows moderate stability (CV = 22–28%), supporting agricultural activities. However, Winter rainfall is highly inconsistent, with CVs exceeding 120%, such as Raipur's Winter CV of 140%. Annual rainfall SD ranges from 228.4 mm (Balodabazar) to 309.6 mm (Raipur), reflecting moderate fluctuations. Stable monsoon rainfall facilitates agriculture, but seasonal variability necessitates irrigation and water conservation efforts.

The Bastar Plateau records the highest annual rainfall, with Sukma (1644.5 mm) and Dantewada (1610.2 mm) receiving the most in the state. Monsoon rainfall dominates and exhibits low variability (CV = 23–25%), supporting rainfed agriculture. However, Pre-Monsoon rainfall is more variable, with Sukma's CV reaching 66%, challenging early agricultural planning. SD for annual rainfall is the highest in the state, peaking at 486.6 mm in Dantewada.

Rainfall variability across Chhattisgarh's ACZs has critical implications for agriculture and water resources. The Northern Hills face challenges due to high seasonal variability, especially in Pre-Monsoon and Winter periods. The Chhattisgarh Plains, while benefiting from stable monsoon rainfall, require adaptive strategies to address seasonal inconsistencies. The Bastar Plateau benefits from abundant monsoon rainfall but needs interventions to manage variability during non-monsoon periods. Fig. 2 illustrates annual and seasonal rainfall distribution,

TABLE 1

Annual and seasonal rainfall (mm) statistics in different districts and ACZs of Chhattisgarh (1971-2021)

Districts/ACZs	Annual			Monsoon			Pre-Monsoon			Post-Monsoon			Winter		
	Mean	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**	**Mean**	**SD**	**CV**
Balrampur	1113.8	269.6	24	998.0	261.8	26	20.0	26.7	134	61.0	51.4	84	34.8	35.1	101
Jashpur	1387.4	341.1	25	1212.1	294.0	24	44.5	46.5	105	83.6	66.5	80	47.1	49.0	104
Koriya	1282.6	330.1	26	1149.3	293.2	26	26.1	31.3	120	63.0	48.8	77	44.2	47.9	109
Surajpur	1244.7	315.0	25	1113.0	293.4	26	26.3	31.5	120	60.5	48.2	80	45.0	45.3	101
Surguja	1330.1	262.6	20	1172.2	244.6	21	33.8	31.0	92	73.5	47.6	65	50.6	48.7	96
Northern Hills ACZ	**1271.7**	**303.7**	**24**	**1128.9**	**277.4**	**25**	**30.1**	**33.4**	**114**	**68.4**	**52.5**	**77**	**44.3**	**45.2**	**103**
Balod	1159.6	269.5	23	1033.2	228.0	22	23.0	28.2	123	75.3	69.3	92	28.1	33.6	120
Balodabazar	1082.1	228.4	21	990.1	210.2	21	16.0	20.0	125	48.8	48.1	99	27.2	32.6	120
Bemetra	1079.5	230.5	21	973.1	198.8	20	17.1	24.0	141	61.4	72.2	118	27.8	36.3	131
Bilaspur	1342.0	239.7	18	1171.4	210.7	18	42.2	32.0	76	70.6	51.5	73	57.8	50.3	87
Dhamtari	1217.8	295.3	24	1098.1	277.3	25	29.0	36.7	127	64.8	62.6	97	25.9	28.1	108
Durg	1141.7	261.7	23	1023.6	229.9	23	21.3	22.3	105	69.8	59.3	85	27.2	35.0	129
Gariabandh	1198.6	286.8	24	1065.5	247.3	23	49.7	58.3	117	64.5	70.3	109	19.0	22.9	120
Janjgir-Champa	1227.4	279.1	23	1117.6	254.4	23	22.6	23.1	102	53.9	48.3	90	33.3	34.9	105
Kanker	1186.8	270.3	23	1052.6	247.7	24	31.1	36.5	117	78.8	70.3	89	24.3	24.7	101
Kawardha	1177.8	367.1	31	1030.2	308.4	30	25.2	23.3	93	76.5	85.3	112	46.0	46.8	102
Korba	1327.8	246.0	19	1186.7	215.3	18	32.1	36.2	113	65.9	49.7	75	43.0	47.1	109
Mahasamund	1131.0	228.7	20	1018.0	195.4	19	29.5	32.0	108	57.6	58.1	101	26.0	28.9	111
Mungeli	1340.9	295.9	22	1186.0	258.4	22	41.4	51.9	125	74.5	70.9	95	38.9	49.9	128
Raigarh	1249.0	242.8	19	1081.5	201.3	19	37.8	35.5	94	74.4	59.2	80	55.3	43.2	78
Raipur	1134.1	309.6	27	1028.0	282.9	28	23.3	31.0	133	57.6	59.8	104	25.3	35.4	140
Rajnandgaon	1213.5	290.3	24	1077.7	259.8	24	24.3	28.5	117	71.1	66.3	93	40.3	41.0	102
Chhattisgarh Plains ACZ	**1200.6**	**271.4**	**23**	**1070.8**	**239.1**	**22**	**29.1**	**32.5**	**113**	**66.6**	**62.6**	**94**	**34.1**	**36.9**	**112**
Bastar	1423.6	284.3	20	1195.8	226.9	19	94.7	72.1	76	110.4	79.3	72	22.6	24.0	106
Bijapur	1524.5	350.2	23	1359.8	351.5	26	39.1	36.7	94	107.1	75.9	71	18.5	25.4	137
Dantewada	1610.2	486.6	30	1430.3	483.1	34	52.0	45.8	88	112.9	81.7	72	15.0	18.2	122
Kondagaon	1319.7	257.6	20	1148.1	207.1	18	59.1	52.6	89	94.1	72.5	77	18.3	21.7	118
Narayanpur	1409.5	285.2	20	1252.8	238.5	19	42.9	52.8	123	93.7	71.9	77	20.1	26.4	132
Sukma	1644.5	384.6	23	1427.2	362.5	25	71.2	47.1	66	129.4	72.4	56	16.8	21.2	126
Bastar Plateau ACZ	**1488.7**	**341.4**	**23**	**1302.3**	**311.6**	**24**	**59.8**	**51.2**	**89**	**107.9**	**75.6**	**71**	**18.6**	**22.8**	**123**
Chhattisgarh State	**1277.8**	**292.9**	**23**	**1133.0**	**262.3**	**23**	**37.6**	**37.7**	**107**	**77.8**	**64.5**	**85**	**31.9**	**34.9**	**114**

highlighting its importance for sustaining the agrarian economy. Annual rainfall ranges from less than 1,100 mm in drier areas to more than 1,500 mm in wetter regions. Monsoon rainfall supports kharif crops, while Pre-Monsoon and Winter rainfall play supplementary roles for rabi cultivation. Strategic water management, climate resilience measures, and adaptive agricultural practices are essential to address rainfall variability and optimize productivity across Chhattisgarh's Agro-Climatic Zones.

TABLE 2

District-wise values of z-statistic for Annual and seasonal rainfall using MK and MMK tests in different ACZs of Chhattisgarh during 1971-2021

ACZs/Districts	Annual		Monsoon		Pre-Monsoon		Post-Monsoon		Winter	
	MK	MMK	MK	MMK	MK	MMK	MK	MMK	MK	MMK
Northern Hills										
Balrampur	-1.71	-1.71	-1.61	-1.61	1.75	1.75	-1.45	-1.33	0.06	0.06
Jashpur	-1.67	-1.67	-1.36	-1.36	-0.02	-0.01	0.00	0.00	-1.21	-1.21
Koriya	-0.41	-0.43	-0.76	-0.76	2.18[b]	2.17[b]	0.00	0.00	1.54	2.05[b]
Surajpur	-1.63	-1.63	-1.74	-1.74	2.05[b]	2.05[b]	-0.29	-0.29	0.24	0.22
Surguja	-1.54	-1.54	-1.90	-1.90	1.18	1.18	0.17	0.15	-0.66	-0.66
Chhattisgarh Plains										
Balod	0.88	0.88	0.24	0.24	4.02[b]	3.26[b]	0.46	0.46	2.17[b]	2.17[b]
Balodabazar	0.68	0.76	-0.05	-0.06	3.02[b]	3.01[b]	0.39	0.39	1.51	1.97[b]
Bemetara	2.14[b]	2.28[b]	2.44[b]	2.44[b]	2.56[b]	2.54[b]	-0.62	-1.57	1.15	1.15
Bilaspur	-0.15	-0.18	-0.62	-0.82	0.98	0.98	-1.00	-1.15	-0.13	-0.13
Dhamtari	-1.02	-1.02	-0.89	-0.89	1.18	1.18	0.19	0.19	0.11	0.14
Durg	1.36	1.36	0.58	0.58	3.94[b]	3.94[b]	0.36	0.36	2.62[b]	2.62[b]
Gariaband	0.49	0.49	0.73	1.05	0.03	0.05	-0.02	-0.02	-1.34	-1.34
Janjgir-Champa	-2.01[a]	-2.59[a]	-2.13[a]	-2.13[a]	1.49	1.49	0.12	0.12	-0.25	-0.25
Kanker	0.71	1.64	0.63	0.63	1.76	2.17[b]	0.96	0.80	0.36	0.49
Kawardha	1.06	1.04	1.58	2.08[b]	1.80	1.80	-1.61	-2.19[a]	0.80	0.80
Korba	-0.94	-0.94	-1.30	-1.30	1.47	1.47	0.14	0.13	-0.13	-0.13
Mahasamund	0.19	0.24	0.02	0.02	0.89	1.22	0.18	0.24	-0.19	-0.27
Mungeli	-0.26	-0.26	-0.12	-0.12	0.01	0.01	0.6	0.60	-0.93	-0.93
Raigarh	0.27	0.27	0.42	0.49	1.25	1.02	-1.26	-1.45	-0.62	-0.57
Raipur	-0.10	-0.15	0.02	0.02	0.77	0.77	0.01	0.02	0.11	0.11
Rajnandgaon	-1.28	-1.28	-1.43	-1.43	1.63	1.63	-1.65	-1.65	1.69	1.29
Bastar Plateau										
Bastar	0.88	1.15	1.12	1.42	0.92	0.92	0.61	0.61	-0.98	-0.97
Bijapur	0.13	0.13	0.02	0.02	2.43[b]	2.43[b]	-0.63	-0.63	1.50	1.50
Dantewada	-0.73	-0.73	-0.71	-0.71	1.97[b]	1.97[b]	-1.10	-0.96	0.71	0.71
Kondagaon	1.27	1.27	0.86	1.06	2.02[b]	2.02[b]	0.81	0.81	1.45	1.45
Nararyanpur	1.51	1.51	1.28	1.28	1.79	1.79	0.01	0.01	1.86	1.84
Sukma	1.66	1.66	1.14	1.14	1.58	1.58	0.98	0.98	0.17	0.13

3.2. *MK and MMK analysis of rainfall trends*

Table 2 presents the results of Mann-Kendall (MK) and Modified Mann-Kendall (MMK) analyses for annual and seasonal rainfall trends across Chhattisgarh's districts. Positive z-statistics indicate increasing rainfall trends, while negative values denote declines. Statistically significant results (5% level) are highlighted.

In the Northern Hills, while most rainfall trends show declines, annual and monsoon rainfall remain relatively stable. However, Koriya exhibits significant positive trends in pre-monsoon (+2.18 MMK) and winter rainfall (+2.05 MMK), while Surajpur shows an increase in pre-monsoon rainfall (+2.05 MMK). Post-monsoon rainfall remains unchanged across the region.

In the Chhattisgarh Plains, mixed trends are evident. Bemetara shows significant increases in annual (+2.28 MMK) and monsoon rainfall (+2.44 MMK), whereas Janjgir-Champa exhibits significant declines in annual (-2.59 MMK) and monsoon rainfall (-2.13 MMK). Positive pre-monsoon trends are observed in Balod (+3.26 MMK), Durg (+3.94 MK), Balodabazar (+3.01 MMK), and Bemetara (+2.54 MMK), whereas Kawardha records a significant decline in post-monsoon rainfall (-2.19 MMK). Winter rainfall increases significantly in Durg (+2.62 MK), Balod (+2.17 MK), and Balodabazar (+1.97 MMK). The Bastar Plateau predominantly shows positive trends in pre-monsoon rainfall, with significant increases in Bijapur (+2.43 MMK), Dantewada (+1.97 MMK), and Kondagaon (+2.02 MMK). However, no significant trends are observed in annual, monsoon, or post-monsoon rainfall.

Overall, the Northern Hills display isolated significant increases in pre-monsoon and winter rainfall, while the Chhattisgarh Plains exhibit a mix of increasing and decreasing trends, emphasizing spatial variability. The Bastar Plateau shows consistent positive trends in pre-monsoon rainfall, suggesting the potential for early cropping improvements.

Fig. 3 integrates rainfall variability and MK/MMK trends, illustrating the coefficient of variation (CV) across seasons. High variability is observed in the Northern Hills, where monsoon rainfall declines in Jashpur and Surguja,

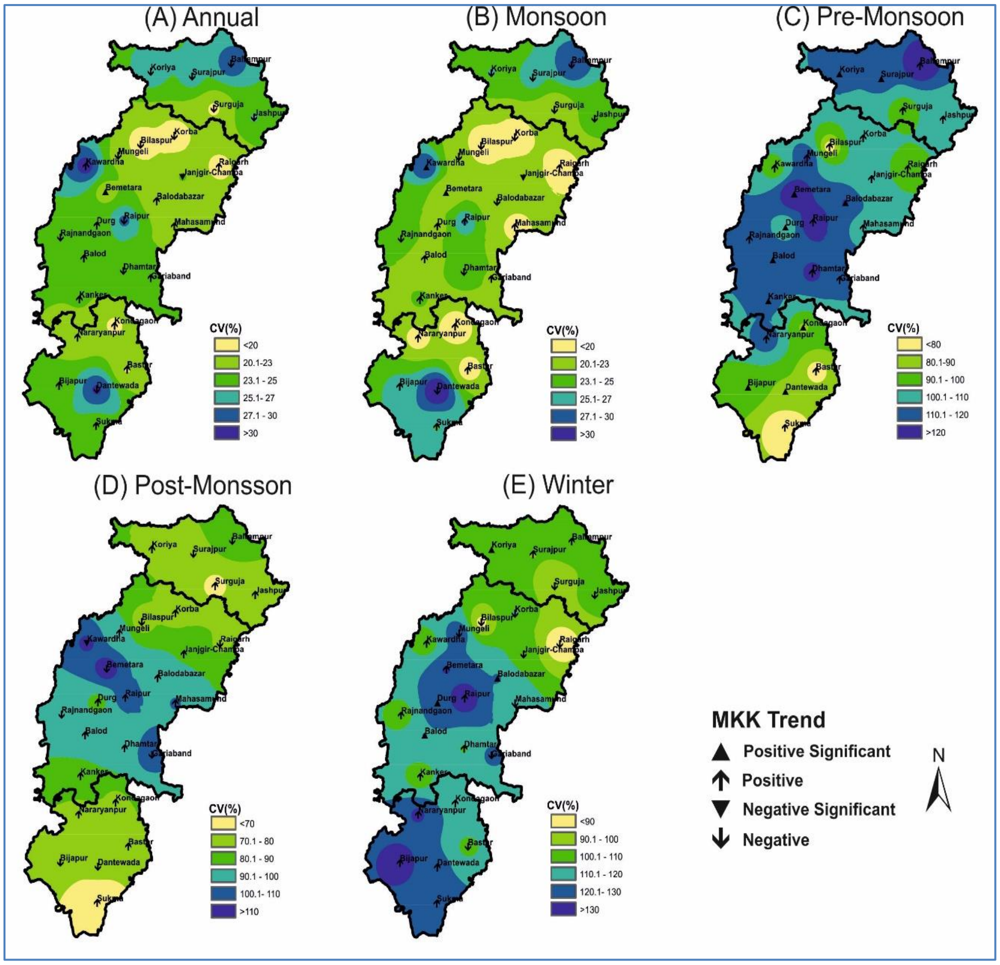

Fig. 3. Annual and seasonal rainfall CV and trends (MKK) in different districts of Chhattisgarh

while pre-monsoon rainfall increases in Koriya and Surajpur. In the Chhattisgarh Plains, districts like Durg and Bemetara show positive trends in monsoon and annual rainfall, while Janjgir-Champa experiences declines. In the Bastar Plateau, significant pre-monsoon rainfall increases in Sukma, Narayanpur, Bijapur, and Kondagaon highlight opportunities for enhancing water resources, despite localized declines in Dantewada. This analysis underscores the region's climatic variability and its implications for agriculture and water management. By combining CV values with MK/MMK results, the findings offer a detailed understanding of rainfall trends and variability, guiding adaptive strategies for water resource planning and climate resilience in Chhattisgarh.

3.3. *Sen's Slope analysis for rainfall trends*

Sen's slope analysis quantifies rainfall changes across Chhattisgarh, complementing MK/MMK results and variability insights from Section 3.1. Table 3 provides district-wise estimates for annual and seasonal rainfall trends, with positive values indicating increases and negative values declines.

In the Northern Hills, Rainfall trends predominantly show declines across seasons, consistent with high variability. Jashpur exhibits the steepest annual decline (-4.91 mm/year), with similar reductions during the monsoon (-4.71 mm/year in Surajpur). Slight positive trends are noted in Pre-Monsoon rainfall, particularly in Koriya (+0.35 mm/year). Winter rainfall remains stable, though Koriya records an increase (+0.47 mm/year).

The Chhattisgarh Plains show Mixed trends reflect moderate variability and significant MK/MMK results. Bemetara records the highest annual increase (+5.04 mm/year) and largest monsoon gain (+4.64 mm/year), aligning with positive MK/MMK trends. Janjgir-Champa shows sharp declines in annual (-3.83 mm/year) and monsoon rainfall (-4.38 mm/year). Positive Pre-Monsoon

TABLE 3

Districts-wise values of Sen's slope for annual and seasonal rainfall (mm) in different ACZs of Chhattisgarh during 1971-2021

Districts/ACZs	Annual	Monsoon	Pre-Monsoon	Post Monsoon	winter
Northern Hills					
Balrampur	-4.73	-4.30	0.21	-0.70	0.01
Jashpur	-4.91	-3.49	0.00	0.00	-0.41
Koriya	-1.24	-2.13	0.35	0.00	0.47
Surajpur	-4.58	-4.71	0.34	-0.11	0.05
Surguja	-4.09	-3.92	0.28	0.07	-0.23
Chhattisgarh Plains					
Balod	1.98	0.36	0.58	0.20	0.35
Balodabazar	1.30	-0.08	0.33	0.18	0.15
Bemetara	5.04	4.64	0.26	-0.19	0.15
Bilaspur	-0.52	-1.27	0.21	-0.52	-0.07
Dhamtari	-2.77	-2.37	0.18	0.07	0.00
Durg	3.12	1.25	0.56	0.21	0.34
Gariaband	1.28	1.76	0.01	-0.02	-0.19
Janjgir-Champa	-3.83	-4.38	0.29	0.04	-0.01
Kanker	1.52	1.16	0.29	0.52	0.04
Kawardha	2.26	2.29	0.30	-0.68	0.23
Korba	-2.24	-2.93	0.27	0.11	-0.04
Mahasamund	0.55	0.07	0.15	0.07	-0.04
Mungeli	-0.61	-0.36	0.00	0.25	-0.18
Raigarh	0.78	1.10	0.31	-0.68	-0.20
Raipur	-0.41	0.02	0.08	0.00	0.00
Rajnandgaon	-3.59	-3.15	0.16	-0.73	0.43
Bastar Plateau					
Bastar	2.23	2.17	0.33	0.36	-0.11
Bijapur	0.57	0.12	0.56	-0.45	0.11
Dantewada	-2.94	-3.23	0.47	-0.72	0.05
Kondagaon	3.33	1.99	1.00	0.49	0.20
Nararyanpur	3.87	3.23	0.46	0.01	0.16
Sukma	5.41	4.57	0.69	0.73	0.01

trends are noted, with Kawardha showing a notable increase (+0.30 mm/year). Post-Monsoon and Winter rainfall exhibit localized variability (*e.g.*, Kanker gains +0.52 mm/year post-monsoon, while Rajnandgaon declines -0.73 mm/year). with increasing trends and the need for mitigation strategies in regions with declining patterns.

In the Bastar Plateau, rainfall trends show consistent increases across various periods. Sukma leads the region with significant gains in both annual (+5.41 mm/year) and monsoon (+4.57 mm/year) rainfall. Kondagaon exhibits a notable Pre-Monsoon increase (+1.00 mm/year), aligning with positive MK/MMK results. While most districts show upward trends, Dantewada demonstrates localized declines in annual (-2.94 mm/year) and post-monsoon (-0.72 mm/year) rainfall.

The Sen's slope analysis underscores the evolving rainfall dynamics across Chhattisgarh, aligning with variability and MK/MMK trends. While increasing trends in regions like the Bastar Plateau and parts of the Chhattisgarh Plains provide opportunities for improved agricultural practices, declining trends in the Northern Hills and certain Plains districts highlight the need for adaptive strategies to ensure sustainable water resource management and climate resilience.

4. Conclusions

Rainfall variability and trends across Chhattisgarh's three Agro-Climatic Zones (Northern Hills, Chhattisgarh Plains, and Bastar Plateau) present distinct challenges and opportunities for water resource management and agricultural planning. The Northern Hills exhibit high seasonal variability and predominantly declining trends, with Jashpur showing the steepest annual reductions. However, localized increases in Pre-Monsoon and Winter rainfall in districts like Koriya and Surajpur provide potential for targeted interventions. The Chhattisgarh Plains demonstrate mixed trends. While Bemetara and Durg show increasing annual and monsoon rainfall, districts like Janjgir-Champa experience significant declines, requiring adaptive measures to ensure water availability. Positive Pre-Monsoon trends in districts like Balod and Kawardha highlight opportunities for early crop sowing. The Bastar Plateau stands out with consistently increasing rainfall, particularly in Sukma and Kondagaon, suggesting robust potential for rainfed agriculture. Nonetheless, localized declines in Dantewada call for tailored strategies. These findings underscore the need for climate-resilient planning, equitable water distribution, and enhanced agricultural practices to optimize resource utilization amid evolving rainfall patterns.

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References

Ayanlade, A., Radeny, M., Morton, J. F. and Muchaba, T., 2018, "Rainfall variability and drought characteristics in two agro-climatic zones: an assessment of climate change challenges in Africa" *Science of the Total Environment*, **630**, 728-737.

Bárdossy, A., and Pegram, G., 2014, "Infilling missing precipitation records–A comparison of a new copula-based method with other techniques" *Journal of hydrology*, **519**, 1162- 1170.

Boorman, D. B., and Sefton, C. E. M., 1997, "Recognising the uncertainty in the quantification of the effects of climate change on hydrological response" *Climatic Change*, **35,** 4, 415- 434.

Brunsell, N. A., Jones, A. R., Jackson, T. L., and Feddema, J. J., 2010, "Seasonal trends in air temperature and precipitation in IPCC AR4 GCM output for Kansas, USA: evaluation and implications" *International Journal of Climatology*, **30**, 8, 1178-1193.

Chiang, L. C., Lin, Y. P., Huang, T., Schmeller, D. S., Verburg, P. H., Liu, Y. L., and Ding, T. S., 2014, "Simulation of ecosystem service responses to multiple disturbances from an earthquake and several typhoons" *Landscape and Urban Planning*, **122**, 41-55.

Choudhury, B. U., Das, A., Ngachan, S. V., Slong, A., Bordoloi, L. J., and Chowdhury, P., 2012, "Trend analysis of long-term weather variables in mid altitude Meghalaya, North-East India*" Journal of Agricultural Physics*, **12**, 1, 12-22.

Conway, D., Allison, E., Felstead, R., and Goulden, M., 2005, "Rainfall variability in East Africa: implications for natural resources management and livelihoods" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **363,** 1826, 49-54.

Cooper, P. J., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B., and Twomlow, S., 2008, "Coping better with current climatic variability in the rain-fed farming systems of sub- Saharan Africa: An essential first step in adapting to future climate change?" *Agriculture, ecosystems & environment*, **126**, 1-2, 24-35.

Dickinson, R. E. and Cicerone, R. J., 1986, "Future global warming from atmospheric trace gasses". *Nature*, **319**, 6049, 109-115.

Easterling, D. R., Evans, J. L., Groisman, P. Y., Karl, T. R., Kunkel, K. E., and Ambenje, P., 2000, "Observed variability and trends in extreme climate events: a brief review" *Bulletin of the American Meteorological Society*, **81**, 3, 417-426.

Gebremichael, A., Quraishi, S., and Mamo, G., 2014, "Analysis of seasonal rainfall variability for agricultural water resource management in southern region, Ethiopia" *J. Nat. Sci. Res*, **4**, 11, 56-79.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., and Xavier, P. K., 2006, "Increasing trend of extreme rain events over India in a warming environment" *Science*, **314**, 5804, 1442-1445.

Gouda, K.C., Nikhilasuma, P., Benke, M. and Agnihotri, G., 2024. Assessment of rainfall variability over Karnataka state in India. Natural Hazards Research, **4**, 2, 246-254.

Gumus, V., Avsaroglu, Y. and Simsek, O., 2022, "Streamflow trends in the Tigris river basin using Mann− Kendall and innovative trend analysis methods" *Journal of Earth System Science*, **131**, 1, 34-43.

Gümüş, V., Avşaroğlu, Y., Şimşek, O. and Dinsever, L.D., 2023, "Evaluation of meteorological time series trends in Southeastern Anatolia, Turkey" *Geofizika*, **40**, 1, 1-25.

Hamed, K.H. and Rao, A.R., 1998. "A modified Mann-Kendall trend test for autocorrelated data" *Journal of hydrology*, **204,** 1-4, 182-196.

Hammouri, N., M., El-Naqa, A., Jaber, M., and Abu-Allaban, 2015, "Water scarcity impact of climate change in semi-arid regions: a case study in Mujib basin, Jordan" *Arabian Journal of Geosciences*, **8**, 2, 951-959.

IPCC-2007 Climate change, 2007, "Climate change impacts, adaptation and vulnerability. Working Group II contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report" *Summary for policymakers*. 23.

Kendall, M. G., 1975, "Multivariate analysis", **2**. *London: Griffin.*

Khan, F., Hassan, A., Shah, S. N. A., Nazeer, N., Khan, A. A., and Bukhari, S., 2022, "Analysis of the Historical Temperature of Different Cities of Pakistan to Determine the Trends and Shift in Temperature" *Journal of Innovations in Science and Technology*, **4**, 3, 801-808.

Kumar, R., Singh, M. P., Kumar, P., and Singh, J. P., 2015, "Crop Selection Method to maximize crop yield rate using machine learning technique". *In 2015 international conference on smart technologies and management for computing, communication, controls, energy and materials (ICSTM)*, *IEEE*, 138-145.

Kumar, V., and Jain, S. K., 2010, "Rainfall trend in Ganga-Brahmaputra-Meghna river basins of India (1951–2004)" *Hydrology Journal*, **33**, 59-66.

Landsea, C. W., and Gray, W. M., 1992, "The strong association between western Sahelian monsoon rainfall and intense Atlantic hurricanes" *Journal of Climate*, **5**, 5, 435-453.

Meshram, S. G., Singh, V. P., and Meshram, C., 2017, "Long-term trend and variability of precipitation in Chhattisgarh State, India" *Theoretical and Applied Climatology*, **129**, 3, 729-744.

Mkuhlani, S., Crespo, O., Rusere, F., Zhou, L., and Francis, J., 2020, "Classification of small- scale farmers for improved rainfall variability management in South Africa" *Agroecology and Sustainable Food Systems*, **44**, 1, 7-29.

Murphy, J. M., Sexton, D. M., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M., and Stainforth, D. A., 2004, "Quantification of modeling uncertainties in a large ensemble of climate change simulations" *Nature*, **430**, 7001, 768-772.

Peterson, T. C., Zhang, X., Brunet- India, M., and Vázquez- Aguirre, J. L., 2008, "Changes in North American extremes derived from daily weather data" *Journal of Geophysical Research: Atmospheres*, 113, D7.

Rajeevan, M., Bhate, J., Kale, J. D., and Lal, B., 2006, "High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells" *Current Science*, 296-306.

Seidenfaden, I. K., Sonnenborg, T. O., Stisen, S., and Kidmose, J., 2022, "Quantification of climate change sensitivity of shallow and deep groundwater in Denmark" *Journal of Hydrology: Regional Studies*, **41**, 101100.

Senanayake, S., Pradhan, B., Huete, A., and Brennan, J., 2022, "Spatial modeling of soil erosion hazards and crop diversity change with rainfall variation in the Central Highlands of Sri Lanka" *Science of the Total Environment*, **806**, 150405.

Simsek, O., 2021, "Hydrological drought analysis of Mediterranean basins, Turkey" Arabian *Journal of Geosciences*, **14**, 20, 2136.

Singh, R. B., and Mal, S., 2014, "Trends and variability of monsoon and other rainfall seasons in Western Himalaya, India" *Atmospheric Science Letters*, **15**, 3, 218-226.

Singh, R. B., and Sen Roy, S., 2002, "Climate variability and hydrological extremes in a Himalayan catchment" *In ERB and Northern European FRIEND Project 5 Conf., Slovakia*.

Srivastava, P., Singh, R., Tripathi, S., and Raghubanshi, A. S., 2016, "An urgent need for sustainable thinking in agriculture–An Indian scenario" *Ecological indicators*, **67**, 611- 622.

Sushant, S., Balasubramani, K., and Kumaraswamy, K., 2015, "Spatio-temporal analysis of rainfall distribution and variability in the twentieth century, over the Cauvery Basin, South India" *Environmental management of river basin ecosystems*. Springer, Cham, 21-41

Sylla, M. B., Giorgi, F., Coppola, E., and Mariotti, L., 2013, "Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation" *International Journal of Climatology*, **33**, 7, 1805-1817.

Theil, H., 1950, " A rank invariant method of linear and polynomial regression analysis" *Part-III Proceeding of the Royal Netherlands Academy of Sciences*, **53**, 1397–1412

Wang, X., and Xie, H., 2018, "A review on applications of remote sensing and geographic information systems (GIS) in water resources and flood risk management" *Water*, **10**, 5, 608.

Xie, S. P., Deser, C., Vecchi, G. A., Collins, M., Delworth, T. L., Hall, A., ... and Watanabe, M., 2015, "Towards predictive understanding of regional climate change" *Nature Climate Change*, **5**, 10, 921-930.

Zwiers, F. W., Alexander, L. V., and Westra, S. ,2013, "Global increasing trends in annual maximum daily precipitation" *Journal of climate*, **26**, 11, 3904-3918.